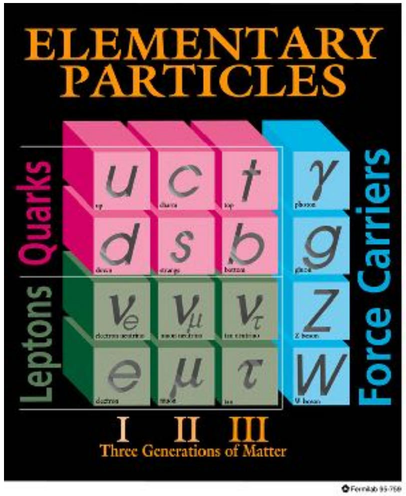
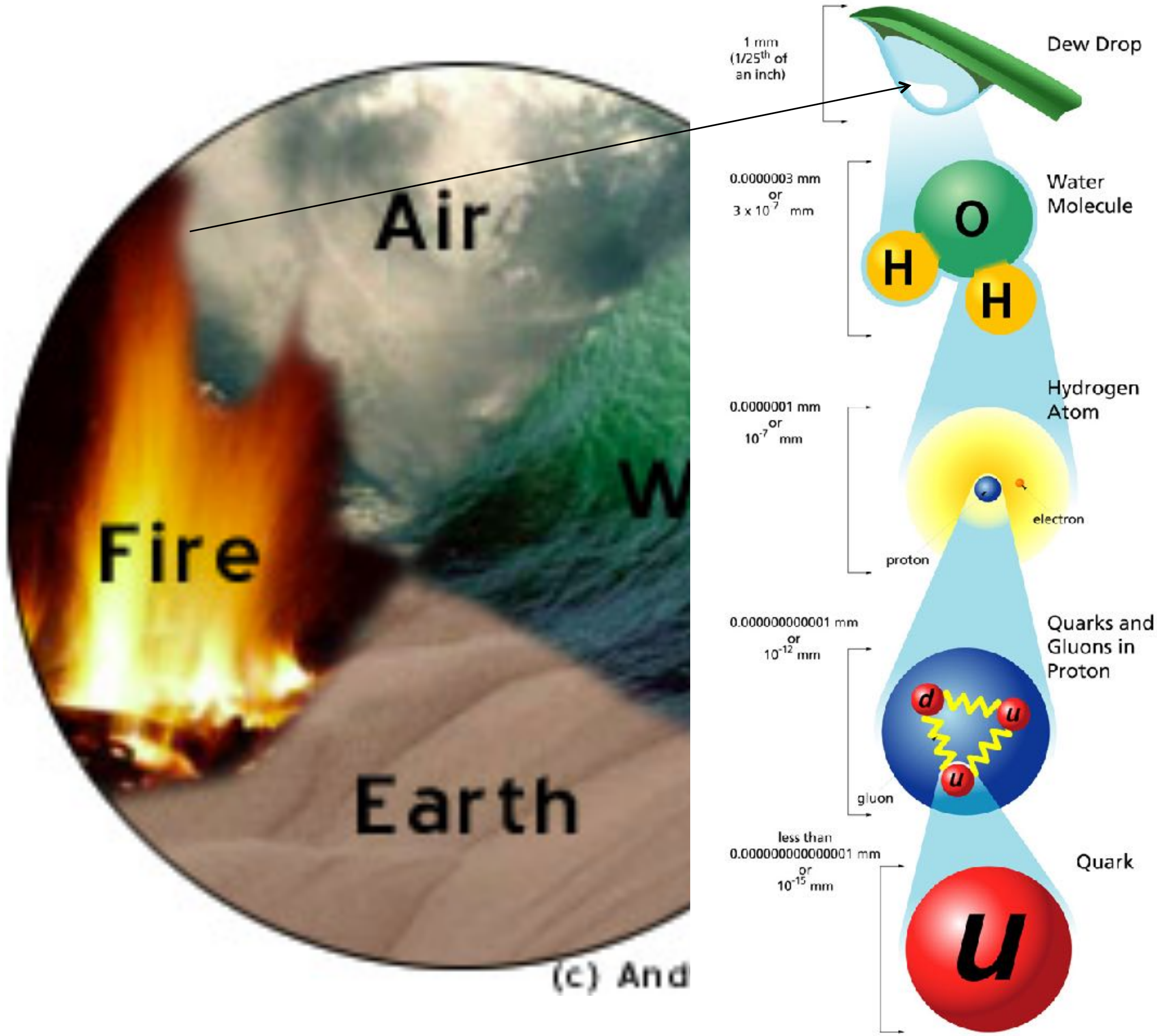
Higgs Mechanism Investigations at the LHC

