Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

Muon Collider in the P5 Report

Exploring the Quantum Universe

2023p5report.org

U.S. DEPARTMENT OF ENERGY

NSF

US Muon Collider Meeting Aug 7, 2024

Hitoshi Murayama

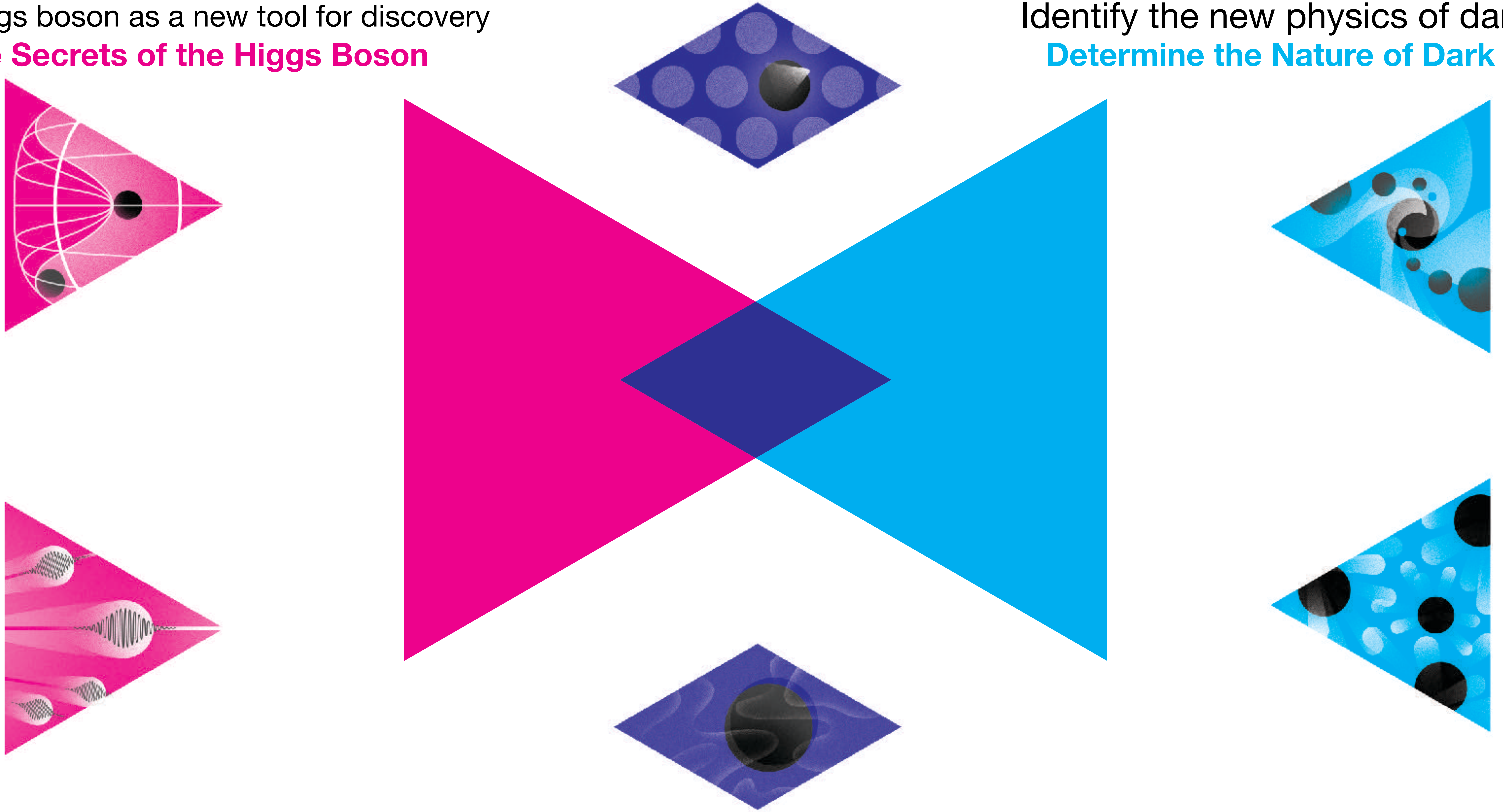
Search for Direct Evidence for New Particles

Use the Higgs boson as a new tool for discovery

Reveal the Secrets of the Higgs Boson

Identify the new physics of dark matter

Determine the Nature of Dark Matter



Pursue Quantum Imprints for New Phenomena

Explore the unknown: new particles, interactions, and physical principles

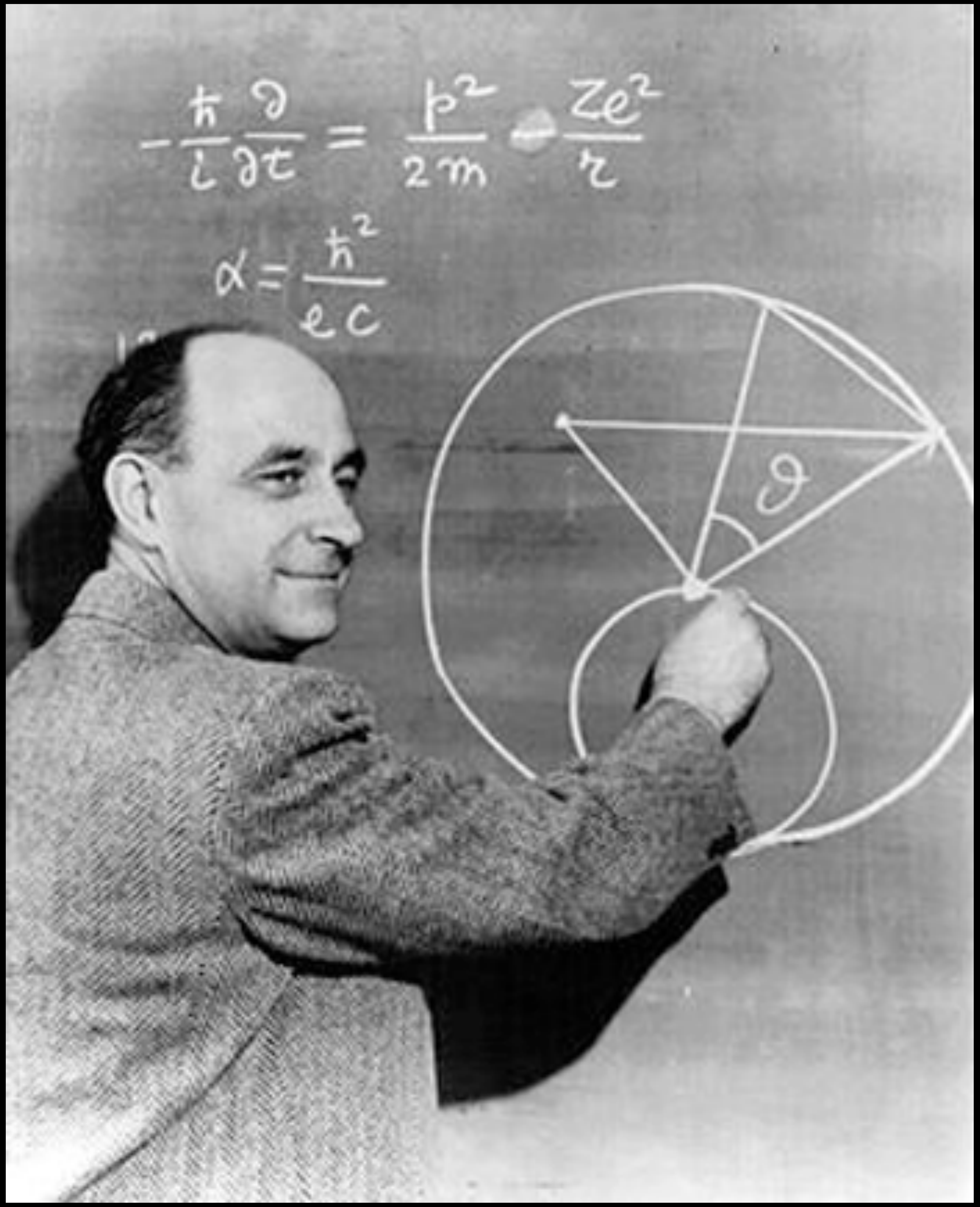

early cyclotron

Fermi's dream era

- Fermi formulated the first theory of the weak interaction (1932)

