July 2, 2024

THE BEGINNING, THE FUTURE, AND THE **HIGGS BOSON**

Jim Brau,
University of Oregon

UNIVERSITY OF OREGON

Research partially supported
by the U.S. Department of Energy

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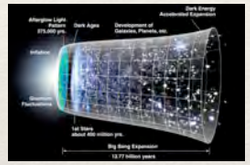

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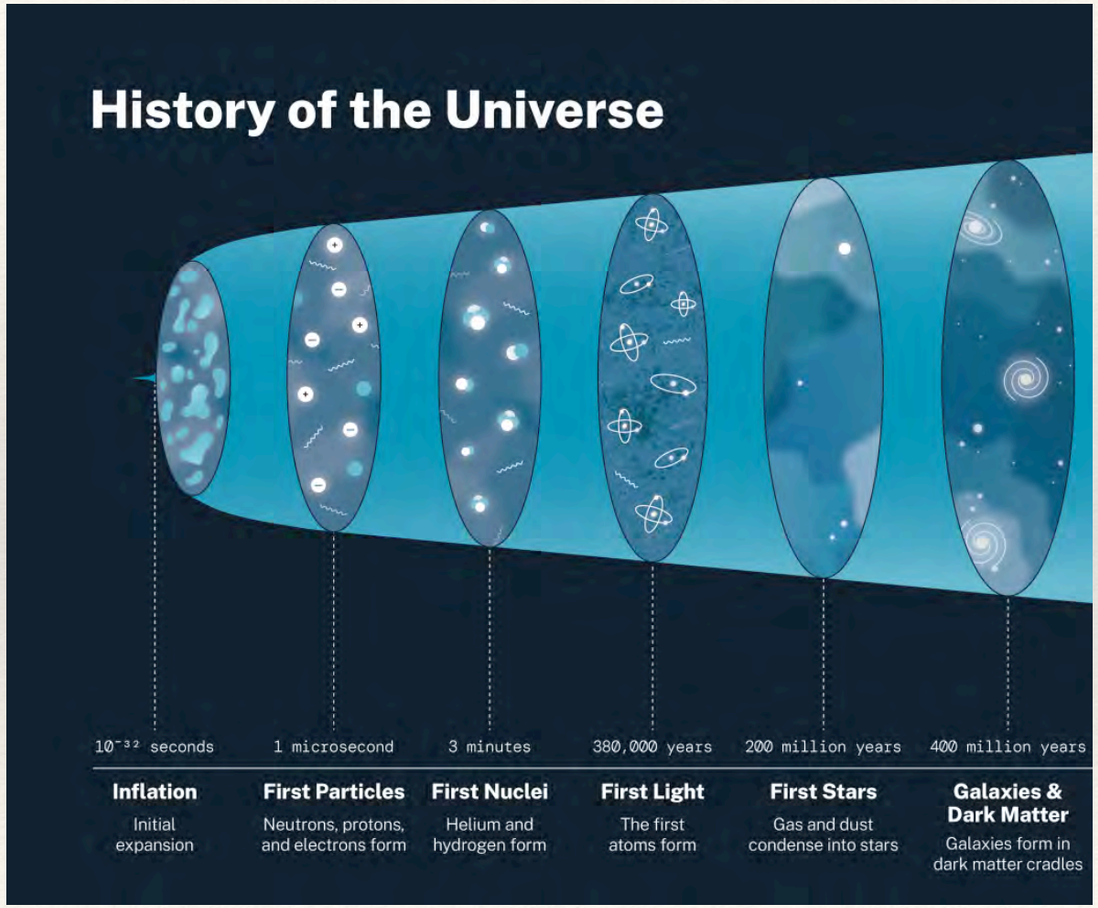
In the beginning

- 13.8 billion years ago,
- FIRST, there was energy:
  - Lots of energy.
- THEN particles appeared:
  - They were massless,
  - Equal matter and anti-matter,
  - All traveling at the speed of light,
  - Very hot “primordial soup”.

Image credit: Shutterstock

Very soon after the beginning

- The **Higgs boson** field turned on during a fraction of a second.
- Particles acquired mass by interacting with this fundamental field.
- What caused this? (or why did it happen?)
  - We don't know.
  - And we don't know answers to many other fundamental questions.
  - So, we must try to learn as much as we can about and from the **Higgs boson.**



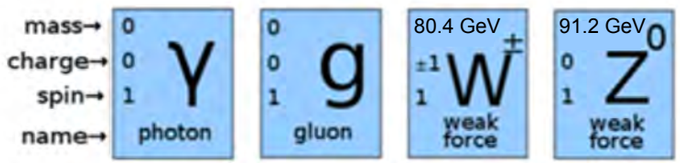
How we know about the **Higgs boson**

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

In a recent note[1] it was shown that the Gold-stone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of



- Why the weak interaction bosons (W,Z) are massive (80.4 & 91.2 GeV) while photon is massless?
- **Higgs** solves this puzzle - interaction with **boson** field gives mass to W & Z (not photon) — and other particles.

BUT DOES THE **HIGGS BOSON** EXIST?

The Superconducting Super Collider (SSC)

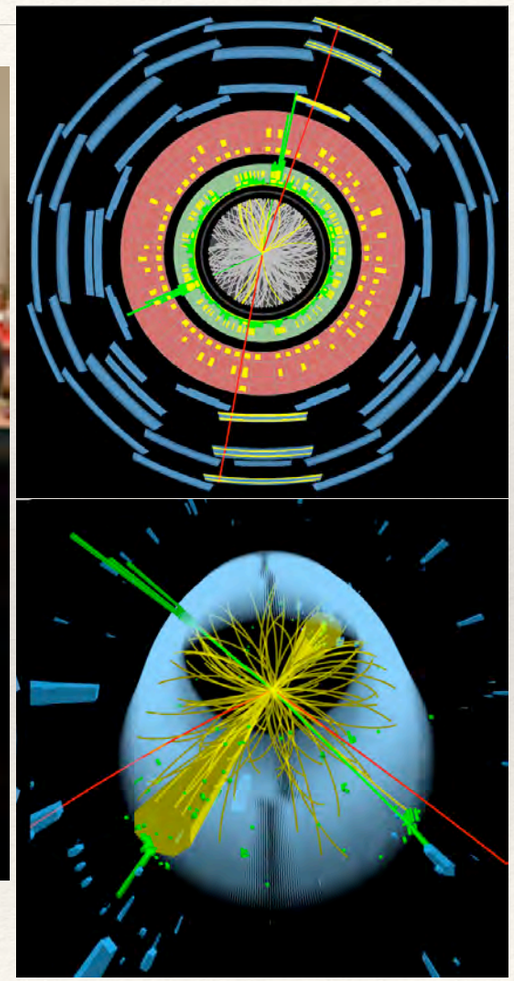
- 1983/1984 - Proposal developed by US Dept of Energy.
- 1987/1988 - Pres. Reagan approved SSC and it starts in Texas.
  - Reagan said “Throw Deep!”
  - 54 mile circumference
  - 20 + 20 = 40 TeV collisions - “no lose theorem”
    - Will produce **Higgs bosons**, IF THEY EXIST
- 1993 - project cancelled - after 20% completion
  - LHC moves ahead at CERN.
  - 14 TeV collisions, but much higher collision rate than SSC.