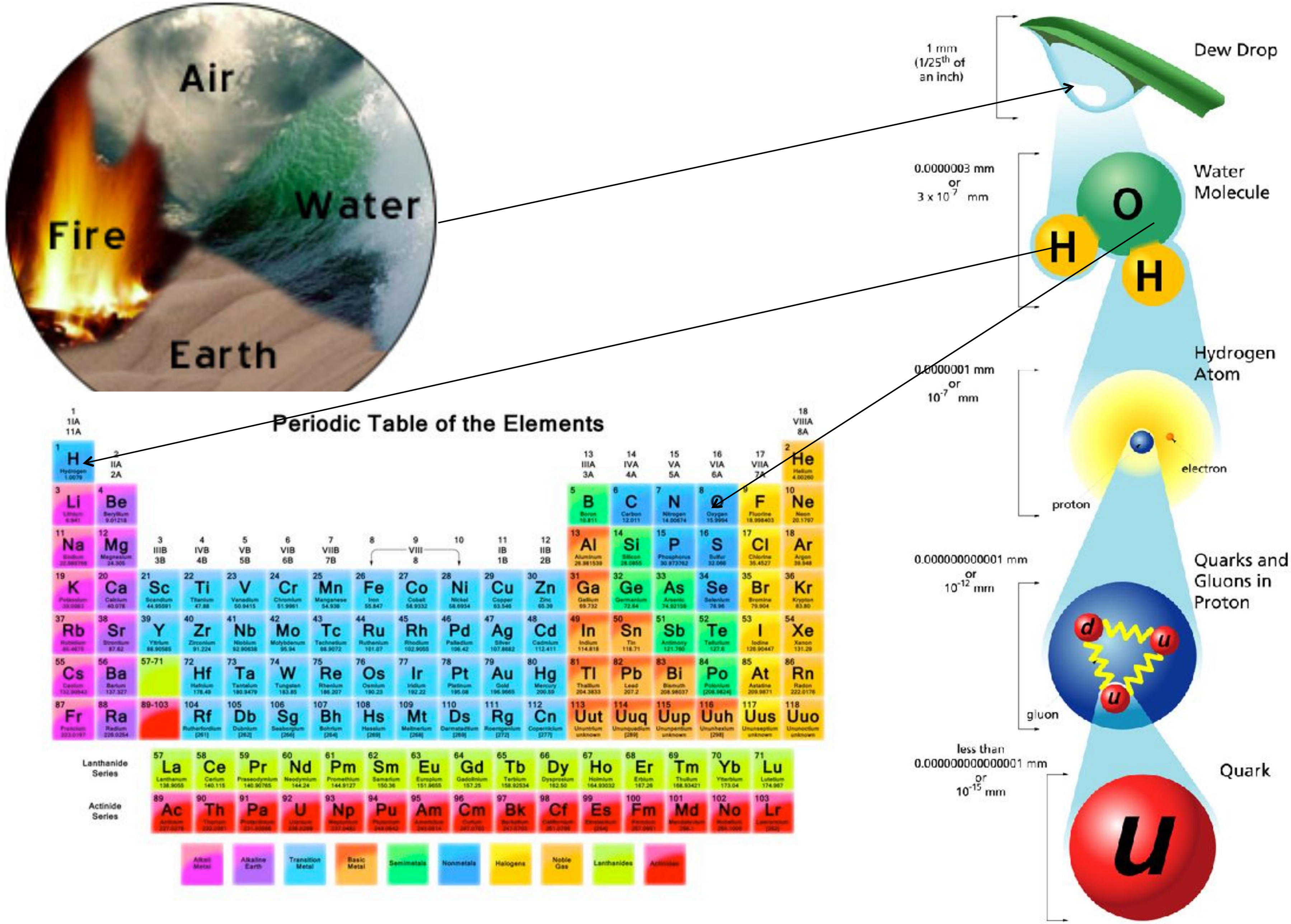


Yuri Gershtein

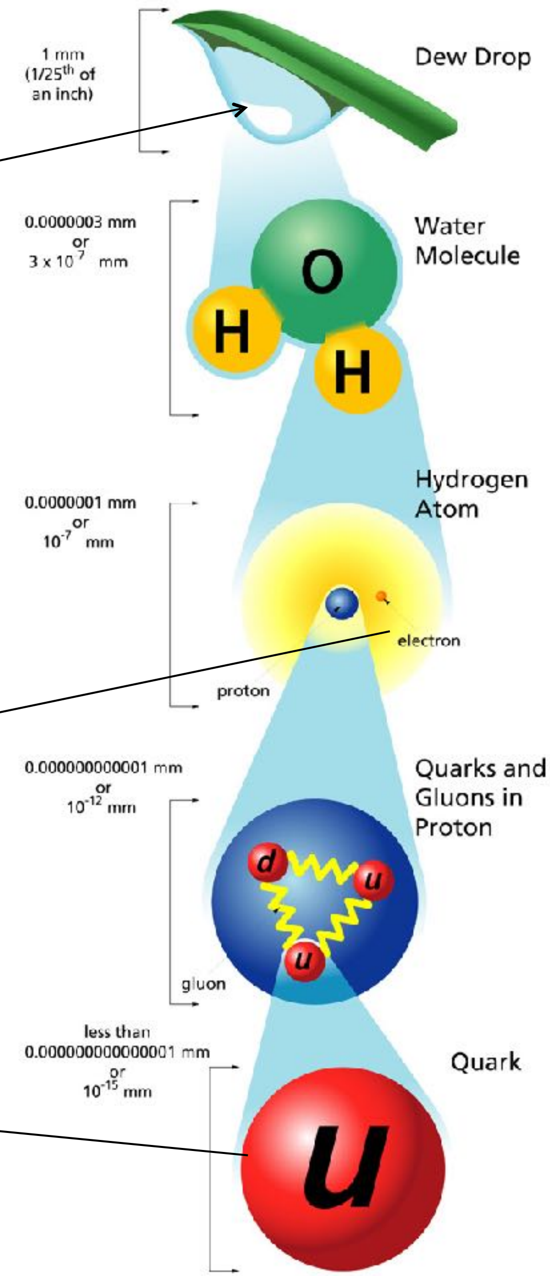
Particle physics: reductionism at work



Particle physics: reductionism at work



Particle physics: reductionism at work

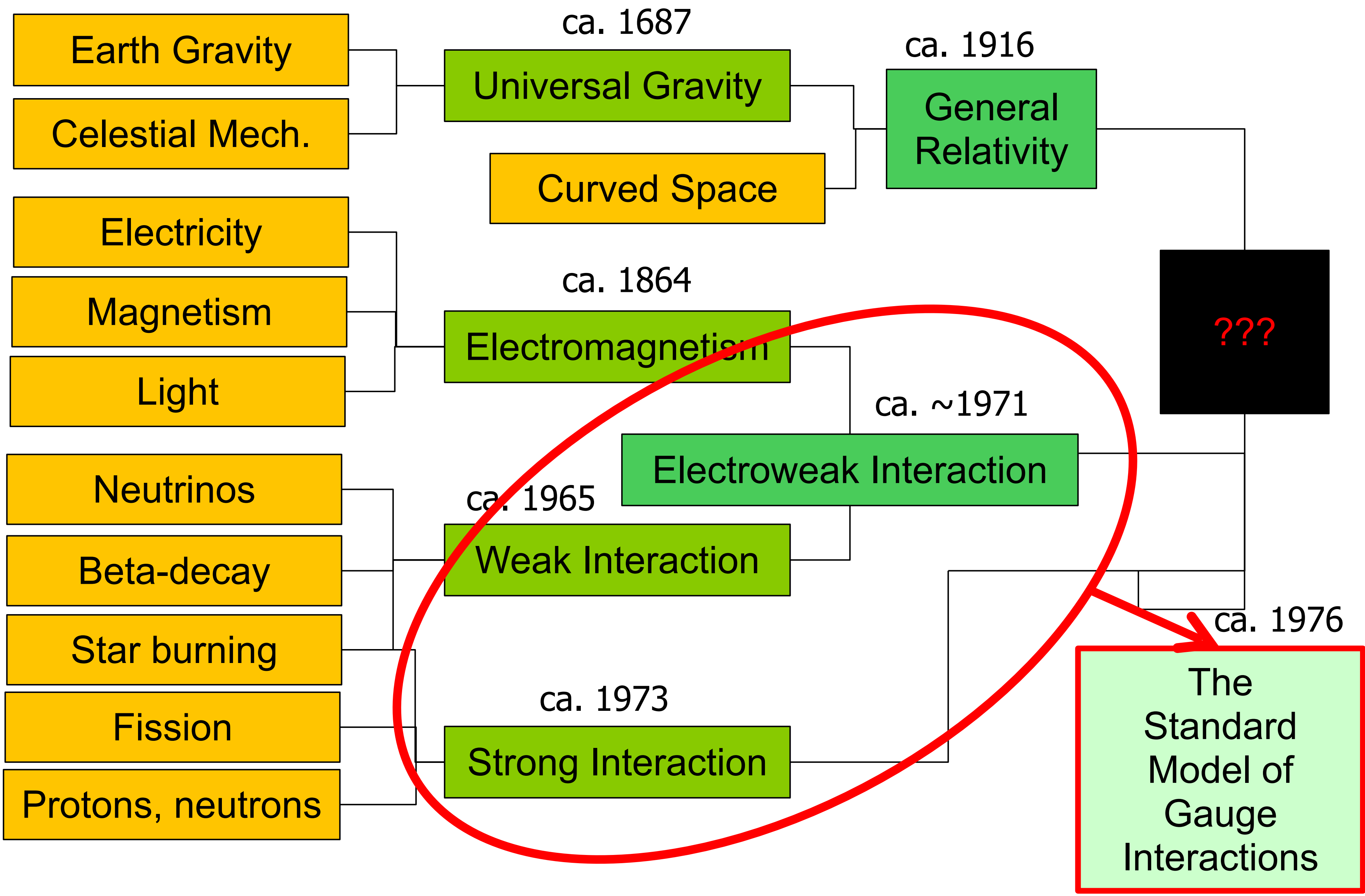