- *The required energy scale to study the problem known since then:* ~TeV

- We are finally got there with LHC!



fixed target vs collider

- fixed target experiment:

$$\sqrt{s} = \sqrt{2E_{\rm beam}M_{\rm target}}$$

$$\simeq \mathrm{GeV}\left(\frac{E_{\rm beam}}{\mathrm{GeV}}\right)^{1/2}$$

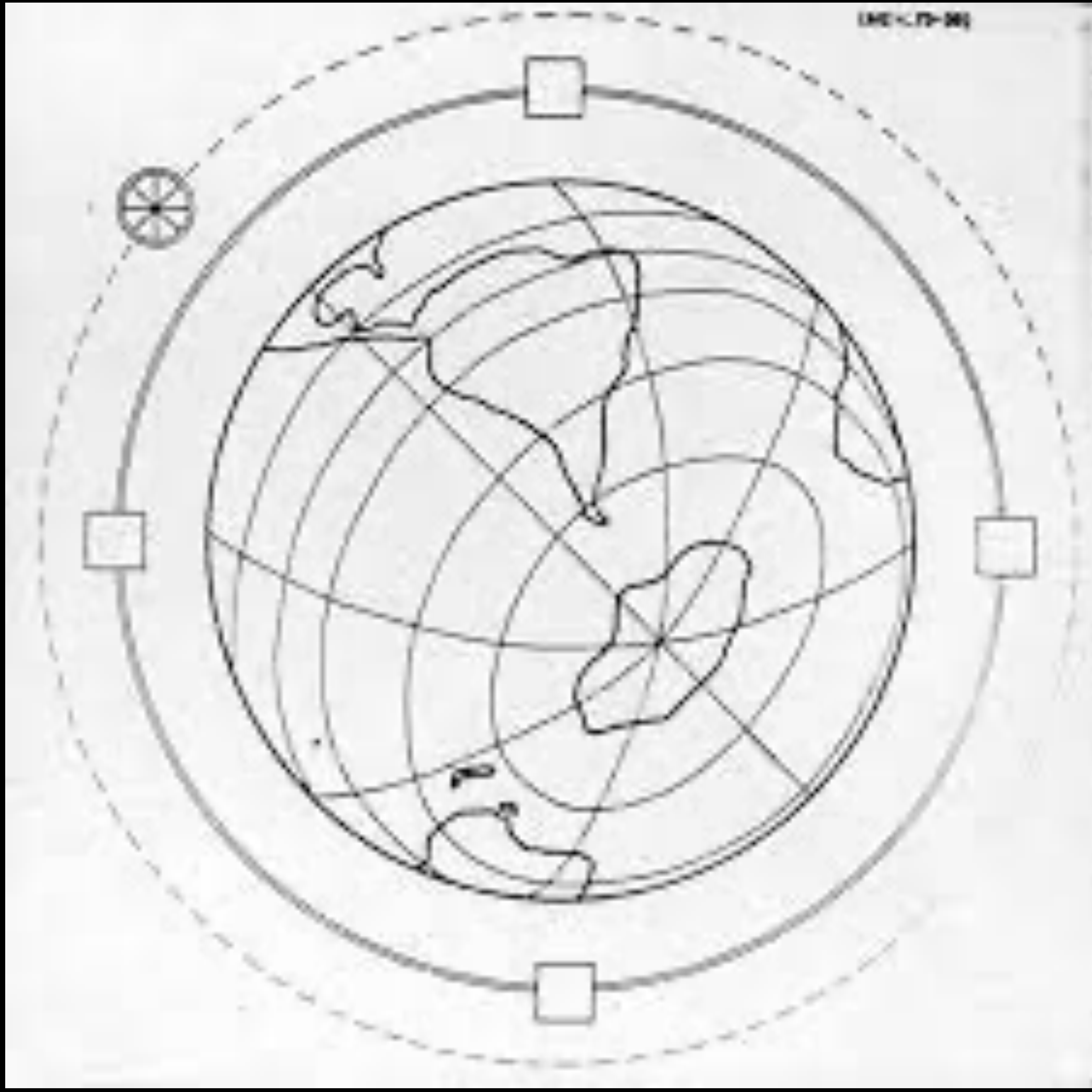
$$\sqrt{s} \simeq 14\ \mathrm{TeV}$$

$$\Rightarrow E_{\rm beam} \simeq 100,000\mathrm{TeV}$$

- need R~10 $R_{\rm Earth}$ with 8T magnets
- collider: R=27km

$$\sqrt{s} = 2E_{\rm beam} = 2\times 7\ \mathrm{TeV}$$

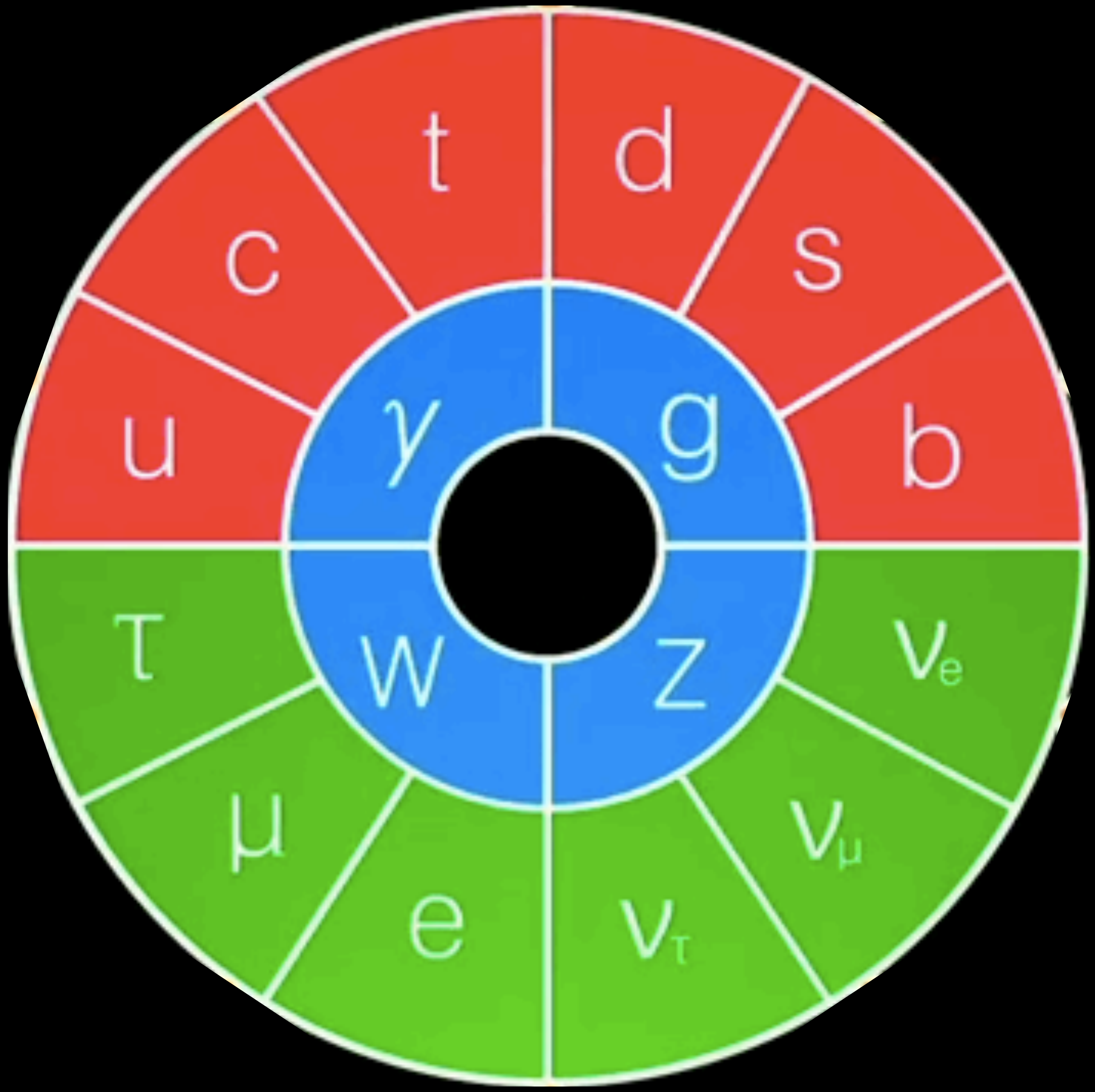
kudos to our accelerator friends who make unthinkable a reality