The Large Hadron Collider

- 1993 - SSC cancellation gives CERN big boost for LHC.
  - 17 mile circumference - 1/3 SSC
    - 7 + 7 = 14 TeV (compared to 40 TeV of SSC)
    - Higher planned interaction rate to make up for lower collision energy.
- 2008 - Starts operations
- 2012 - LHC experiments announce discovery of **Higgs boson.**

Discovery of the **Higgs boson**

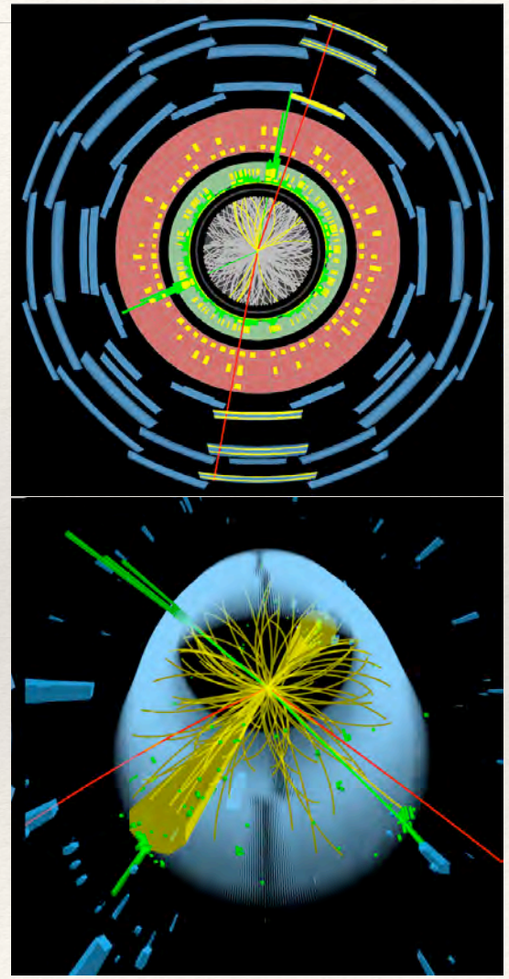
- July 4, 2012



Discovery of the **Higgs boson**

- **July 4, 2012** - announced during international high energy physics conference in Melbourne

CERN announcement connected to Melbourne

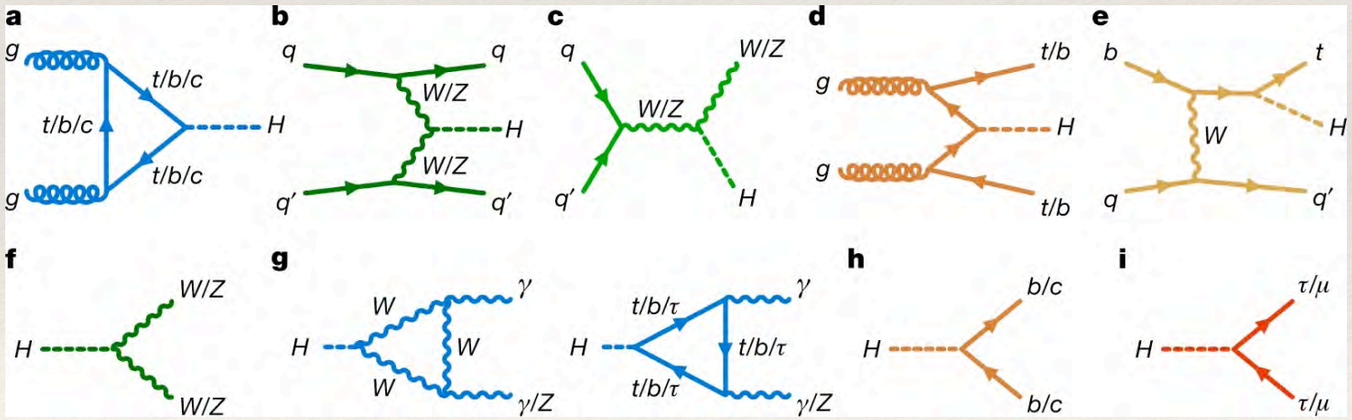


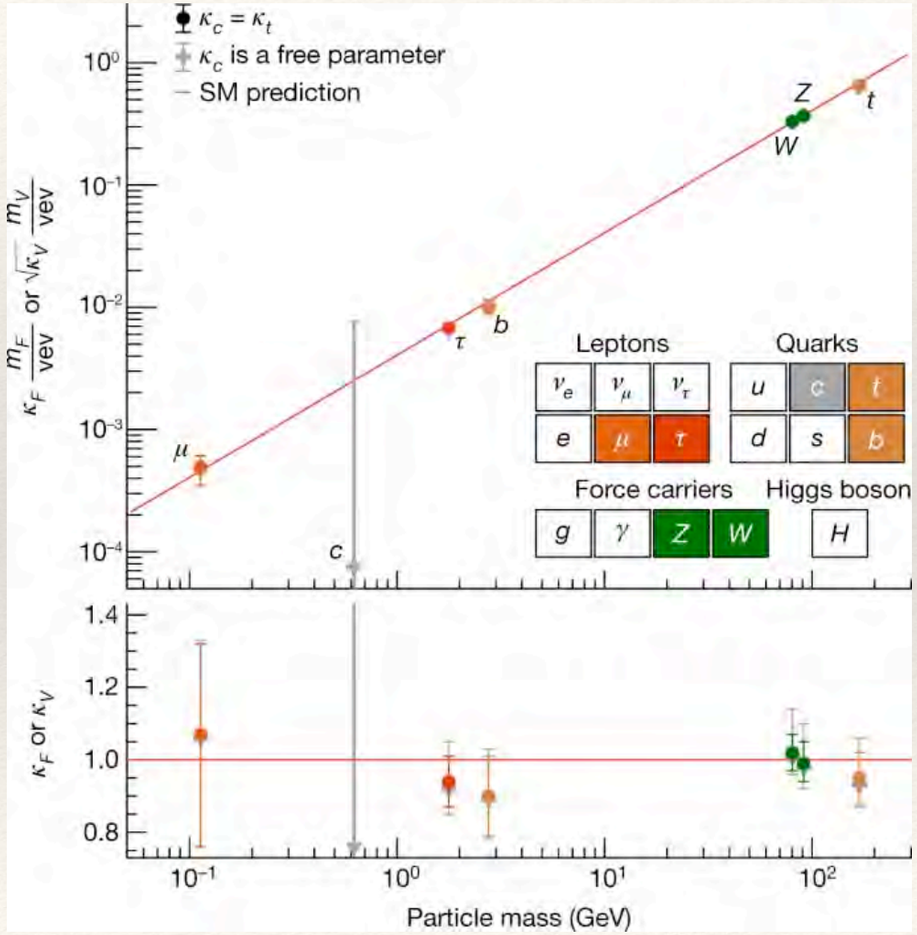
- But is it THE **Higgs boson**? - ATLAS and CMS have since measured details showing it is at least very close.

Is it THE **Higgs boson**

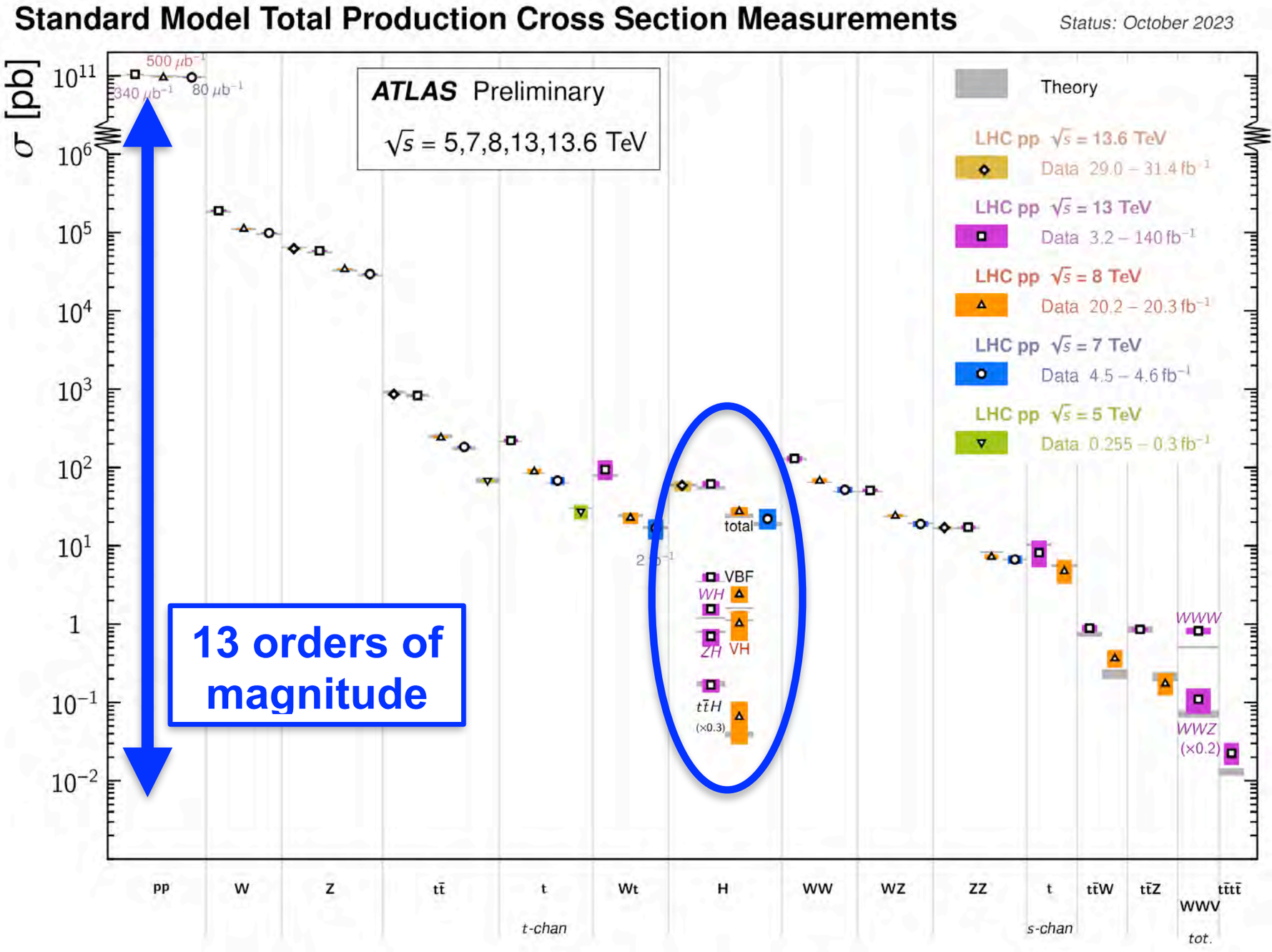
The ATLAS Collaboration. *Nature* **607**, 52–59 (2022)