Elementary Particles

(i.e. point-like, with no internal structure)

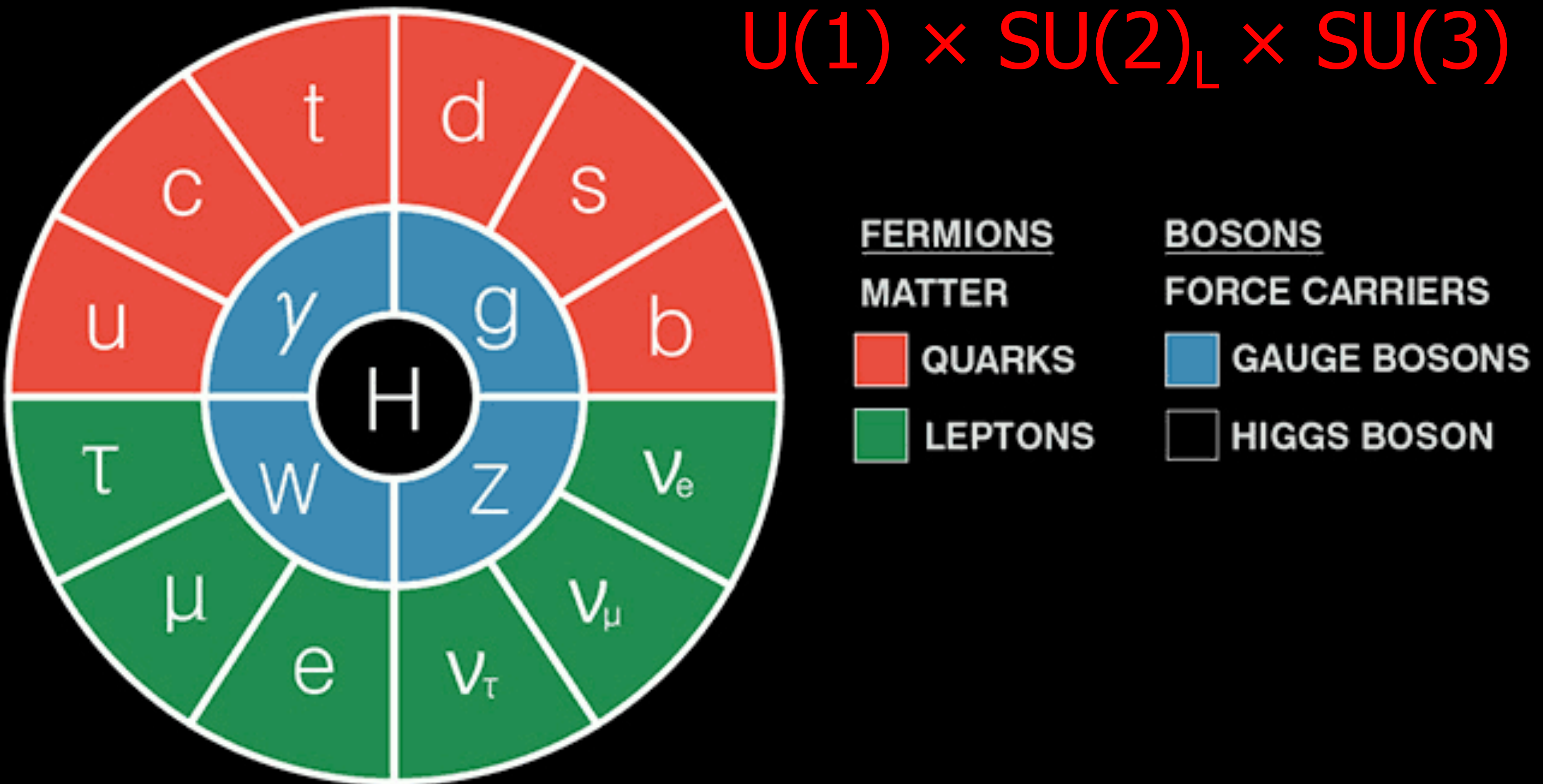
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau
Quarks	*u* up	*c* charm	*t* top
	d down	*s* strange	*b* bottom

