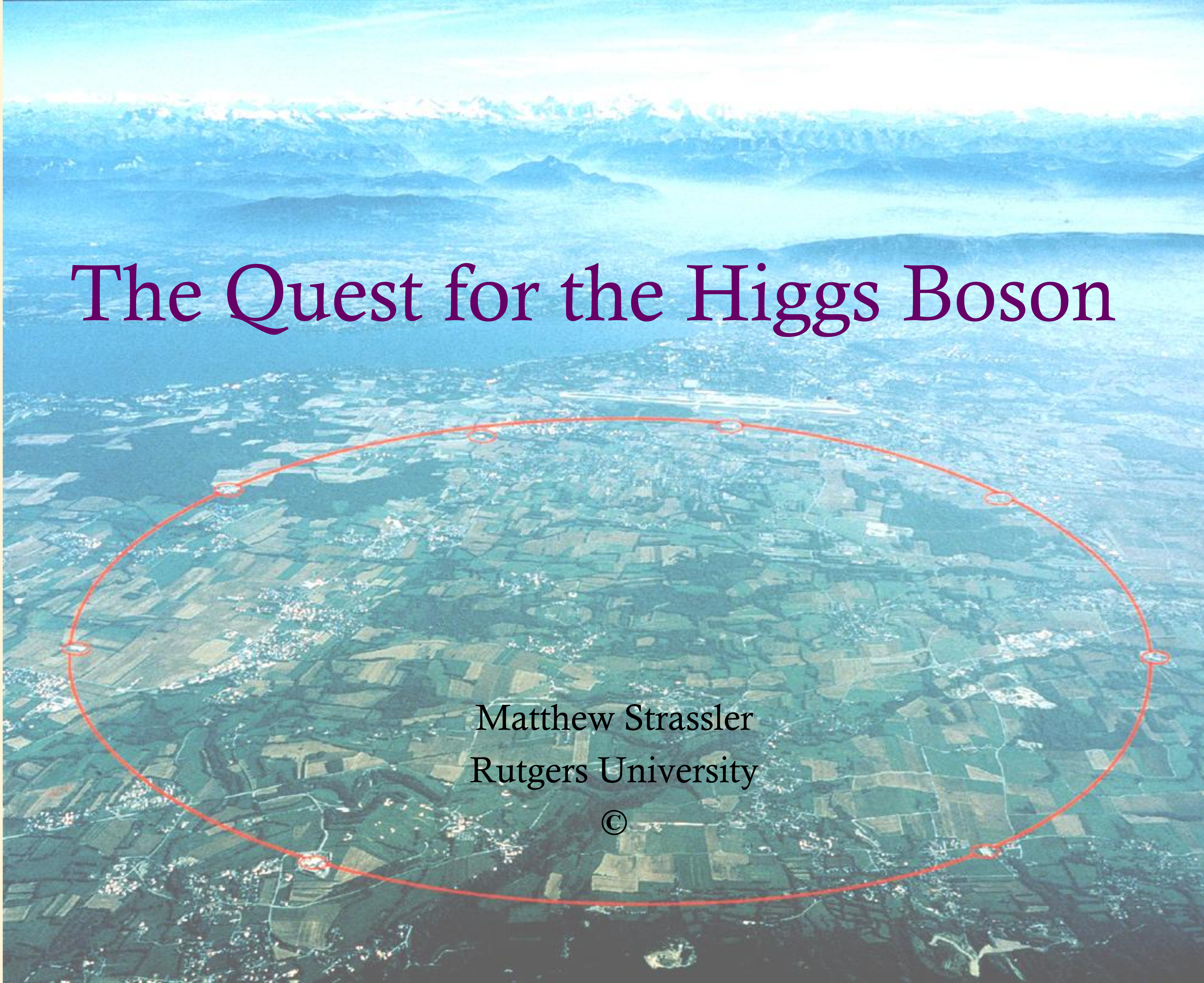
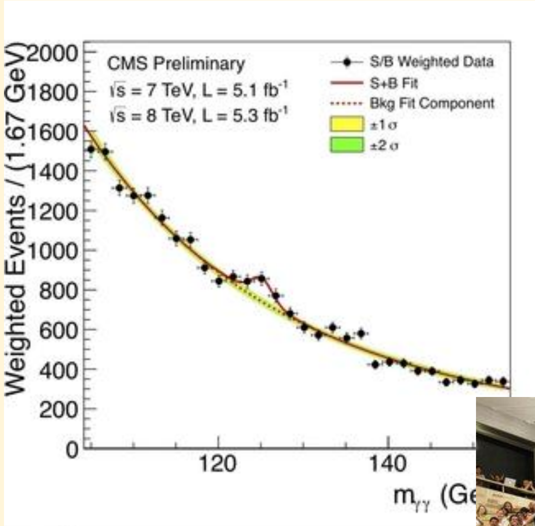


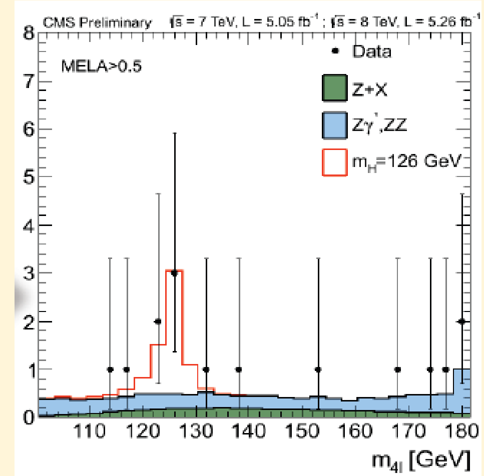
The Quest for the Higgs Boson

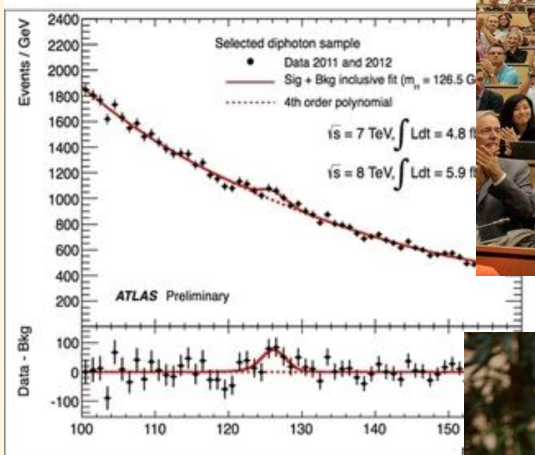
Matthew Strassler
Rutgers University

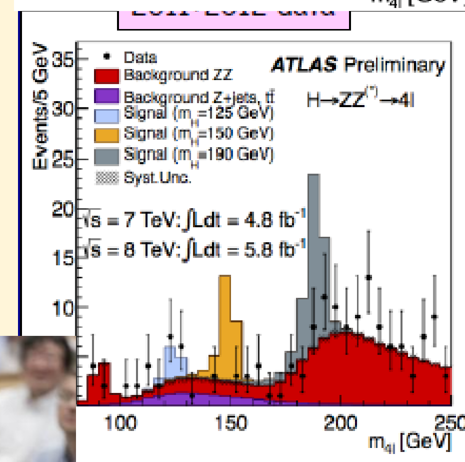
July 4, 2012

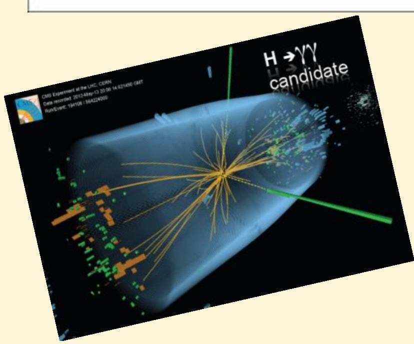
The CERN Laboratory

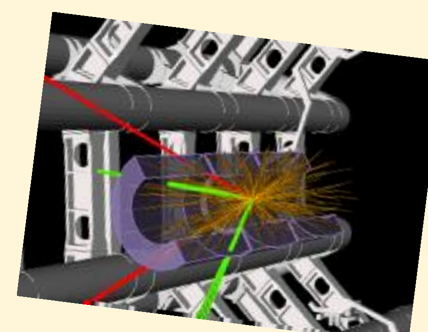










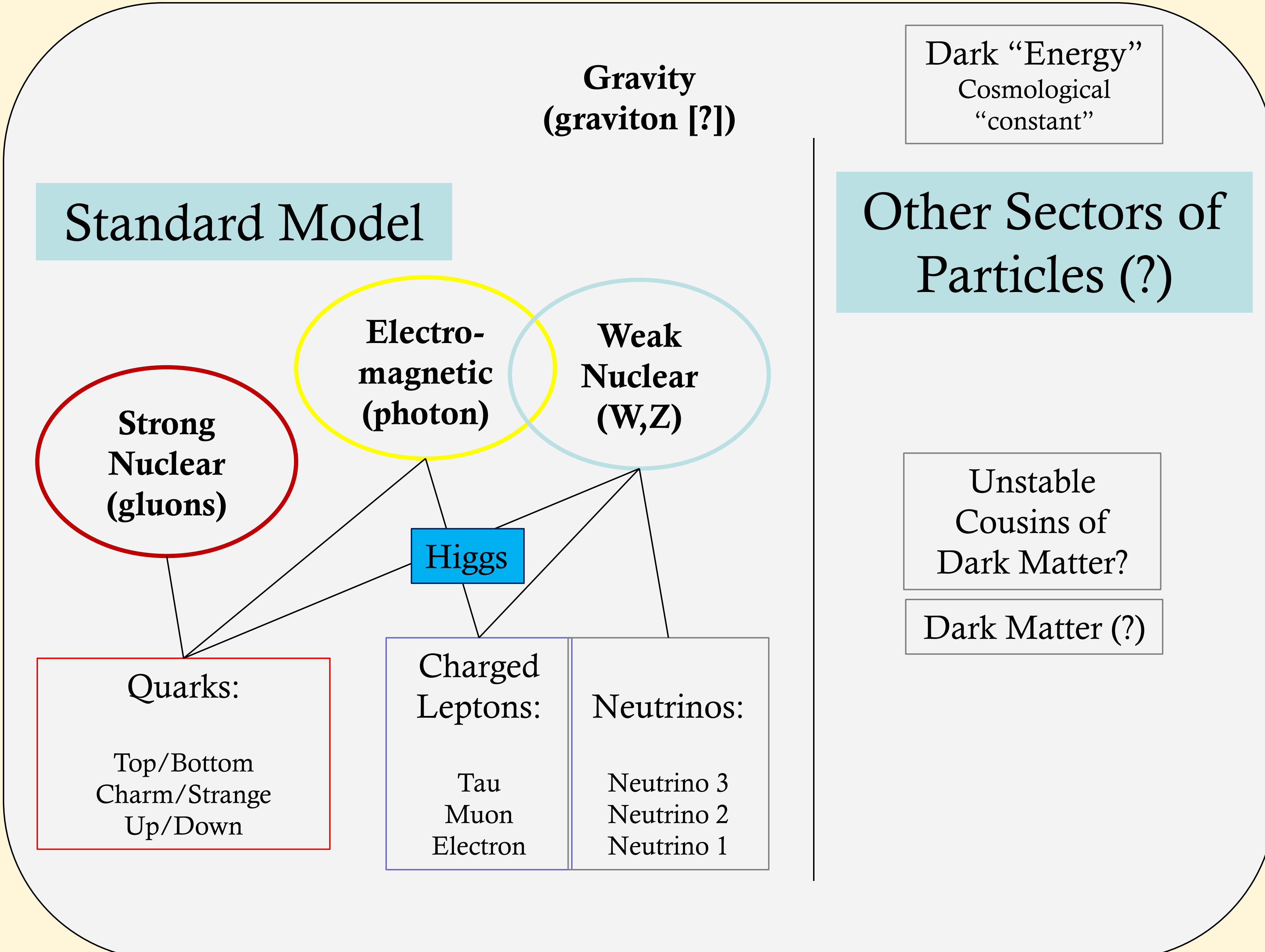


What Does It All Mean?

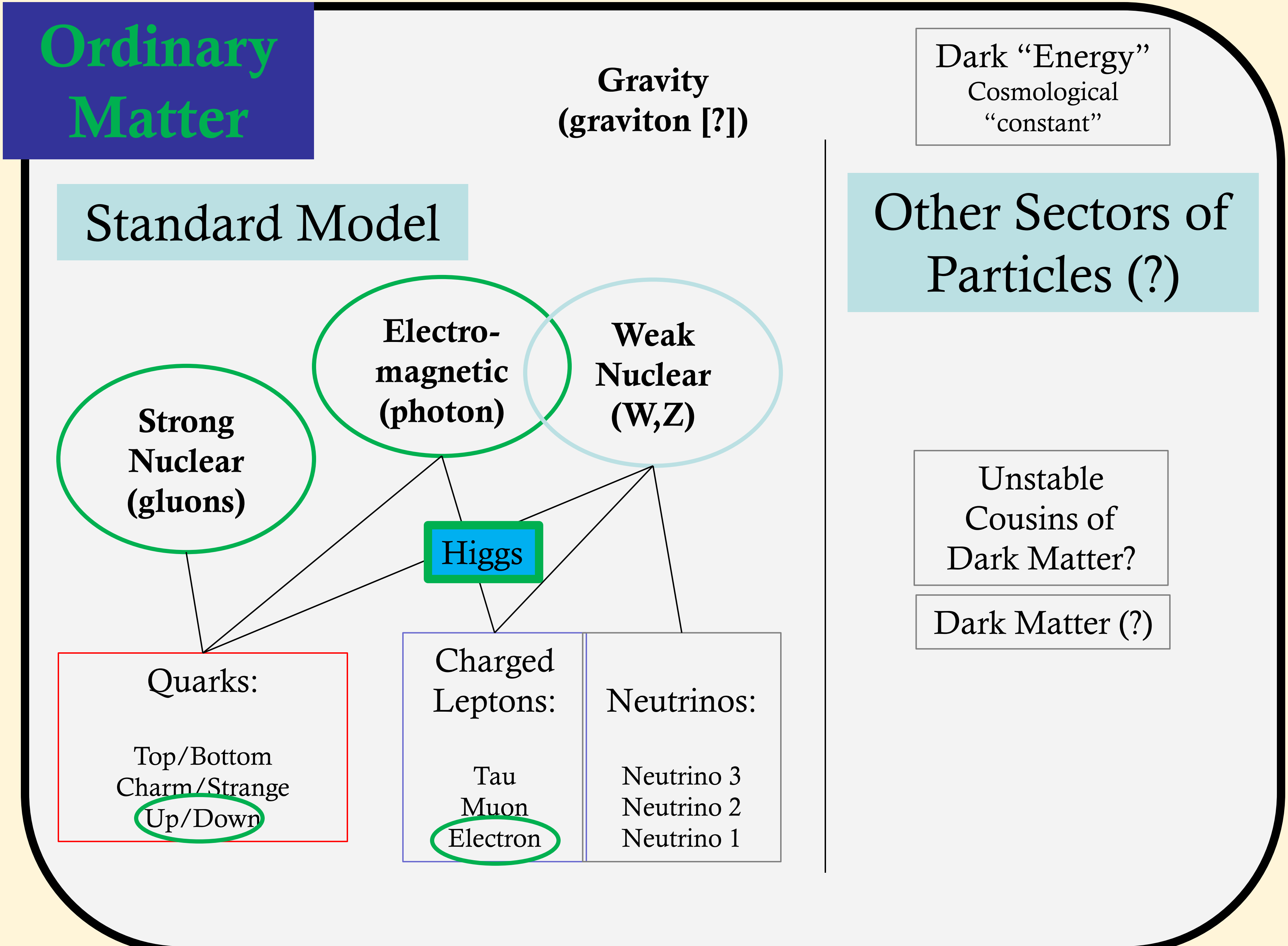
- This is an astounding accomplishment!
- It is important to see it in proper perspective
  - Represents the end of a 50 year quest
  - Just a part of a century-long and still continuing saga
- The meaning and implications of the discovery aren't known yet
- But they will be big in the long term –
  - we just don't know precisely in what way