- The **Higgs boson** has no spin (scalar particle, only one known)
- Interactions with other particles consistent with standard model expectations

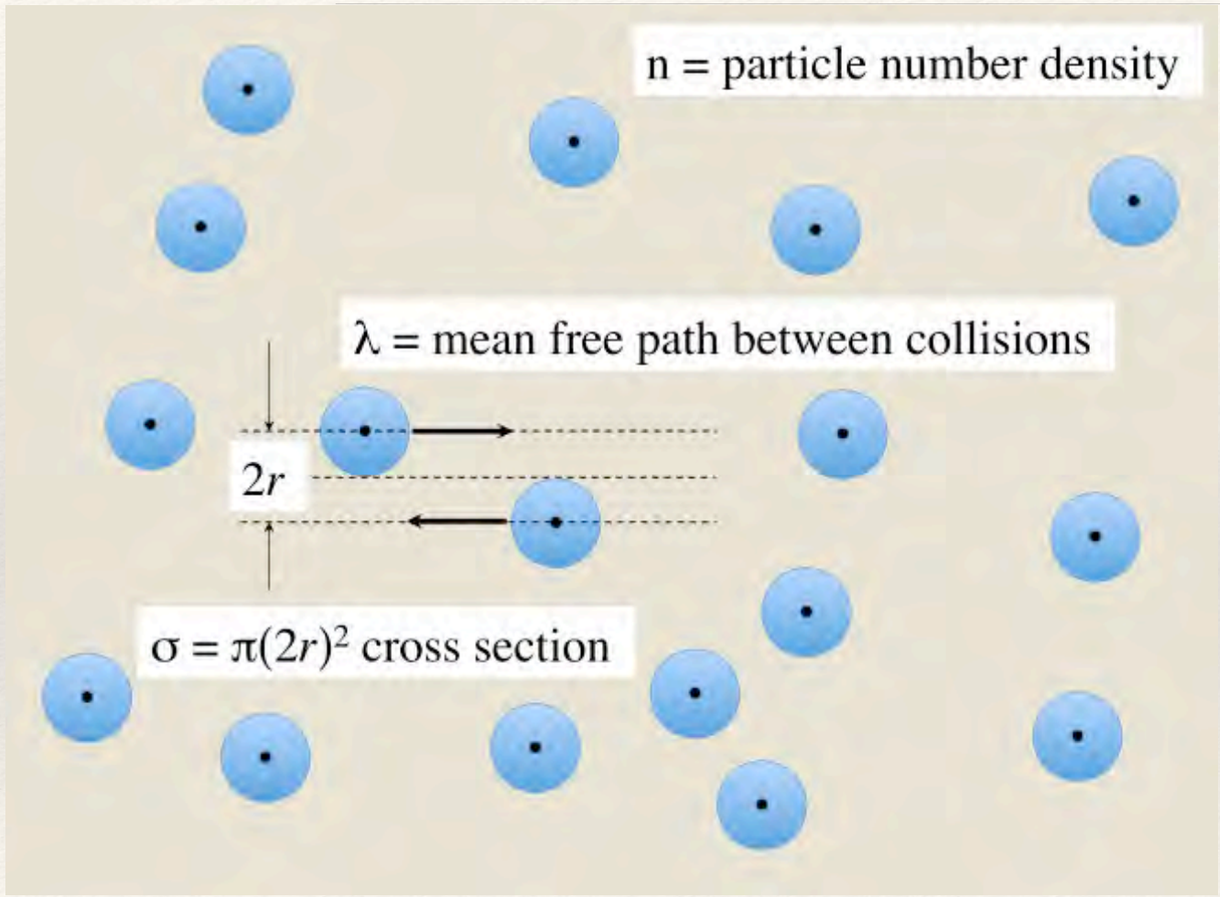




- LHC measurements match Standard model theory over 13 orders of magnitude, including the **Higgs boson**
- Looks good!



Cross section



- Units = barns
- 1 barn = 10^{-24} cm^2
- 1 picobarn = 10^{-12} barns = 10^{-36} cm^2

- Event rate = Luminosity x cross section
- Luminosity units = cm^{-2}sec^{-1}
- LHC Luminosity ≈ 10^{34} cm^{-2}sec^{-1}

- Higgs cross section ≈ 60 picobarns
- Rate = Lum x cross section
  - ≈ 60 x 10^{-36} cm^2 x 10^{34} cm^{-2}sec^{-1}
  - ≈ 0.6/second
  - ≈ 2 x 10^7 /year
    - Less due to actual running time

Remaining mysteries of the universe

- **Remaining mysteries of the role of particles in the history of the universe**
  - Why is the visible universe dominated by matter?
    - When our understanding of the early universe is equal matter and anti-matter.
  - Why is the visible universe such a small fraction of the universe?
    - Standard model matter = 5%
    - Dark matter = 27% - what is it?
    - Dark energy = 68% - what is it?
  - Why is the **Higgs boson** so light?
    - It's interactions with the known particles should raise its mass ENORMOUSLY.
  - How does gravity relate to other forces (electroweak and strong)?

Remaining mysteries of the universe

- **Remaining mysteries of the role of particles in the history of the universe**
  - Why are there three generations of standard model particles?
    - Electron, down quark, up quark, electron neutrino
    - Muon, strange quark, charm quark, muon neutrino
    - Tau, bottom quark, top quark, tau neutrino
  - Is the **Higgs boson** the ONLY spin zero (scalar) particle?
    - or are there others?
  - How does the Higgs boson interact with itself?
  - Is the **Higgs boson** fundamental, or built from more fundamental particles?
  - Was the early universe inflation caused by the **Higgs boson**, another fundamental scalar particle (inflaton) or something else, if anything?
  - And many more mysteries to address…

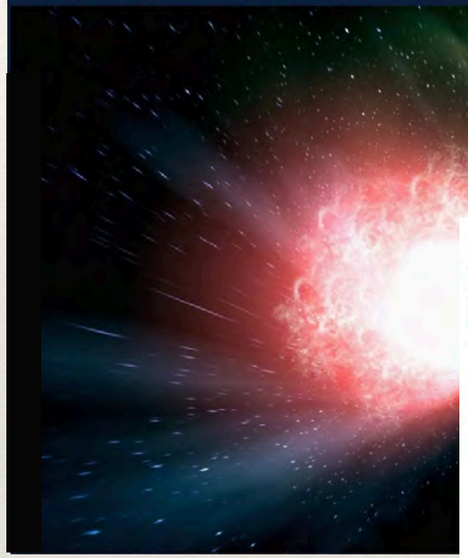
What about the future of the universe?

- Expansion is a known and dominant aspect for billions of years in future.
- Does the **Higgs boson** have a significant role on the future of the universe?
  - Maybe!

Stephen Hawking Fears Higgs Boson Doomsday

The Big Slurp

Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



Here's how the universe could end in a 'false vacuum decay'

News By Paul Sutter published December 8, 2021

The universe may not be as stable as you think.