Unification of Forces



The Standard Model

Gauge Interactions
$U(1) \times SU(2)_L \times SU(3)$



Outline

- What is the Higgs and why we need it
  - how it is different from any other particle / field
  - the long road to its discovery
- What have we actually discovered
- What does it mean?
  - new questions and old
  - why the Higgs sector as it is now is not enough
- The road ahead
  - new particle searches
  - high luminosity LHC: the Higgs factory
  - beyond the LHC

With many slides shamelessly stolen from too many people to list here

Higgs is...

- Particle
- Wave
- Field
- All of the above

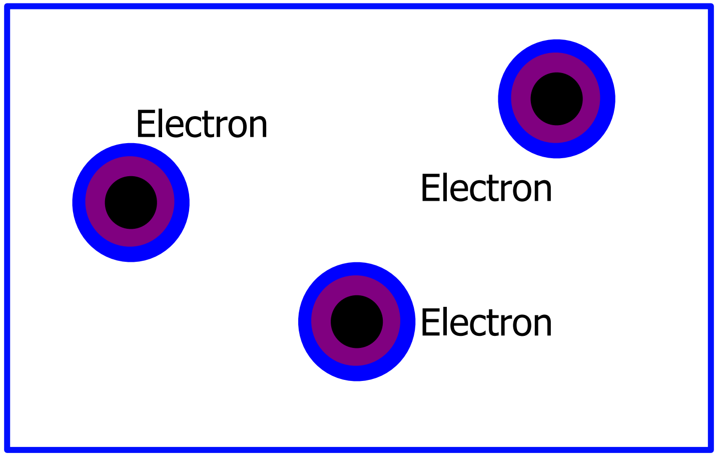
Higgs is…

- Particle
- Wave
- Field
- All of the above

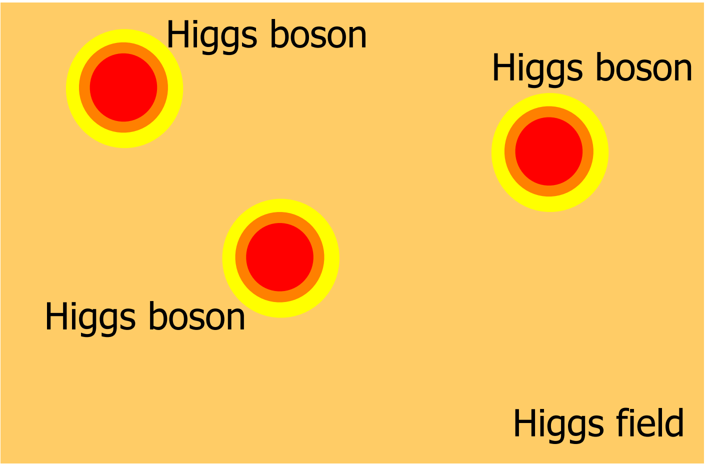
Quantum Fields

- Field is the fundamental underlying object
  - every particle we know can be described as a ripple in a quantum field
  - Experimentalists are more interested in particles, since it's the main source of information about the field

Electron field is mostly zero in a volume where there are no particles



- Higgs field is in several ways fundamentally different from all others we discovered over the years
  - It is non-zero everywhere in space, even if there are no particles (waves, ripples)
  - Scalar field (its excitations are fundamental spin 0 particles)



Mass in Gauge Theories

- If one just puts the masses into Lagrangian the theory breaks: looses gauge invariance
  - becomes unrenormalizable (i.e. nothing can be reliably calculated)
  - no viable theoretical alternatives

Higgs Mechanism

- Separate piece of SM
  - introduced "by hand"
- Mass $\leftrightarrow$ Rest energy
- If we make particle interact with vacuum it will acquire additional energy $\rightarrow$ MASS
- In the Standard Model the vacuum is "skewed" by the Higgs field, and particles get mass from interaction with the Higgs field