Nature as We Currently Know It

- A Quantum Mechanical World
- Quantum Fields in Presumably Quantum Spacetime
  - Electromagnetic Field, Electron Field,…
- Waves in Fields are made from Quanta (“Particles”)
  - Photons, Electrons,…
- The Universe
  - Expanding at an accelerating rate [Dark “Energy”]
  - Most of the matter is of one or more unknown types [Dark Matter]



Gravity
(graviton [?])
Dark "Energy"
Cosmological
"constant"
Standard Model
Other Sectors of
Particles (?)
Electro-
magnetic
(photon)
Weak
Nuclear
(W,Z)
Strong
Nuclear
(gluons)
Higgs
Unstable
Cousins of
Dark Matter?
Dark Matter (?)
Quarks:
Top/Bottom
Charm/Strange
Up/Down
Charged
Leptons:
Tau
Muon
Electron
Neutrinos:
Neutrino 3
Neutrino 2
Neutrino 1



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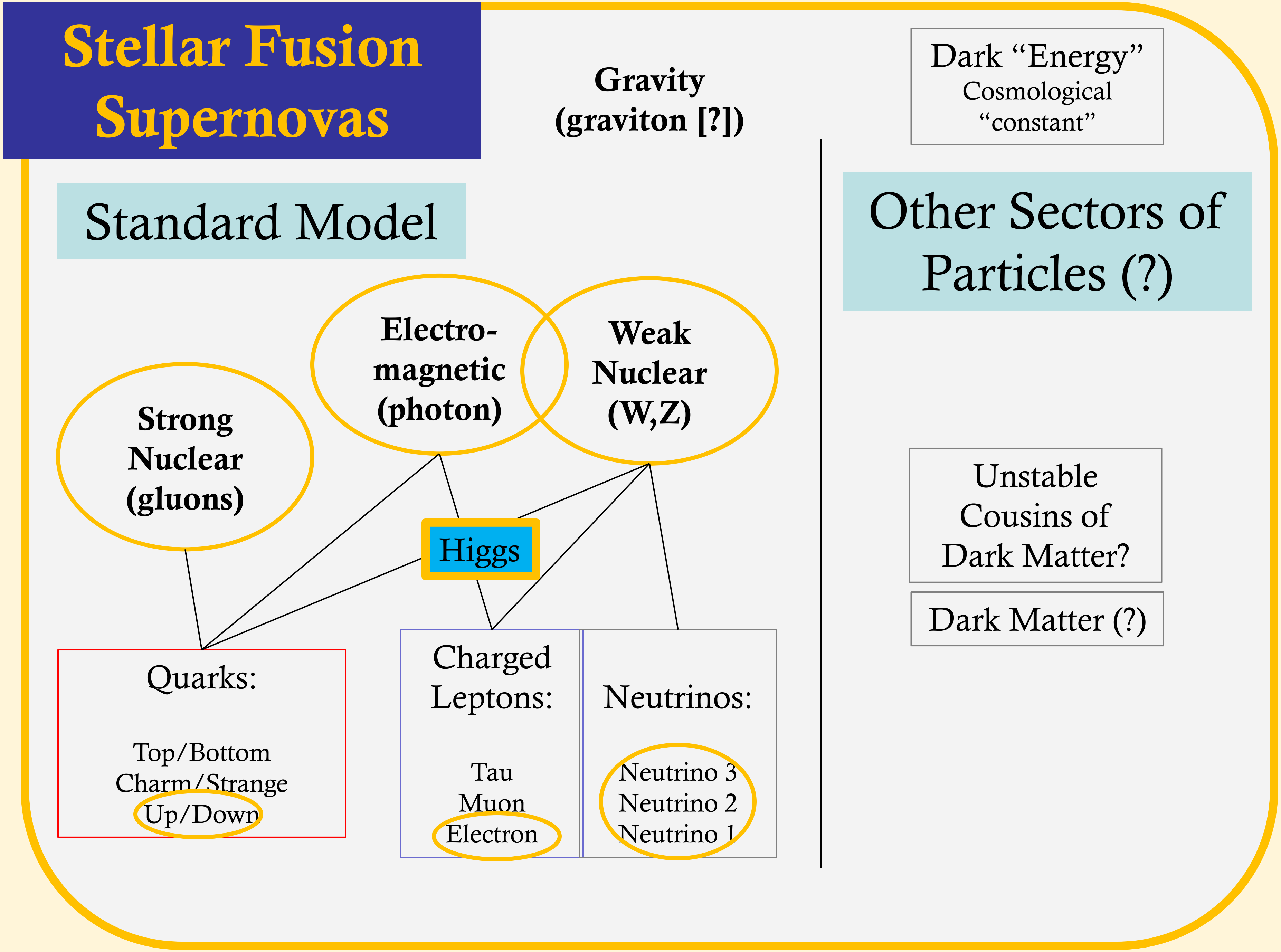

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Four Known Forces ("Interactions") of Nature

All known processes in nature can be classified as one of four types

- Electromagnetic interaction (atomic structure)
- Strong nuclear interaction (nuclear structure, protons/neutrons)
- Weak nuclear interaction (radioactivity, supernovas)
- Gravitational interaction (galaxies, stars, planetary systems,…)

NEW #5! Higgs Interaction…

The "Scales" of the Forces of Nature

Convert distance d to energy E

$$d = \hbar c / E$$

<u>Some important distance scales in nature</u>

- Atomic scale

  (atom radius 10^{-10} m , electron mass 10^{-12} m)
  - Energy eV – MeV [1900-1940]

- Strong nuclear interaction scale (proton size 10^{-15} m)
  - Energy GeV [1930-1980]

- Weak nuclear interaction scale (Higgs mechanism 10^{-18} m)
  - Energy TeV [1930-present]

LHC: first time in 40 years we reach a new physical scale

- Gravitational interaction scale (quantum space-time 10^{-33} m)
  - Energy 10^{27} eV = 10^{15} TeV [2210?!?]

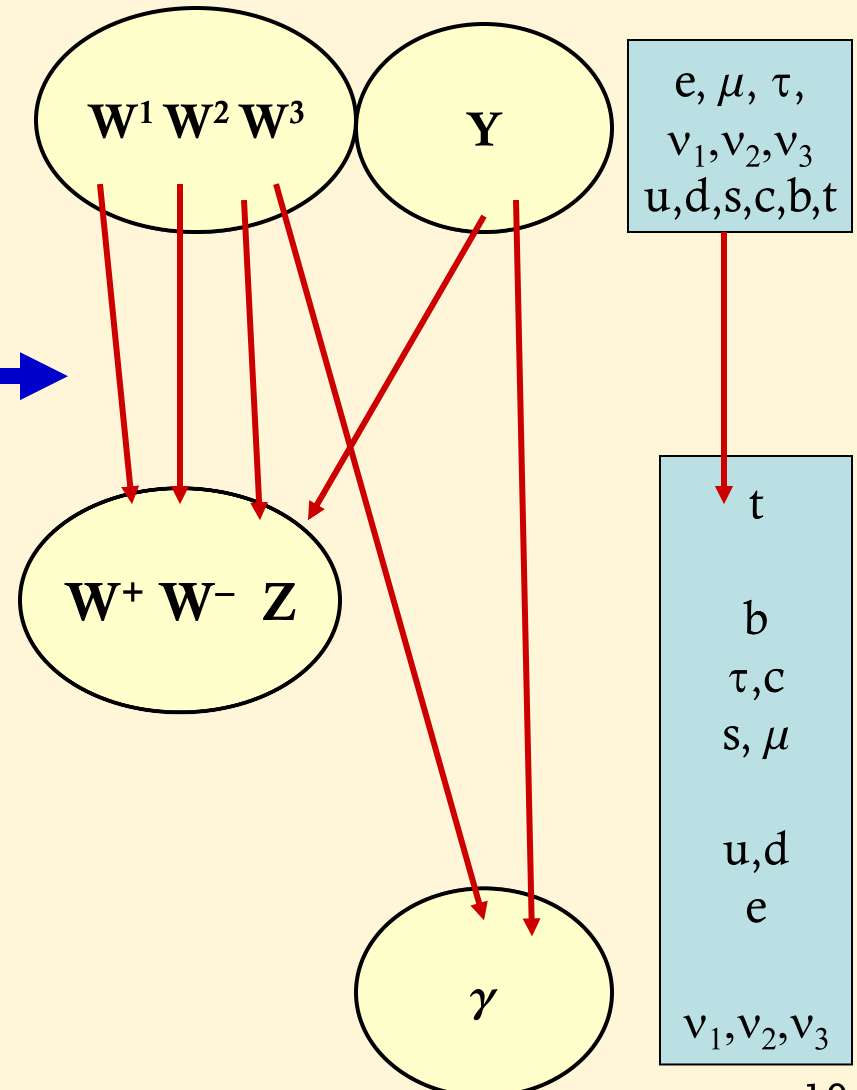
Understanding the Electro-Weak Interaction

Two Long-Range Forces:

- "Weak Isospin" and "Hypercharge"

- Four massless photon-like spin-1 bosons
- Many massless fermions
  - electrons, muons, quarks, neutrinos

"Higgs Mechanism" →



- Rearranges the forces
  - Short-Range Weak Nuclear Force
    - Massive W^+ W^- Z bosons
  - Long-Range Electromagnetic Force
    - Massless photon
- Gives masses to fermions

Understanding the Electro-Weak Interaction

Two Long-R

– "We

• Four mas

• Many ma

– electr

Prediction of Higgs Mechanism:

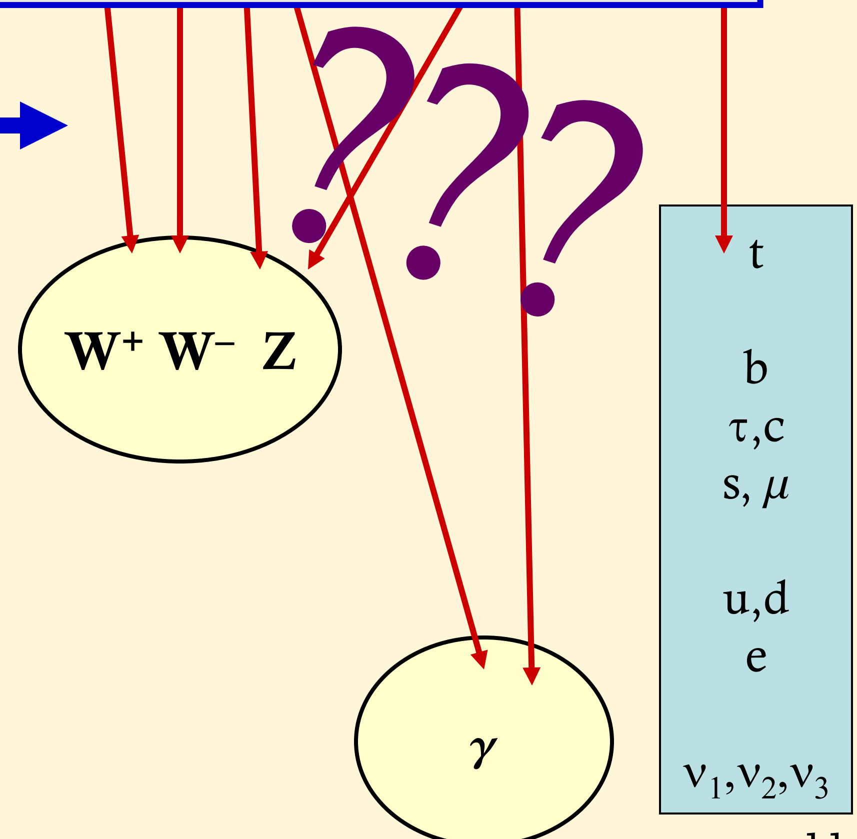
New physics required at or below the LHC energy scale

But in what form? Higgs particle(s)? New forces? …

"Higgs Mechanism" →

• Rearranges the forces
  – Short-Range Weak Nuclear Force
    • Massive W^+ W^- Z bosons
  – Long-Range Electromagnetic Force
    • Massless photon