New Scientist

Your explosive guide to the end of the universe

Our sun will swell, our galaxy will collide with its neighbour and the universe could suddenly b
swallowed by a vacuum bubble

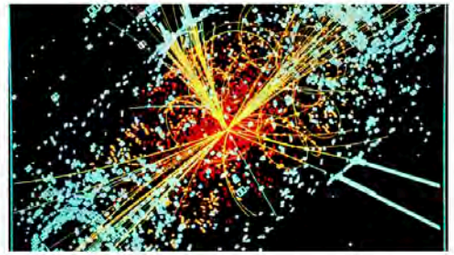
By Daniel Cossins, Macgregor Campbell and Joshua Sokol

BIG THINK

HARD SCIENCE — JANUARY 1, 2019

How 'vacuum decay' could end the universe

It's possible that the Higgs boson is connected to a bizarre doomsday scenario for the universe.



Wikimedia Commons

Smithsonian MAGAZINE

If a Cosmic Bubble Destroys the Universe, Scientists Now Know When It'll Happen

Don't panic yet; the end won't be for at least 10 octodecillion years, if it happens at all

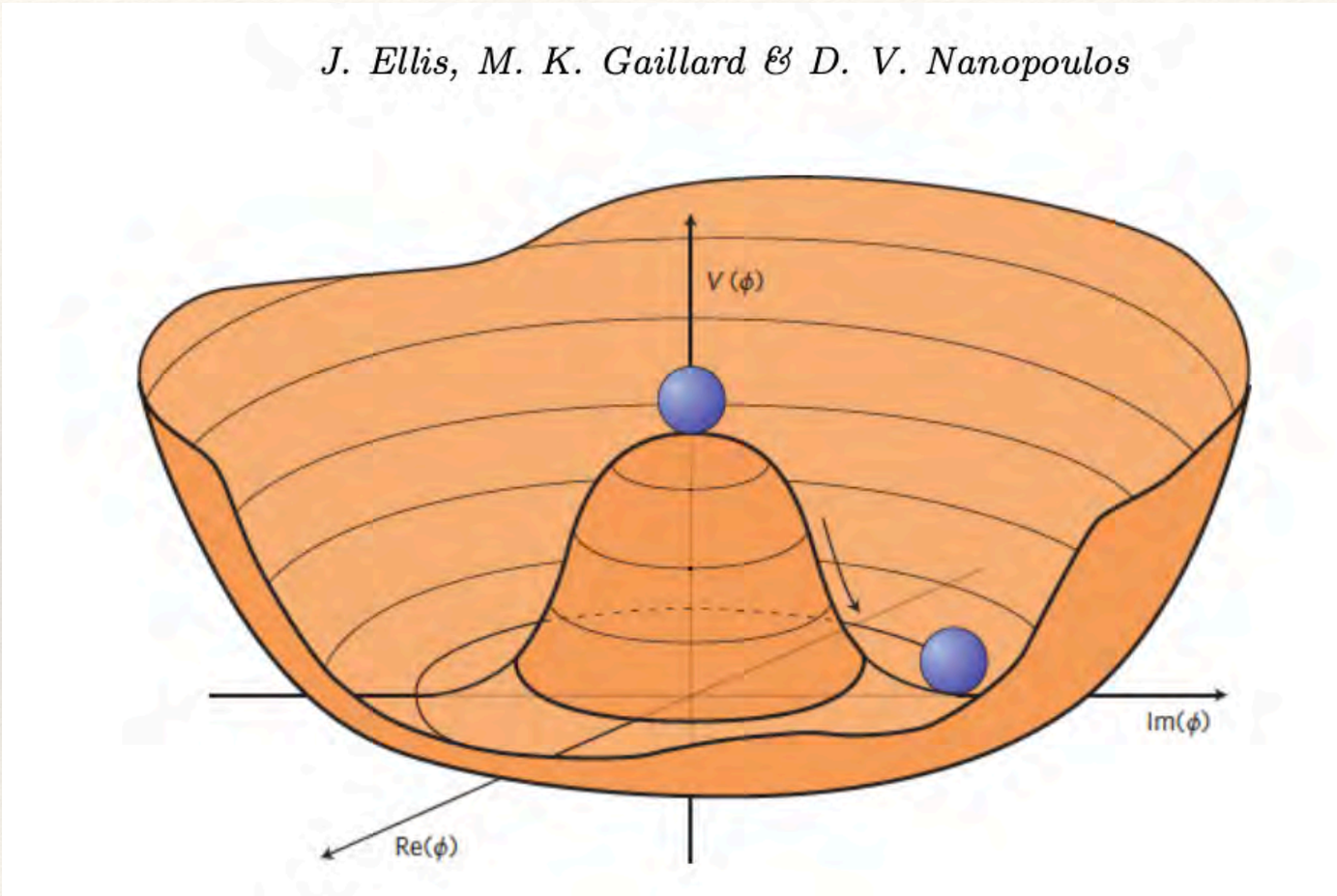
Jason Daley

Correspondent

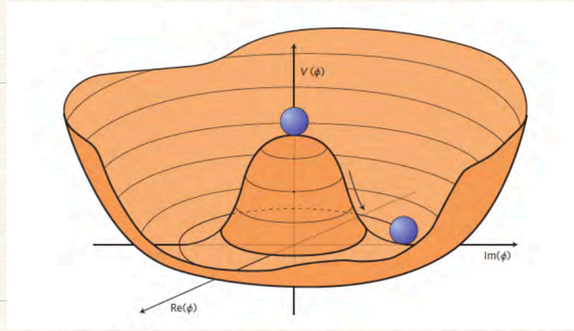
- Is our universe a long lived bubble?

Model of the **Higgs boson** and its potential

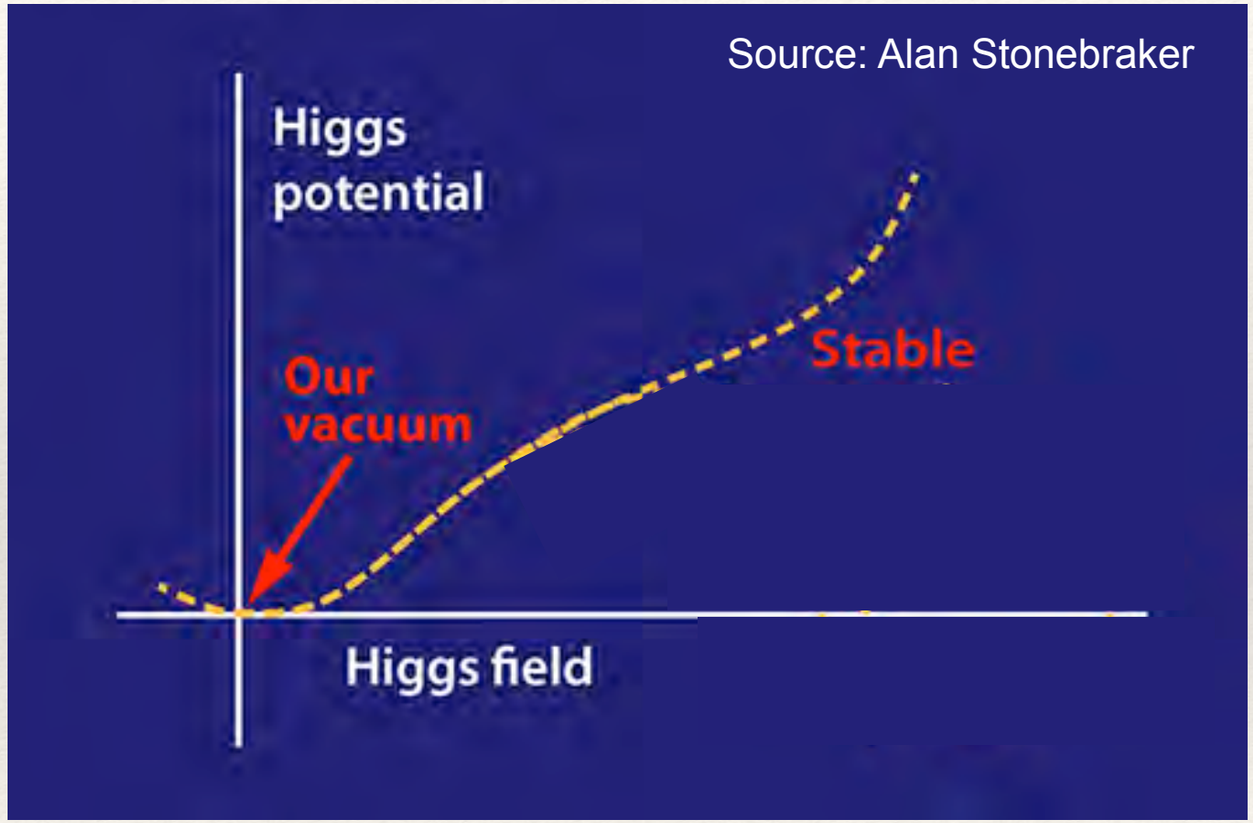
- Model of the **Higgs boson** and the **Higgs boson** field
  - **Higgs boson** is excitation in the radial direction of the **Higgs boson** field potential.



