Where is Particle Physics Going?

Beyond the Standard Model

How do we achieve our goal?

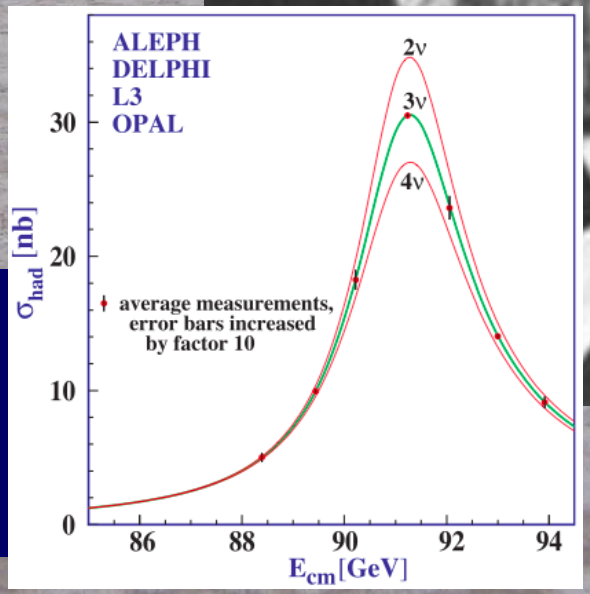
John Ellis

KING'S College LONDON

The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg

Tested by experiments at CERN

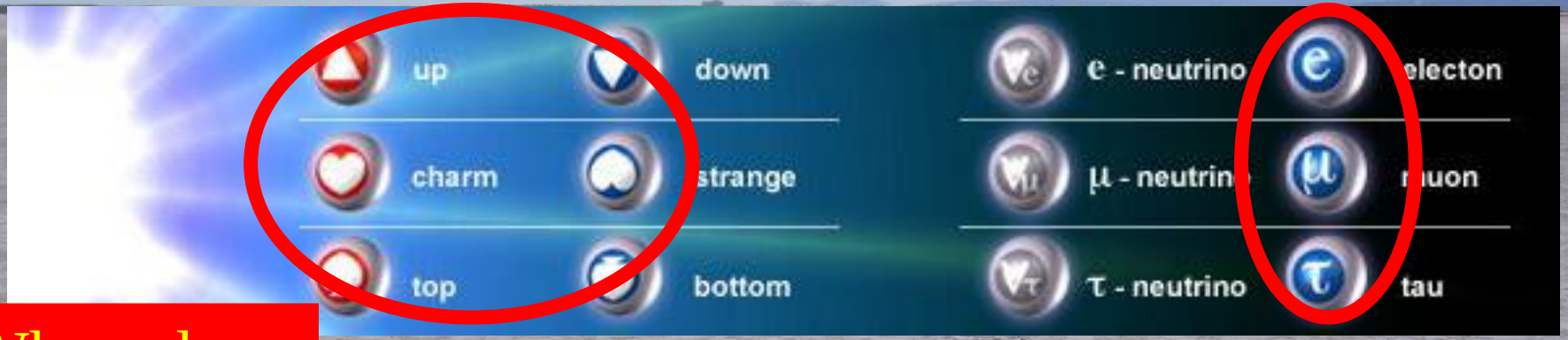


Perfect agreement between theory and experiments in all laboratories

The ‘Standard Model’

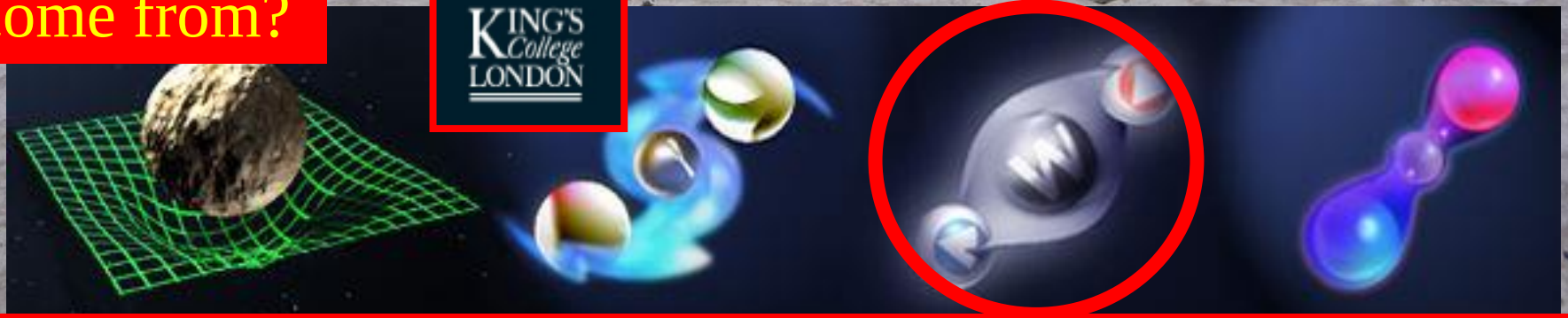
= Cosmic DNA

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Why do Things Weigh?

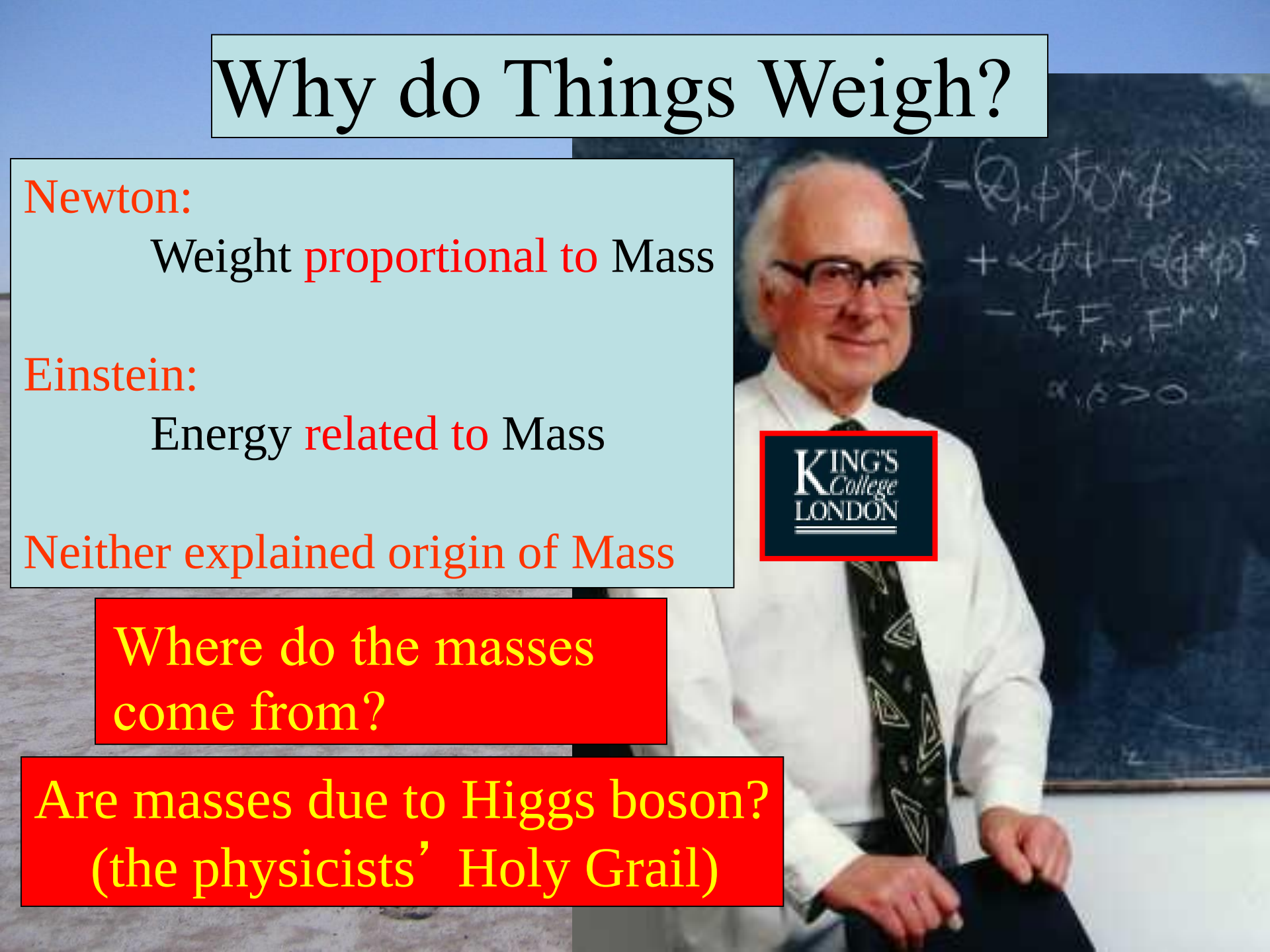
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



Where do the masses come from?

Are masses due to Higgs boson? (the physicists' Holy Grail)

Think of a Snowfield

The LHC looked for the snowflake: The Higgs Boson

Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow, moves slower:
Like particle with mass
e.g., electron

Hiker sinks deep, moves very slowly:
Particle with large mass

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

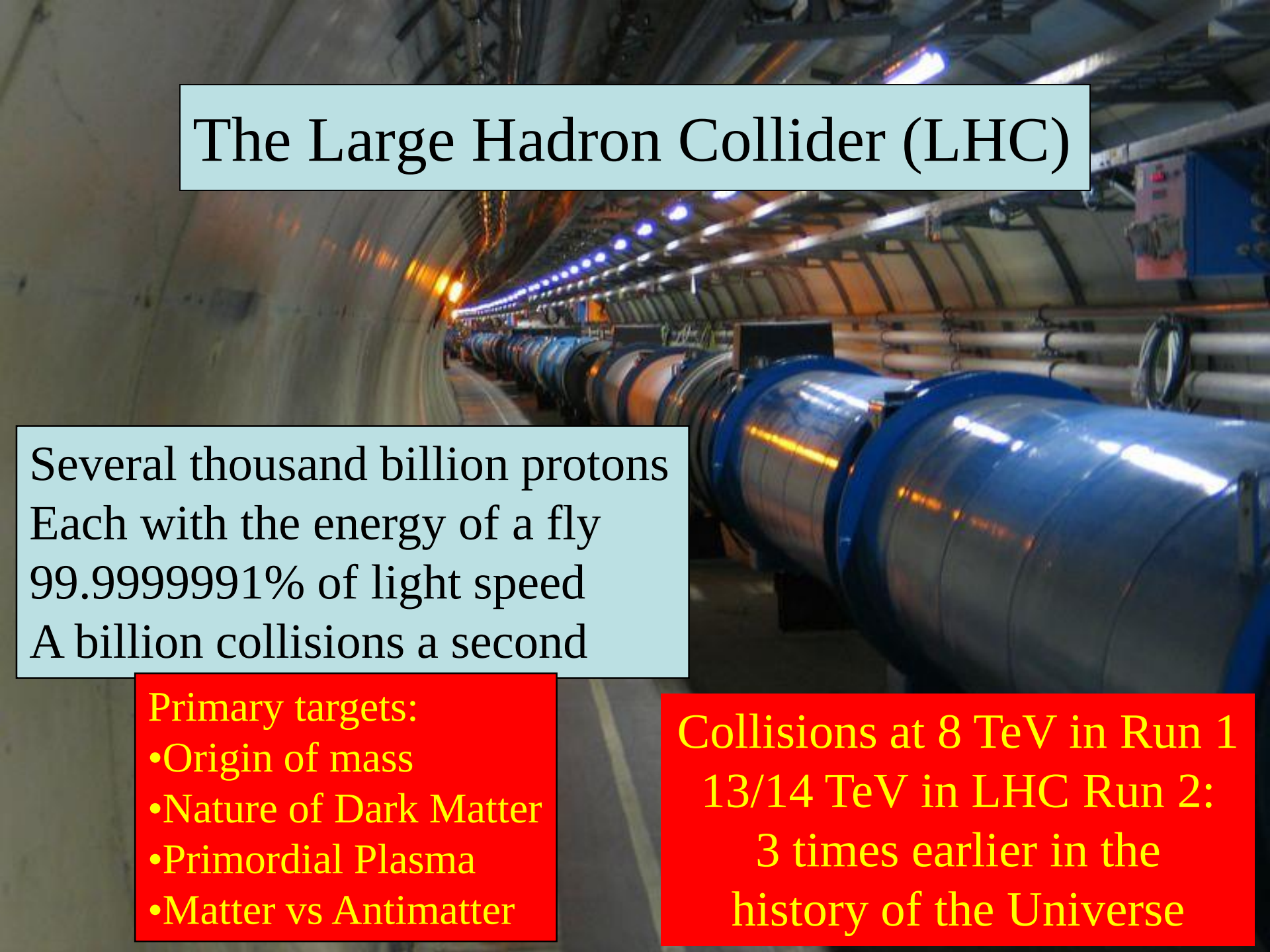
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



The Large Hadron Collider (LHC)

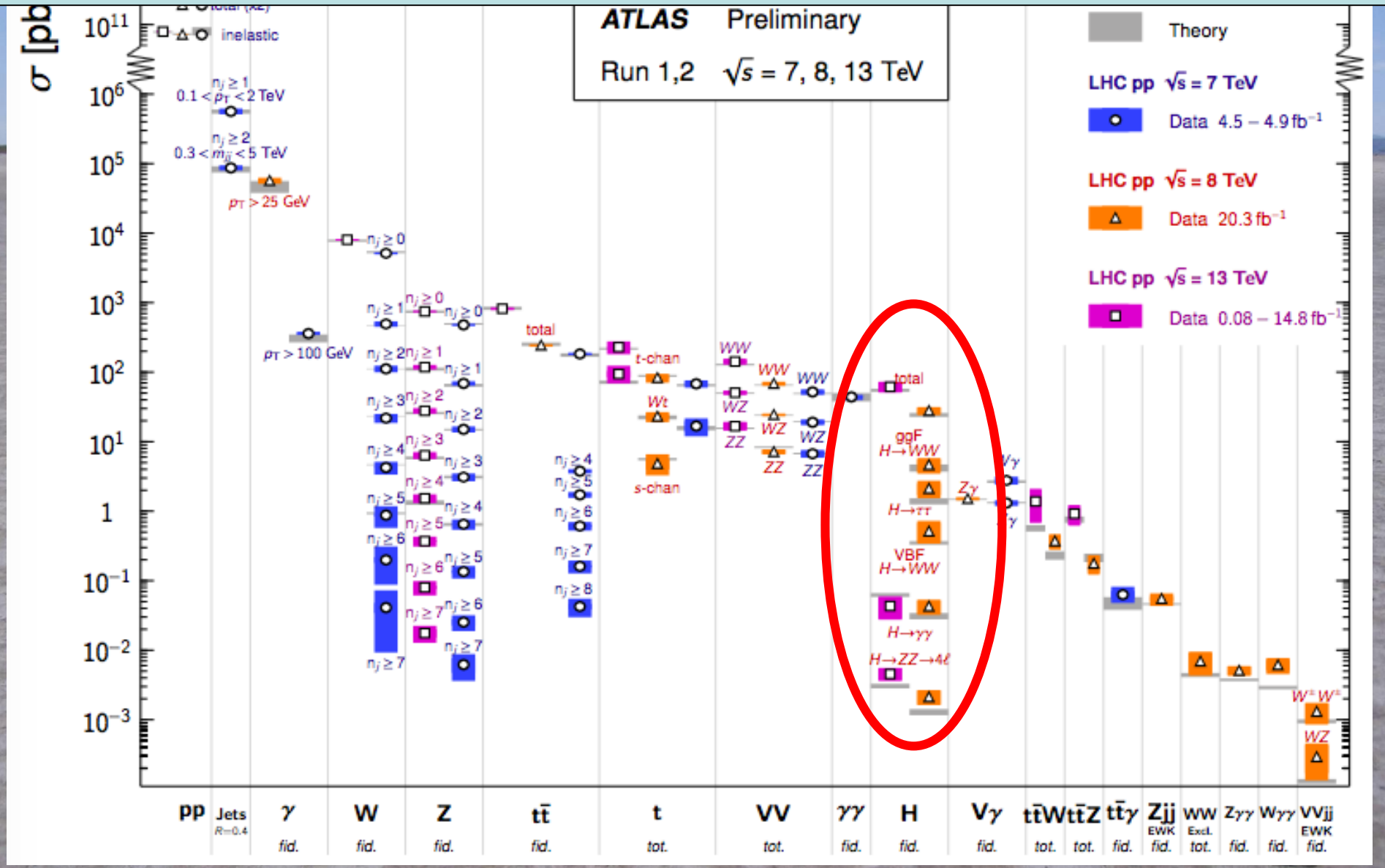
Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
A billion collisions a second

Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

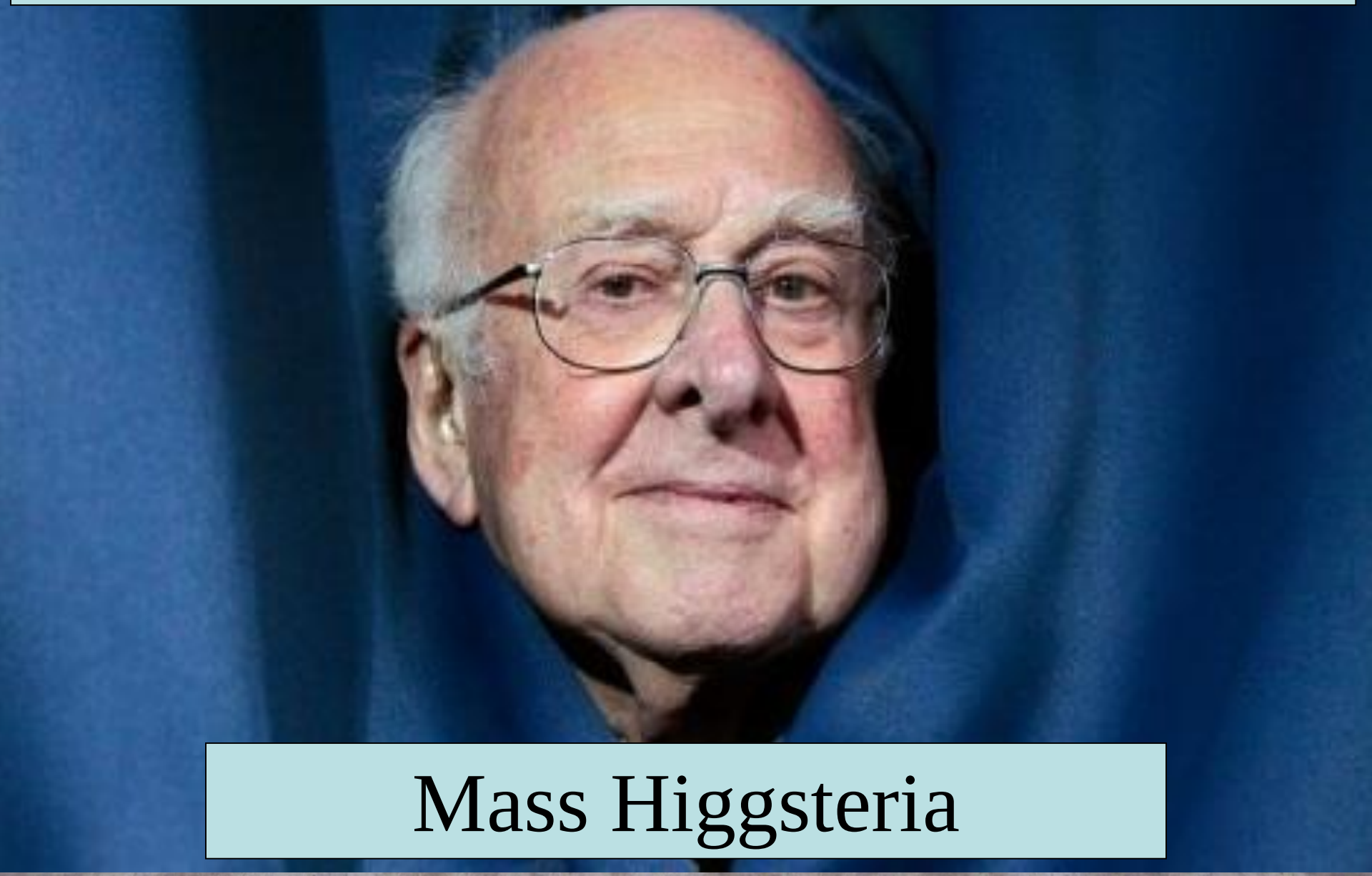
Collisions at 8 TeV in Run 1
13/14 TeV in LHC Run 2:
3 times earlier in the
history of the Universe

“Stairway to Heaven”

Standard Model Cross-Sections @ LHC

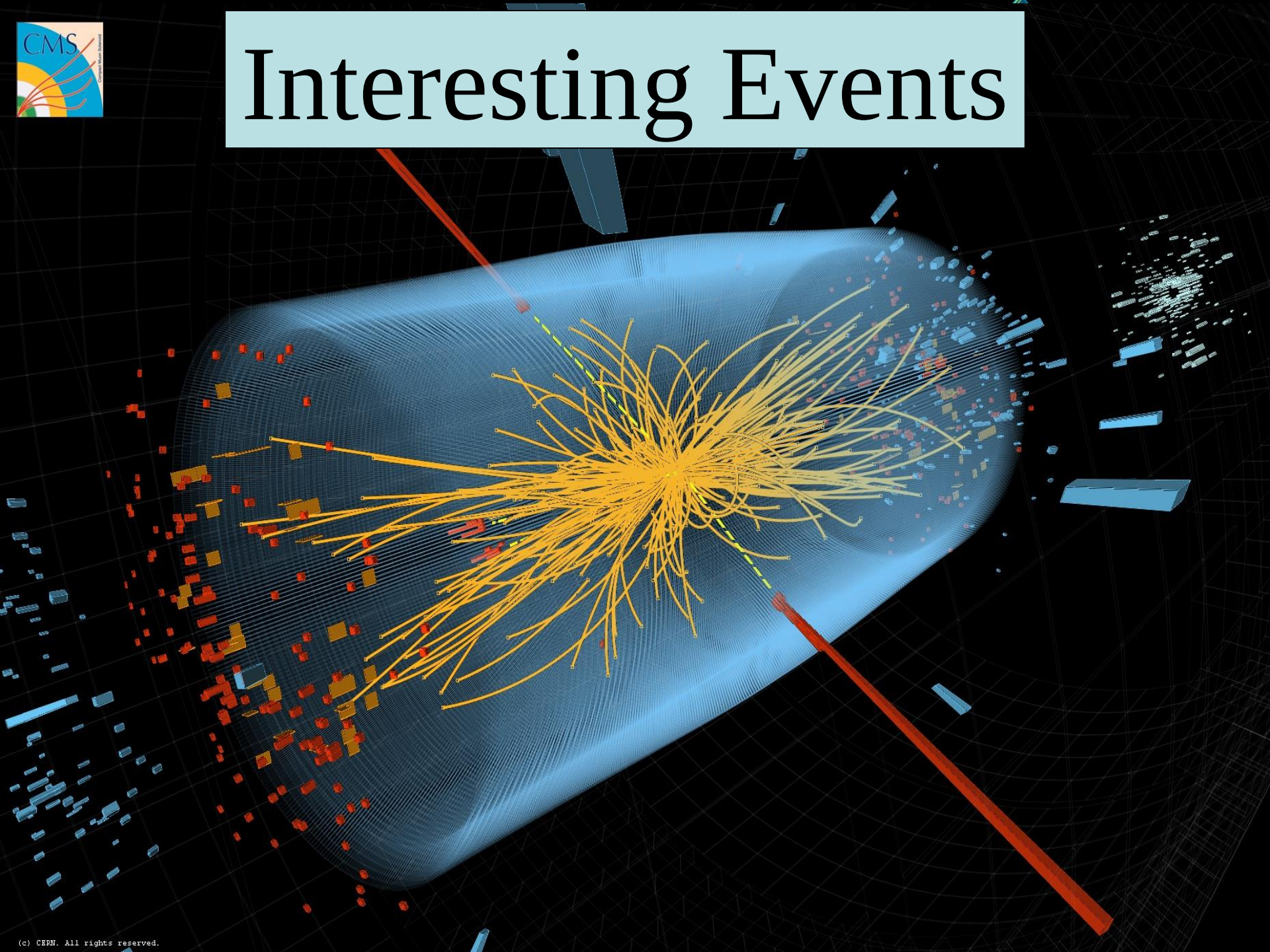


The Discovery of the Higgs Boson

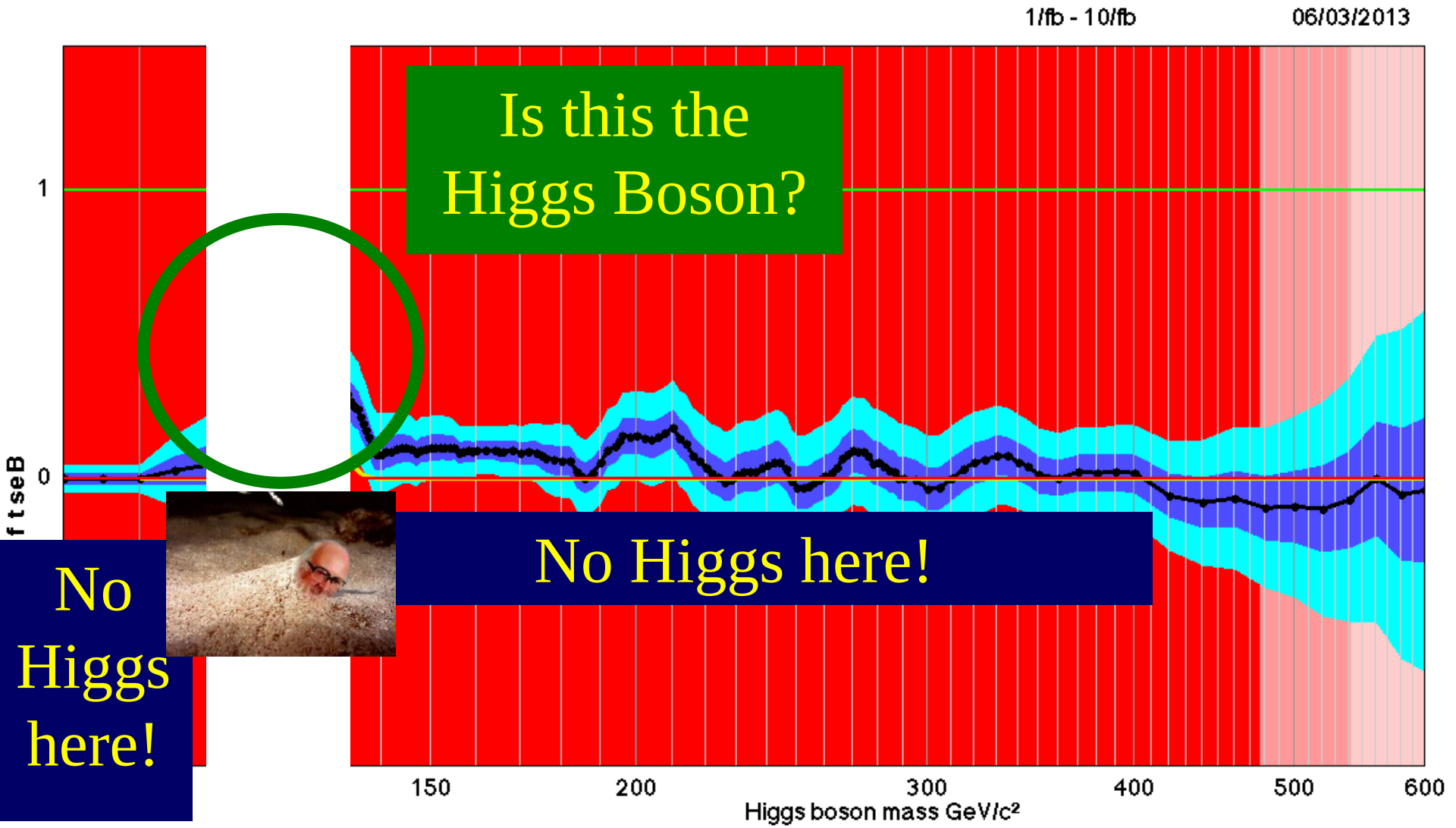


Mass Higgsteria

Interesting Events

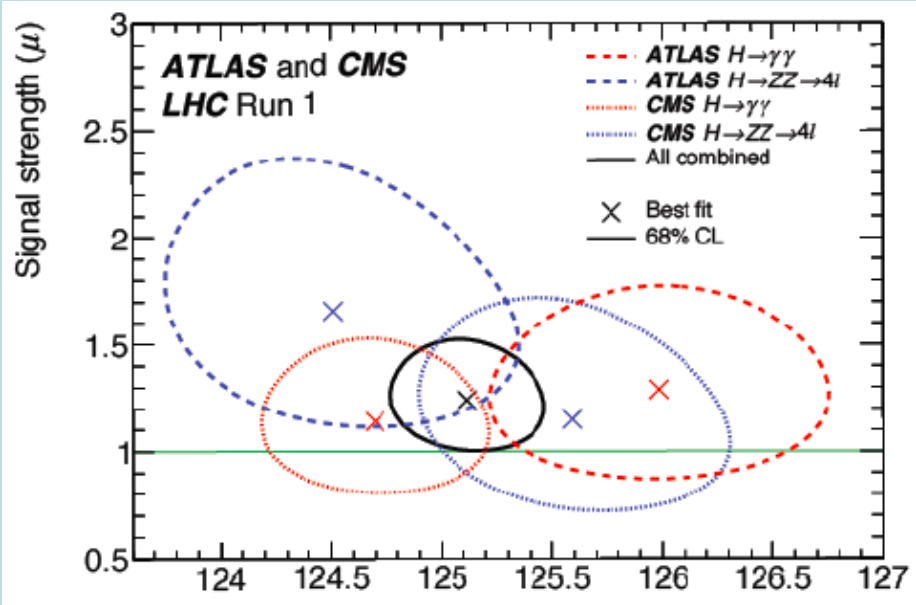


Unofficial Combination of Higgs Data



Higgs Mass Measurements

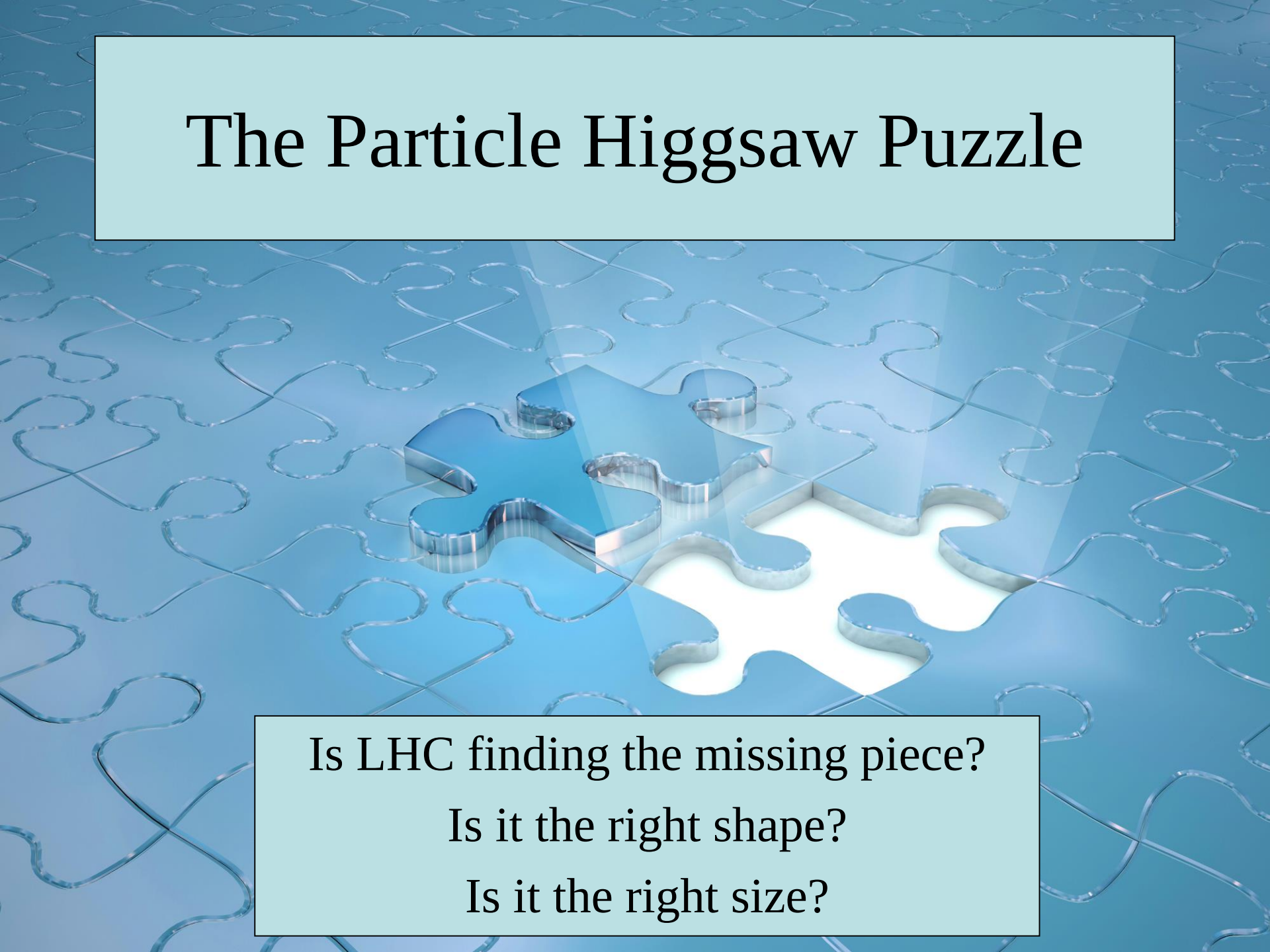
- ATLAS + CMS ZZ^* and $\gamma\gamma$ final states