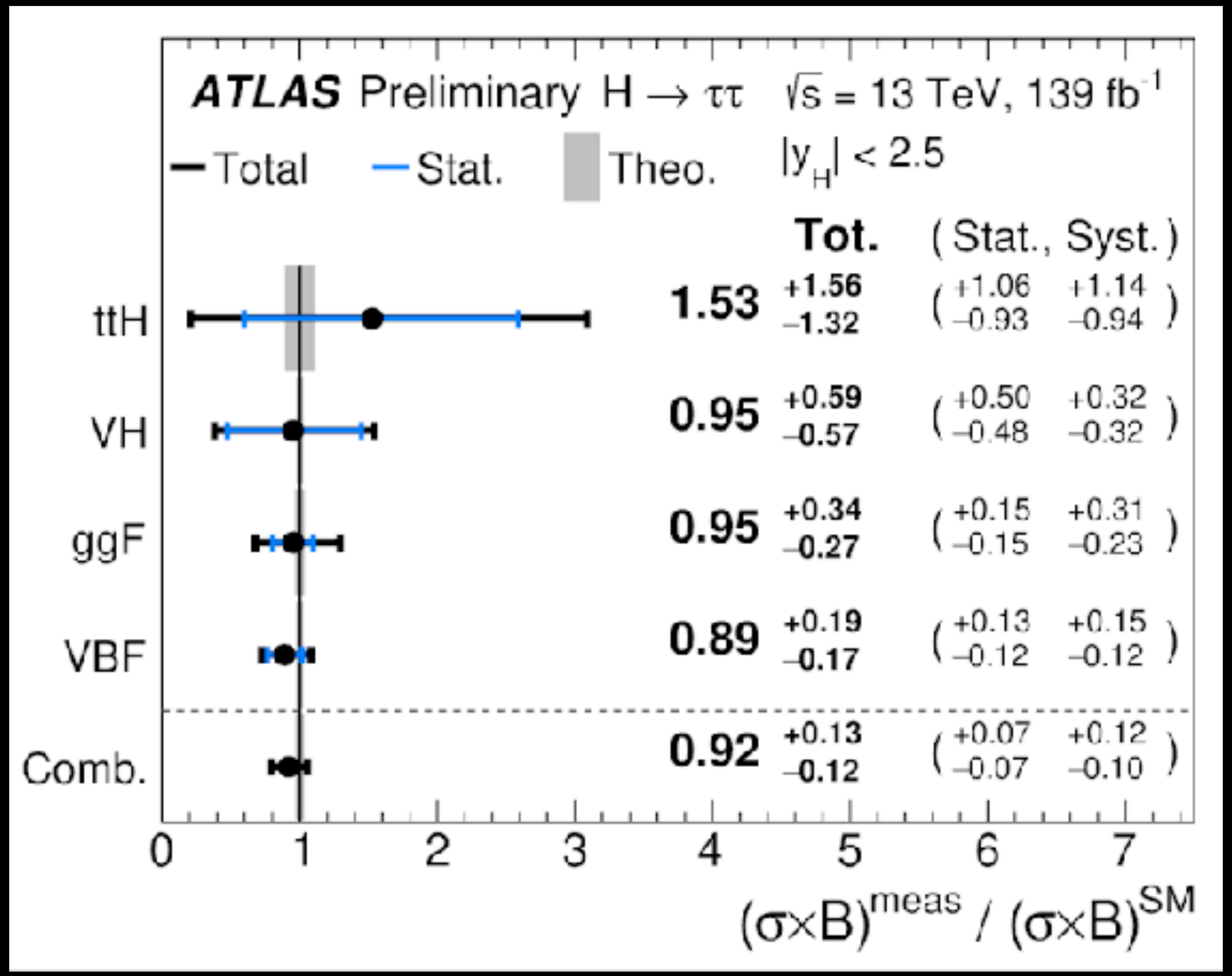


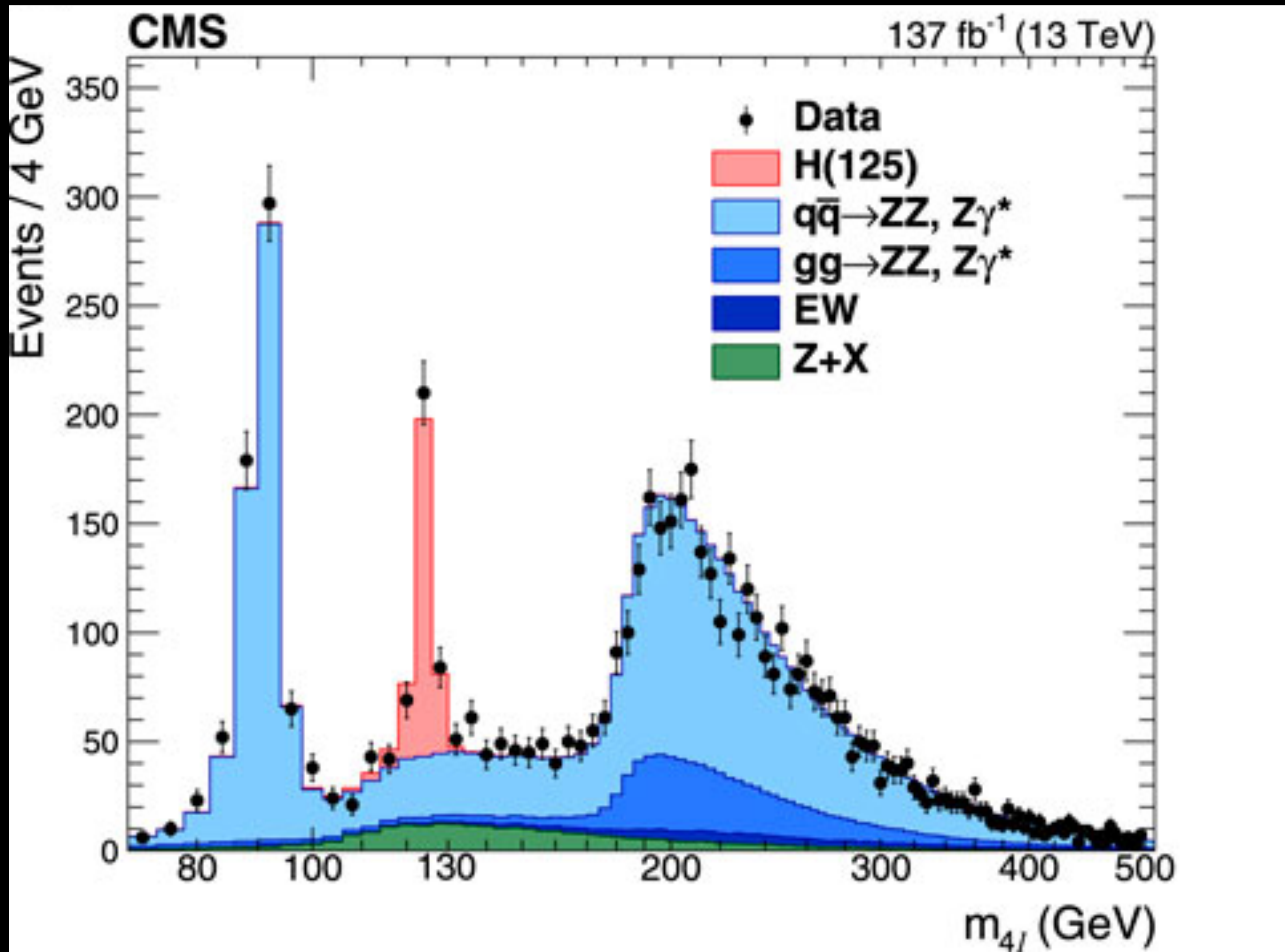
Globatron
40000km


Redo the Big Bang!