Higgs boson potential

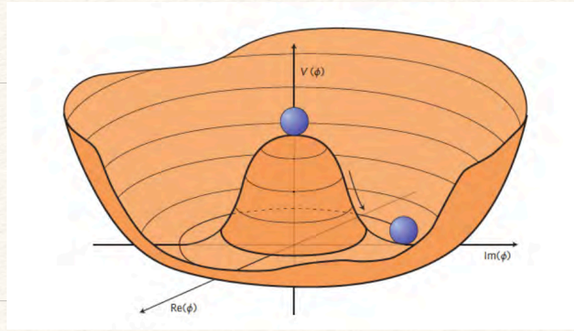


- Is the universe stable to the **Higgs boson** field
  - It depends on the **Higgs boson** potential

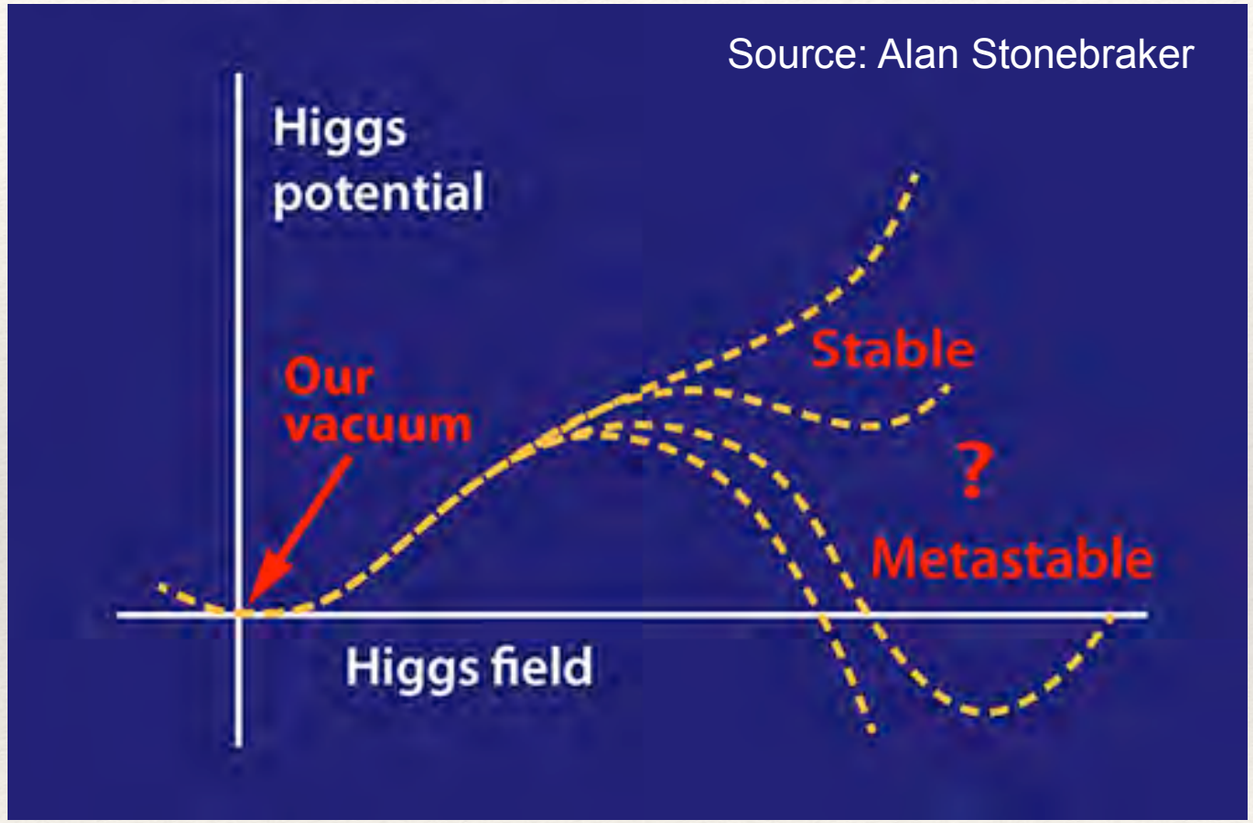


https://physics.aps.org/articles/v8/108

Higgs boson potential



- Is the universe stable to the **Higgs boson** field
  - It depends on the **Higgs boson** potential
- Or might it decay?
  - **The Big Slurp**



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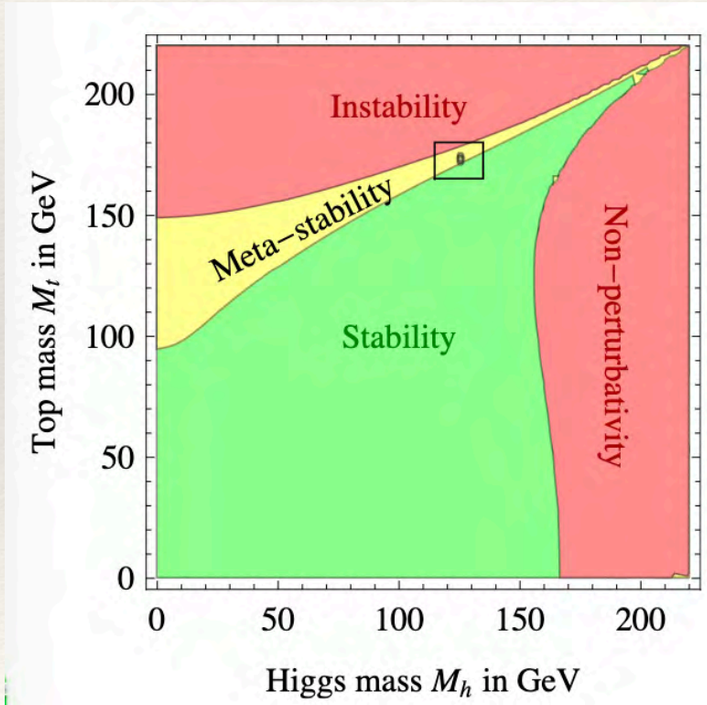
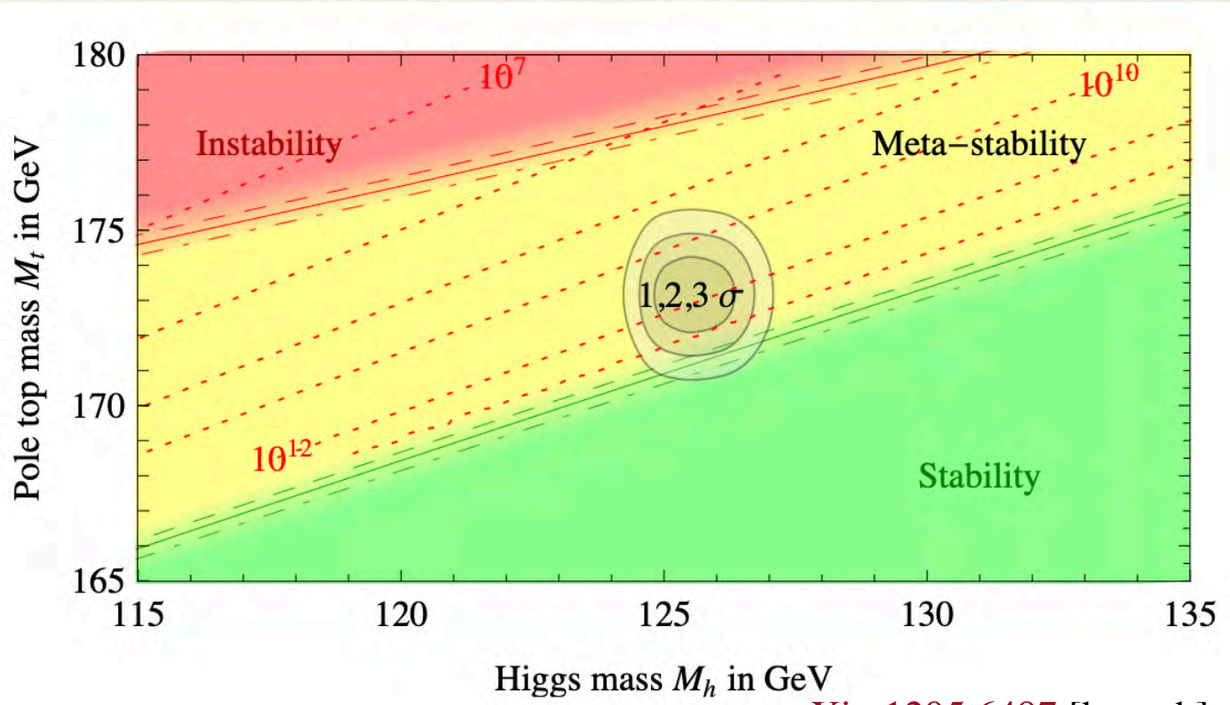
Higgs boson vacuum stability

- Answers depend on the properties of the **Higgs boson** and the other particles of Nature, especially the top quark.