$125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$

- Statistical uncertainties dominate
- Allows precision tests
- **Crucial for stability of electroweak vacuum**

The Particle Higgsaw Puzzle

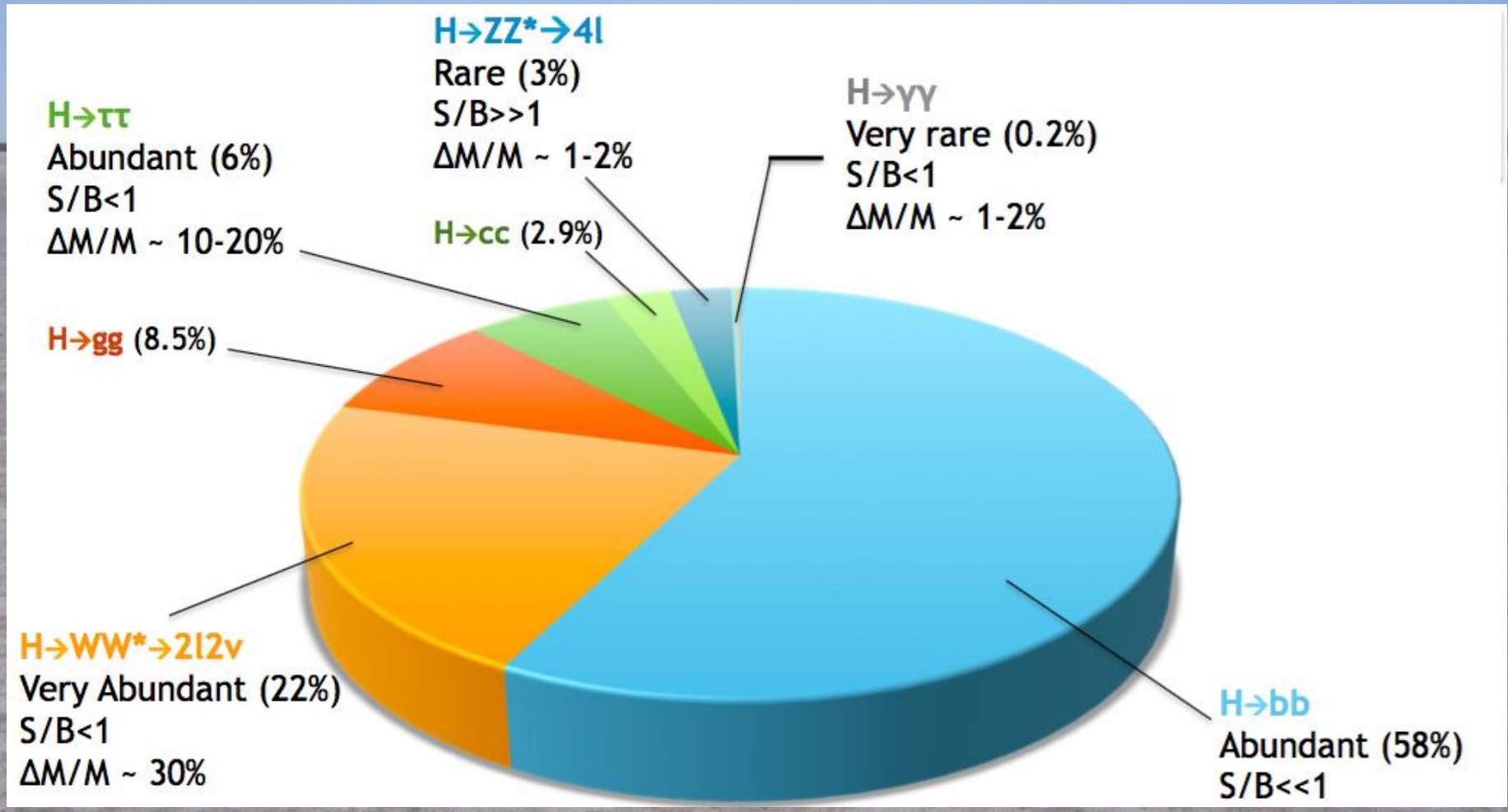


Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

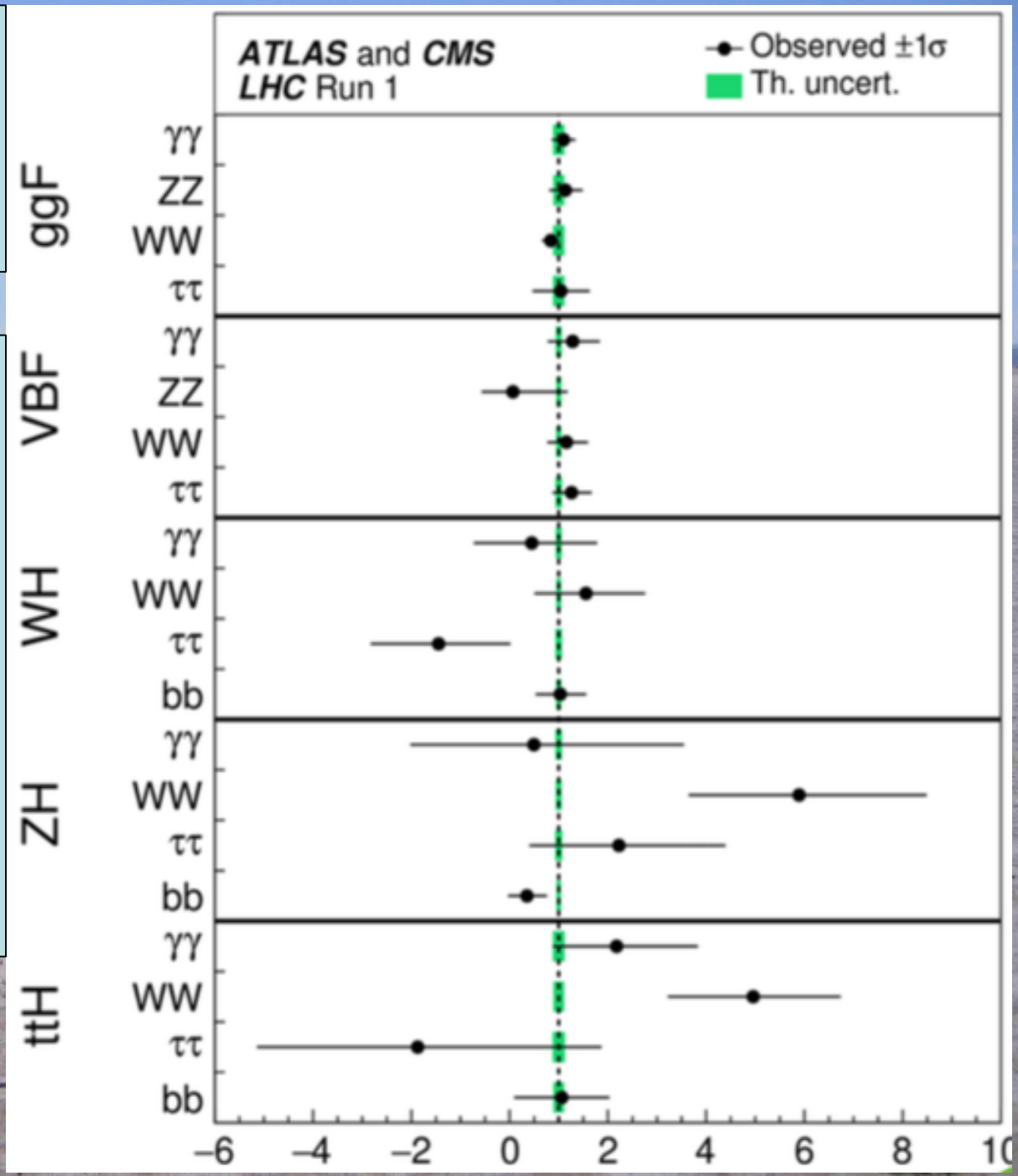
What we Expect



What do we know?

What we Know

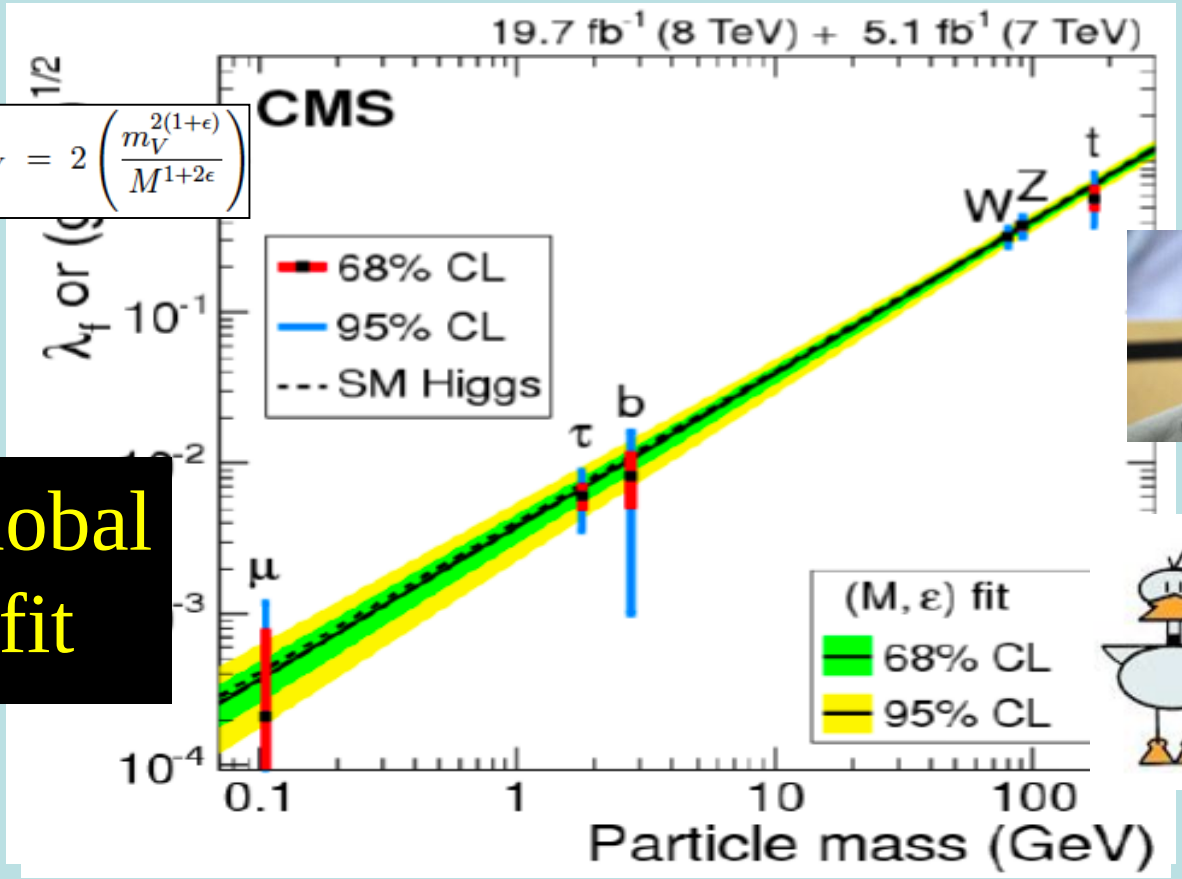
- Open questions:
  - H➔bb?
    - 2.6σ @ LHC
    - 2.8σ @ FNAL
  - H➔μμ?
  - ttH production?
  - tH production?



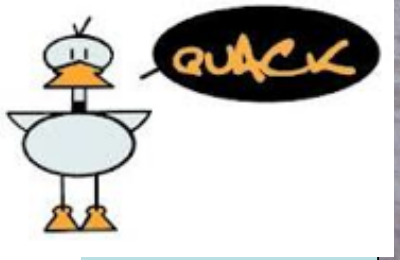
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