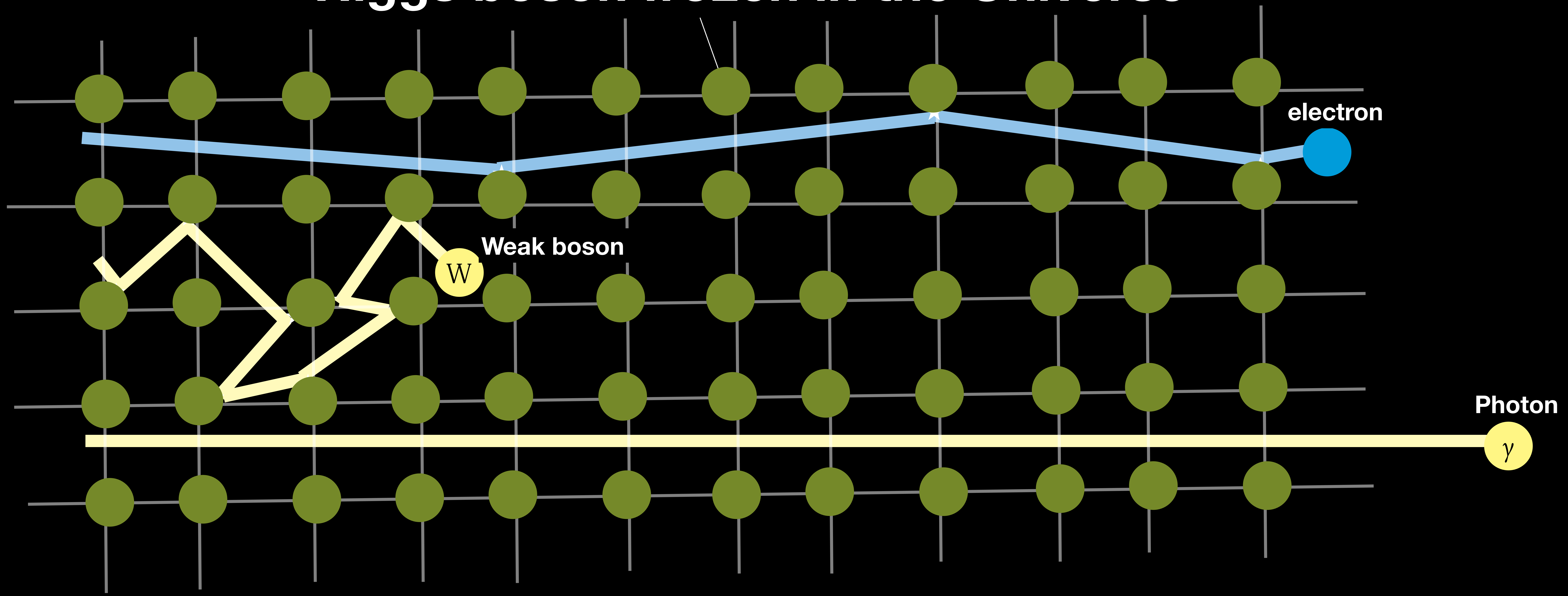
Standard Model





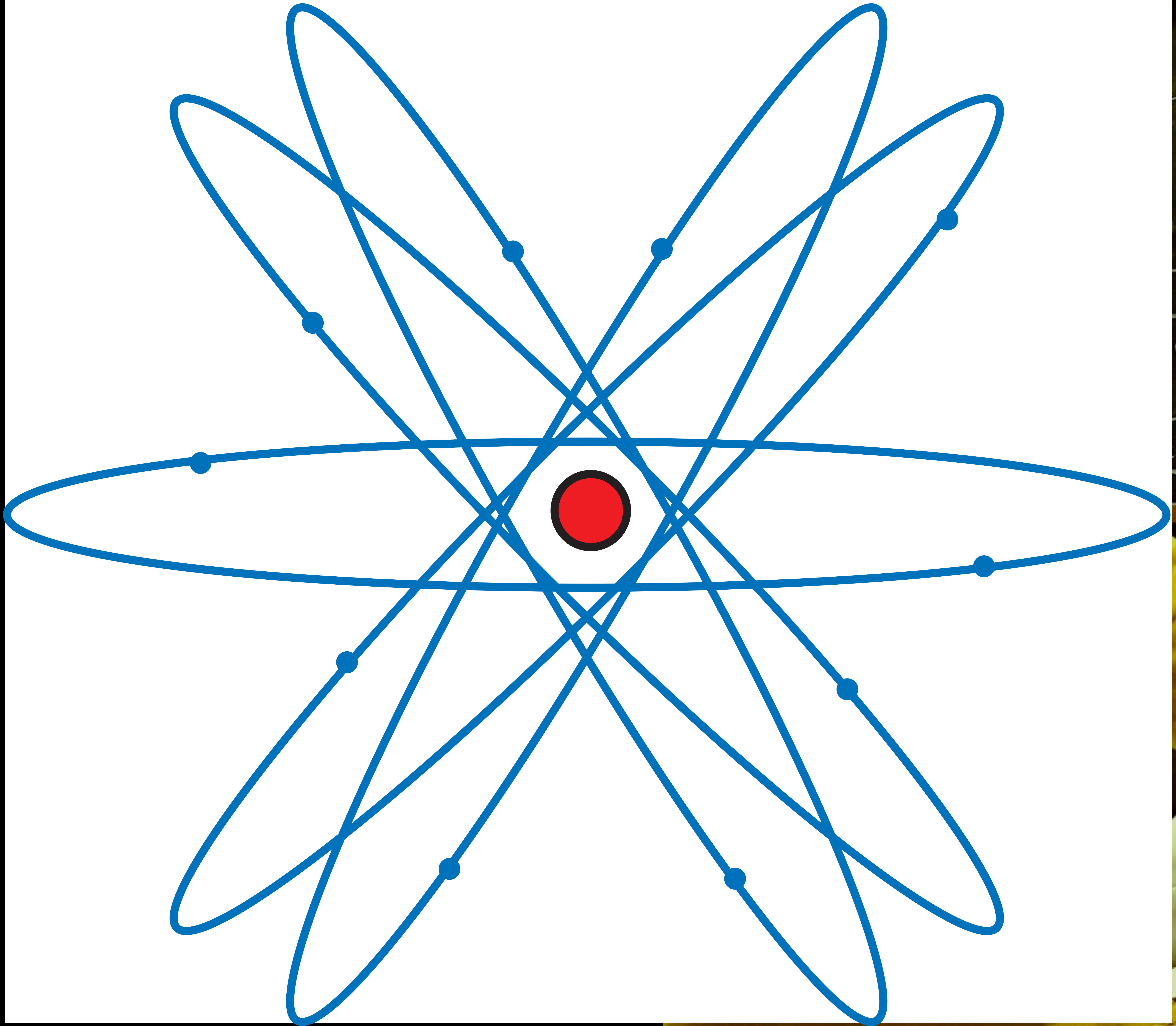


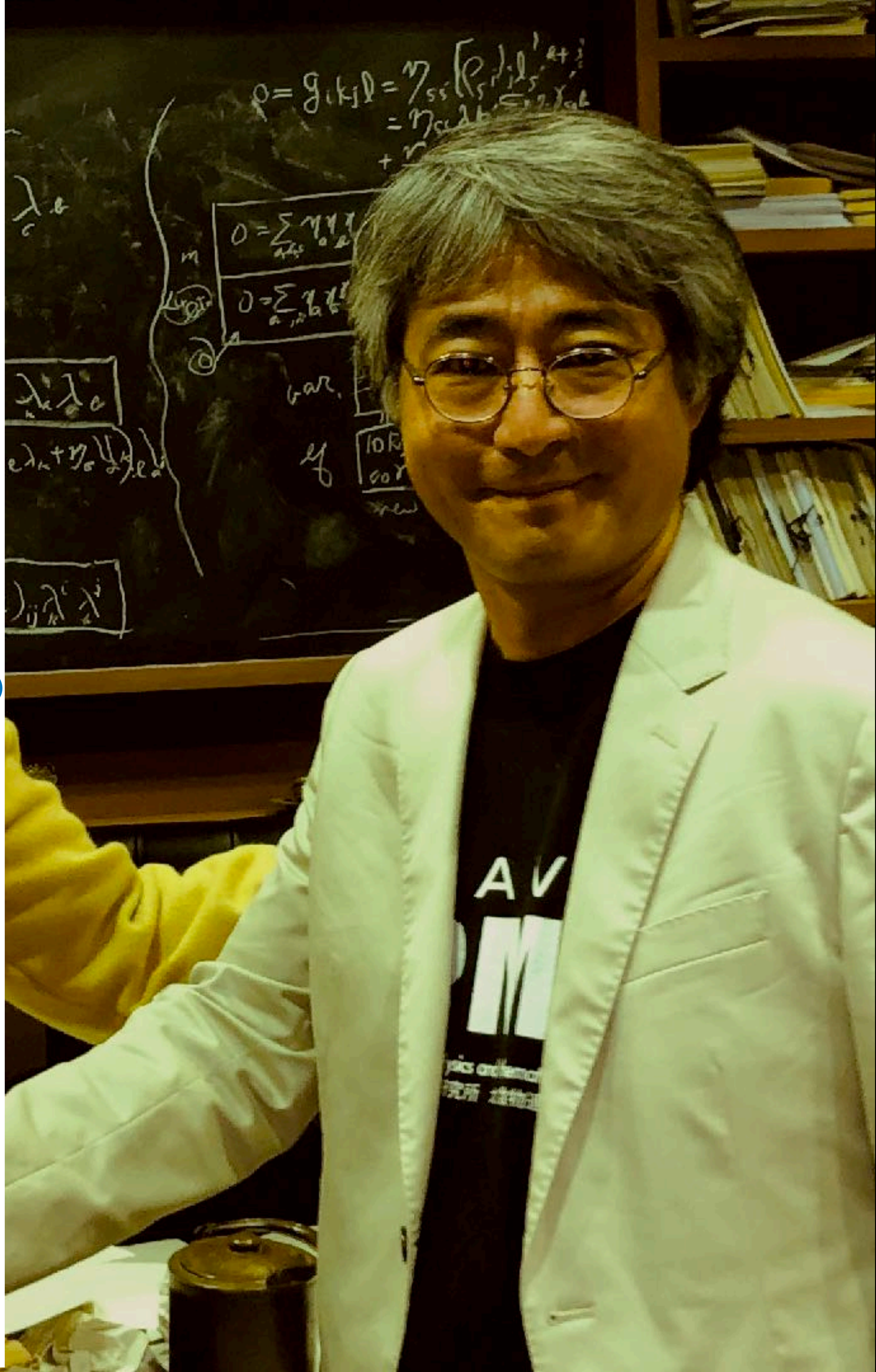
Higgs boson frozen in the Universe