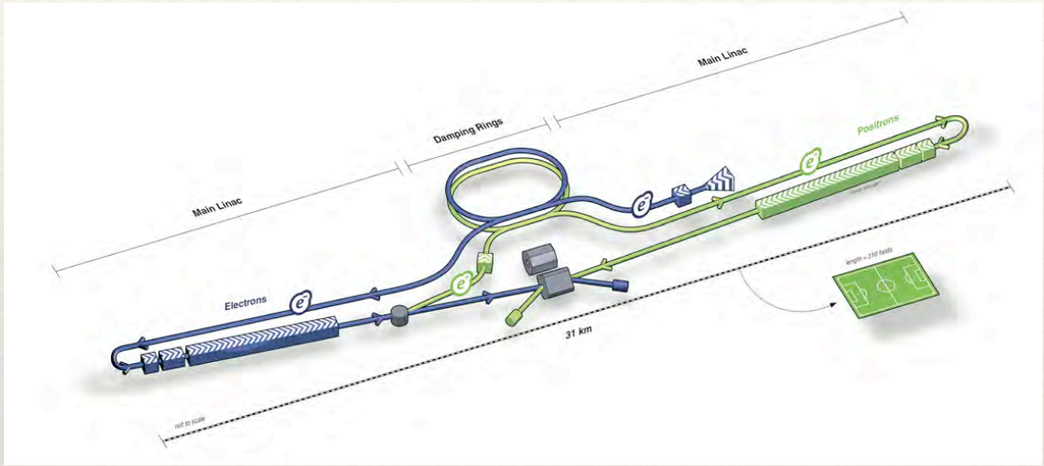
arXiv:1205.6497 [hep-ph]

World-wide planning for future particle physics

- World-wide planning for future particle physics:
  - Separate regional community planning (US, Europe, Japan)
  - The LHC will continue adding to our knowledge, but is ultimately limited in precision.
  - Consensus: next big particle physics collider should be **Higgs boson** factory.
  - The **Higgs boson** is related in many ways to the remaining uncertainties.
  - A **Higgs boson** factory has the potential to reach the level of precision to find deviations from the standard model.

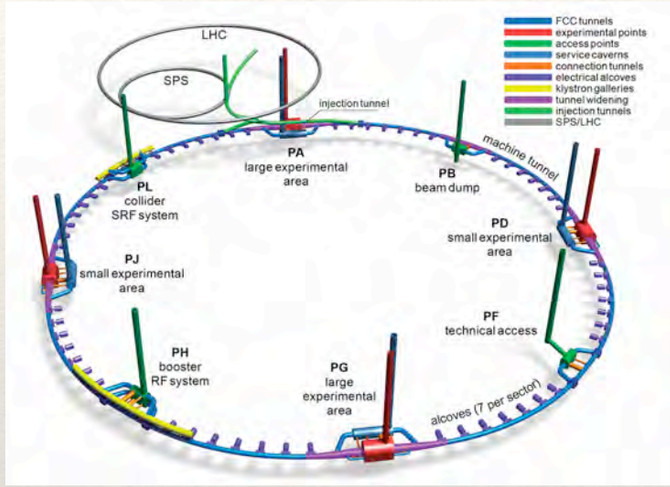
Higgs boson factory proposals

- LINEAR COLLIDERS (ILC,C3,CLIC)



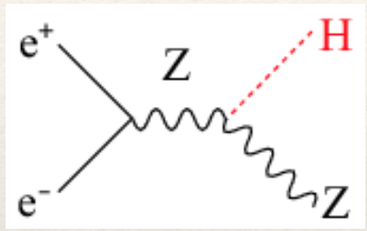
- TeV energy reach
- Longitudinal polarization
- Bunched pulse trains
- Energy efficient
- Single pass collision
- 20-30 km length (250-500 GeV ILC)

- CIRCULAR COLLIDERS (FCCee,CEPC)

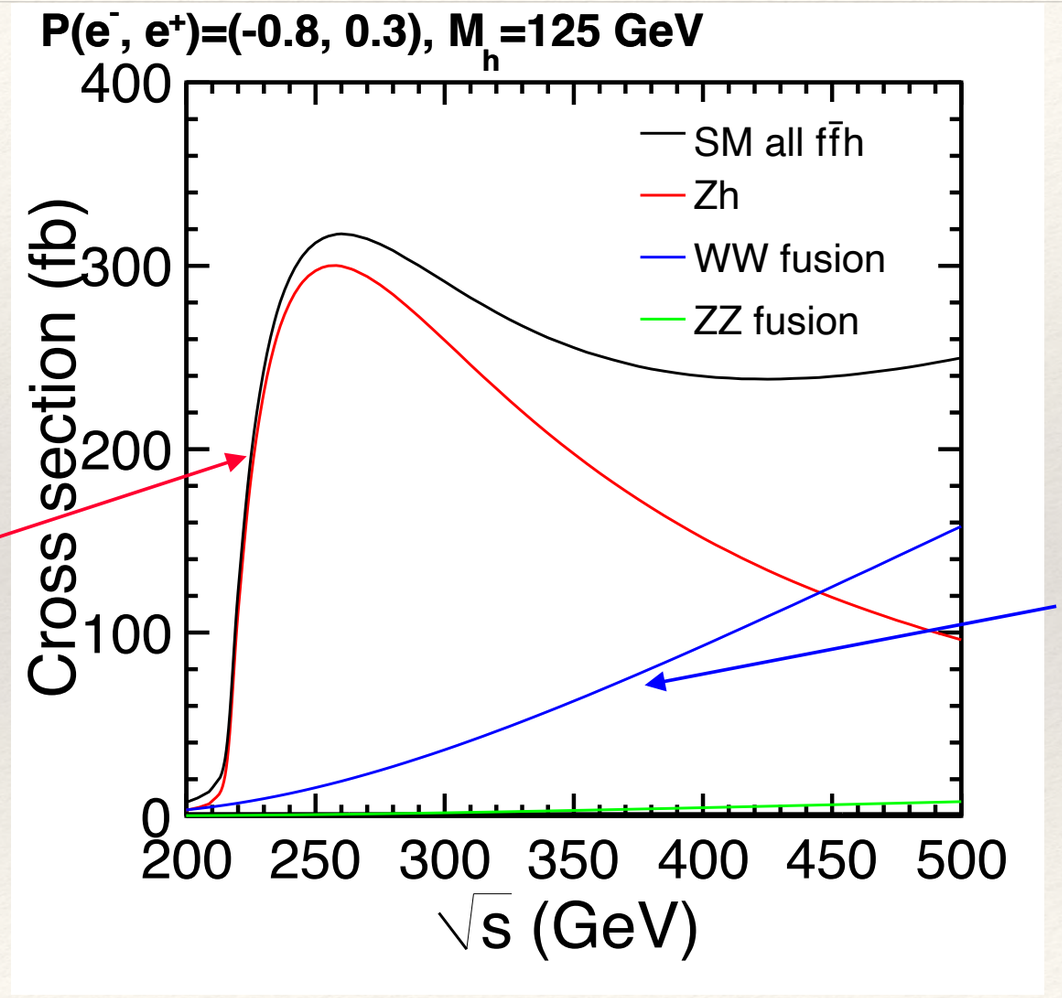


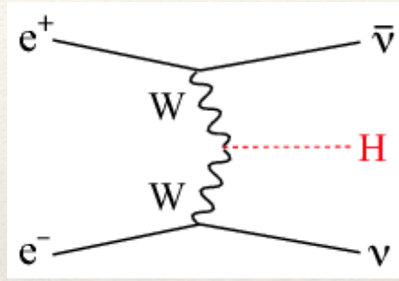
- 400 GeV energy limit
- Beam polarization challenging
- Very high luminosity for Z, WW
- High power required
- Continuous collisions
- 91 km circumference