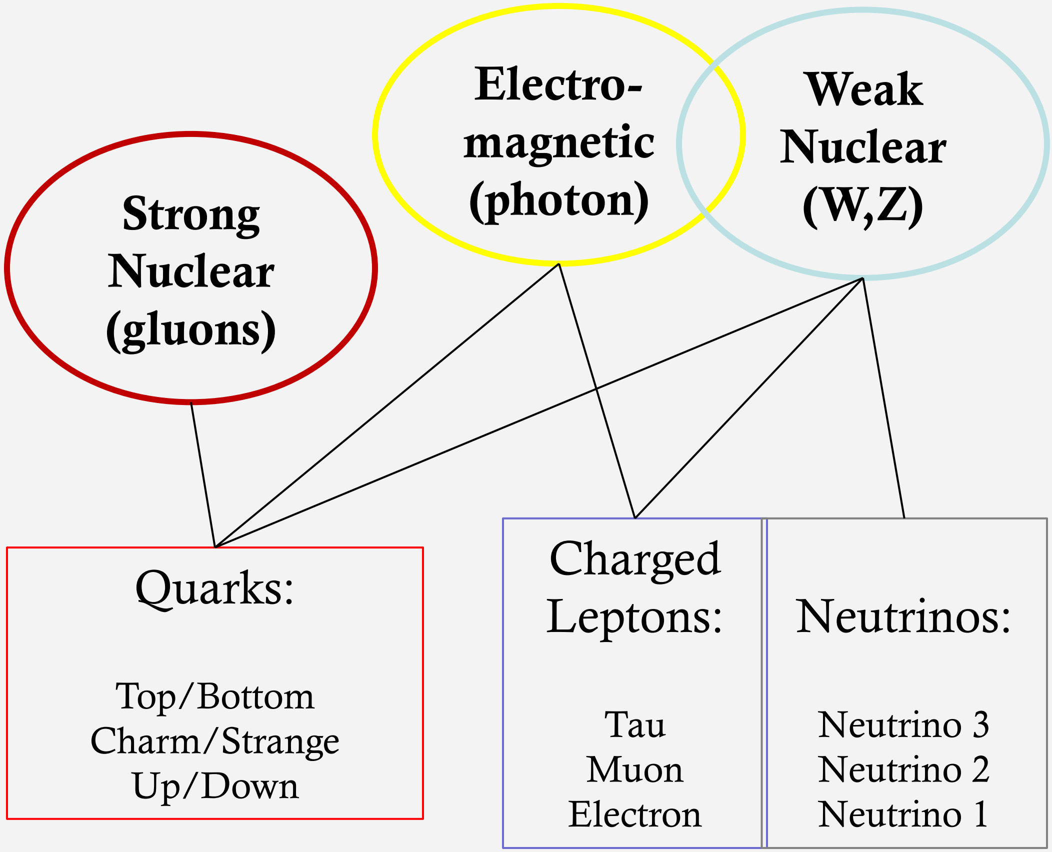
• Gives masses to fermions



SM-minus-Higgs not consistent.

Scattering of W bosons violates unitarity; new forces or particles needed.

Standard Model



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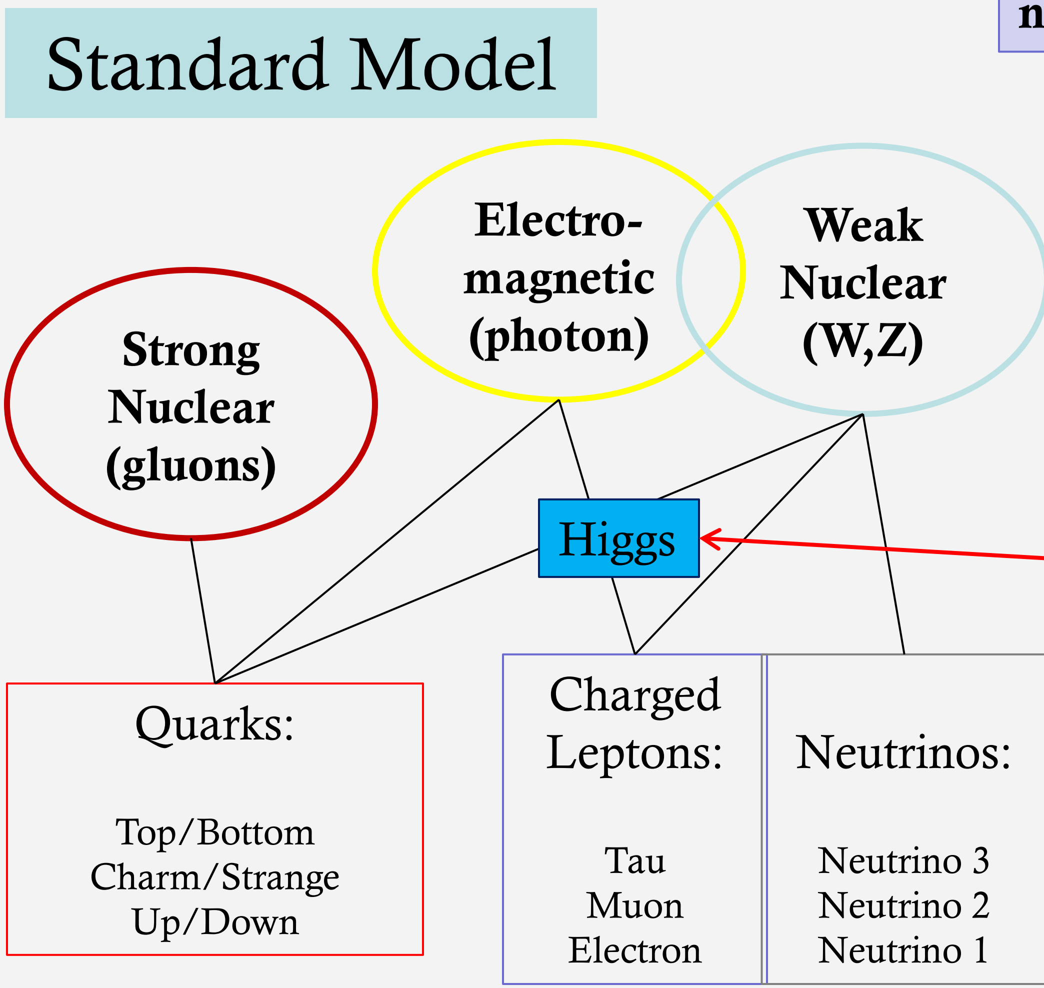


The simplest repair:
one Higgs field
one Higgs particle

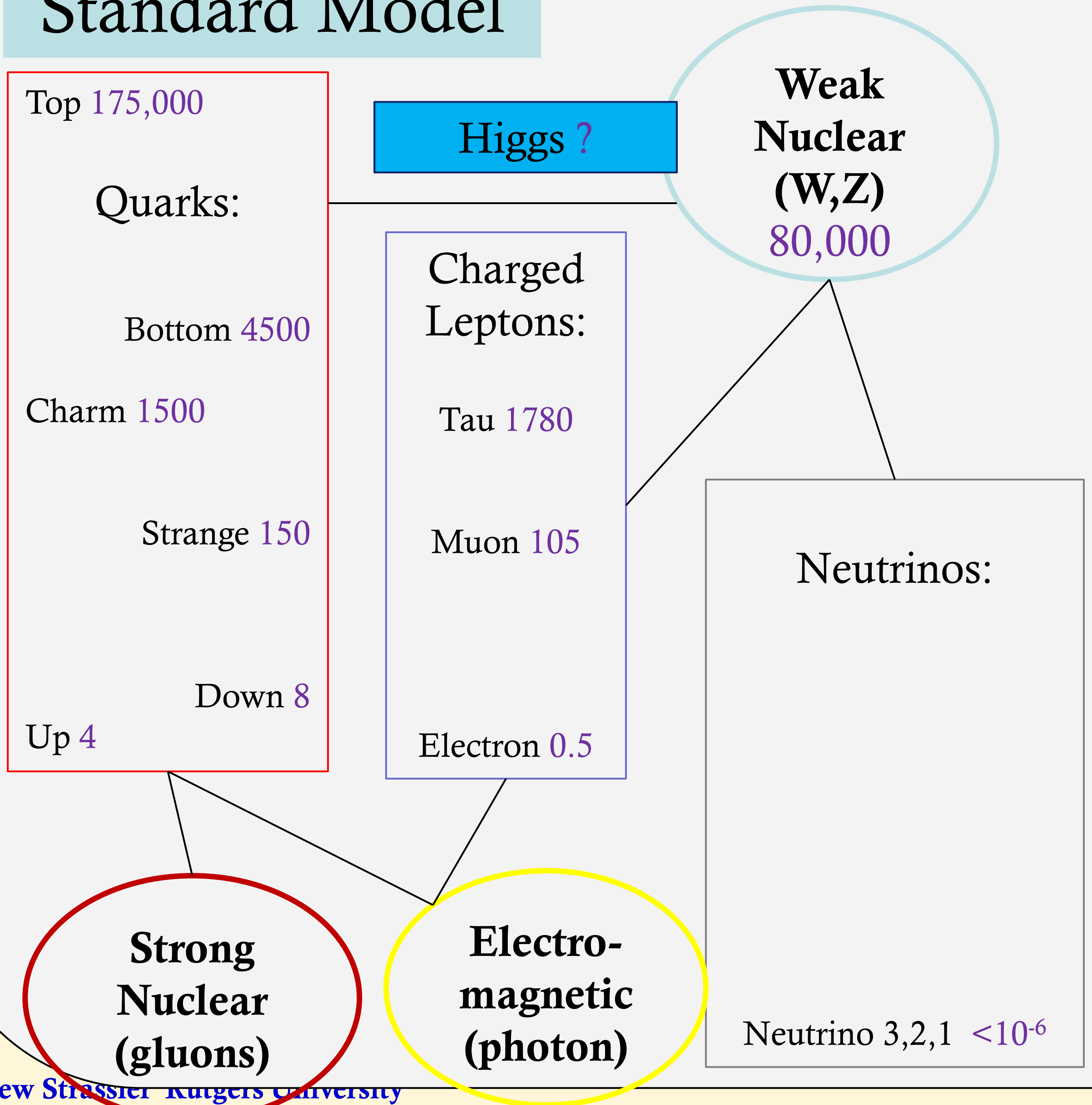
Higgs particle must be lighter than 1 TeV

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1.008 $_{1}$H																	4.003 $_{2}$He
2	6.941 $_{3}$Li	9.012 $_{4}$Be											10.81 $_{5}$B	12.011 $_{6}$C	14.007 $_{7}$N	15.999 $_{8}$O	18.998 $_{9}$F	20.179 $_{10}$Ne
3	22.990 $_{11}$Na	24.305 $_{12}$Mg											26.98 $_{13}$Al	28.09 $_{14}$Si	30.974 $_{15}$P	32.06 $_{16}$S	35.453 $_{17}$Cl	39.948 $_{18}$Ar
4	39.098 $_{19}$K	40.08 $_{20}$Ca	44.96 $_{21}$Sc	47.88 $_{22}$Ti	50.94 $_{23}$V	52.00 $_{24}$Cr	54.94 $_{25}$Mn	55.85 $_{26}$Fe	58.93 $_{27}$Co	58.69 $_{28}$Ni	63.546 $_{29}$Cu	65.38 $_{30}$Zn	69.72 $_{31}$Ga	72.59 $_{32}$Ge	74.92 $_{33}$As	78.96 $_{34}$Se	79.904 $_{35}$Br	83.80 $_{36}$Kr
5	85.47 $_{37}$Rb	87.62 $_{38}$Sr	88.91 $_{39}$Y	91.22 $_{40}$Zr	92.91 $_{41}$Nb	95.94 $_{42}$Mo	(98) $_{43}$Tc	101.1 $_{44}$Ru	102.91 $_{45}$Rh	106.4 $_{46}$Pd	107.87 $_{47}$Ag	112.41 $_{48}$Cd	114.82 $_{49}$In	118.69 $_{50}$Sn	121.75 $_{51}$Sb	127.60 $_{52}$Te	126.90 $_{53}$I	131.29 $_{54}$Xe
6	132.91 $_{55}$Cs	137.33 $_{56}$Ba	138.91 $_{57}$La	178.49 $_{72}$Hf	180.95 $_{73}$Ta	183.85 $_{74}$W	186.2 $_{75}$Re	190.2 $_{76}$Os	192.2 $_{77}$Ir	195.08 $_{78}$Pt	196.97 $_{79}$Au	200.59 $_{80}$Hg	204.38 $_{81}$Tl	207.2 $_{82}$Pb	208.98 $_{83}$Bi	(244) $_{84}$Po	(210) $_{85}$At	(222) $_{86}$Rn
7	(223) $_{87}$Fr	226.03 $_{88}$Rd	227.03 $_{89}$Ac															

Lanthanide Series	140.12 $_{58}$Ce	140.9077 $_{59}$Pr	144.24 $_{60}$Nd	(145) $_{61}$Pm	150.36 $_{62}$Sm	151.96 $_{63}$Eu	157.25 $_{64}$Gd	158.93 $_{65}$Tb	162.50 $_{66}$Dy	164.93 $_{67}$Ho	167.26 $_{68}$Er	168.93 $_{69}$Tm	173.04 $_{70}$Yb	174.97 $_{71}$Lu
Actinide Series	232.04 $_{90}$Th	231.0359 $_{91}$Pa	238.03 $_{92}$U	237.05 $_{93}$Np	(244) $_{94}$Pu	(243) $_{95}$Am	(247) $_{96}$Cm	(247) $_{97}$Bk	(251) $_{98}$Cf	(254) $_{99}$Es	(257) $_{100}$Fm	(258) $_{101}$Md	(259) $_{102}$No	(260) $_{103}$Lr