Just the right amount of Higgs boson for us to exist!

Credit: Newton Japan





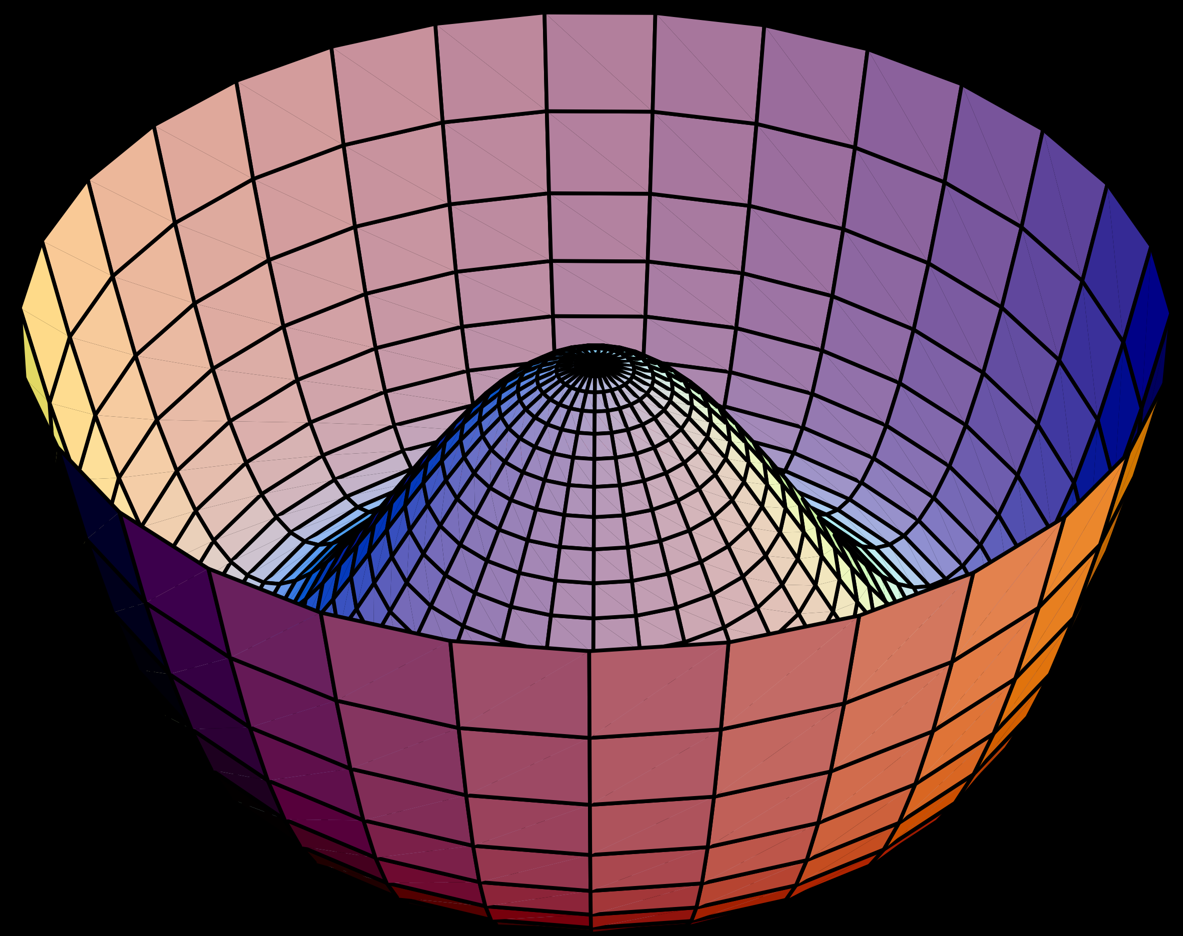
Who are they?
Why are they frozen?
Why do we exist?