Higgs Boson Cross Section



Higgs-strahlung peaks and falls with center-of-mass energy





WW fusion rising with center-of-mass energy

Higgstrahlung at 250 GeV

Higgs Factory observes Higgs recoiling from a Z, with known CM energy⇓

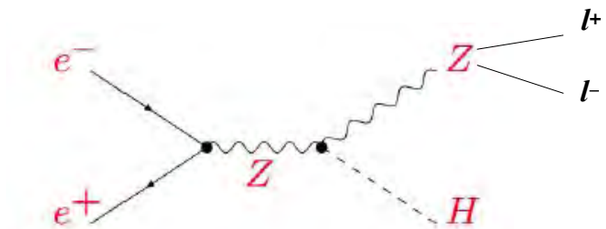
- powerful channel for unbiassed tagging of Higgs events
- measurement of even invisible decays

(⇓ - some beamstrahlung)

1. KNOWN INTIAL STATE

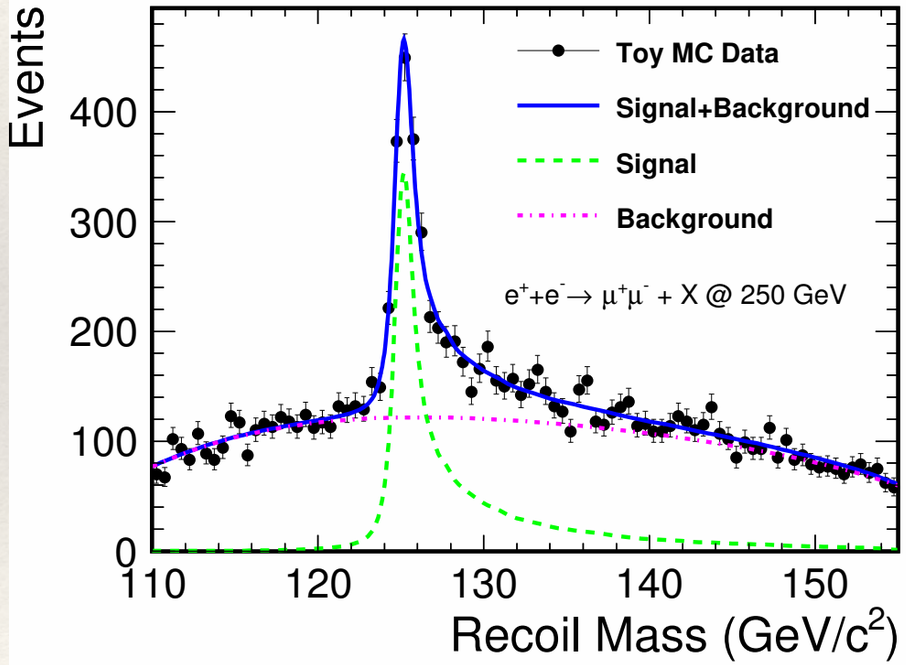
2. MEASURE Z→ l^+l^-

3. SELECT E(Z boson) = 110 GeV
M(recoil) = 125 GeV



4. MEASURE RECOIL
AND OBSERVE DECAY

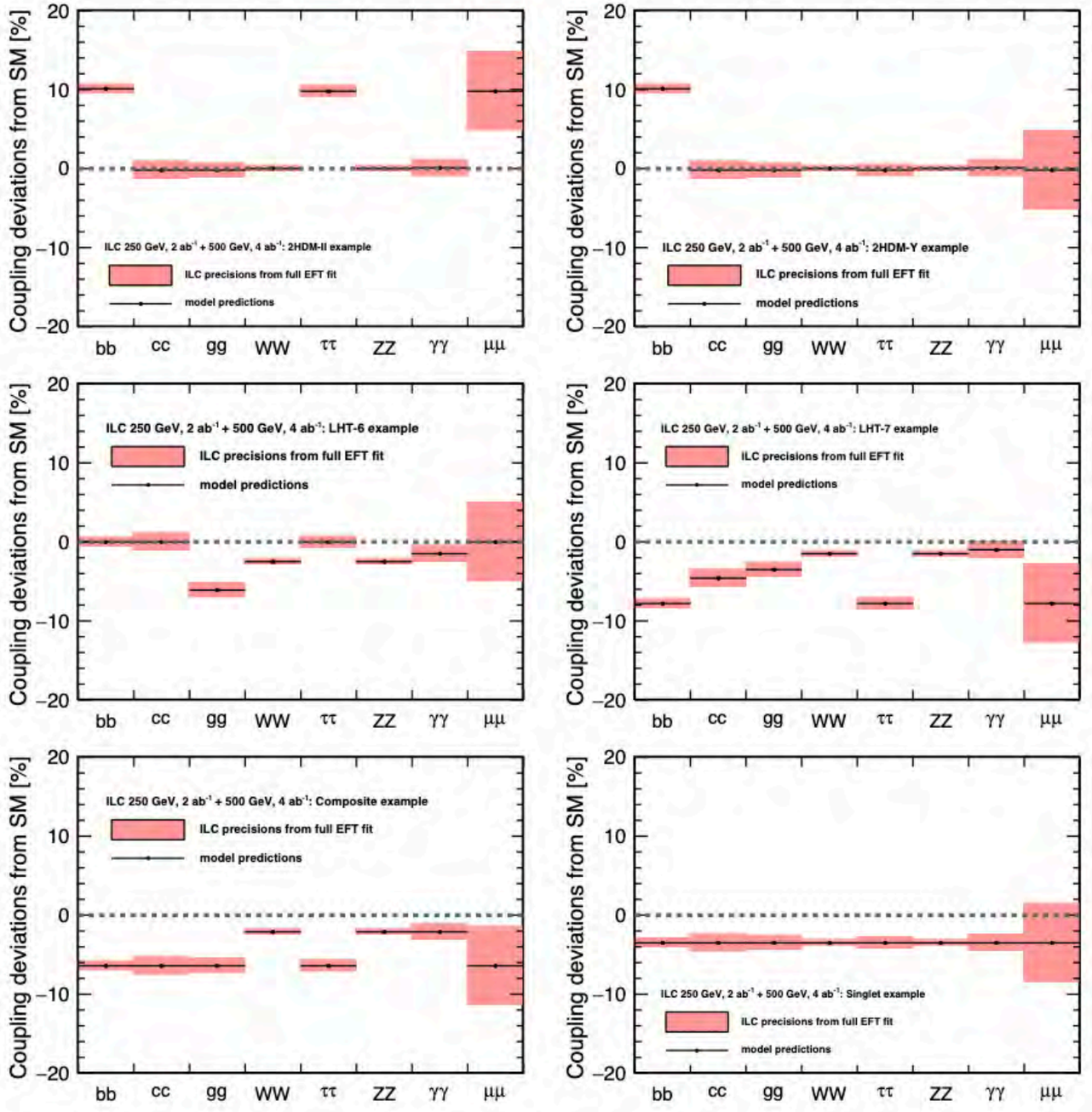
Invisible decays are included



arXiv:1604.07524, PRD94 (2016) 113002

New physics

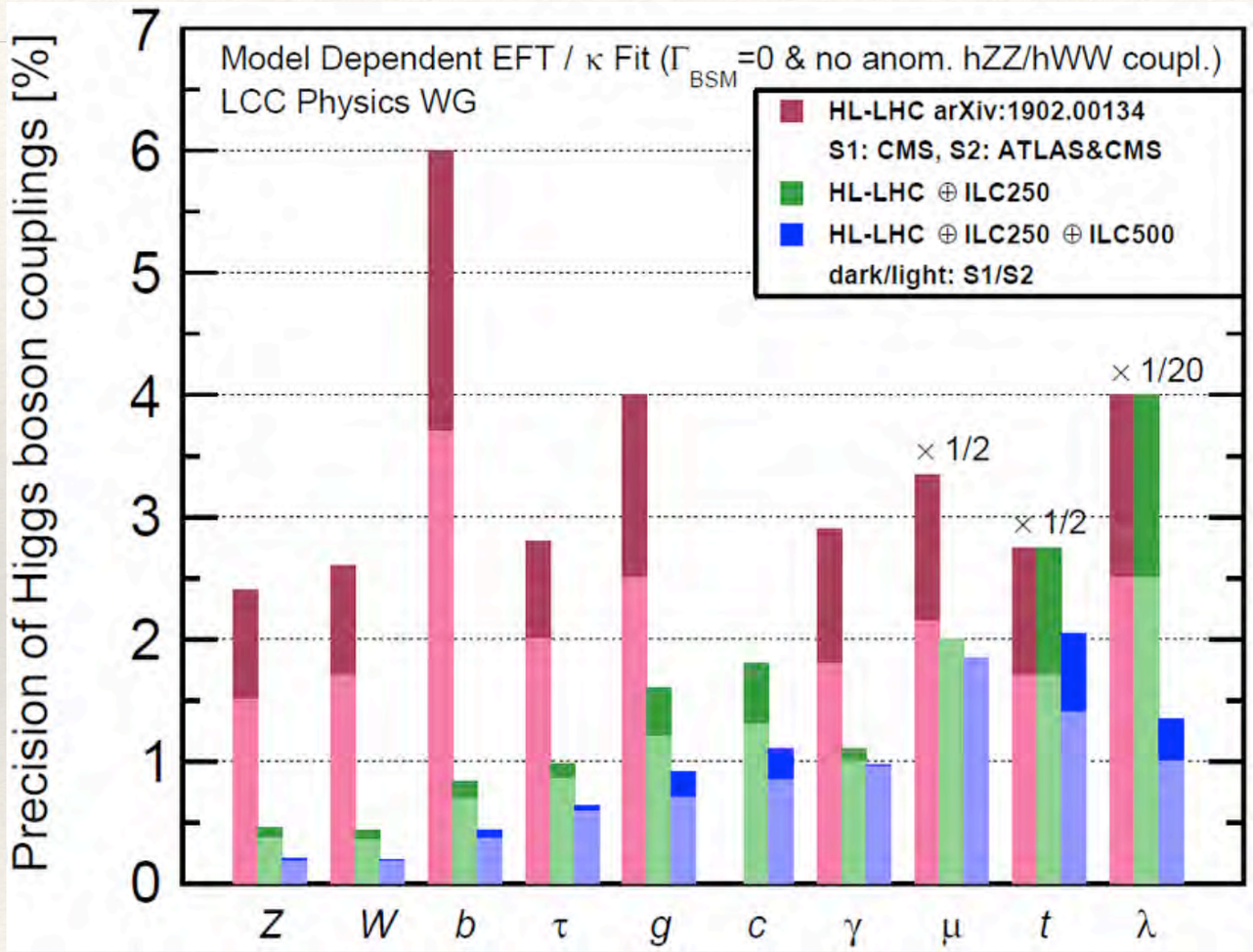
- Each potential new physics
  - Dark matter models
  - Exotic Higgs
  - Etc.
- Has distinct effect on **Higgs boson** couplings
- This is what the **Higgs boson** factory will look for



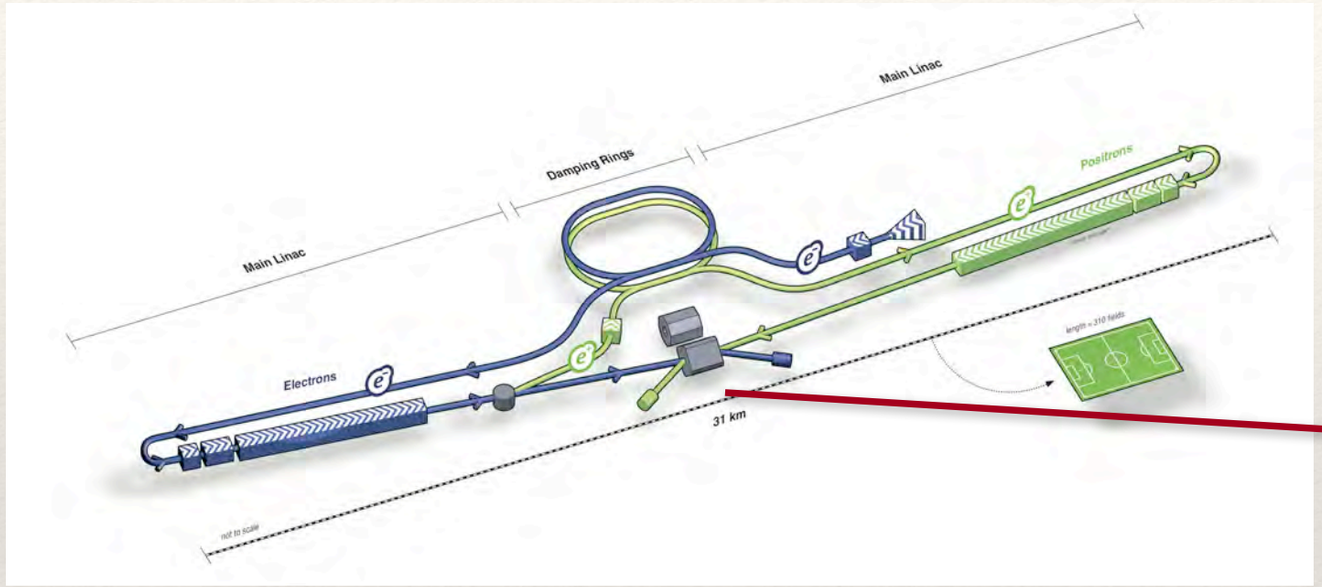
arXiv:2203.07622 [physics.acc-ph]

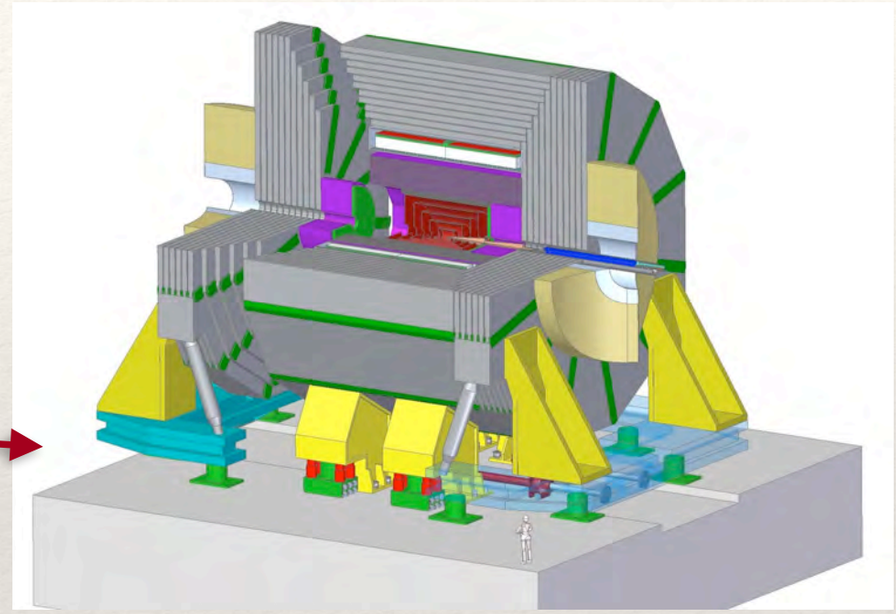
Higgs boson couplings (LHC vs. **Higgs boson** factory)

- **Higgs boson** factory can significant improve measurement
- Reveal new physics interacting through the **Higgs boson**



International Linear Collider





- **Higgs boson** project best prepared to start construction now
- Ten year construction period