Standard Model



Masses in MeV
M = 10^6
eV = electron-volt

Proton mass = 938 MeV
1 GeV = 1000 MeV
1 TeV = 1000 GeV

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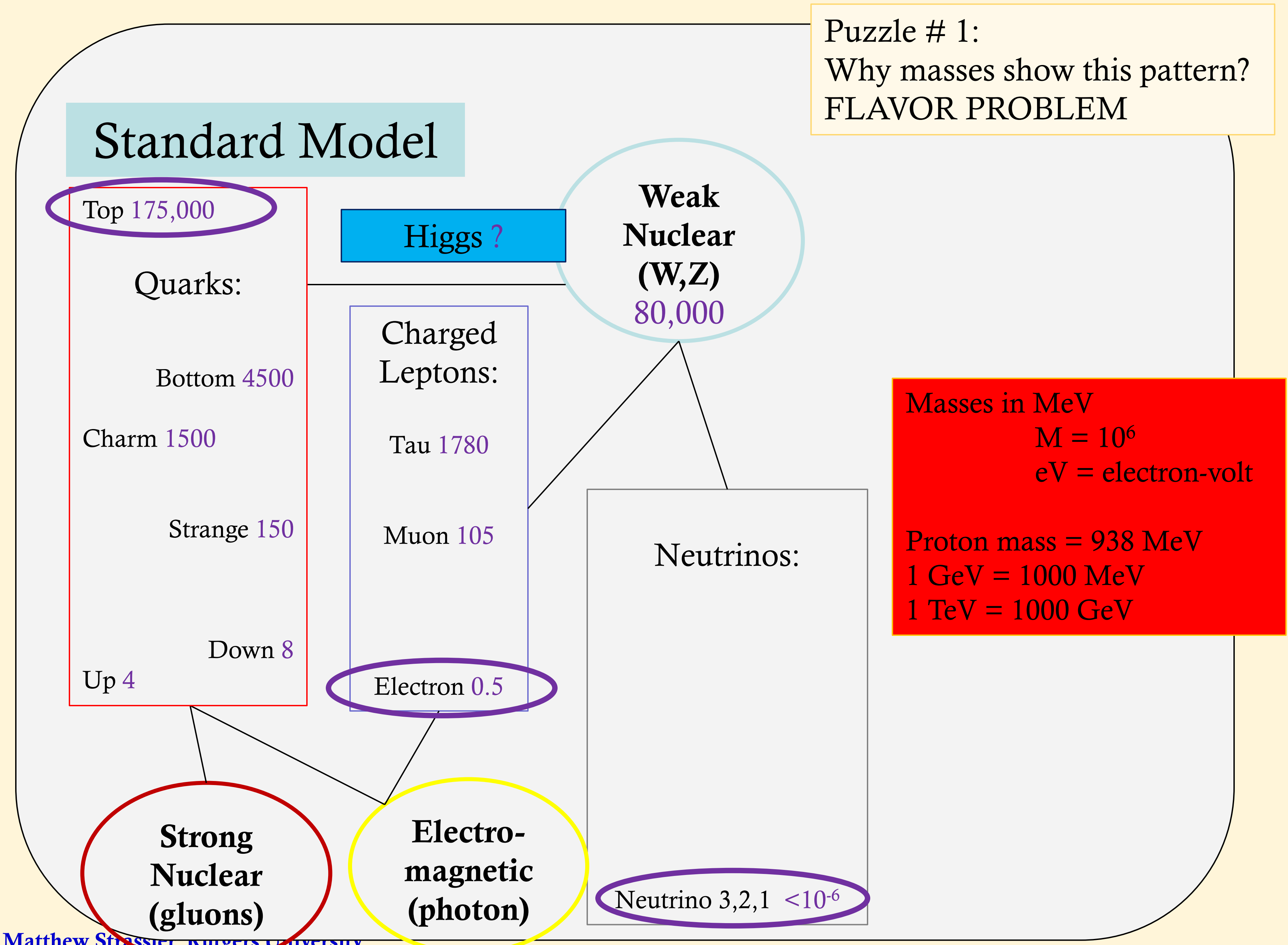
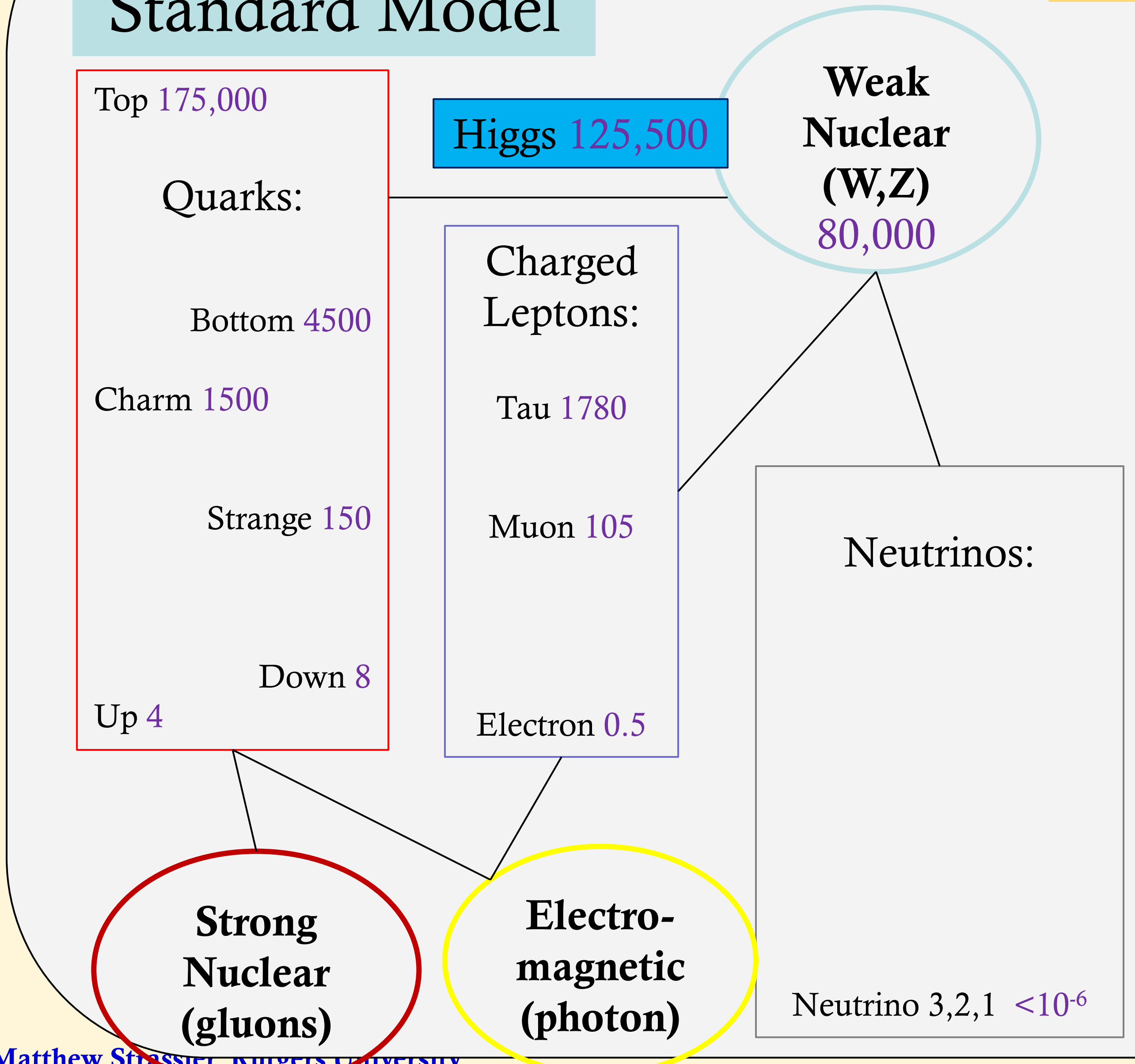

Puzzle # 1:
Why masses show this pattern?
FLAVOR PROBLEM
Standard Model
Top 175,000
Quarks:
Bottom 4500
Charm 1500
Strange 150
Down 8
Up 4
Higgs ?
Weak Nuclear (W,Z) 80,000
Charged Leptons:
Tau 1780
Muon 105
Electron 0.5
Neutrinos:
Neutrino 3,2,1 <10-6
Masses in MeV
M = 10^6
eV = electron-volt
Proton mass = 938 MeV
1 GeV = 1000 MeV
1 TeV = 1000 GeV
Strong Nuclear (gluons)
Electro-magnetic (photon)

Standard Model



Puzzle # 1:
Why masses show this pattern?
FLAVOR PROBLEM

Masses in MeV
M = 10^6
eV = electron-volt

Proton mass = 938 MeV
1 GeV = 1000 MeV
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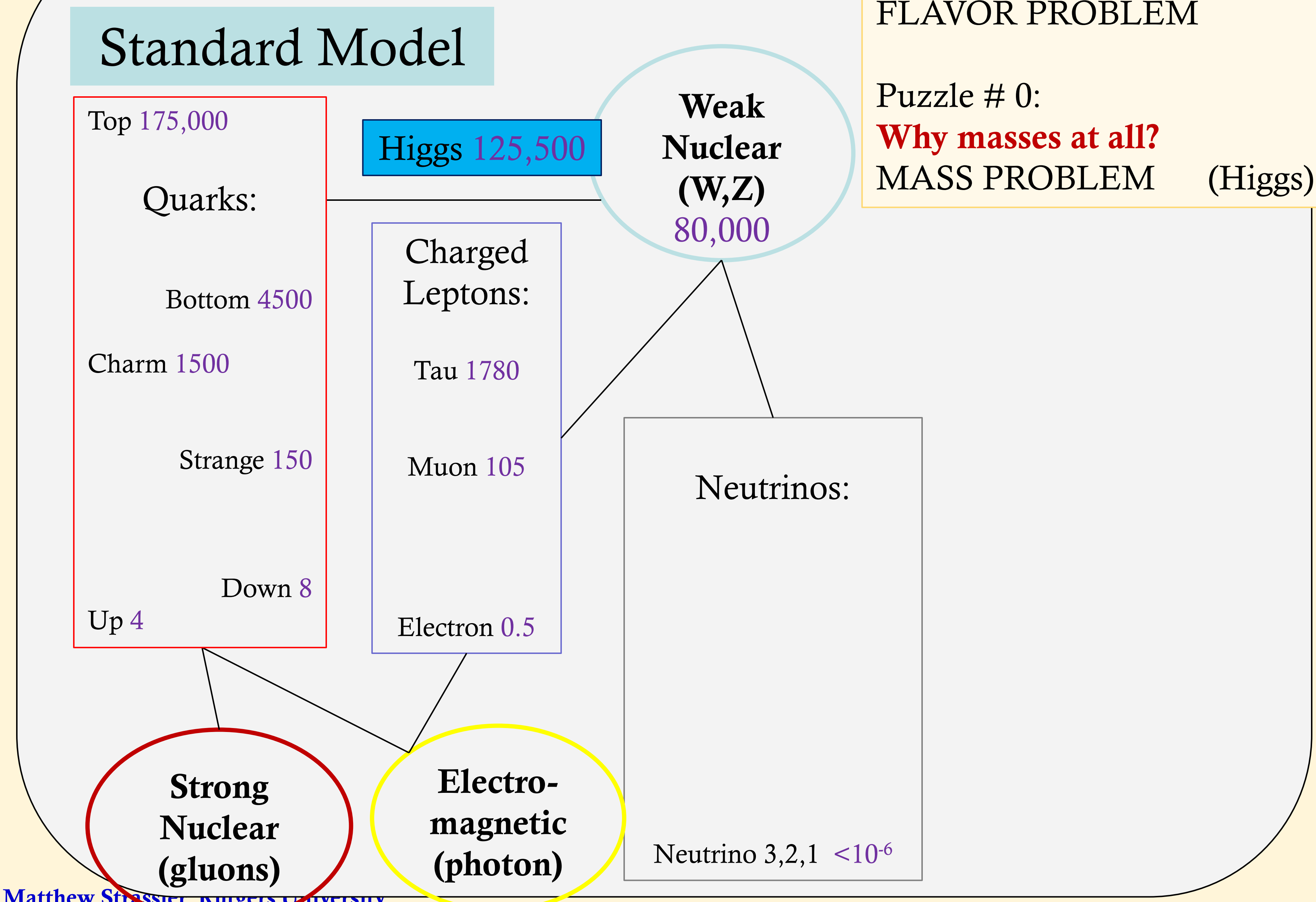
Puzzle # 1:
Why masses show this pattern?
FLAVOR PROBLEM

Puzzle # 0:
Why masses at all?
MASS PROBLEM (Higgs)



Why Masses at All? Fermions

- In quantum mechanics class, we put the electron mass **m** in by hand

$$[p^2/2\mathbf{m} + V(x)]\,\Phi(x) = E\,\Phi(x)$$

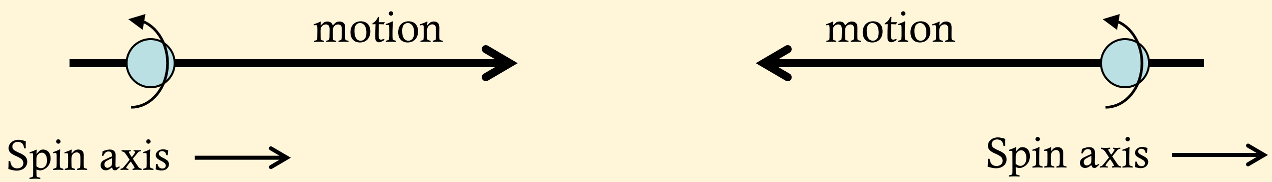
It's not something to explain, we just take it for granted.

- In quantum field theory, it was initially the same

$$\bar{\Psi}(\, i \not\partial + m)\,\Psi = 0$$

- But then a problem arose: the Weak Nuclear Force violates parity (1957)

Fermion Mass vs. Weak Nuclear Force

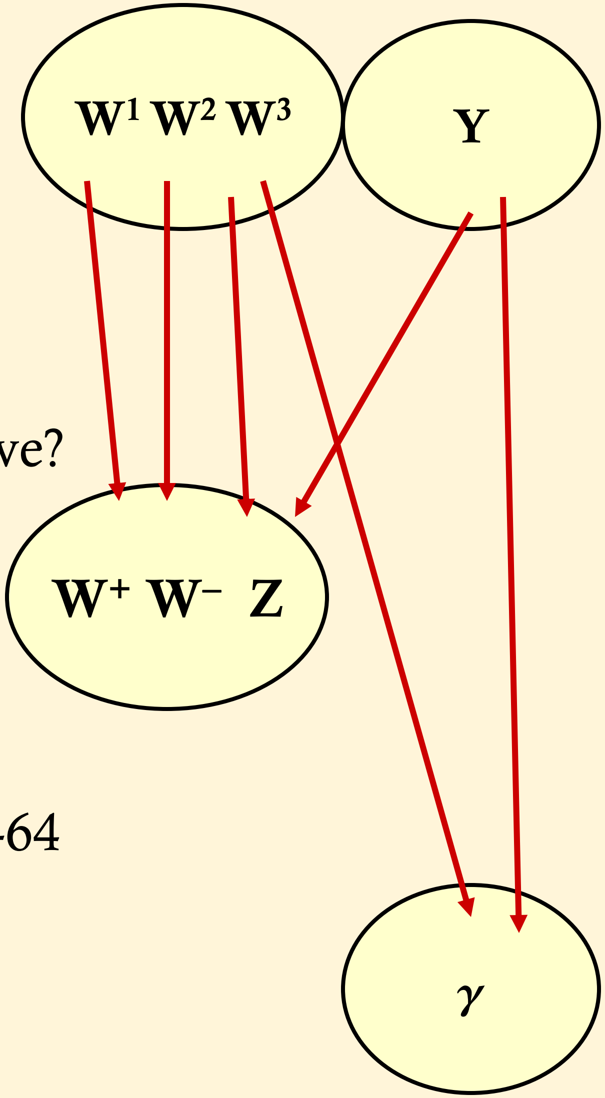


- For massless spin-½ particle, helicity is conserved
  - All observers agree on what a particle's helicity is
- For spin-½ particle with mass, helicity isn't a good quantum number
  - Different observers disagree

Mass relates positive and negative helicity particles

- But weak nuclear force violates "parity" [invariance under mirror]
  - Converts neutrinos to electrons and back again
  - Always create neutrinos with negative helicity
  - Electrons of negative and positive helicity behave differently
- Can't simply write $\overline{\Psi}(i \not\partial + m) \Psi = 0$ and combine it with the weak force

The Higgs Mechanism



Question:

How can the W and Z particles become massive?