Higgs filling up the space keeping us in one piece

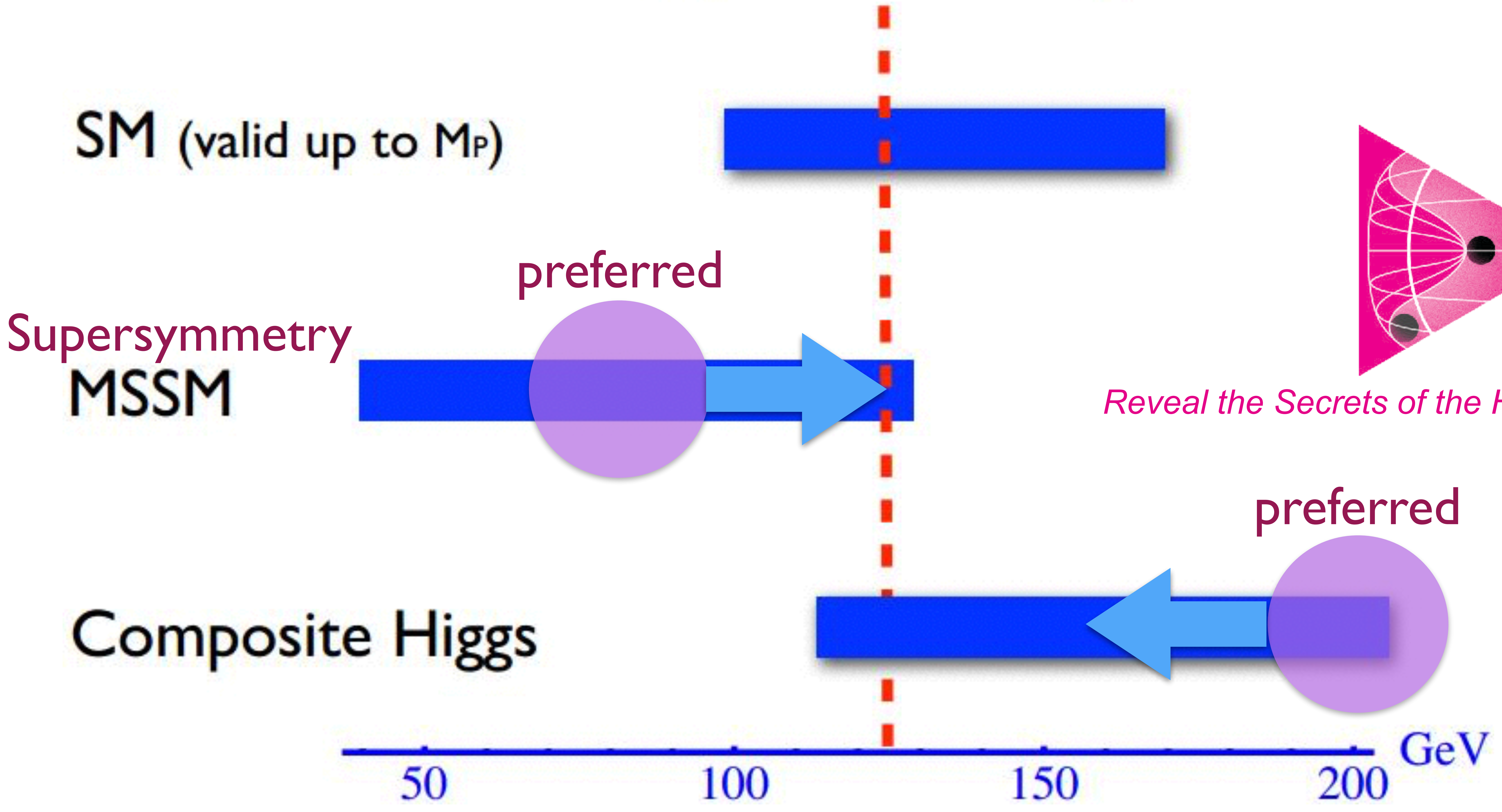
What is Higgs?
Is it alone?
Any siblings?
Any relatives?
Why frozen?

I didn't believe it

- Higgs boson is the *only spin 0 particle* in the standard model
  - it is *faceless*
  - one of its kind, no context
  - but does the most important job
- looks very artificial
- we still don't know *dynamics* behind the Higgs condensate
- *Higgsless theories*: now dead



Higgs mass range



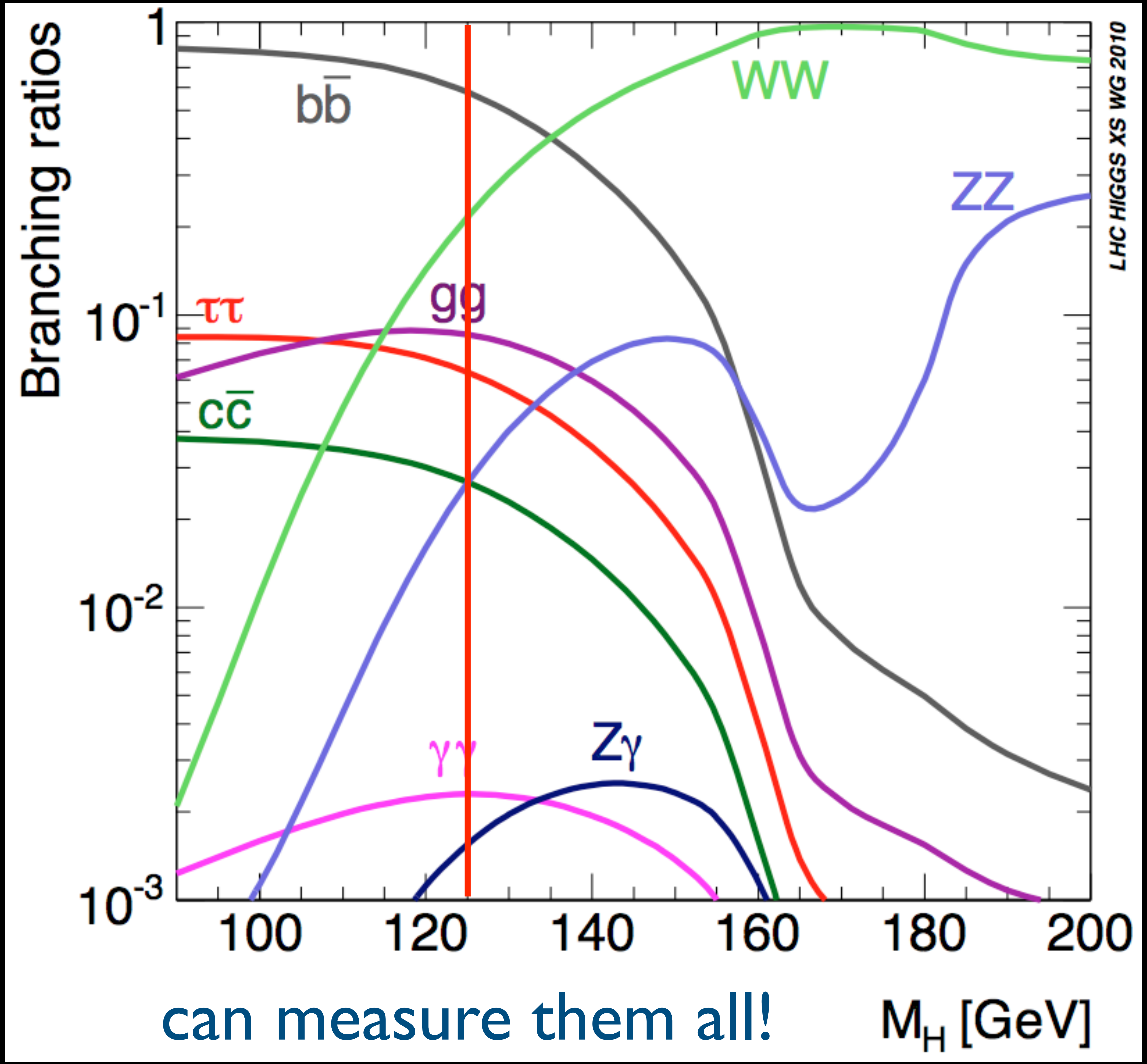
Reveal the Secrets of the Higgs Boson

Alex Pomarol

Nima's anguish

m_H=125 GeV seems almost maliciously designed to prolong the agony of BSM theorists….

dream case for experiments



but Higgs self-interaction?

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Recommendation 2

Rank-Ordered

New exciting initiatives

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. **An off-shore Higgs factory**, realized in collaboration with **international partners**, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