Mass in Gauge Theories

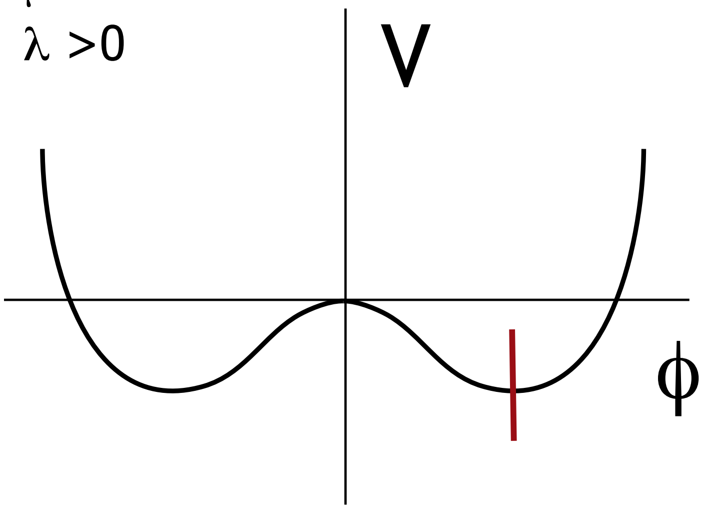
Postulate Higgs field ϕ

Postulate that it has a potential

$$V(\phi) = \mu^2 |\varphi|^2 + \lambda |\varphi|^4$$

$\mu^2 < 0$

$\lambda > 0$



spontaneous symmetry breaking: potential is symmetric, but the solution is not

Higgs Mechanism

- Separate piece of SM
  - introduced "by hand"
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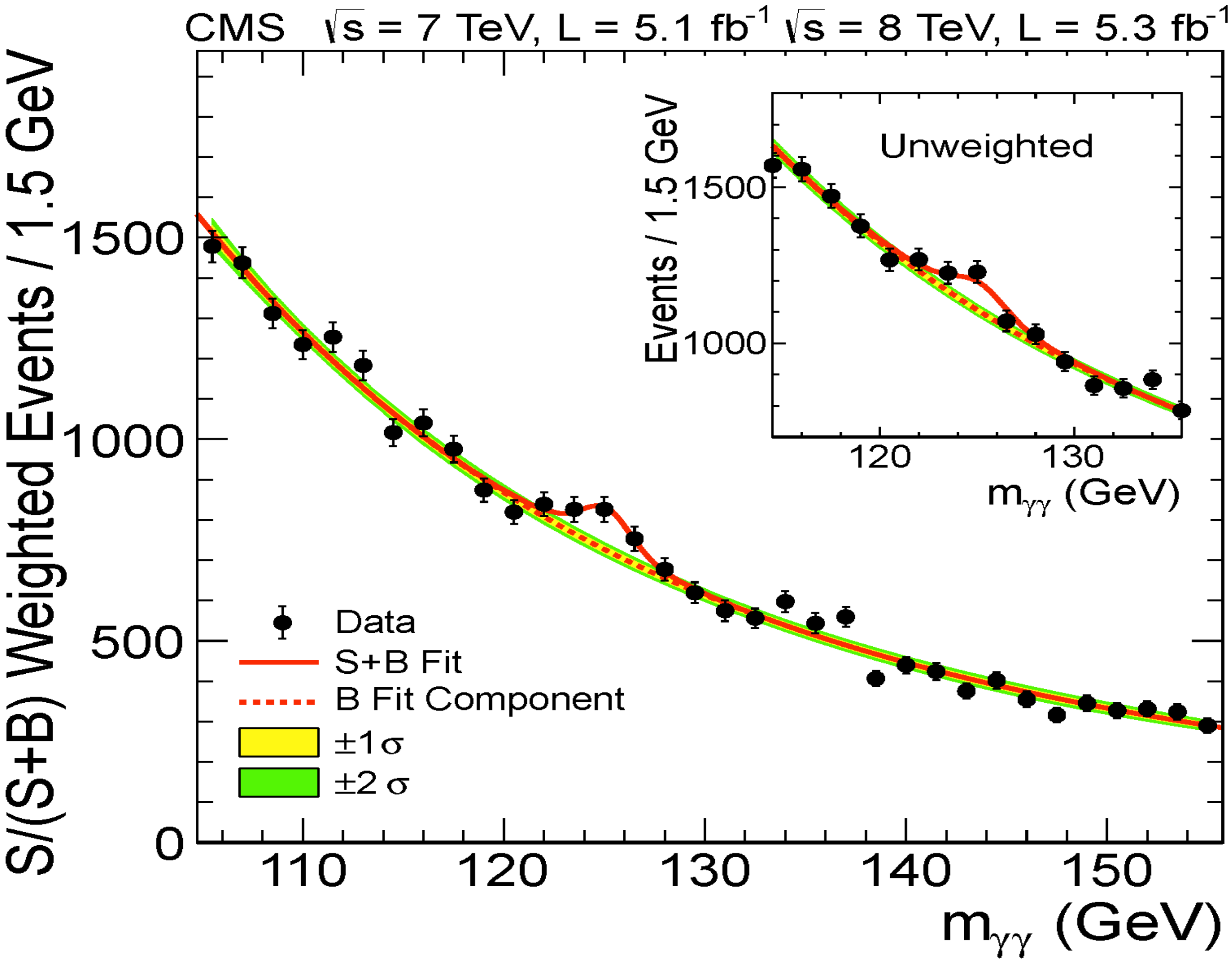
physical manifestation – a new particle: *Higgs boson*