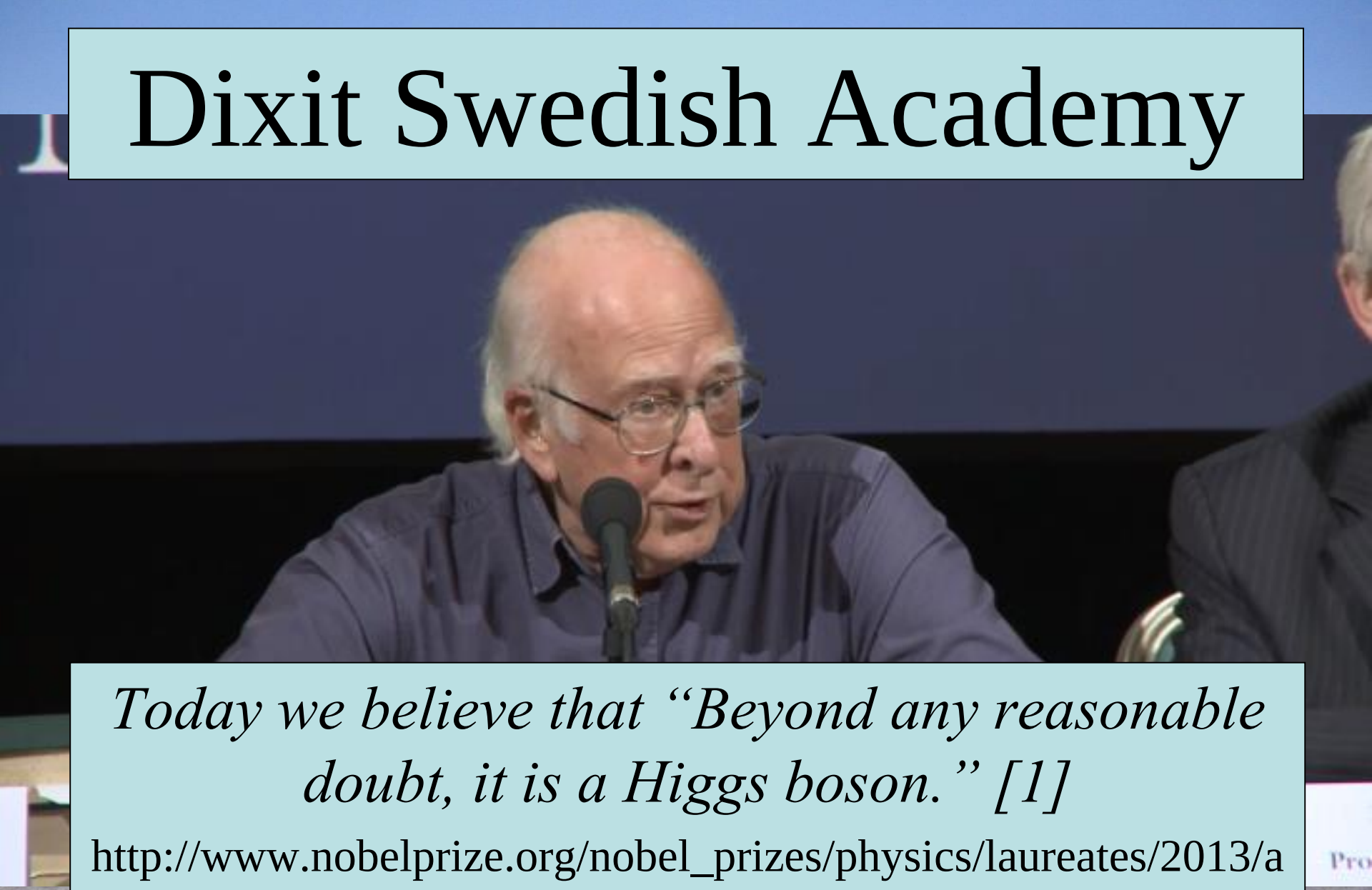


Global fit



- **Blue** dashed line = Standard Model

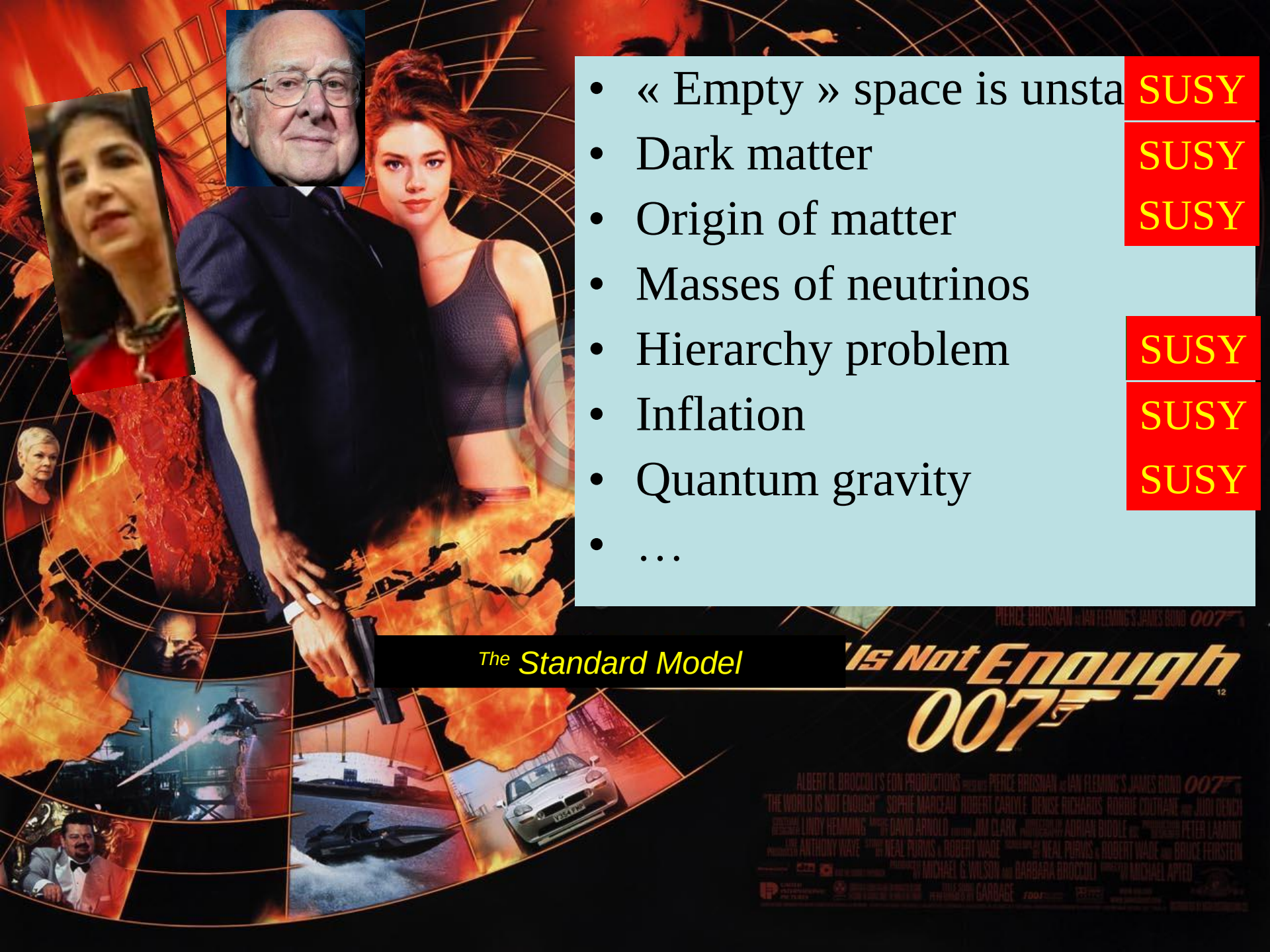
Dixit Swedish Academy



Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879

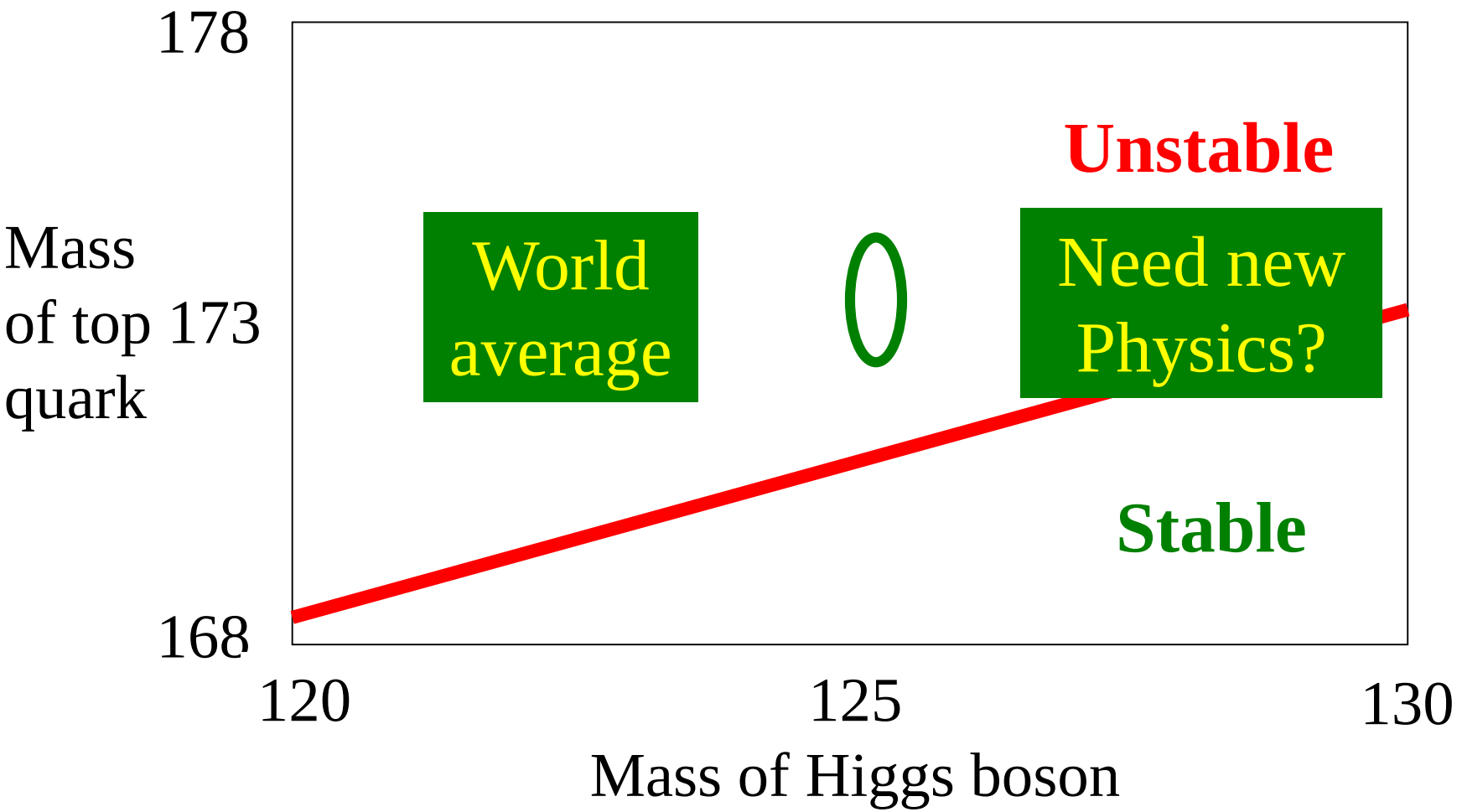


- « Empty » space is unsta SUSY
- Dark matter SUSY
- Origin of matter SUSY
- Masses of neutrinos
- Hierarchy problem SUSY
- Inflation SUSY
- Quantum gravity SUSY
- …

The Standard Model

Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark



Should it have Collapsed already?

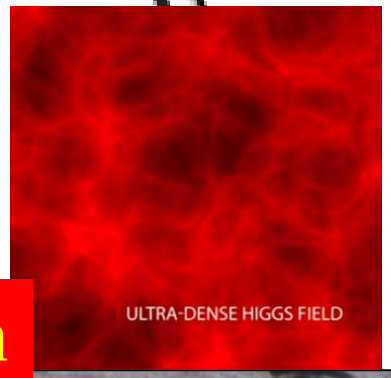
Fluctuate over barrier in the early Universe?

Not if supersymmetry: infinite barrier

We are here

Tunnel through barrier now?

Quantum fluctuations



The Big Crunch

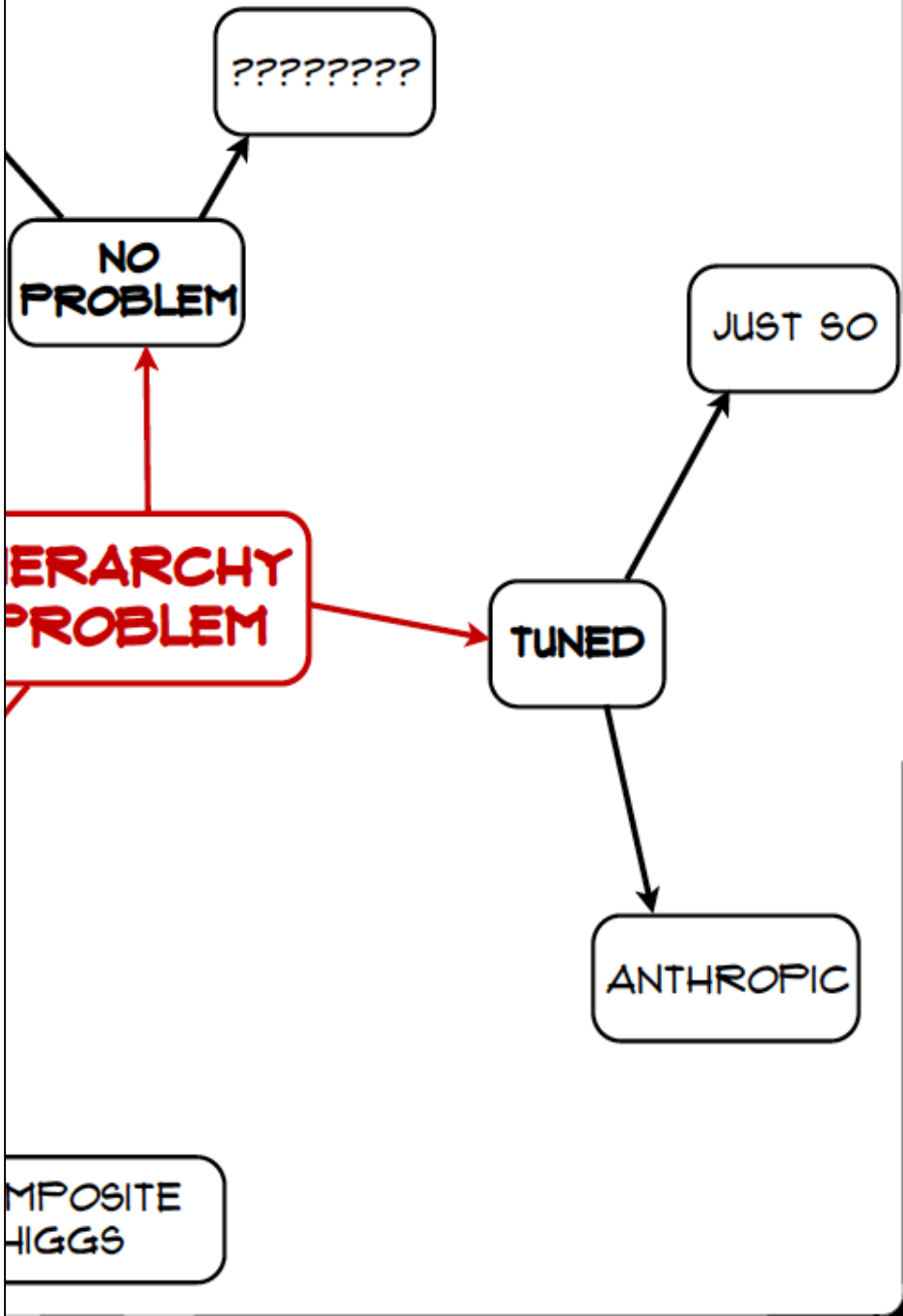
What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