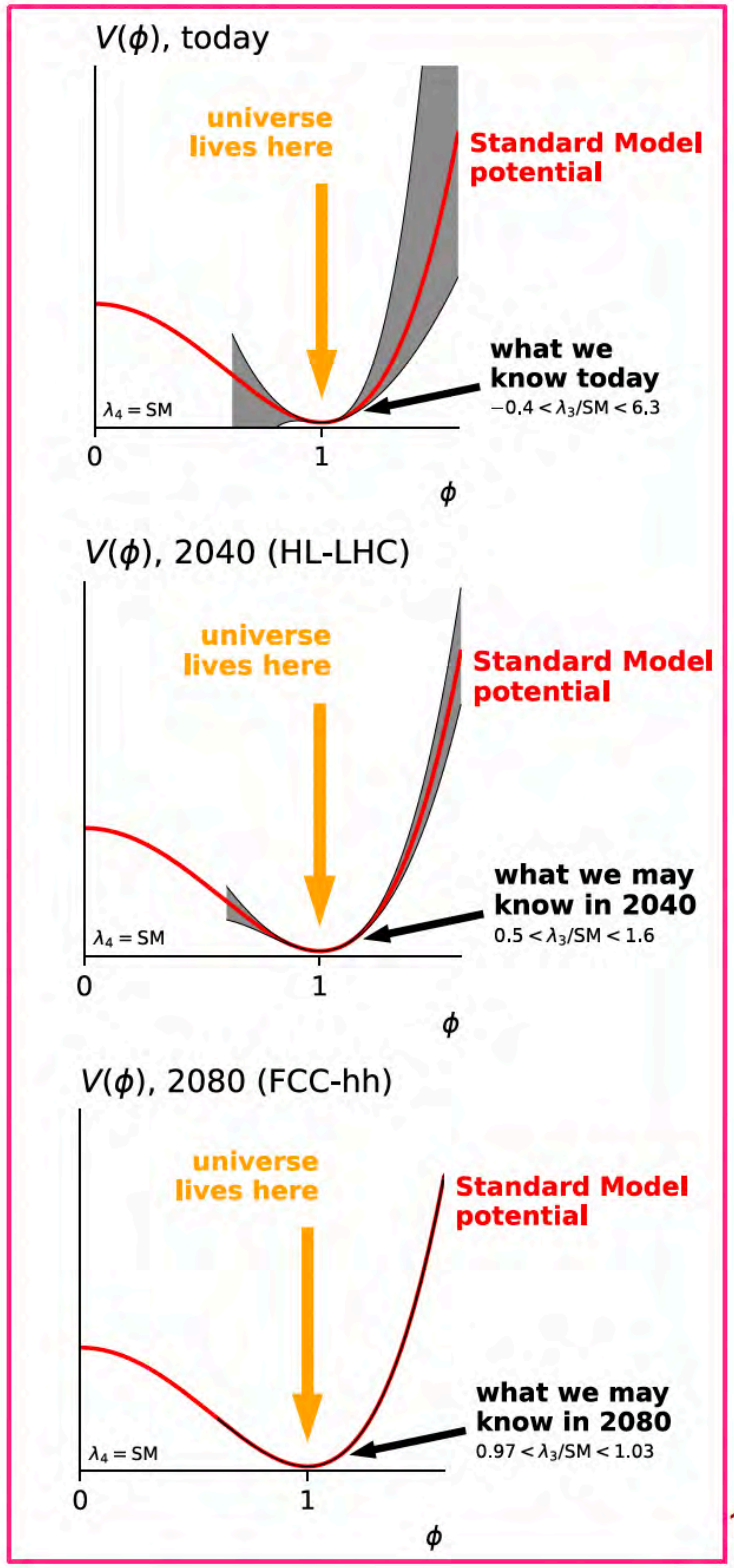
e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1).

Towards 10 TeV pCM

- Ultimate direct discovery reach of TeV scale phenomena
- Possible with hadron (FCC-hh @ 100 TeV) or muon colliders, but R&D is needed

- Higgs physics:
  - Probe the electroweak phase transition; Higgs self coupling measurements to 5% precision

- Direct beyond the SM searches:
  - Direct discovery of the particles responsible for any deviations observed in Higgs factory
  - Dark matter: “reach the thermal WIMP target for minimal WIMP candidates”



J. Gonski
USLUA meeting

Testing the simplest WIMPs

FCC-hh or a μCol is needed!

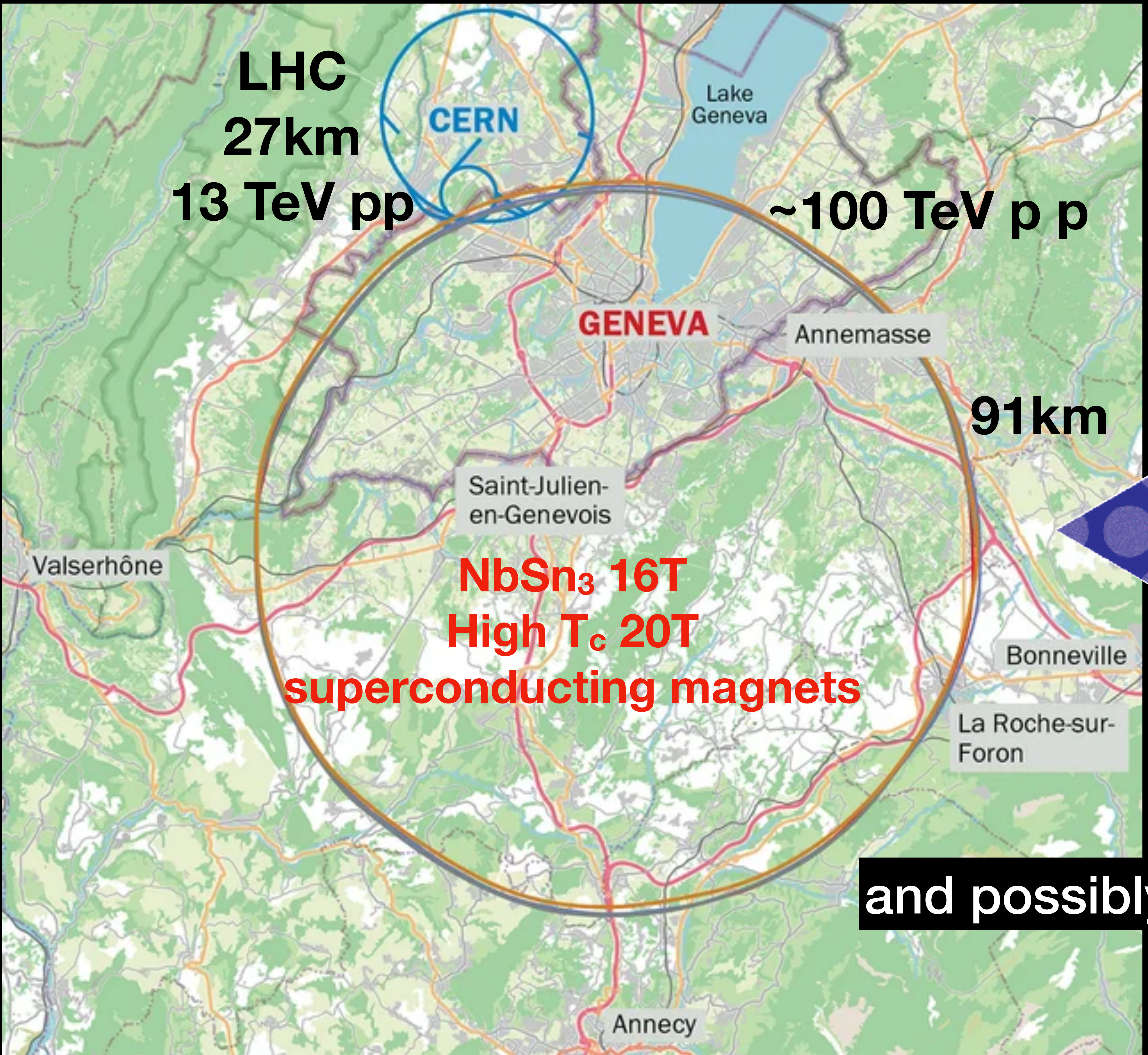
Patrick Meade
Brookhaven P5 Town Hall

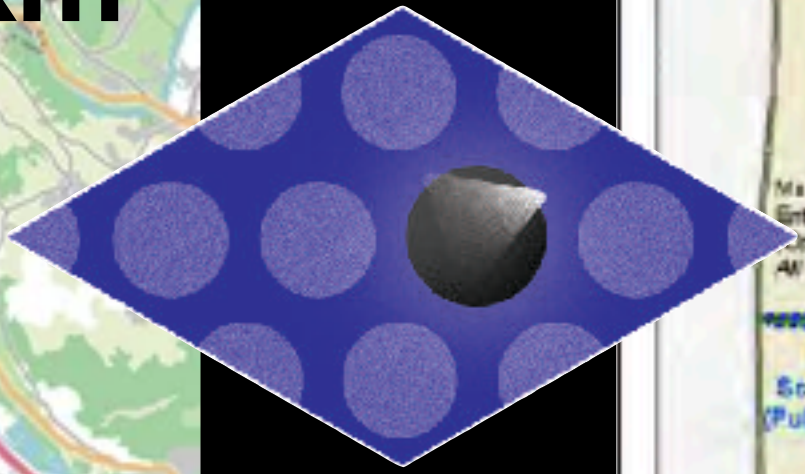
R&D will allow Fermilab to continuously expand the accelerator complex while producing world class science: *our Muon Shot!*