Higgs boson: the timeline

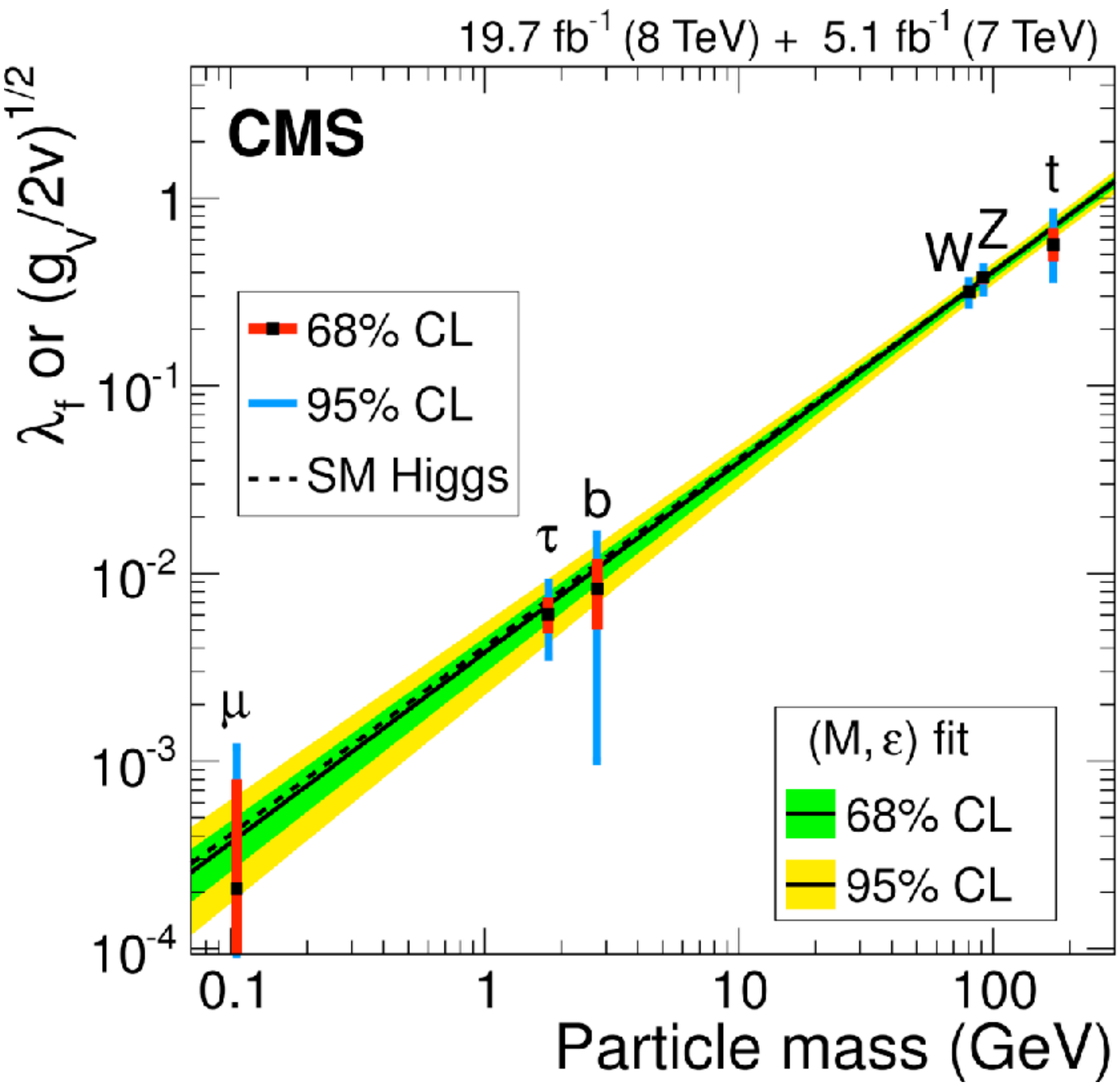
- A solution for particle masses in gauge theories: 1964
  - pure math, no connection to actual physical world
  - Andersen
  - Higgs
  - Englert and Brout
  - Guralnik, Hagen, and Kibble
- Higgs as a part of Standard Model: 1967-1976
  - Glashow, Weinberg, Salam
- Higgs search as "number 1 problem": 1981
  - L. Okun Lepton-Photon 1981 proceedings
    http://lss.fnal.gov/conf/C810824/p1018.pdf

- Existence of Higgs potential is supported by LEP: 2000
- Higgs boson discovered at the LHC: 2012

New particle discovery!