If you know of a better hole, go to it

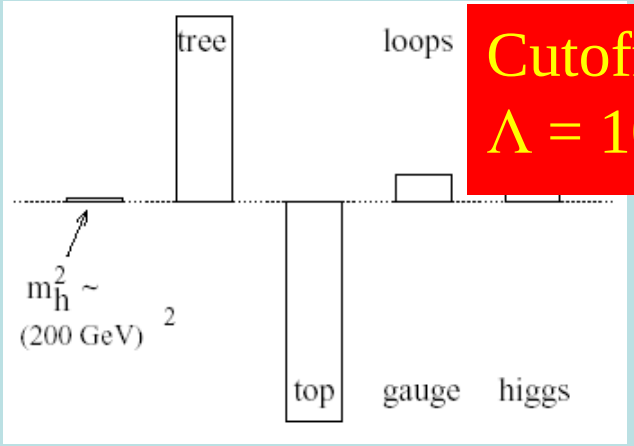


Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff
Λ = 10 TeV

Cut-off Λ ~ 1 TeV with
Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

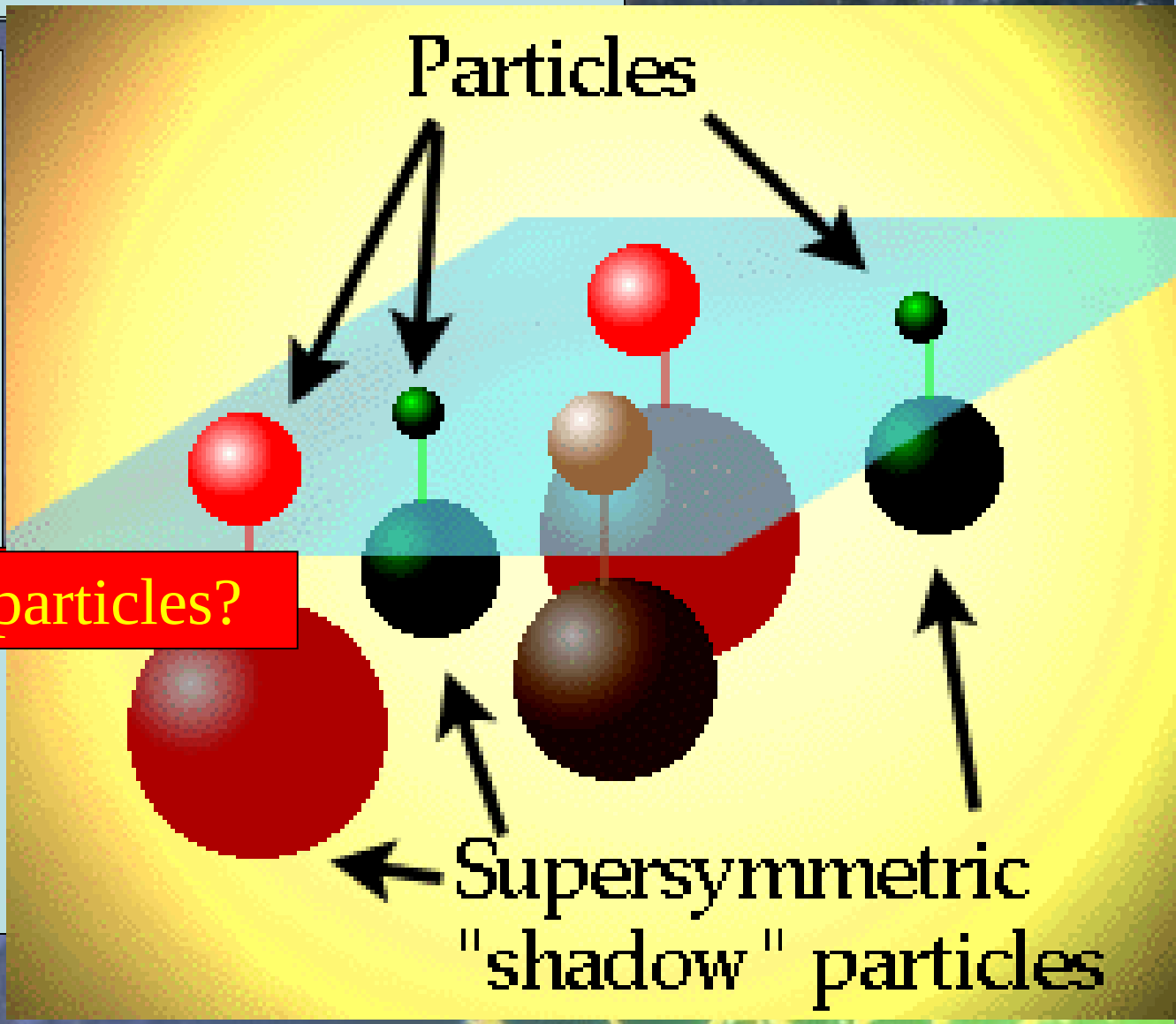
New strong interactions?
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?
- Pseudo-Nambu-Goldstone?

Dark Matter in the Universe

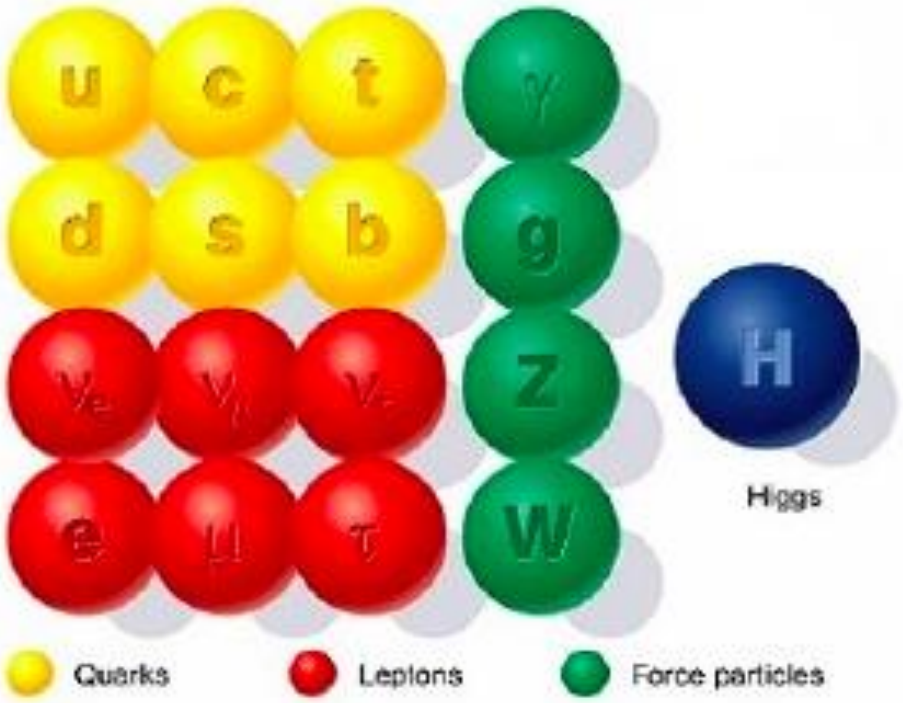
Astronomers say that most of the matter in the Universe is invisible Dark Matter

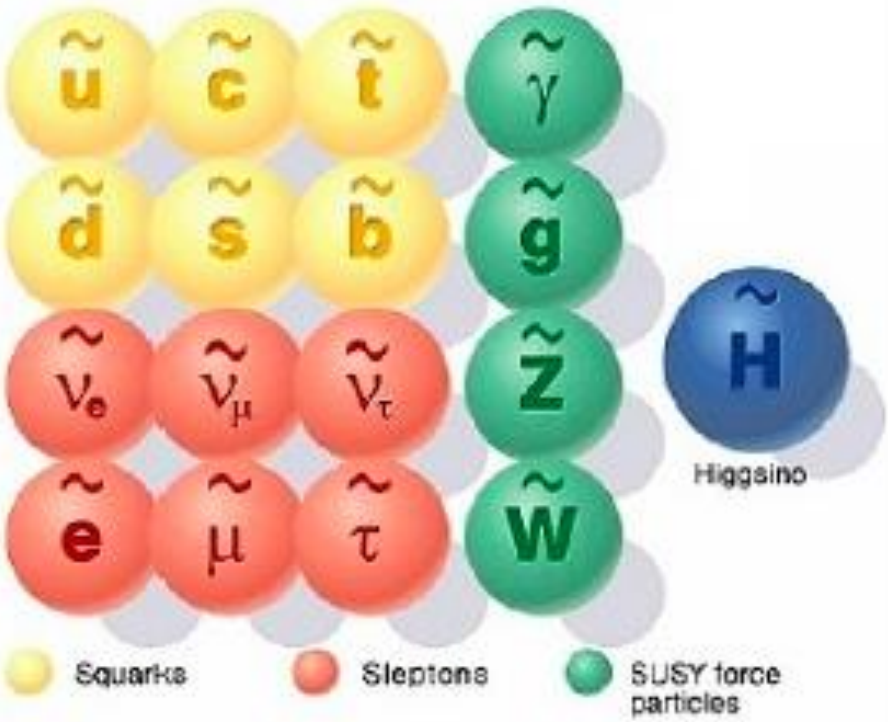
Supersymmetric particles?

Searching for them at the LHC



Minimal Supersymmetric Extension of the Standard Model

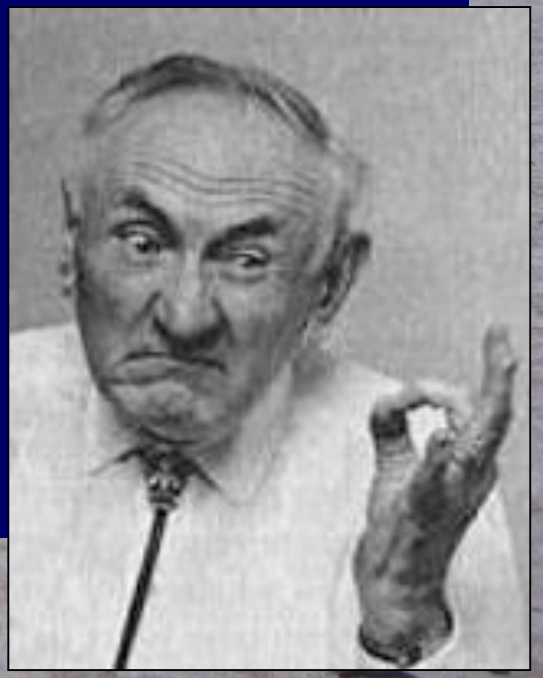




Standard particles **SUSY particles**

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**

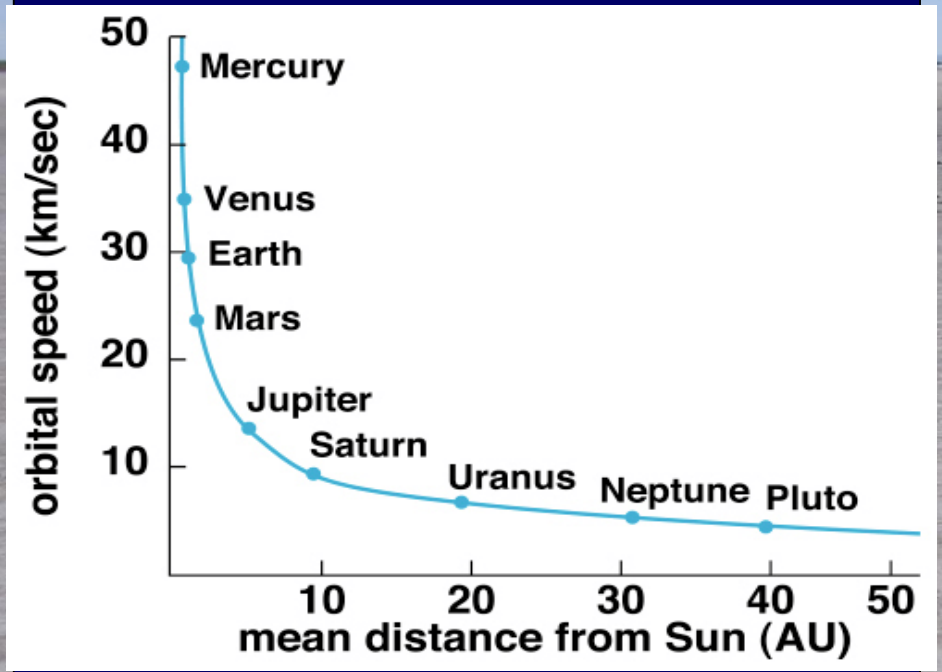


The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**

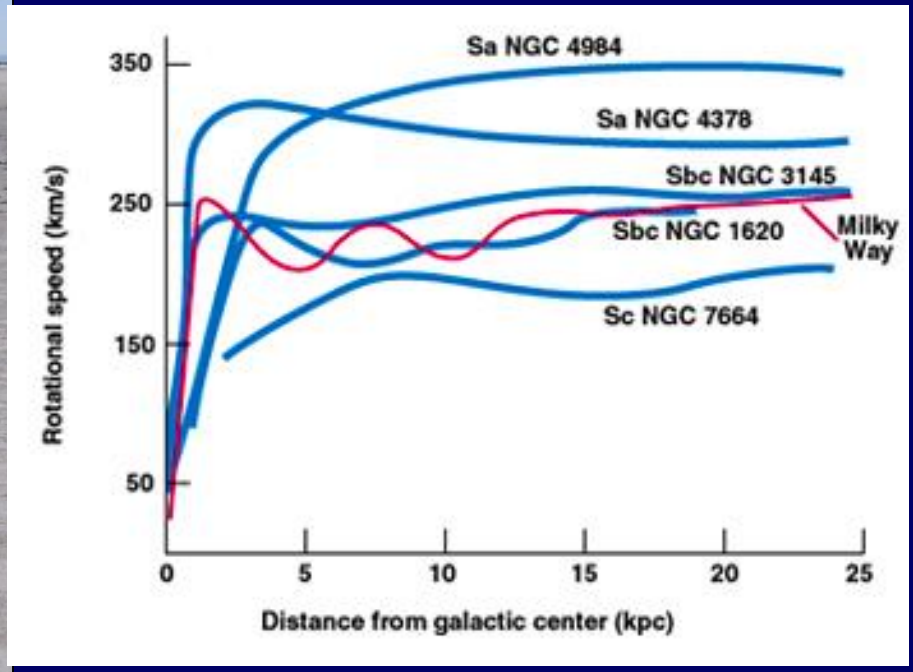
Rotation Curves

- In the Solar System



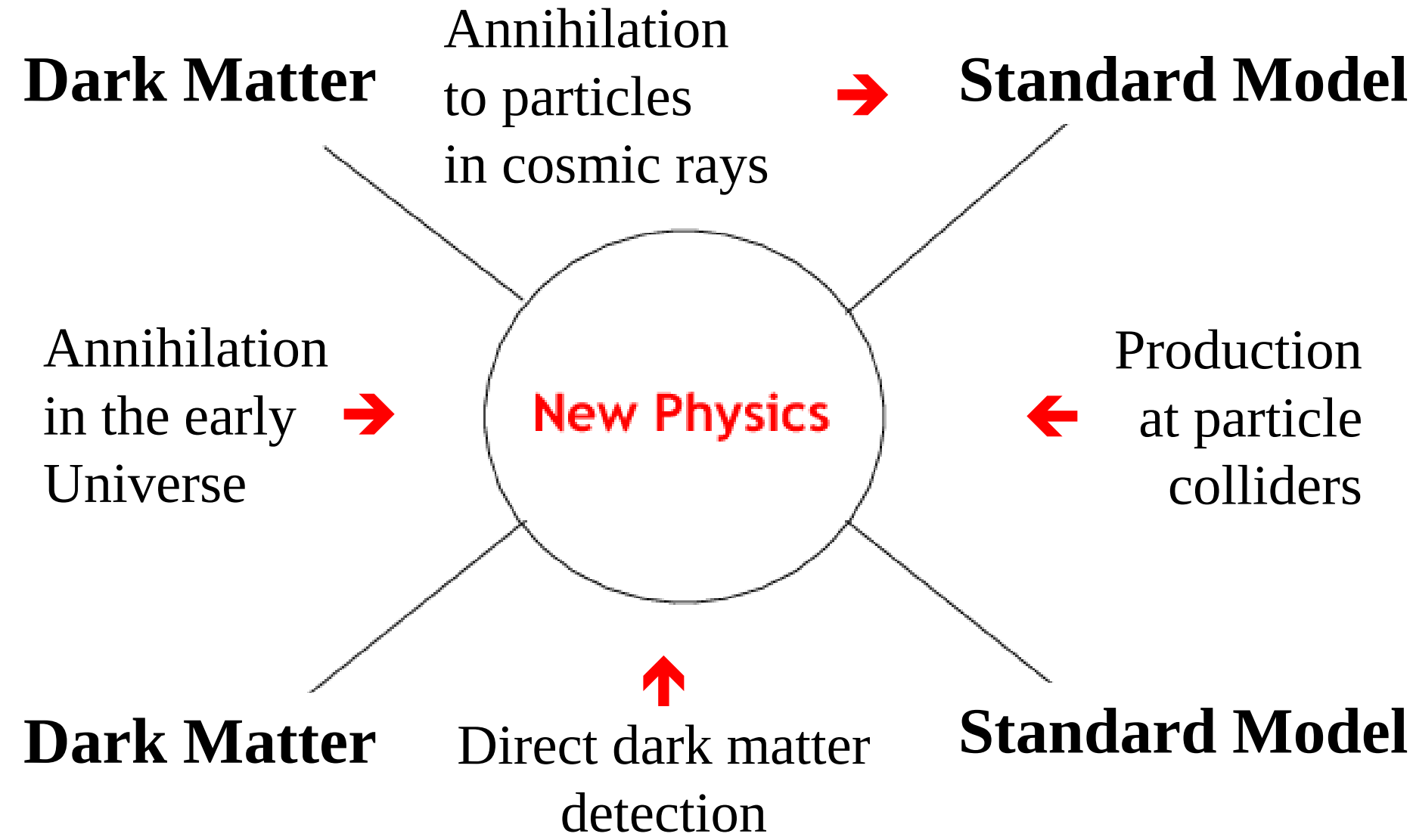
- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies

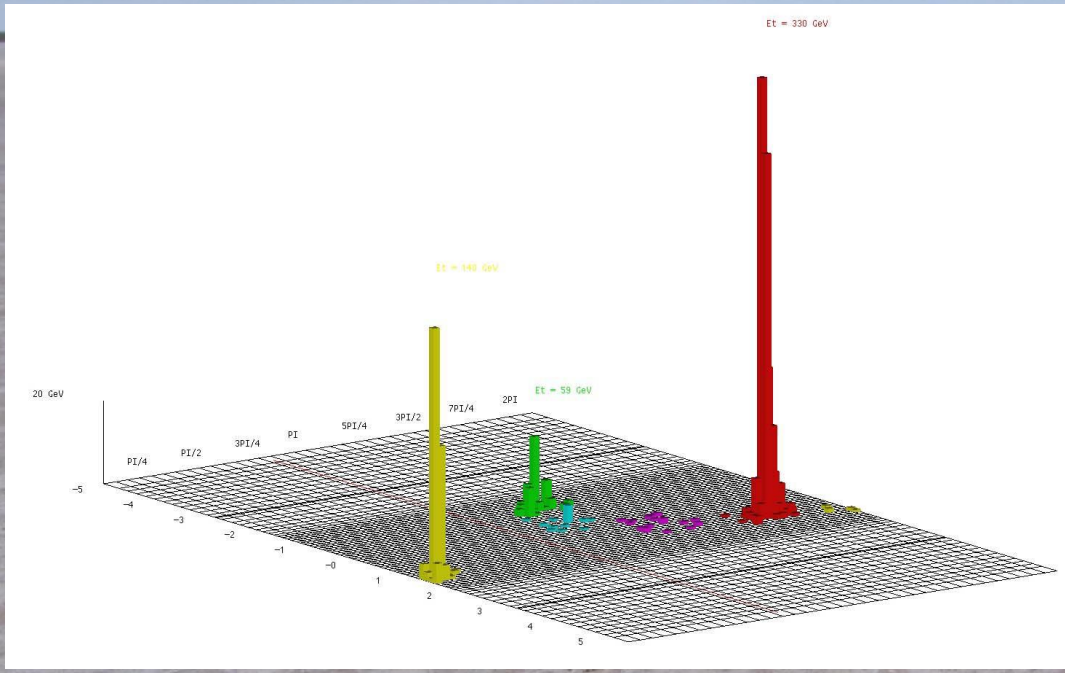


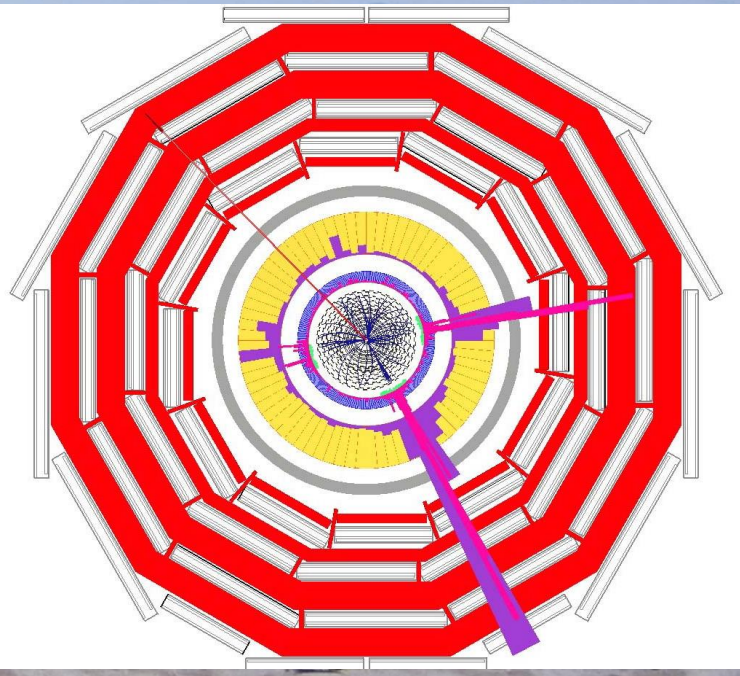
- The velocities do not decrease with distance
- Dark matter spread out

Searches for Dark Matter



Classic Dark Matter Signature



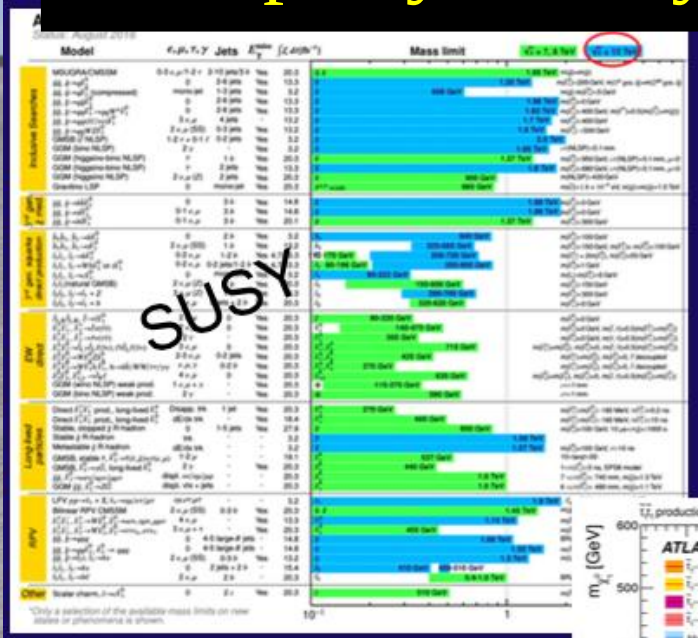


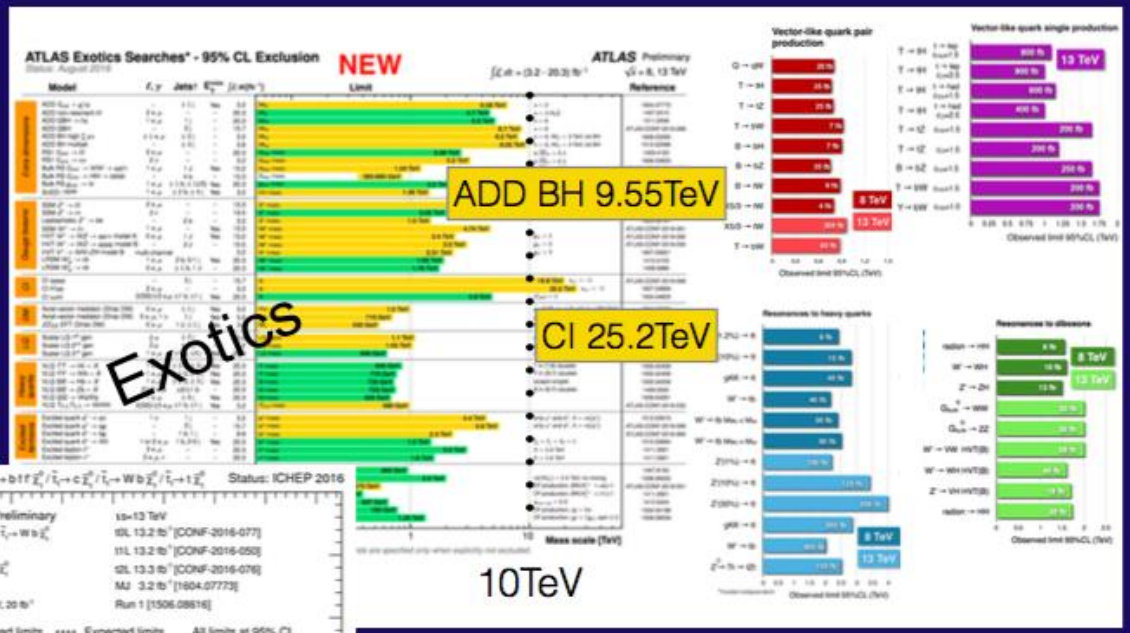
Missing transverse energy
carried away by dark matter particles

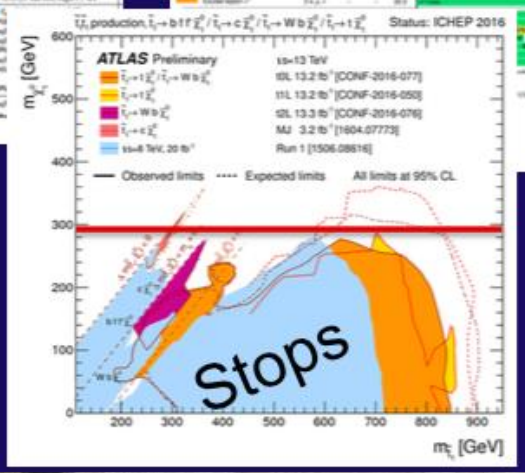
Nothing (yet) at the LHC

No supersymmetry

Nothing else, either

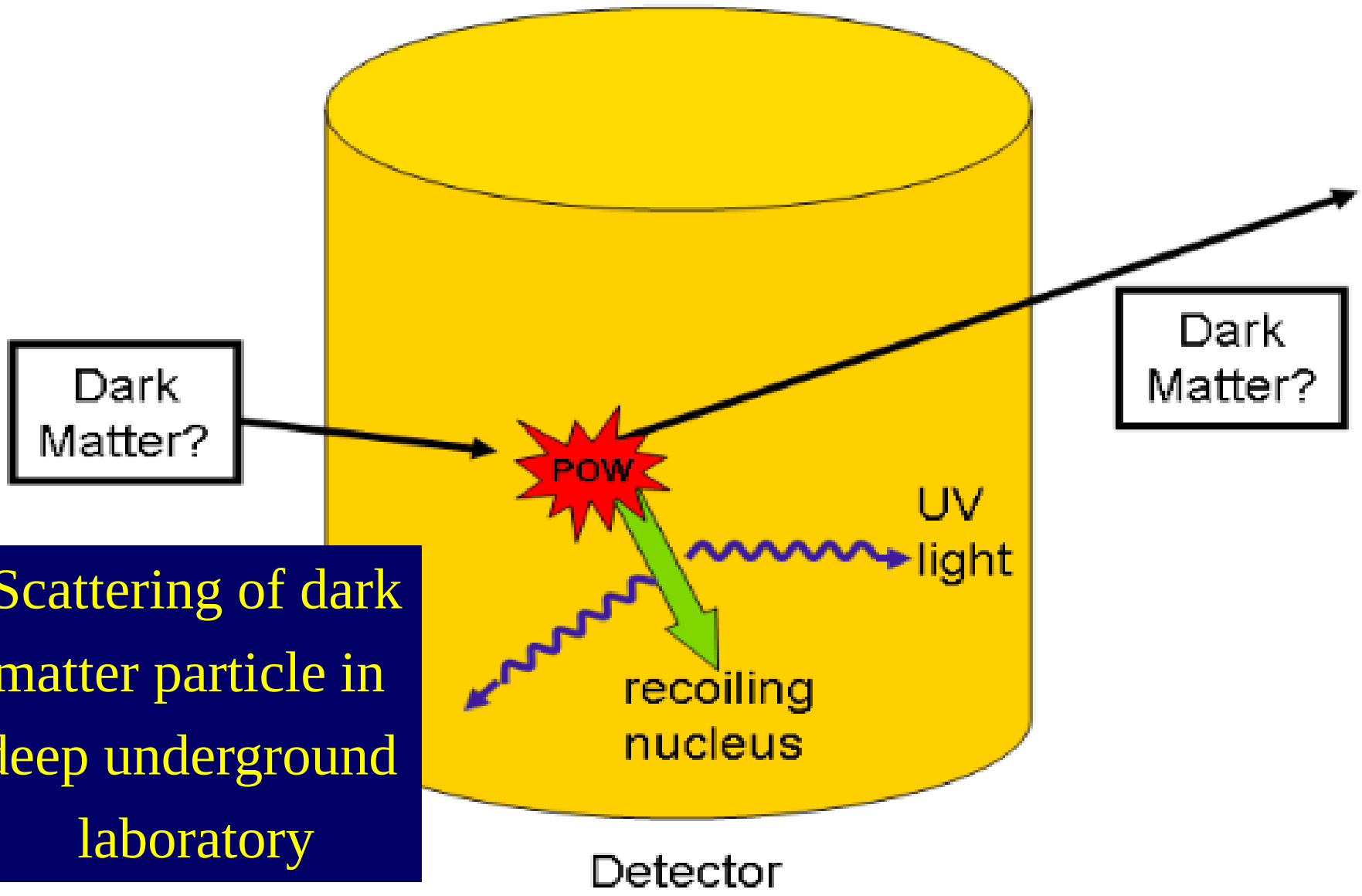






More of same?
Unexplored nooks?
Novel signatures?