New enabling technologies

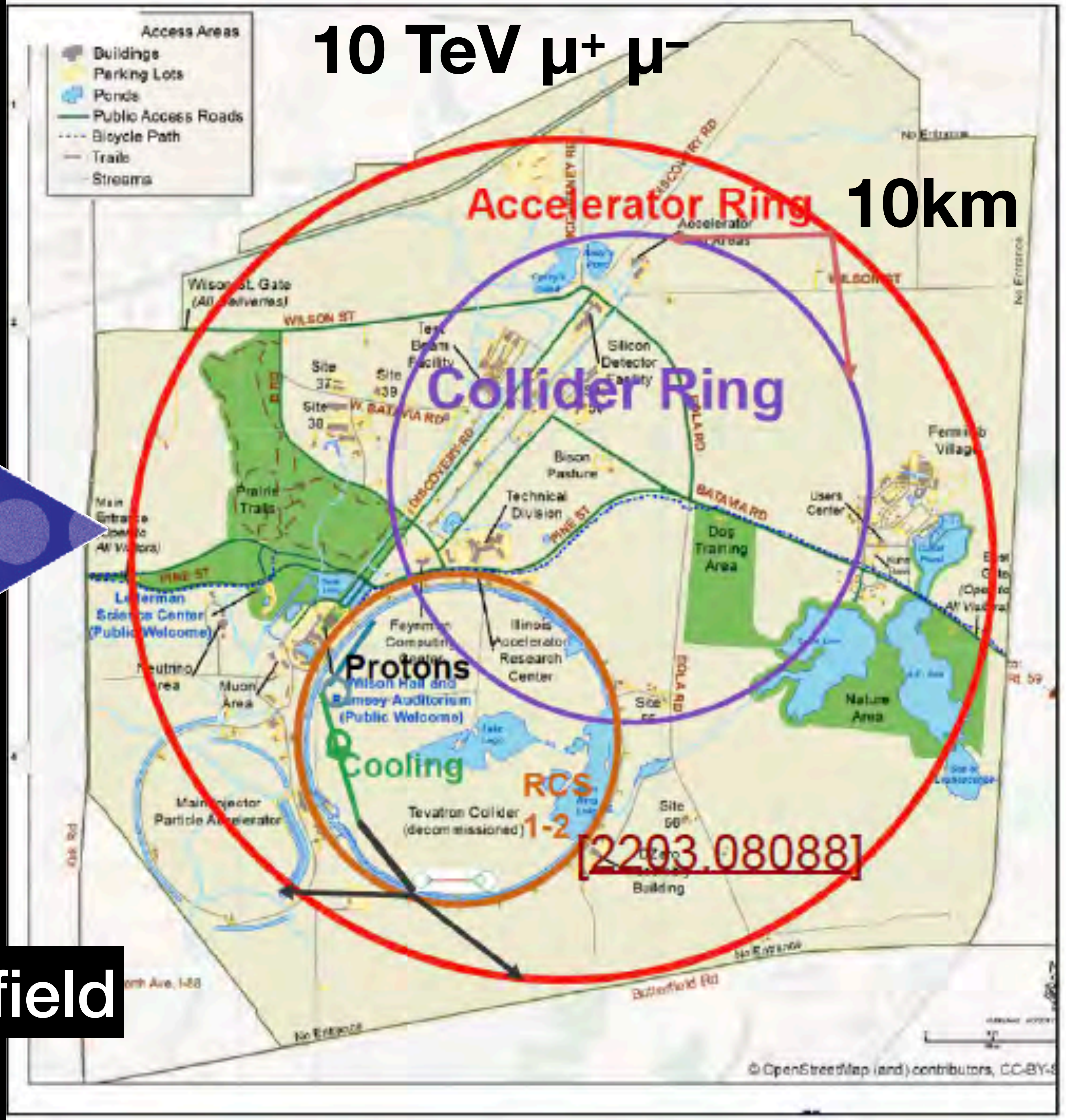
5% measurement of Higgs self coupling

Energy 10xLHC
Size 1/3 x LHC
Fits inside the Fermilab site





and possibly wakefield



Muon production and cooling

Colliders with high parton CM energy (10 – 15 TeV) summary table

- Main parameters of the colliders with 10 - 15 TeV parton CM energy.
- Total peak luminosity for multiple IPs is given in parenthesis.
- The cost range is for the single listed energy.
- Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes.
- The relevant energies for the hadron colliders are the parton CM energy, which can be substantially less (~ 1/10) than hadron CM energy quoted in the table.

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} $cm^{-2}s^{-1}$]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

Implementation Task Force, Thomas Roser

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Not Rank-Ordered

Recommendation 4

Investment in the future

a. Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).

b. Enhance research in **theory** to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe (section 6.1). **$15M/yr increase**

c. Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4). **$10M/yr increase**

d. Invest in R&D in **instrumentation** to develop innovative scientific tools (section 6.3). **$20M/yr increase**

e. Conduct **R&D** efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3). **$8+9M/yr increase**

f. Support key **cyberinfrastructure** components such as shared software tools and a sustained R&D effort in computing, to fully exploit emerging technologies for projects. Prioritize **computing and novel data analysis techniques** for maximizing science across the entire field (section 6.7).

g. Develop plans for improving the **Fermilab accelerator complex** that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

We recommend specific budget levels for enhanced support of these efforts and their justifications as **Area Recommendations** in section 6.

1.2.4 – Interconnected Opportunities

We do not yet have a technology capable of building a 10 TeV pCM energy machine, but the case for one is clear. Extensive R&D is required to develop cost-effective options. Possibilities include proton beams with high-field magnets, muon beams that require rapid capture and acceleration of muons within their short lifetime, and conceivably electron and positron beams with wakefield acceleration. All three approaches have the potential to revolutionize the field.

A demonstrator facility along the path to a 10 TeV pCM muon collider could fit into the evolution of the accelerator complex at Fermilab. Such a demonstrator might produce intense muon and neutrino beams in addition to performing critical R&D; it could leverage expertise in muon and neutrino beam facilities developed over the past decade. The improved accelerator complex could also support beam-dump and fixed-target experiments for direct searches and quantum imprints of new physics. This R&D path therefore aligns with five of the six science drivers.

2.3 The Path to 10 TeV pCM

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

Each of these steps presents considerable technical challenges, many of which have never been confronted before. This P5 plan outlines an aggressive R&D program to determine the parameters for a muon collider test facility by the end of the decade. This facility would test the feasibility of developing a muon collider in the following decade. With a 10 TeV pCM muon collider at Fermilab as the long-term vision, a clear path for the evolution of the current proton accelerator complex at Fermilab emerges naturally: a booster replacement with a suitable accumulator/buncher ring would pave the way to a muon collider demonstration facility (Recommendation 4g, 6). The upgraded facility would also generate bright, well-characterized neutrino beams bringing natural synergies with studies of neutrinos beyond DUNE. It would also support beam dump and fixed target experiments for direct searches of new physics. Another synergy is in charged lepton flavor violation. The current round of searches at Mu2e can reveal quantum imprints of new physics at the 100 TeV energy scale, beyond the reach of direct searches at collider facilities in the foreseeable future. An intense muon facility may push this search even further.

Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D toward a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

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Recommendation 6

Decision without waiting for the next P5

Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

The panel would consider the following:

1. The level and nature of **US contribution in a specific Higgs factory** including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
2. Mid- and large-scale **test and demonstrator facilities** in the accelerator and collider R&D portfolios.
3. A plan for the evolution of the **Fermilab accelerator complex** consistent with the longterm vision in this report, which may commence construction in the event of a more favorable budget situation.


Accelerators
LHC heavy ions
LHC protons
High-energy cosmic rays
is visible
Size of visible universe
TODAY
Big Bang
Higgs
WIMP
telescopes
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 = 3×10^{5} Y
E = 3×10^{-10} GeV
t = 10^{9} Y
E = 10^{-12} GeV
Credit: Particle Data Group
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A "muon shot" aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

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A tunnel of the Superconducting Super Collider project in 1993, which was abandoned by Congress. Ron Heflin/Associated Press

By Dennis Overbye and Katrina Miller

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