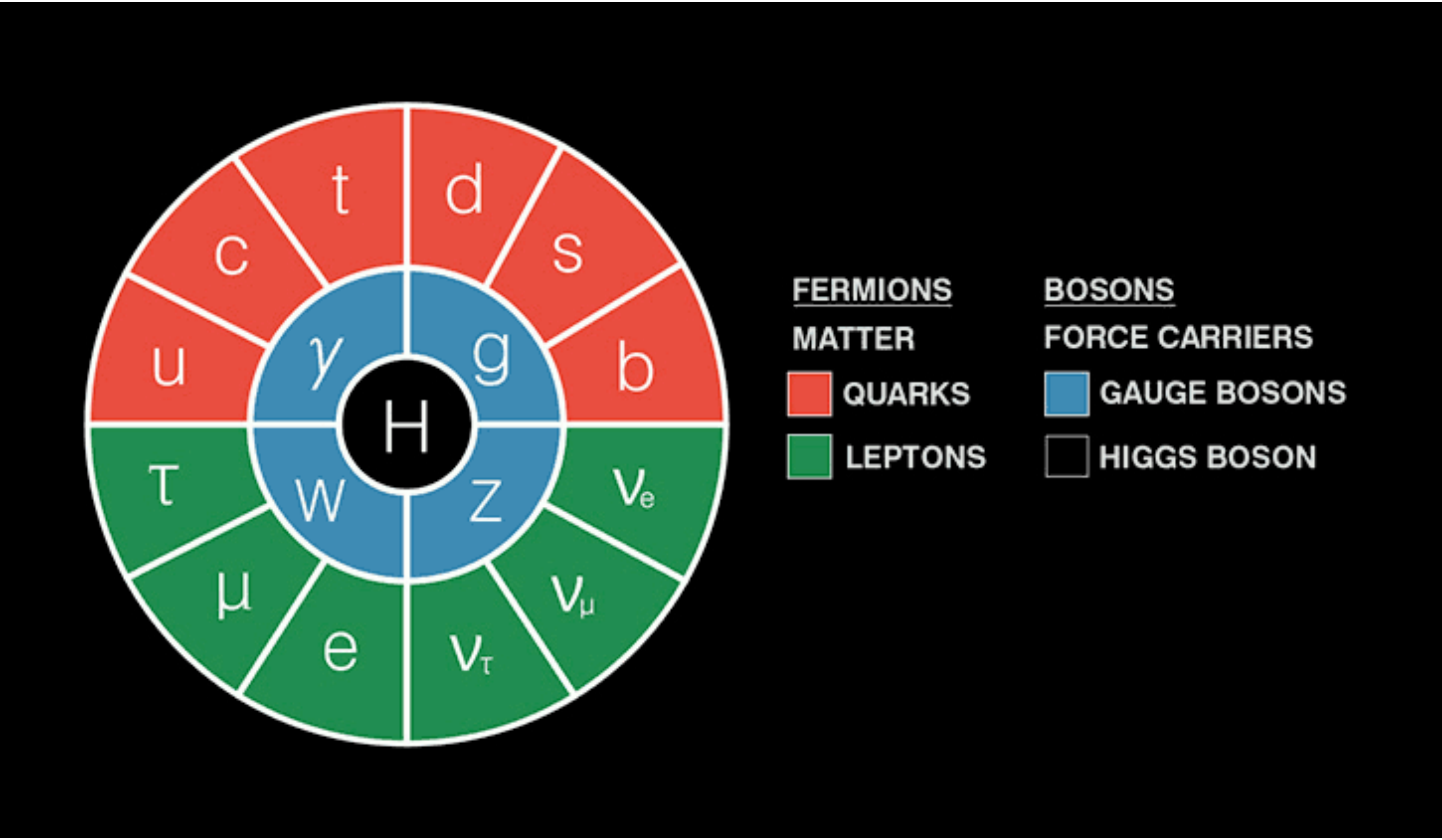


Higgs Couplings



Consistent with the hypothesis that all particle masses come from interactions with the Higgs

So, what's left to be done?



Lt. Cmdr. Albert A Michelson

"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote."

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1894, seven years <u>after</u> his experiment disproving existence of aether

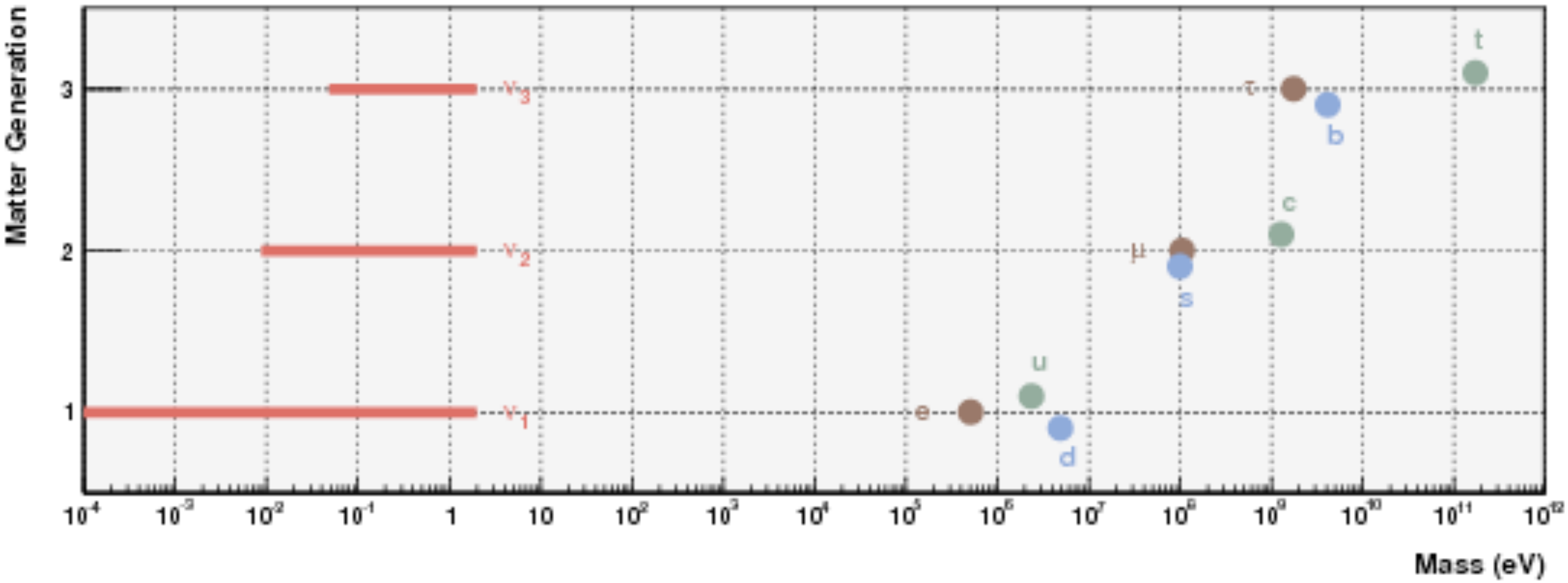
We've discovered what appears to be a fundamental spin 0 particle, a quantum of a scalar field with non-zero v.e.v.

We've discovered what appears to be a fundamental spin 0 particle, a quantum of a scalar field with non-zero v.e.v.

Aether is back!

Suppose the SM is all there is

- SM flavor structure is untenable!