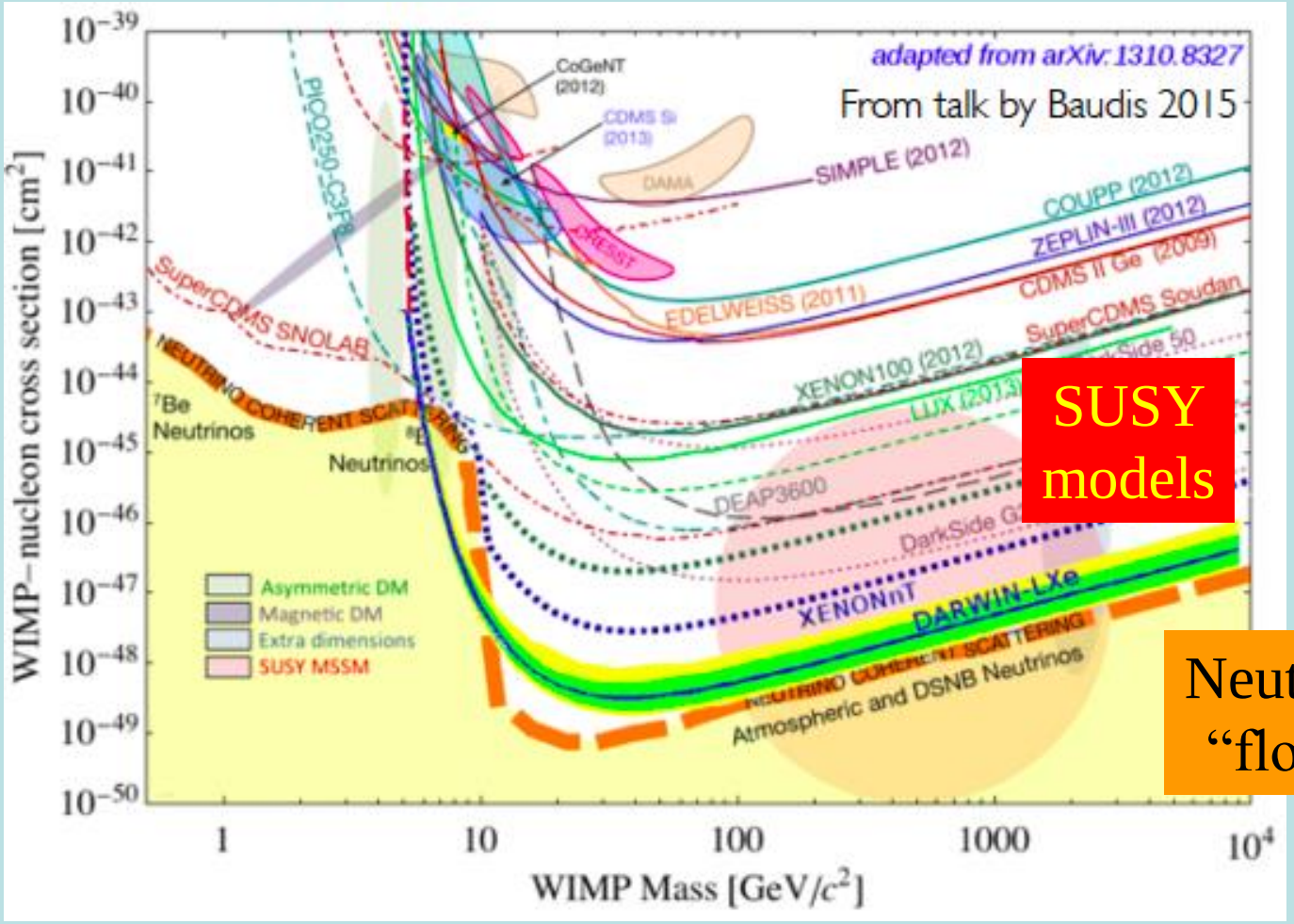
Direct Dark Matter Detection



Scattering of dark matter particle in deep underground laboratory

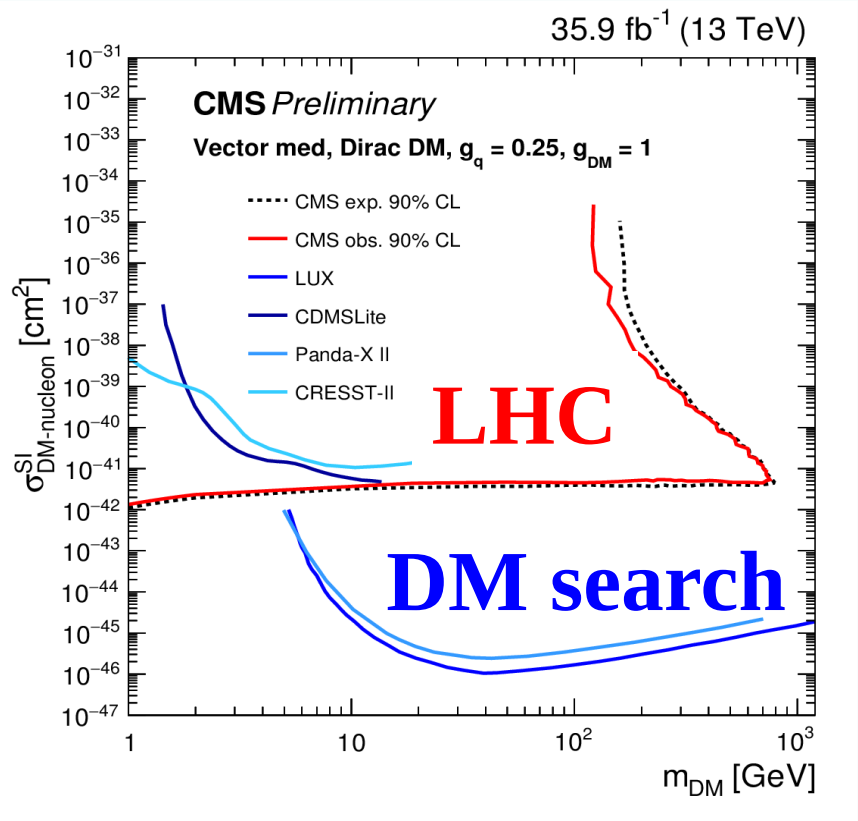
Direct Dark Matter Searches

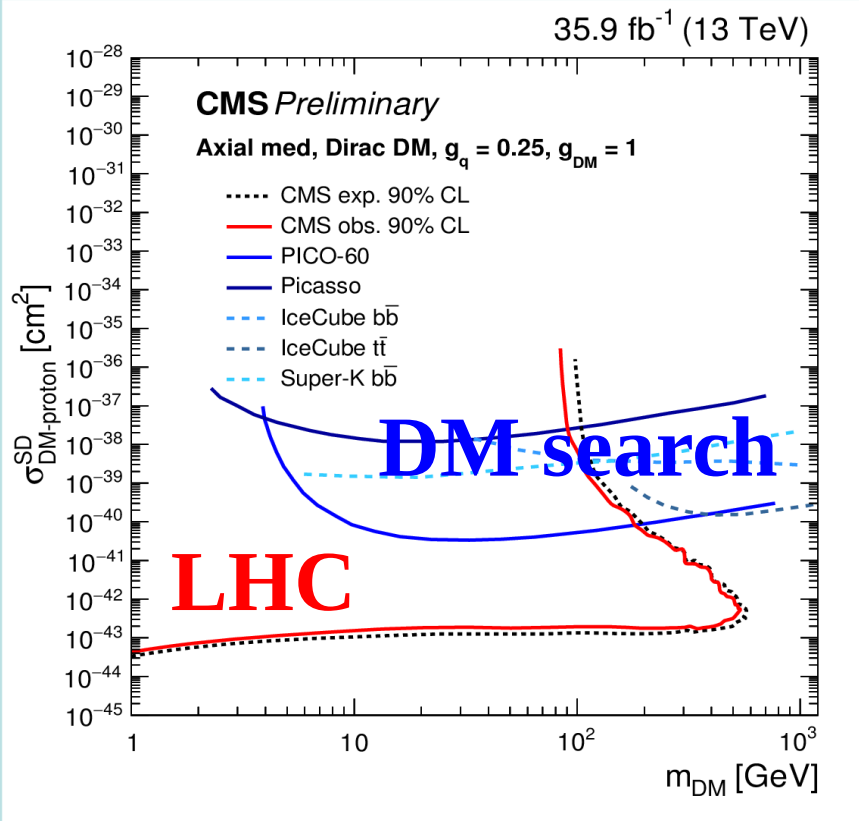
- Compilation of present and future sensitivities



LHC vs Dark Matter Searches

- Compilation of present sensitivities





- Complementarity between LHC and direct searches

SUSY: Dusk or Dawn?

General Interest in Antimatter Physics

Physicists cannot make enough for
Star Trek or Dan Brown!

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:
- same mass
- opposite internal properties:
  - electric charge, …

Discovered in cosmic rays

Studied using accelerators

Used in PET scanners

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

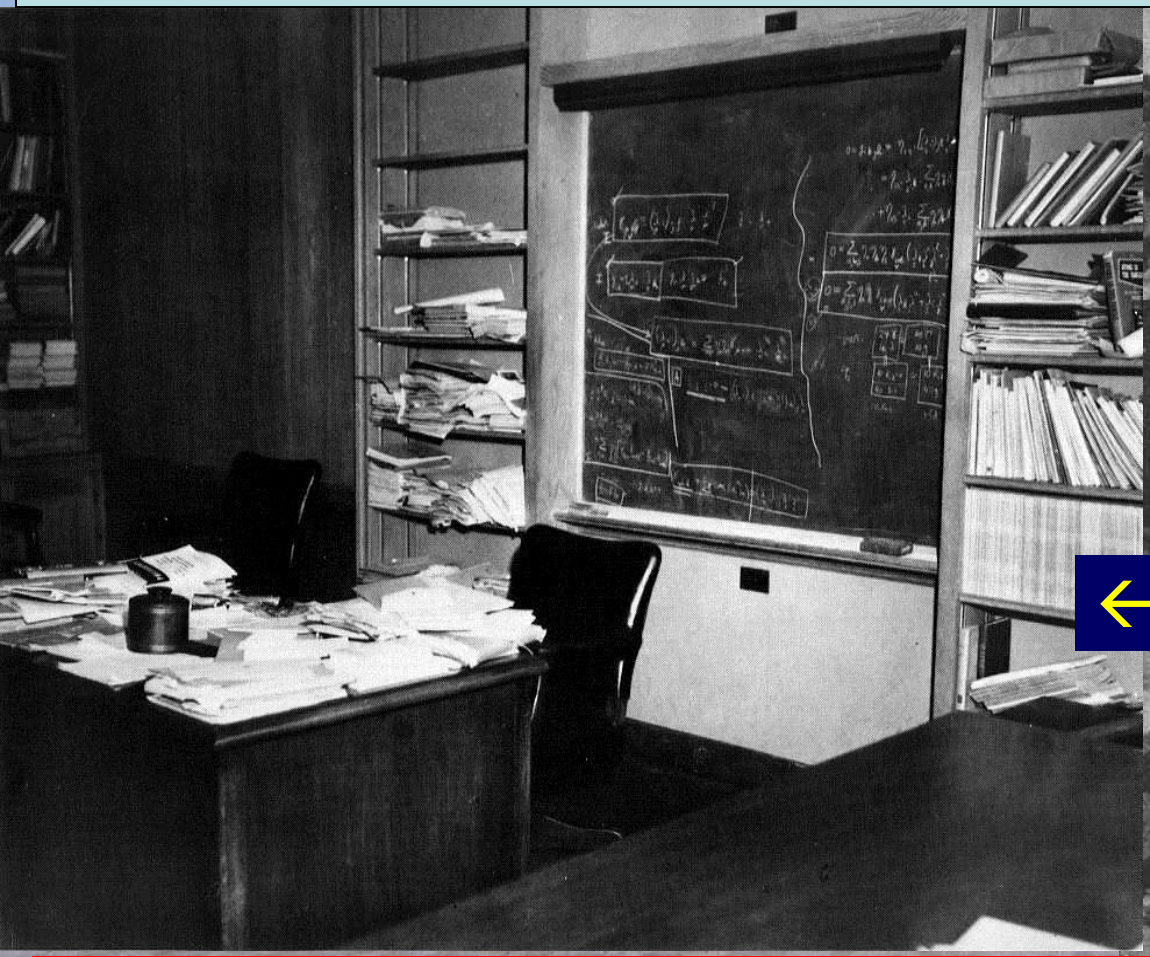
How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter
  observed in the laboratory
- Need interactions able to create matter
  predicted by theories
  not yet seen by experiment
- Need the expansion of the Universe
  a role for the Higgs boson?

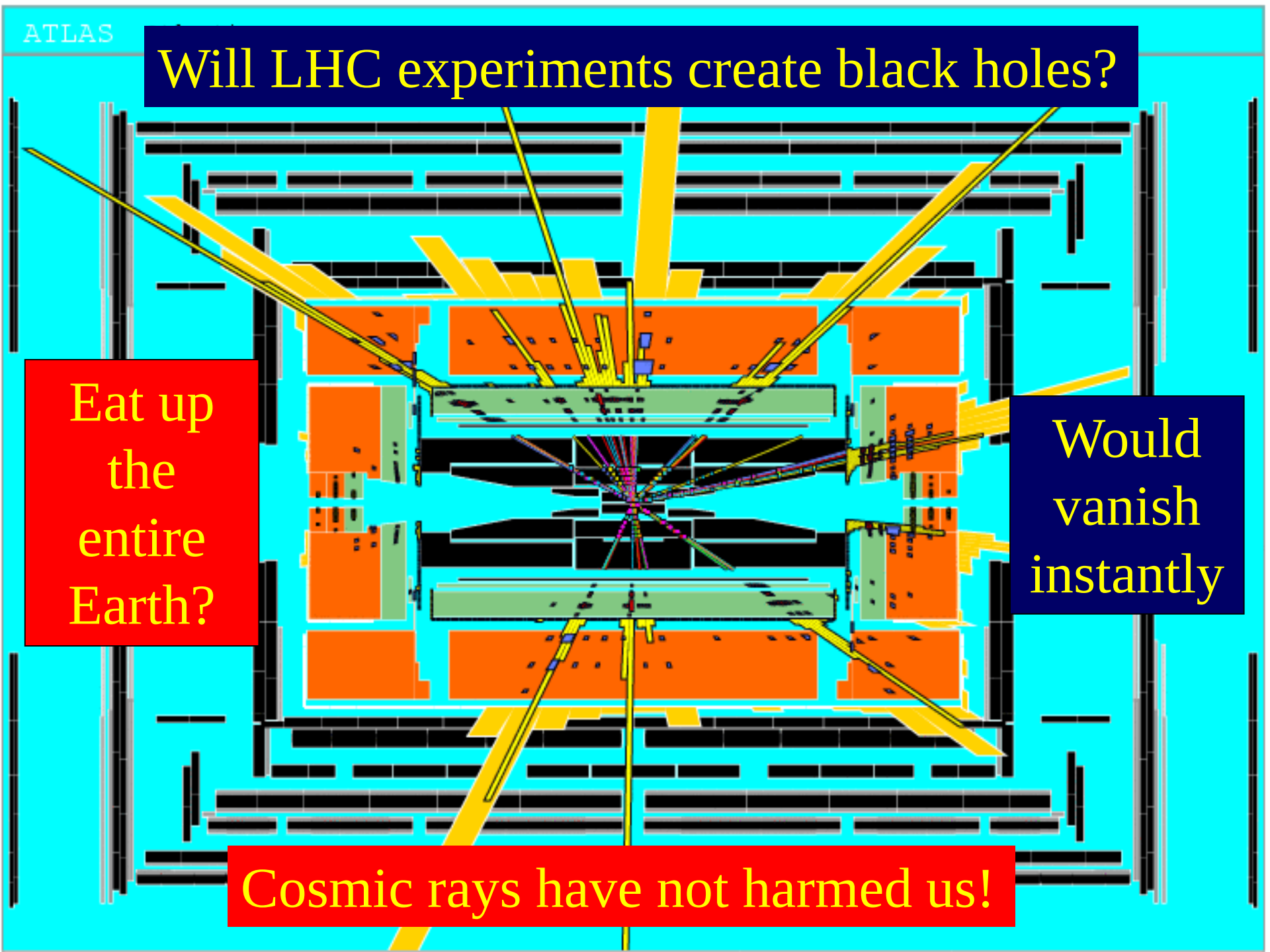
Will we be able to calculate using laboratory data?

Unify the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

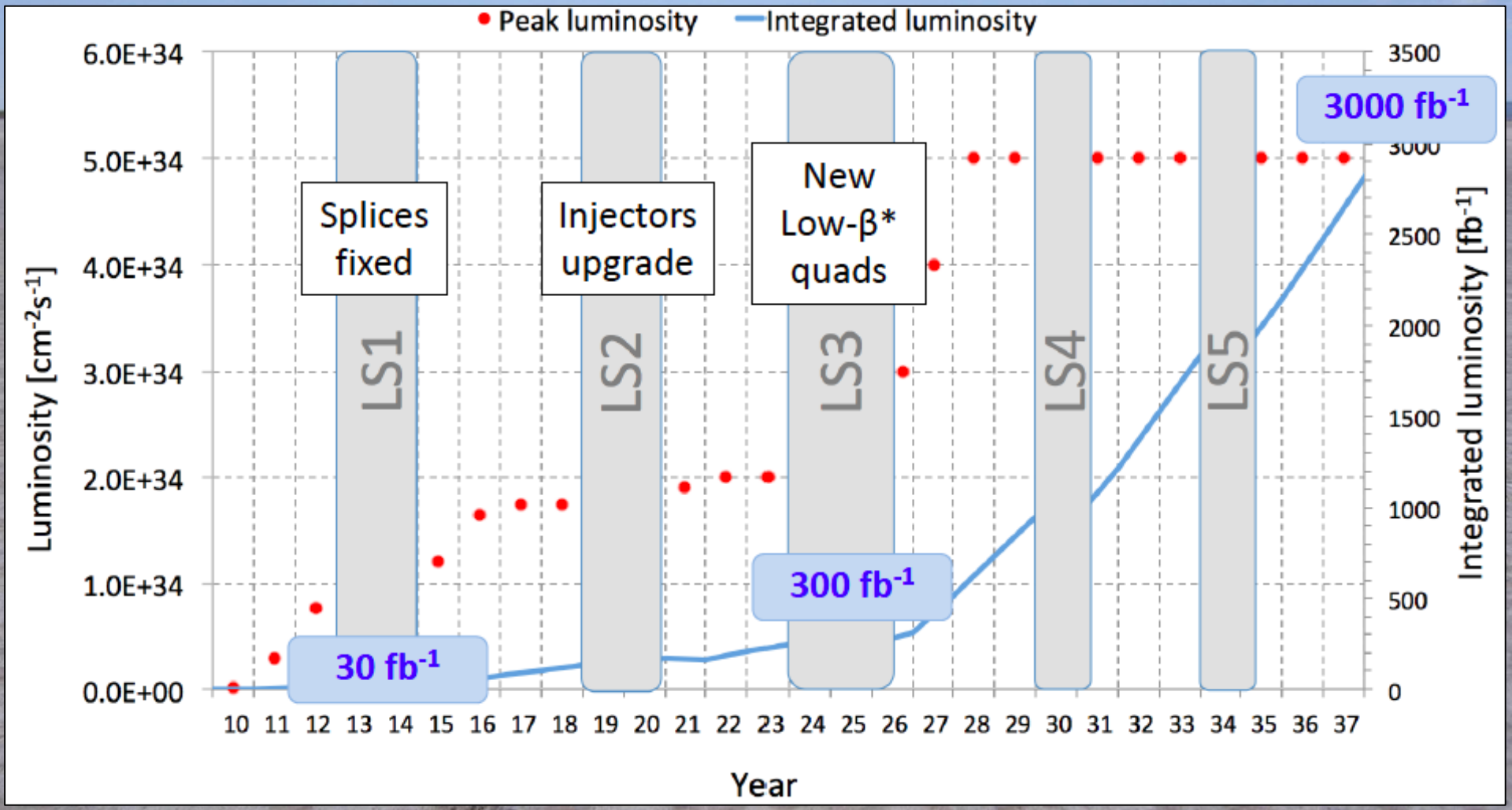
Unification via extra dimensions of space?