How can electrons and other fermions become massive?

Answer: Higgs Mechanism

- Invented a number of times in quick succession 1963-64
  - Condensed matter (non-relativistic) first – Anderson
  - Within a year, relativistic version, largely independent
    - Higgs; Englert & Brout; Guralnik, Hagen, Kibble
    - Goldstone?

The Higgs Mechanism

Spin-0 ("scalar") fields $\Phi(x,y,z,t)$

Classical eq of motion is wave eq.

- $(d^2/dt^2 - c^2\nabla^2)\,\Phi = 0$
  - Each wave mode $e^{i\omega t\text{-}ikx}$ acts as independent oscillator

$$\omega^2 - k^2c^2 = 0$$

Quantize: De Broglie: $E = \hbar\omega$, $p = \hbar k$

$\Longrightarrow$ spin-0 particles with $E^2 - p^2c^2 = 0$ MASSLESS

The Higgs Mechanism

- $(d^2/dt^2 - c^2\nabla^2)\,\Phi = -\,(m^2\,c^4/\hbar^2)\,\Phi$

Add a mass term

  - Each wave mode $e^{i\omega t - ikx}$ acts as independent oscillator

$$\omega^2 - k^2c^2 = m^2\,c^4/\hbar^2$$

Quantize: De Broglie: $E = \hbar\omega$, $p = \hbar k$

$\Longrightarrow$ spin-0 particles with $E^2 - p^2c^2 = m^2\,c^4$ MASSIVE

The Higgs Mechanism

- $(d^2/dt^2 - c^2\nabla^2)\,\Phi = -\,(m^2 c^4/\hbar^2)\,\Phi$
- $(d^2/dt^2 - c^2\nabla^2)\,\mathbf{A} = 0$

Also for electromagnetic waves:
(with vector potential **A**)

– Each wave mode $e^{i\omega t - ikx}$ acts as independent oscillator

$$\omega^2 - k^2c^2 = 0$$

Quantize: De Broglie: $E = \hbar\omega$, $p = \hbar k$

$\Longrightarrow$ spin-0 particles with $E^2 - p^2c^2 = m^2 c^4$ MASSIVE

$\Longrightarrow$ spin-1 particles with $E^2 - p^2c^2 = 0$ MASSLESS

The Higgs Mechanism

- $(d^2/dt^2 - c^2\nabla^2)\,\Phi = -\,(m^2\, c^4/\hbar^2)\,\Phi + ig\mathbf{A}\cdot\nabla\Phi + g^2\mathbf{A}^2\,\Phi$
- $(d^2/dt^2 - c^2\nabla^2)\,\mathbf{A} = -\,g^2\,\Phi^*\Phi\,\mathbf{A} + ig\Phi^*\nabla\Phi - ig\Phi\nabla\Phi^*$

  – Nonlinear coupled wave equations

Couple the two fields together (coupling strength g)

$\Longrightarrow$ spin-0 particles with $E^2 - p^2c^2 = m^2\, c^4$ MASSIVE

$\Longrightarrow$ spin-1 particles with $E^2 - p^2c^2 = 0$ MASSLESS

The Higgs Mechanism

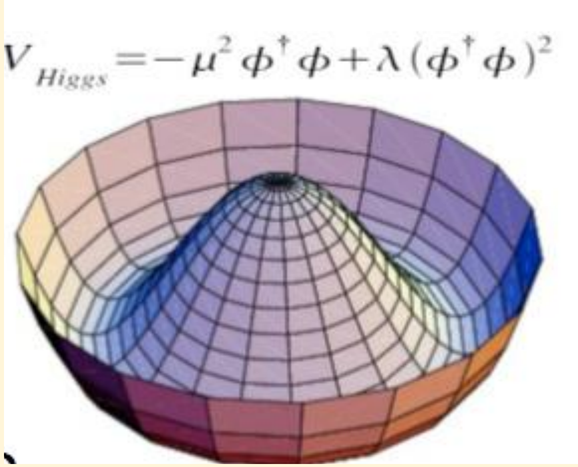
- $(d^2/dt^2 - c^2\nabla^2)\,\Phi = -\,(m^2 c^4/\hbar^2)\,\Phi + ig\mathbf{A}\cdot\nabla\Phi + g^2\mathbf{A}^2\,\Phi + \ldots$
- $(d^2/dt^2 - c^2\nabla^2)\,\mathbf{A} = -\,g^2\,\Phi^*\Phi\,\mathbf{A} + ig\Phi^*\nabla\Phi - ig\Phi\nabla\Phi^*$
  - Nonlinear coupled wave equations
  - Add potential $V(\Phi)$,

    minimum at $\Phi = v$

Let $\langle 0|\Phi|0\rangle = v$ nonzero
Write $\Phi = v + \delta\Phi$

$\Longrightarrow$ spin-0 particles with $E^2 - p^2c^2 = m^2 c^4$

$\Longrightarrow$ spin-1 particles with $E^2 - p^2c^2 = 0$



The Higgs Mechanism

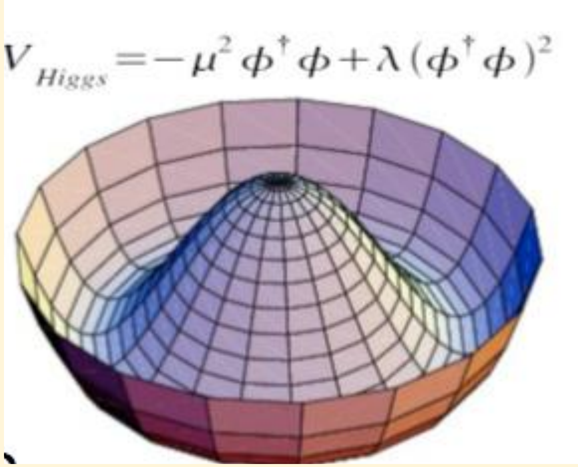
- $(d^2/dt^2 - c^2\nabla^2)\,\Phi = -\,(m^2\, c^4/\hbar^2)\,\Phi + ig\mathbf{A}\cdot\nabla\Phi + g^2\mathbf{A}^2\,\Phi + \ldots$
- $(d^2/dt^2 - c^2\nabla^2)\,\mathbf{A} = -\,g^2\, v^2\, \mathbf{A} + ig\Phi^*\nabla\Phi - ig\Phi\nabla\Phi^* + \ldots$

Let $< 0|\Phi|\, 0 > = v$ nonzero
Write $\Phi = v + \delta\Phi$

– The expectation value for Φ generates mass for A !!

$\Longrightarrow$ spin-0 particles with $E^2 - p^2c^2 = m^2\, c^4$

$\Longrightarrow$ spin-1 particles with $E^2 - p^2c^2 = g^2\, v^2\, \hbar^2$



The Higgs Mechanism

- $(d^2/dt^2 - c^2\nabla^2)\,\Phi = -\,(m^2 c^4/\hbar^2)\,\Phi + ig\mathbf{A}\cdot\nabla\Phi + g^2\mathbf{A}^2\,\Phi + \ldots$
- $(d^2/dt^2 - c^2\nabla^2)\,\mathbf{A} = -\,g^2\ v^2\ \mathbf{A}\ +\ ig\Phi^*\nabla\Phi - ig\Phi\nabla\Phi^* + \ldots$

Let $< 0|\Phi|\ 0 > = v$ nonzero
Write $\Phi = v + \delta\Phi$

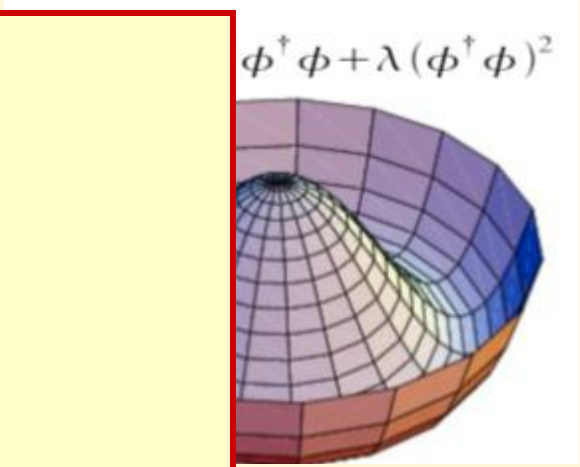
– The expectation value for Φ generates mass for A !!

Superconductor: Φ Cooper pair density

- Photon massive
- Electric screening; Meissner effect

Particle Physics: $\Phi \Longrightarrow H$ "Higgs Field"

- $<H> = v = 246$ GeV
- W^+, W^-, Z massive (80,91 GeV) [photon massless]
- Fermions couple to H $\Longrightarrow$ they also become massive
- Standard Model: δH is a massive scalar field: the Higgs boson



The Higgs Mechanism

- Spin-zero field H gets expectation value v = 246 GeV
- W, Z bosons get mass of order v (photon remains massless)
- Standard model fermions get mass less than or of order v
- Quantum of waves oscillating around v is the Higgs particle

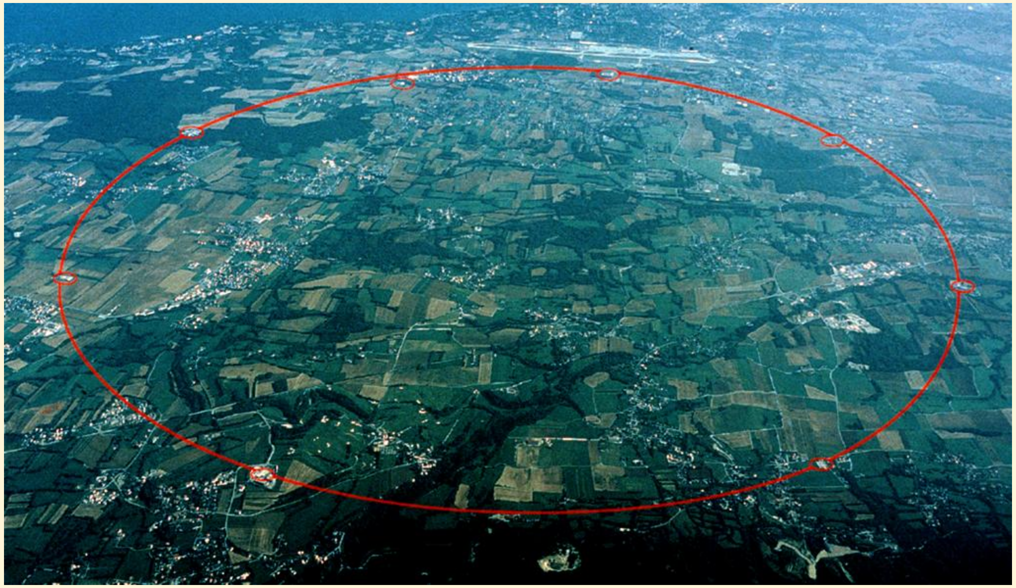
Saga of a Century!! And Not Over Yet

- 1897 – Electron discovered, mass measured, source of mass unknown
- 1905-20 – Massless photon suggested; discovered 1924
- 1957 – Discovery that weak nuclear force is mirror-asymmetric!
- 1964 – Higgs Field papers (Higgs, Brout & Englert, and Guralnik, Kibble & Hagen)
- 1967 – Weinberg (and Salam) theory of weak nuclear force, based on crucial work by Glashow, using Higgs Field to give masses for the then-known particles

- Mid-1970s – Serious consideration of how to make/discover Higgs Particle
- 1980s–90s – proposal of the ~~U.S. SSC,~~ European Large Hadron Collider (LHC)
- 1990s–2000s– searches elsewhere for simplest Higgs: 0 – 115, 140 – 170 GeV
- 2012 LHC data reveals new particle consistent with Higgs at about 125 GeV

Proton mass = 0.938 GeV

The Large Hadron Collider



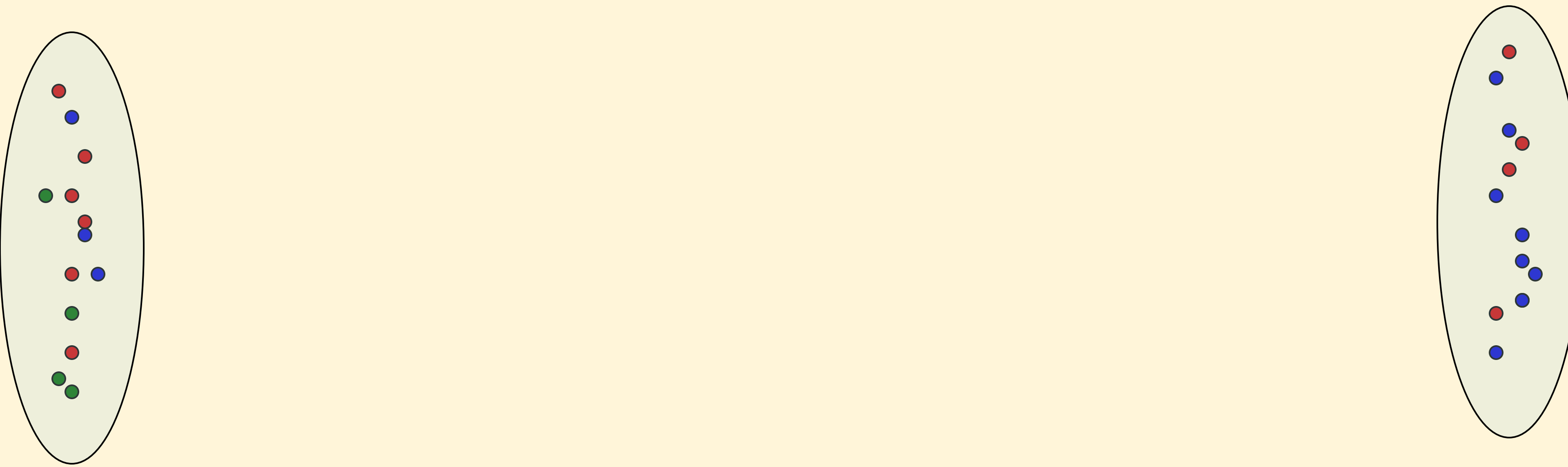
The Design:

- Underground tunnel
- Store bunches of high-energy protons going in opposite directions
- Accelerate, steer, focus bunches using electric and magnetic fields
- Adjust until collision location, rate matches requirements

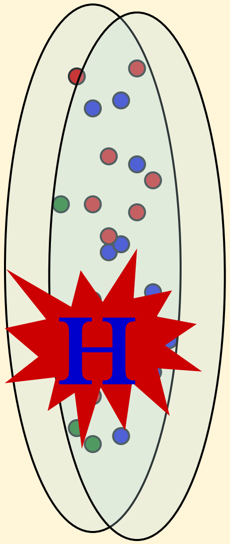
In proton-proton collisions, hope to produce

- Higgs particles, at a bare minimum
- Other new and unexpected particles or phenomena, if they are there

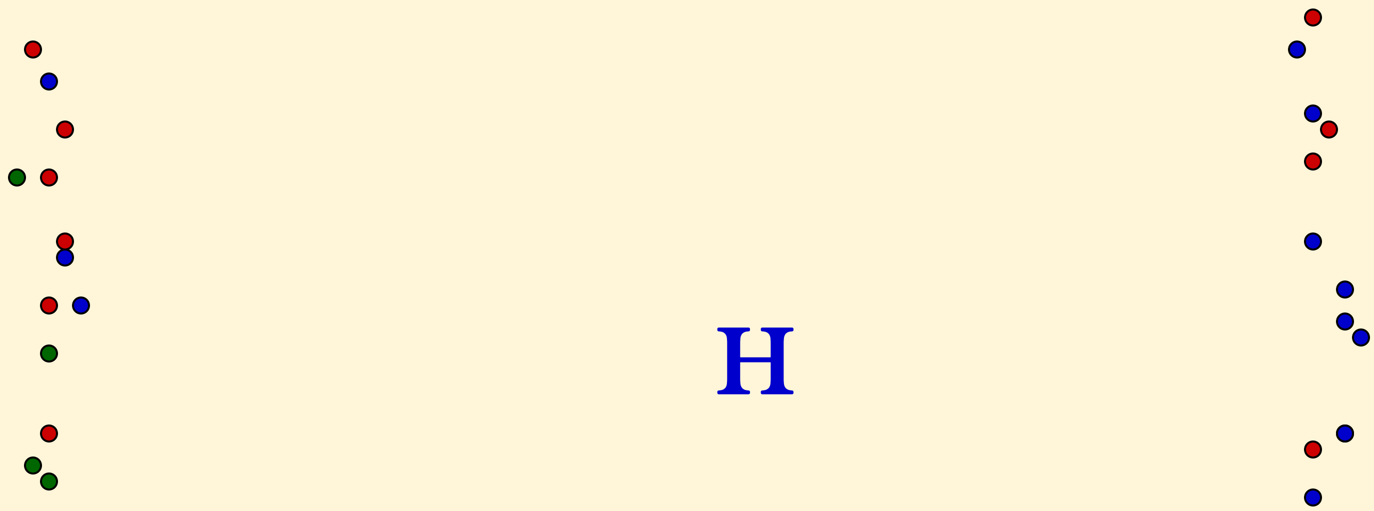
gluon gluon ⟹ Higgs ⟹ photon photon



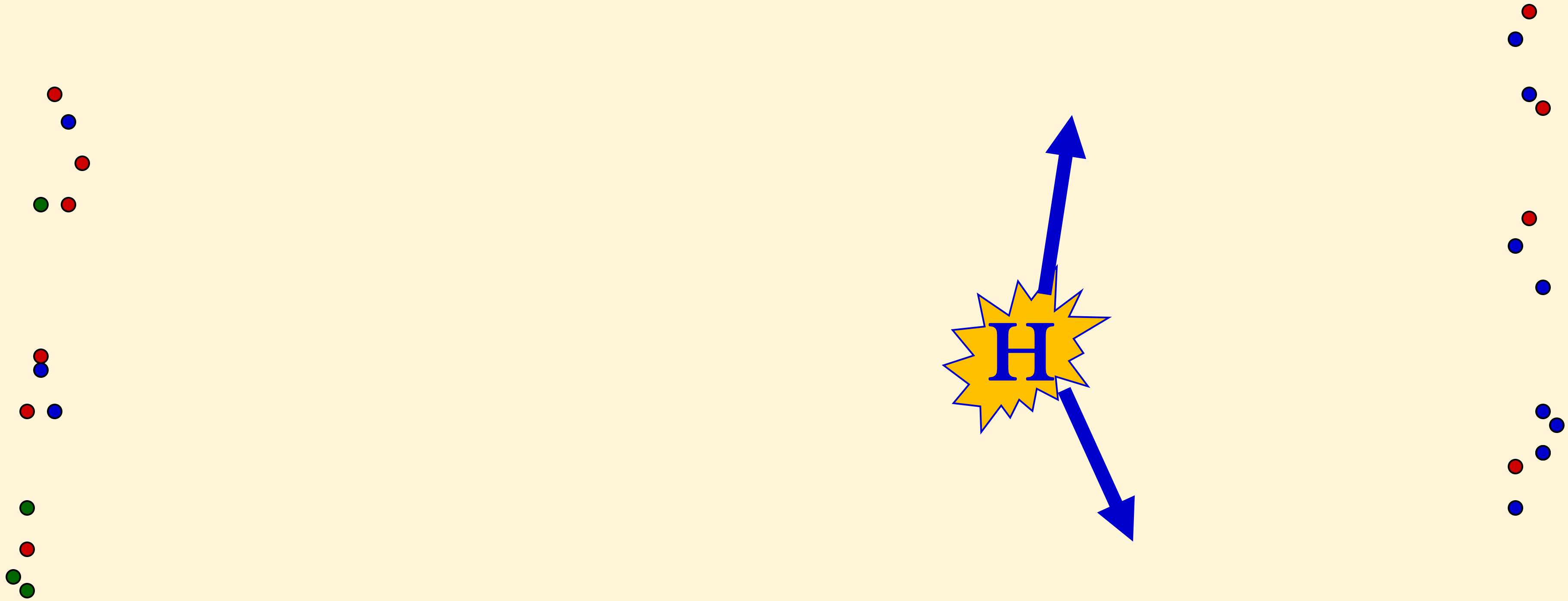
gluon gluon ⟹ Higgs ⟹ photon photon



gluon gluon ⟹ Higgs ⟹ photon photon



gluon gluon ⟹ Higgs ⟹ photon photon



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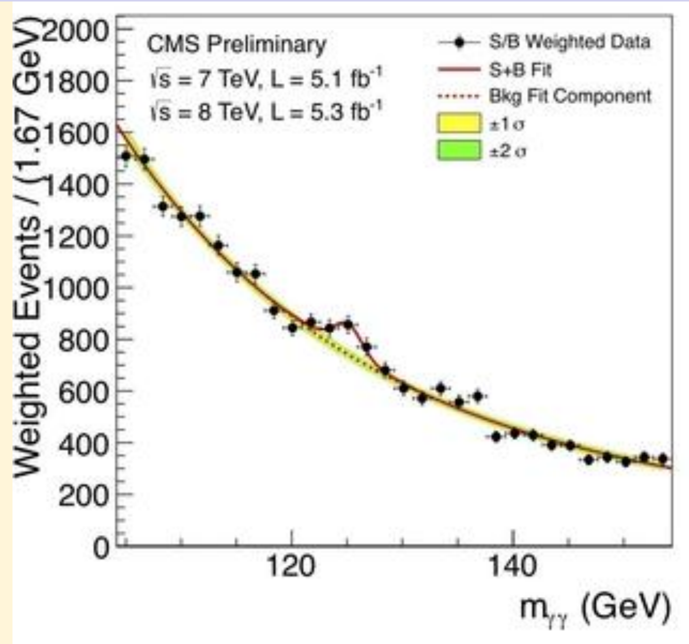
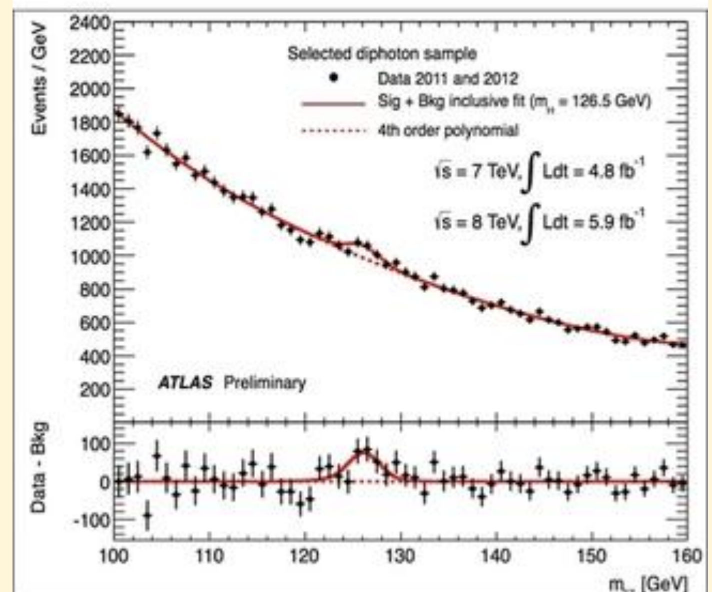
Number of Collisions with Two Photons
vs.
Invariant Mass of the Two Photons

Proton + Proton → Higgs? → Two photons





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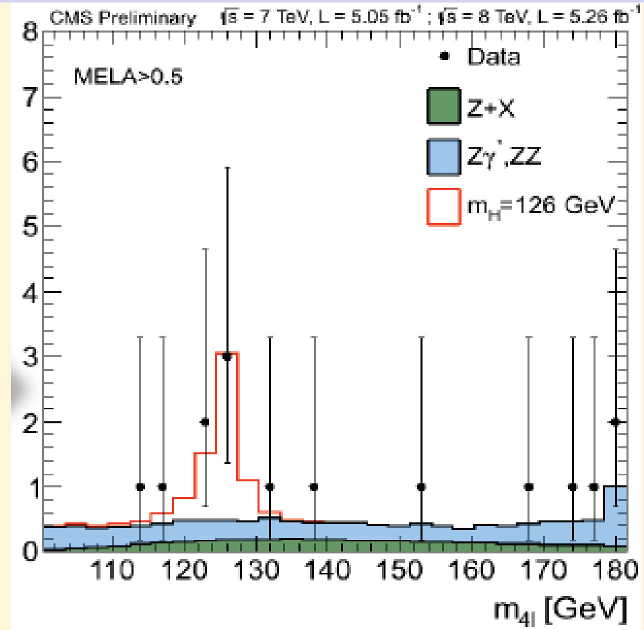
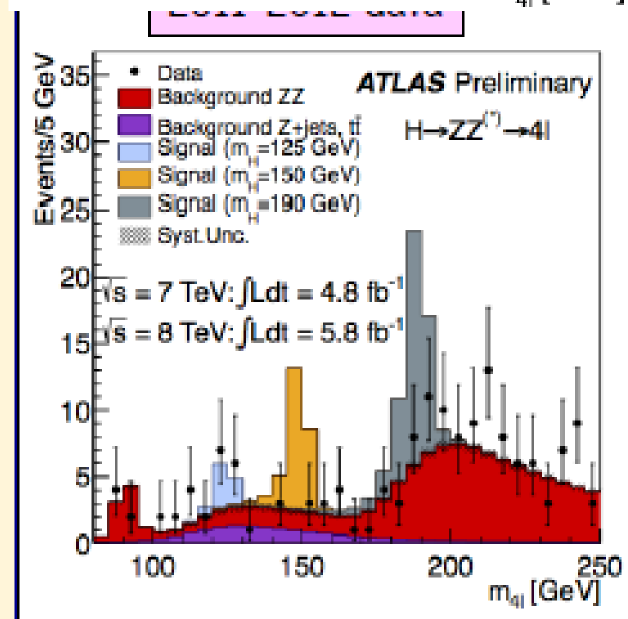
Number of Collisions with Four Leptons
vs.
Invariant Mass of the Four Leptons

Proton + Proton → Higgs? → Two "lepton pairs"