- Could operate by 2035-2040

- SiD (Silicon detector)
- Silicon tracking (MAPS)
- Silicon calorimeter (MAPS)

Conclusion

- The Big Bang happened 13.8 billion years ago
- The particles produced in the “primordial soup” were initially massless, traveling and the speed of light
- Then, the **Higgs boson** field appeared, and the particles acquired mass
- Our knowledge of that early era, and the nature of structure of matter today, relies on our knowledge of the **Higgs boson**
- Globally, the physics world is preparing for the era of the **Higgs boson** factory
  - Many remaining unknowns may be revealed
- In the **very, very, very distant future**, there is the possibility that the **Higgs boson** field could result in the **Big Slurp**

Recent paper of interest

Scale-invariant Instantons and
the Complete Lifetime of the Standard Model

Anders Andreassen*, William Frost†, and Matthew D. Schwartz‡

Department of Physics, Harvard University, Cambridge, MA 02138, USA

arXiv:1707.08124 [hep-ph]

- we produce the first complete calculation of the lifetime of our universe: 10^{161} years. With 95% confidence, we expect our universe to last more than 10^{65} years.

Combining all our results together we produced a complete prediction for the lifetime of our metastable vacuum in the Standard Model. We find the lifetime to be

$$\tau_{\rm SM} = 10^{161^{+160}_{-59}} \qquad (8.1)$$