ATLAS
Will LHC experiments create black holes?
Eat up the entire Earth?
Would vanish instantly
Cosmic rays have not harmed us!

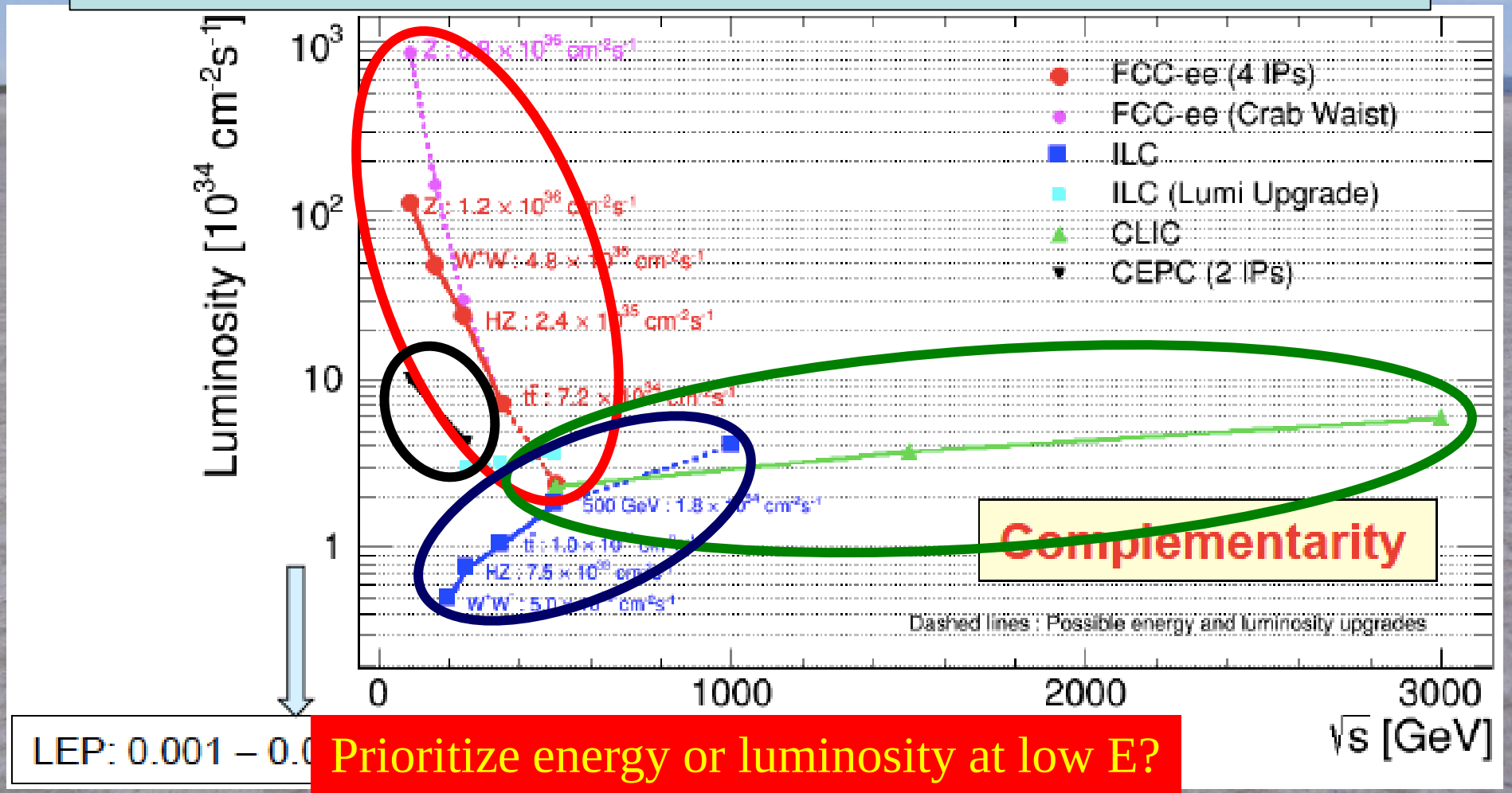
Paraphrasing George Harrison

If you don’t know where you’re going,
Any road **may** take you there

The LHC in Future Years



Projected e^+e^- Colliders: Luminosity vs Energy



FCC
hh ee he

CEPC-SPPC

Preliminary Conceptual Design Report

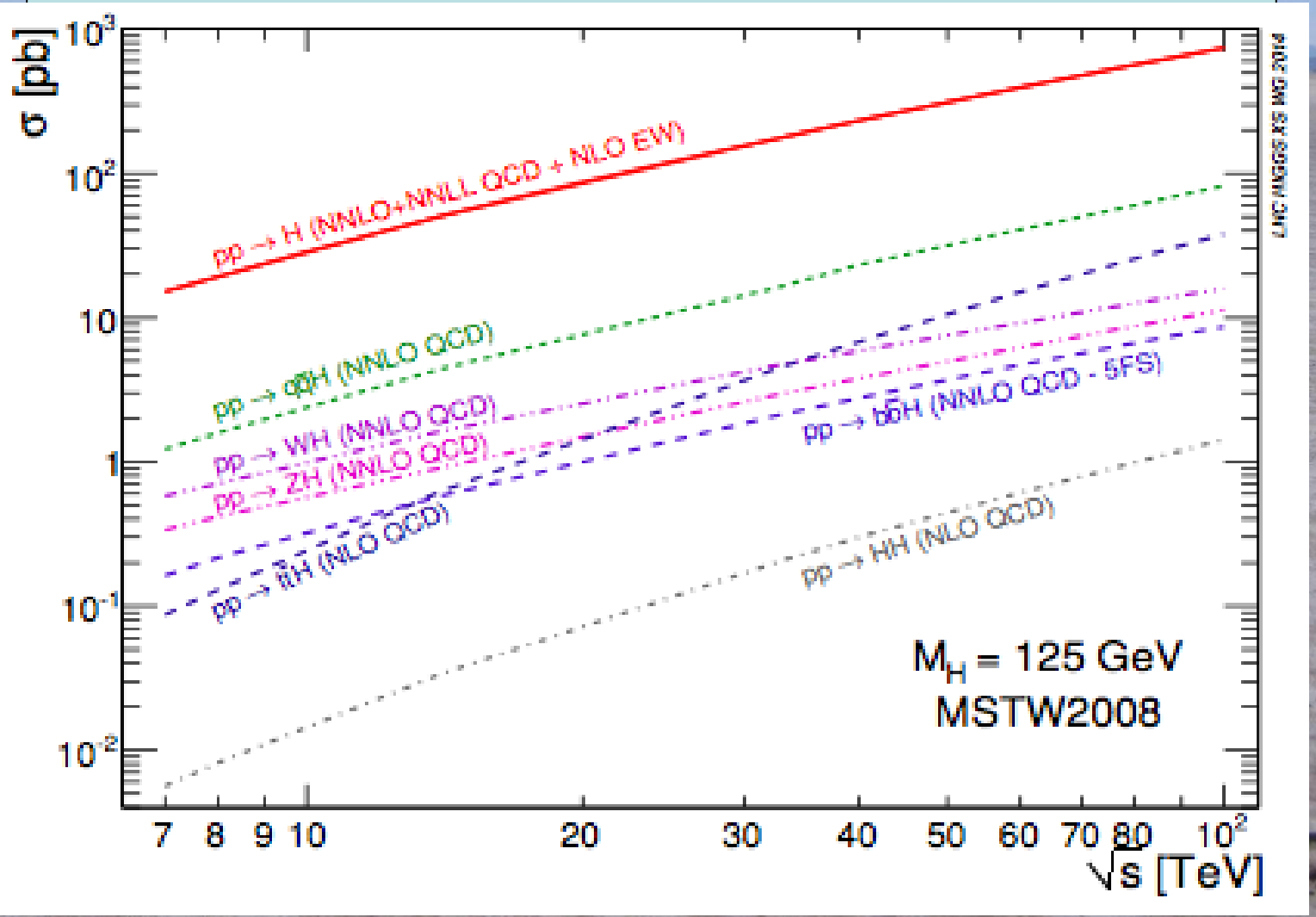
Future Circular Colliders

The vision:

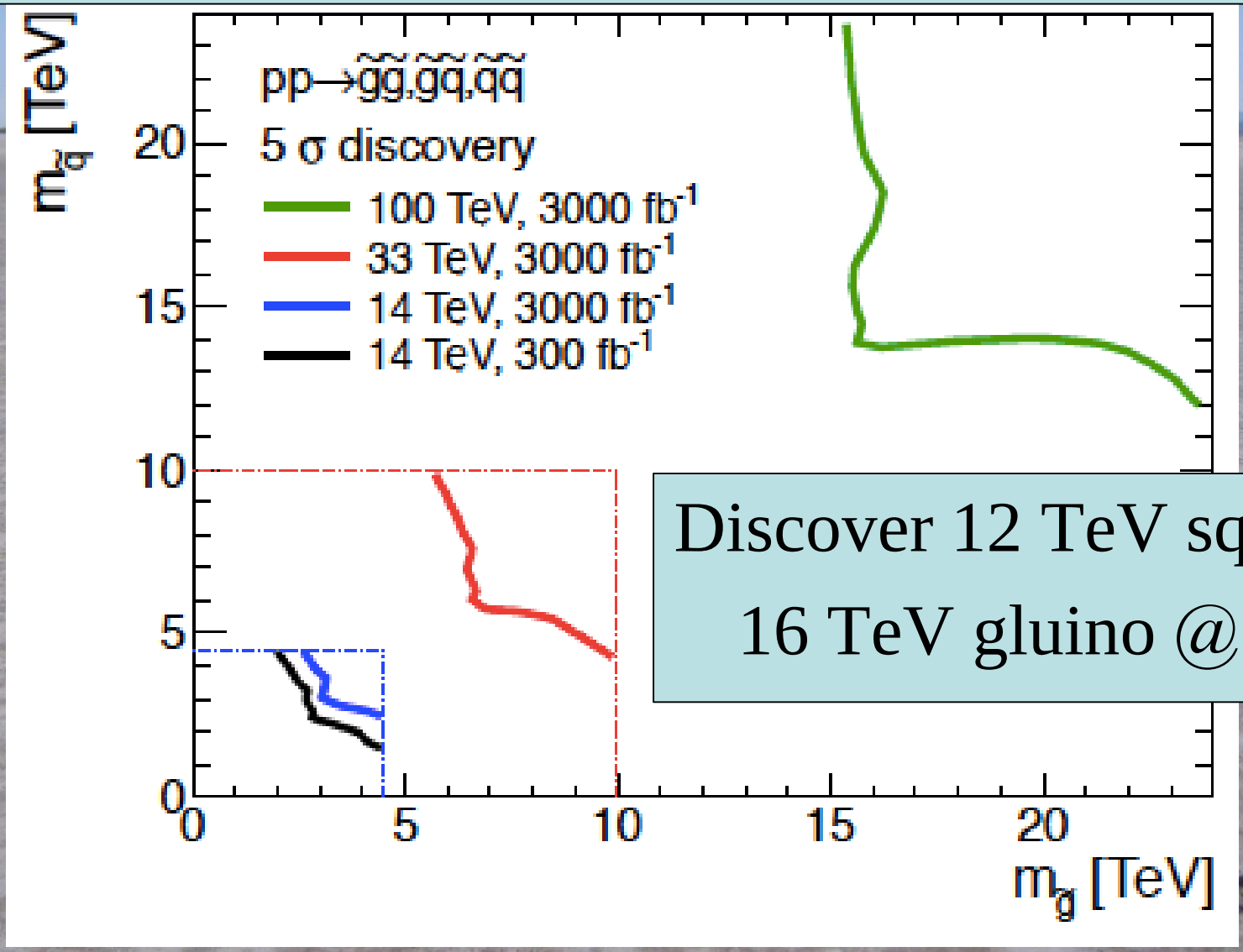
explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

Higgs Cross Sections

- At the LHC and beyond:

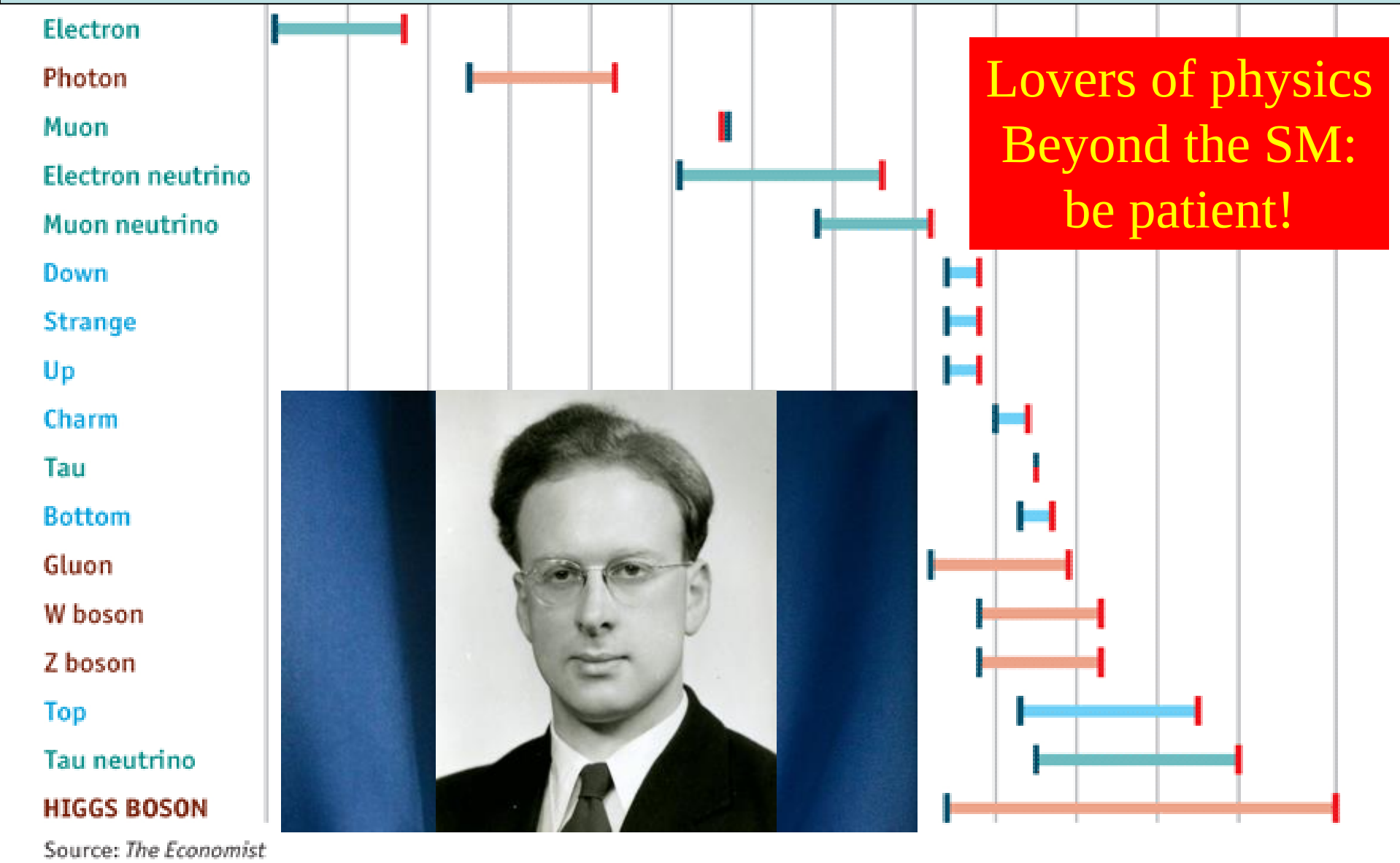


Squark-Gluino Plane



Discover 12 TeV squark,
16 TeV gluino @ 5σ

Standard Model Particles:
Years from Proposal to Discovery



Summary