"lepton pair" = electron + positron or
muon + anti-muon





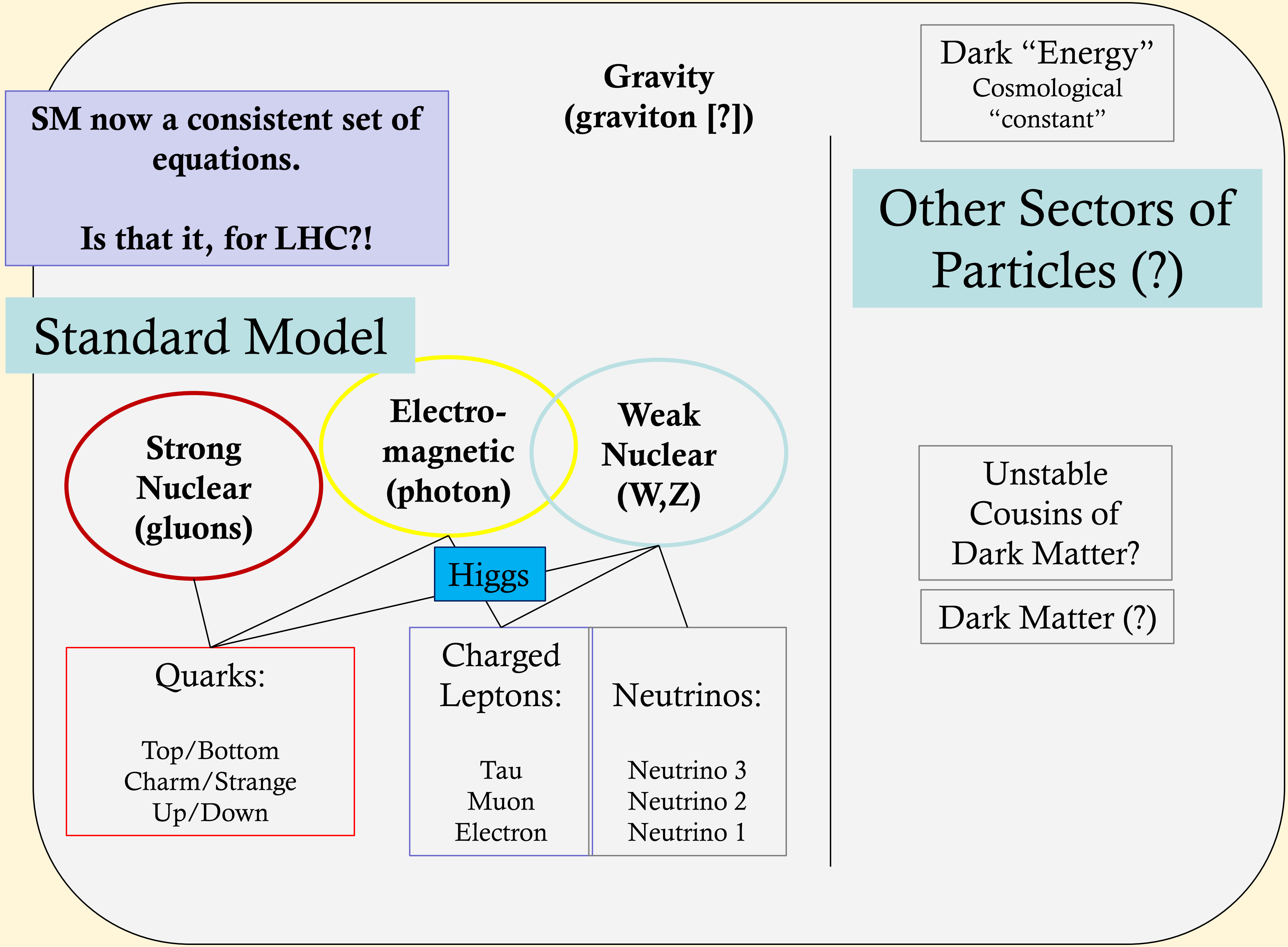
So Much We Still Don't Know

- Is this a Higgs particle? (probably, in my view)
- Could this be anything else? (yes, but similarity to a Higgs will then be accidental)
  - Know more by November and March
  - Then not much for a while
    - 2013-2014 LHC shutdown, some continuing data analysis

- SM or not SM: One Higgs field or several, each with its own type of Higgs particle?

- SM or not SM: An elementary field, or made from other elementary fields
  - Higgs particle elementary like electron? Or composite like proton?

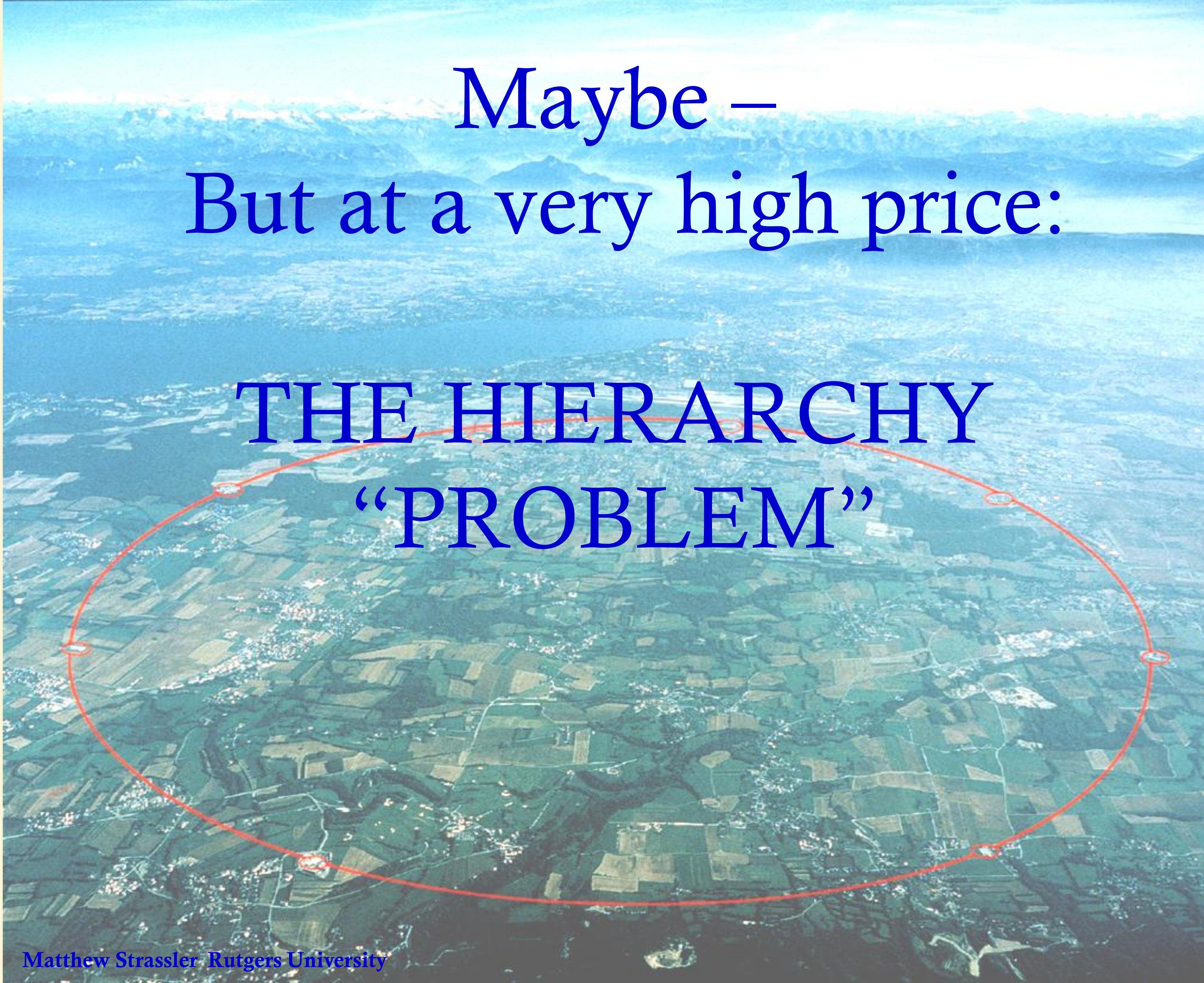
- I~~s it possible the Higgs field has no particle at all~~? (It was; but data apparently says no!)



SM now a consistent set of equations.
Is that it, for LHC?!
Gravity
(graviton [?])
Dark "Energy"
Cosmological "constant"
Other Sectors of Particles (?)
Standard Model
Strong Nuclear (gluons)
Electro-magnetic (photon)
Weak Nuclear (W,Z)
Higgs
Quarks:
Top/Bottom
Charm/Strange
Up/Down
Charged Leptons:
Tau
Muon
Electron
Neutrinos:
Neutrino 3
Neutrino 2
Neutrino 1
Unstable Cousins of Dark Matter?
Dark Matter (?)

Maybe –
But at a very high price:

THE HIERARCHY “PROBLEM”



The Hierarchy Paradox

- Quantum Harmonic Oscillator: Zero Point Energy $E_0 = \frac{1}{2} \hbar \omega$

- Quantum Field: Infinite # of Coupled Oscillators per Unit Vol.
  - Zero-Point Energy Density E_0 /Vol➔ Infinity

Is this infinite constant a problem?

- Probably not infinite
- Spacetime probably changes at Gravitational scale, E_0 /Vol not infinite
  - Probably E_0 / Vol = 10^{15} TeV / $(10^{-34}$ m$)^3$ [still huge]

The Hierarchy Paradox

- Quantum Harmonic Oscillator: Zero Point Energy $E_0 = \frac{1}{2} \hbar \omega$
- Quantum Field: Infinite # of Coupled Oscillators per Unit Vol.
  - Zero-Point Energy Density E_0 /Vol ➔ ~~Infinity~~ 10^{15} TeV / $(10^{-34}$ m$)^3$

Is this huge constant a problem?

- Not if you ignore gravity…
  - *Gravity ➔ This is a Huge Cosmological Constant*
    - *By rights this should destabilize cosmos – ??!??*

But wait – **it isn't even constant**! Even without gravity, must pay attention!

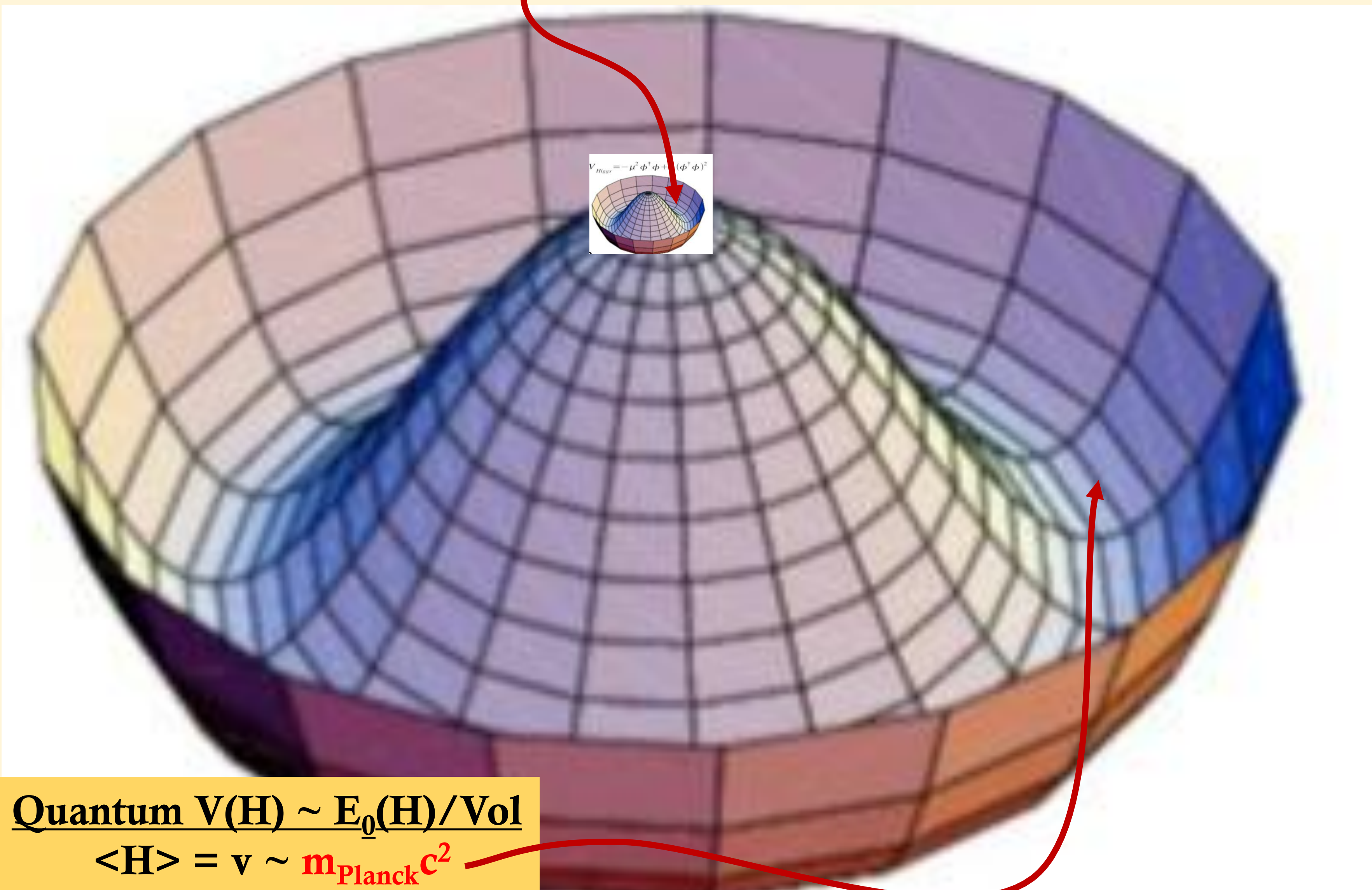
- For each field, value of ω depends on mass of the field
- Masses of many fields depend on value of Higgs field <H> = v

- E_0 is really **E_0(H)**

➔ Big Quantum Correction to Higgs Potential V(H) from E_0/Vol

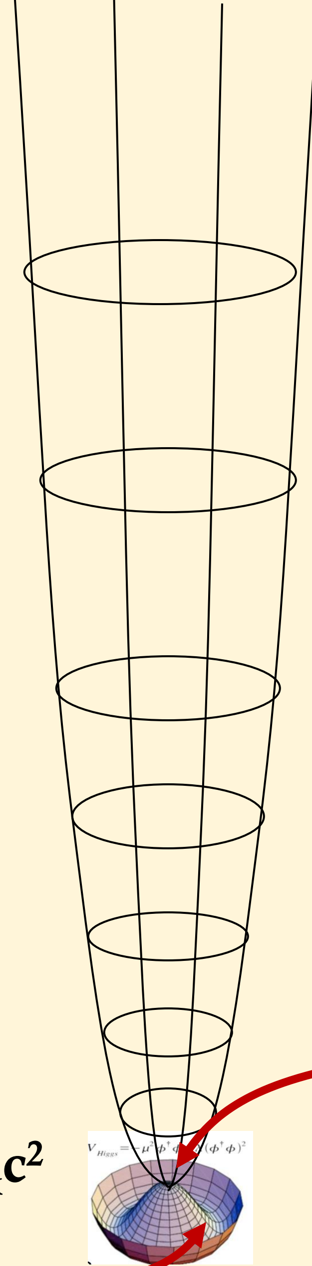
Classical V(H)

$\langle H \rangle = v = 246$ GeV $= 10^{-15}\, m_{Planck} c^2$



Quantum V(H) ~ E_0(H)/Vol

$\langle H \rangle = v \sim m_{Planck} c^2$



Quantum V(H) ~ E_0(H)/Vol

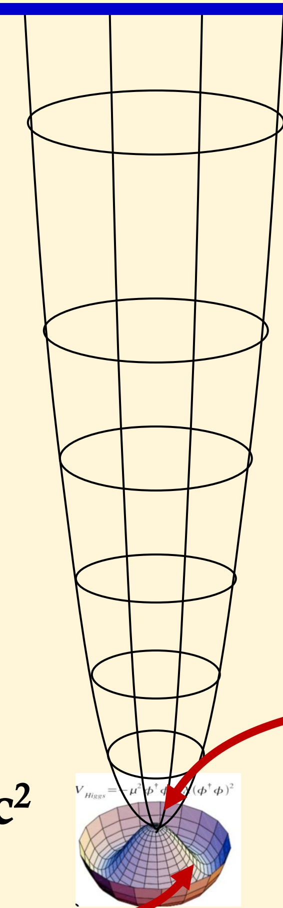
$\langle H \rangle = v = 0$

Classical V(H)

$\langle H \rangle = v = 246\ \mathrm{GeV} = 10^{-15}\ m_{Planck}c^2$

The Hierarchy Problem:

How is it that $v / m_{Planck}c^2 \sim 10^{-15}$ instead of $= 0$ or ~ 1



Quantum V(H) ~ E_0(H)/Vol
<H> = v = 0

Classical V(H)
<H> = v = 246 GeV = 10^{-15} $m_{Planck}c^2$

Light and Lonely Higgs Is "Unnatural"

- In either case:
  - The Higgs boson should have an **enormous** mass
  - The energy scale of the weak nuclear force should be **huge** or <u>zero</u>

- Unnatural for there to be an observable Higgs boson, by this argument
- But we ***need*** one for the SM to make theoretical sense
    - And there's something like one in the data
  - So either the SM is incomplete, or the hierarchy argument is wrong

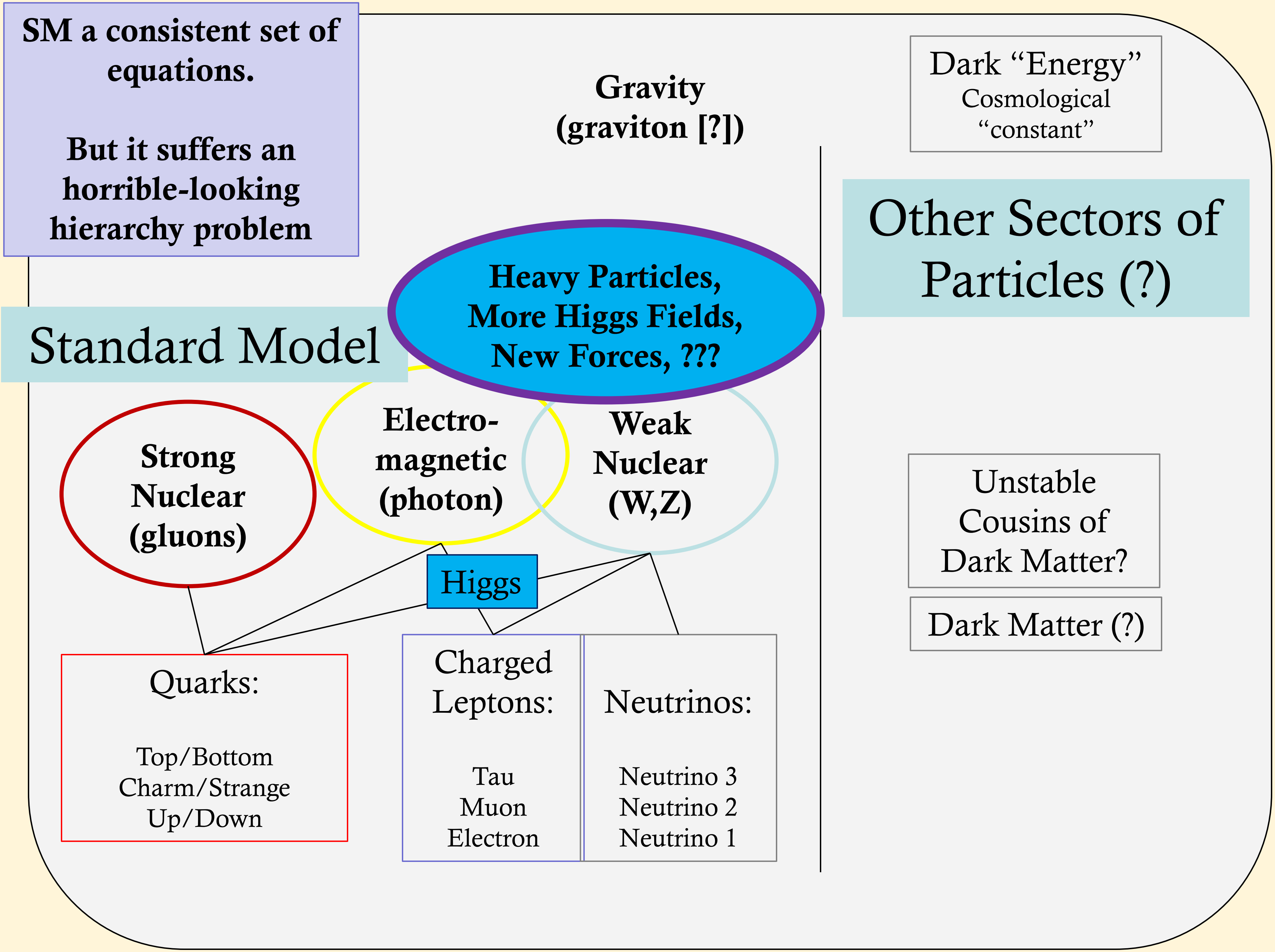
- Light spin-0 particle, with nothing additional to explain its presence, would fly in face of our understanding of quantum field theory
  - Such "Naturalness" arguments have worked throughout particle physics and condensed matter physics in the past
  - Failure here would be jaw-droppingly mysterious
    - "SM is simplest repair" – but also most radical of all

The Standard Model + Gravity + Dark Stuff

If what we have at LHC is just the SM, leaves many deep unsolved problems:

- #10^{15} – **Hierarchy Problem: Why is v nonzero but very small?**
    - Why spin-zero particle with nothing new near its mass scale?
- #0 – ~~Mass Problem: Why is there mass at all?~~ *Apparently solved.*
- #1 – Flavor Problem: Why the wacky pattern of masses? Of decays?
    - Why is top quark so heavy?
- #2 – CP Problem: CP symmetry violated in weak nuclear force, but not strong nuclear force (even though latter seems natural)

- And more --
    - #3 – Why are there three generations of particles in SM?
    - #4 – Why are there four types of forces in SM?
    - #X – What is dark matter?
    - #10^{120} – C.C. Problem: Why is universe accelerating, but very slowly?
    - #ω – Why is quantum mechanics the world's way of being?



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Popular Potential Solutions?

The Hierarchy Problem:

How is it that $v / m_{Planck}c^2 \sim 10^{-15}$ instead of $= 0$ or ~ 1

- Higgs field is a composite field held together by new forces at the TeV scale
  - *Calculation of zero point energy is wrong above that point*

- Supersymmetry:
  - *"Superpartner" particles for every known particle near TeV scale*
  - *Cancel the zero-point energy of fermions and bosons of similar mass*

- Gravity, Extra Dimensions at TeV scale, not 10^{15} TeV
  - *Planck scale, spacetime, etc. are not what we think*

These and others predict new particles/forces/phenomena that LHC can find

(sooner or later)

Searching for Signs

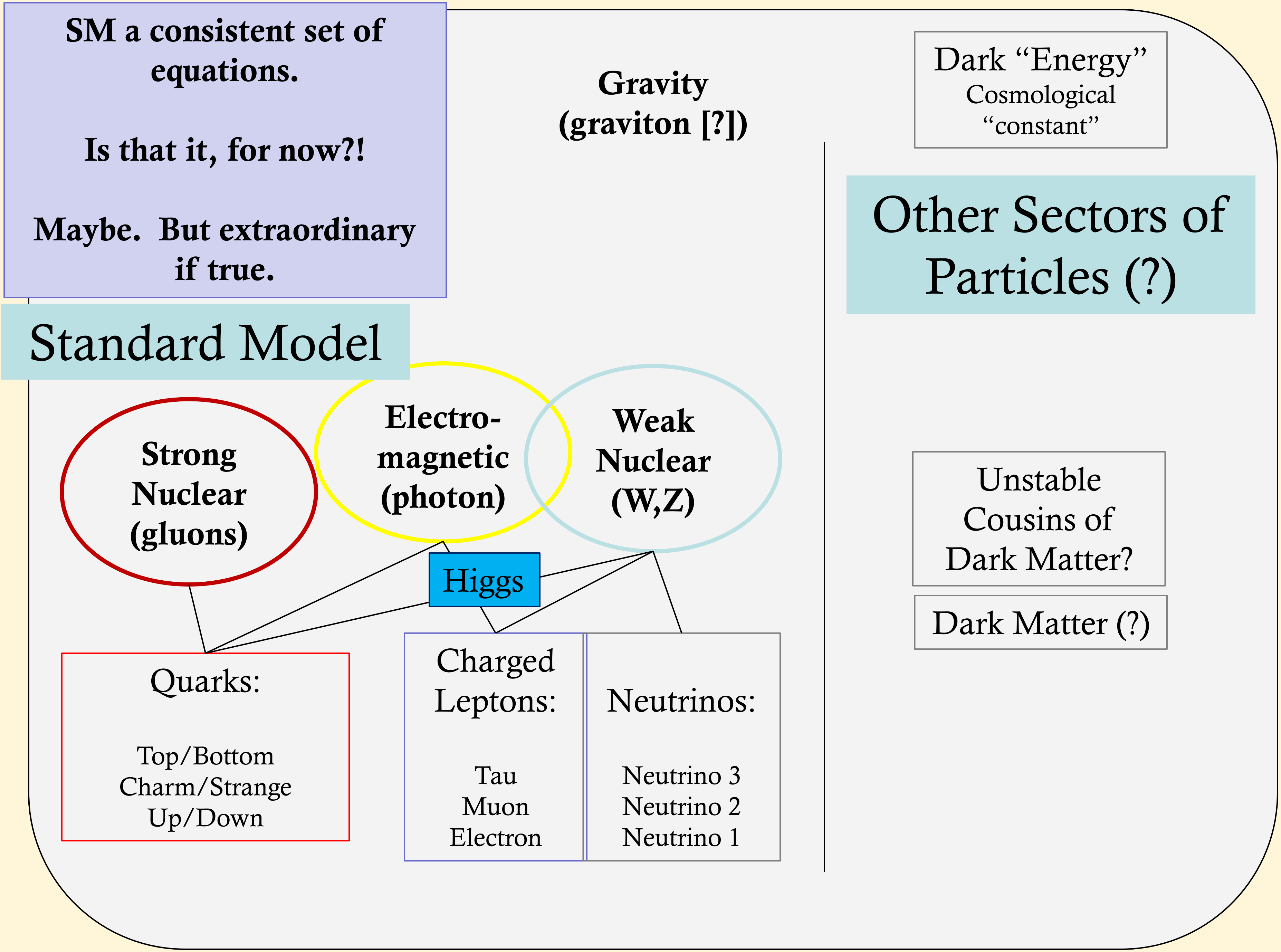
- Dozens of different search strategies in use
  - Still looking mostly for relatively high rate, easily-detected processes
  - Testing SM predictions for the Higgs particle itself in detail

- So far? Nothing.
  - Big breakdown in quantum field theory unlikely
  - Many (but not all) composite-Higgs scenarios excluded
  - Otherwise still ambiguous
    - Disfavors many versions of supersymmetry (others remain)
    - Disfavors some classes of extra dimension models (others remain)
    - Some sensitivity to some types of hidden sectors (many remain)

- **But still in early stages of LHC!**

  less than few % of total data collected

  many types of data analysis strategies not tried yet



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Is it the SM (for now), or Isn't it?

- Theoretically: SM or **not** SM is **night** vs. **day**
  - Not SM at LHC? then great puzzles of SM – especially the hierarchy problem – may be on the verge of solution.
  - Only SM at LHC? Hierarchy problem unsolved; a lightweight lonesome **elementary** scalar particle… And all the other puzzles to remain unsolved for now as well. Very deep mysteries.

- Experimentally: SM or **not** SM may be **night** vs. **deep twilight**.
  - Plenty of non-SM theories may differ from SM by
    - Subtle effects on the Higgs particle's properties of order 10%
    - Hard-to-discover new particles
  - Thus all possible information must be squeezed from LHC's data
    - Can prove SM is false; can't prove it true!
      - *Maybe just need a bit more precision…?*

Goals of Next Phase of LHC

2012 at 8 TeV per collision; 2015-2018 or later at 13-14 TeV per collision

- Precision measurements of the new particle
  - Is it really a Higgs particle?
  - Do all of its properties agree perfectly with the predictions of the SM?
    - Spin, Parity
    - Production rates
    - Decay rates
    - Any exotic properties?

- Continued search for non-SM particles, forces, phenomena
- Precision tests of many other SM predictions

- Aim to determine as far as possible: SM or **not** SM

The Higgs Era Has (probably) Begun

- A new particle has been discovered at the Large Hadron Collider
  - Consistent with **some** type of Higgs particle
  - Consistent so far with the **simplest** type, that of the Standard Model

- The Standard Model has numerous profound puzzles; is it really right?
  - The Higgs field gives mass to most Standard Model particles
    - Explains how particles can have mass at all
  - But we have no idea what sets the precise values of the masses
  - And then there's the huge Hierarchy Problem
    - Why is weak scale neither zero nor at Planck scale?
    - How/why is a lightweight spin-0 particle like Higgs reasonable?

- Solutions to Hierarchy Problem all give discoverable particles at LHC
  - No sign of them yet, but it is still early days at the LHC

- **So stay tuned as we test the Standard Model from all sides**