- Fermion masses arise from coupling with the Higgs

$$\Delta L = -y \cdot \bar{\psi}\phi\psi$$

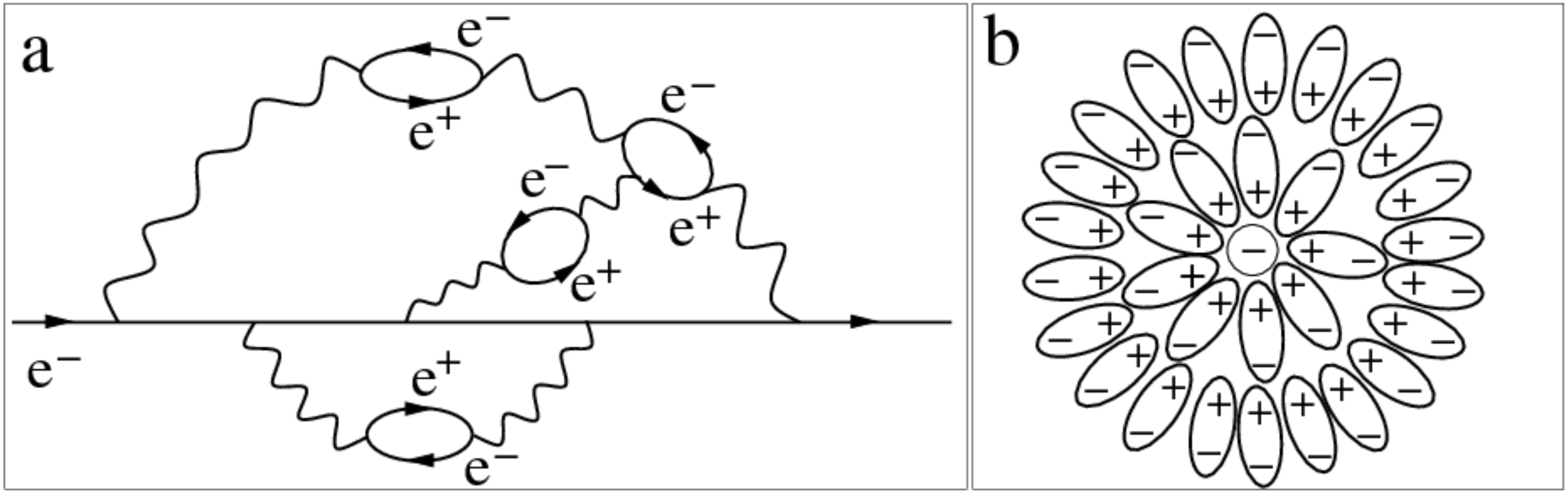
$$m = y \cdot \frac{\mu}{\sqrt{2\lambda}}$$

12 fundamental constants spanning eleven (!) orders of magnitude?!

Why do we need second and third generation of matter?!

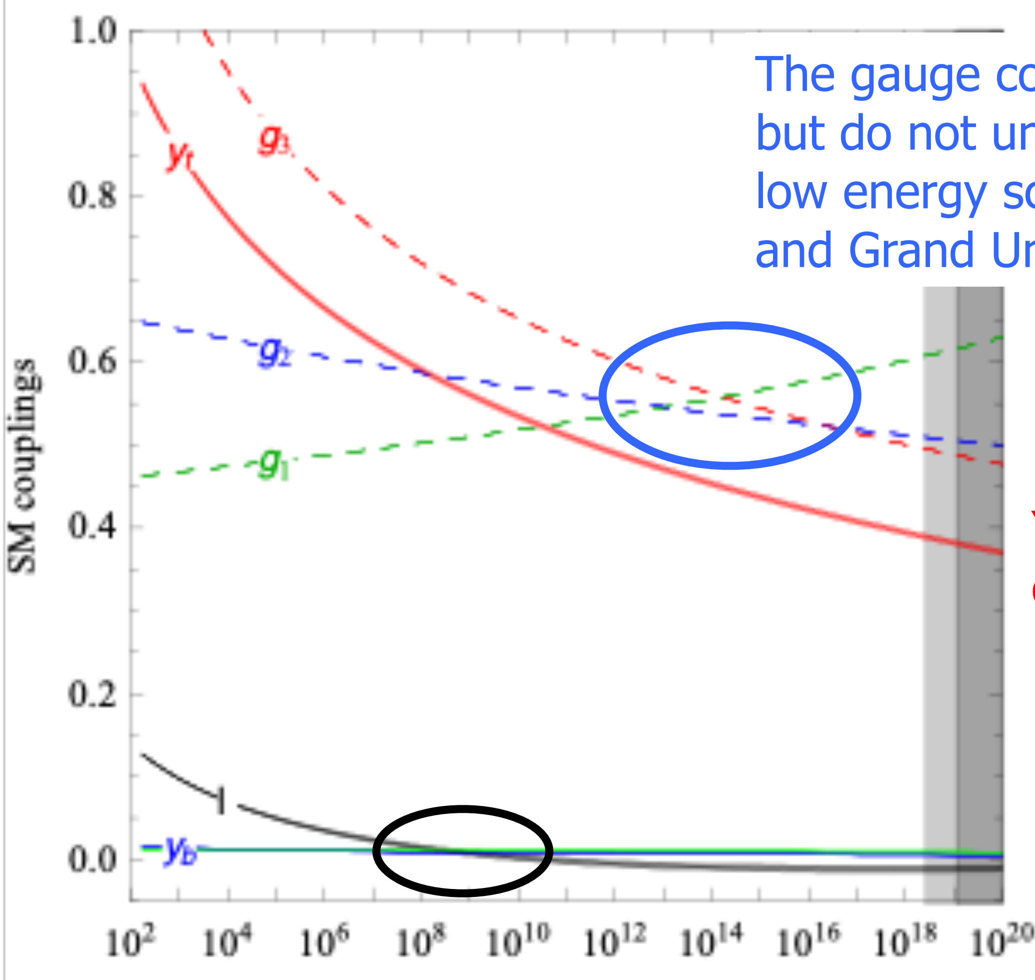
Suppose the SM is all there is

- Until gravity is incorporated – at M_{planck}
  - Electroweak scale ~ 100 GeV
  - Planck scale ~ 10,000,000,000,000,000,000 GeV
- That's a long way to extrapolate
  - Gauge couplings (aka charges) "run" with energy



Running of Couplings

- Luckily, Landau pole is above M_{Planck}



Energy scale (GeV)

The gauge couplings become very close but do not unify. If there is new physics at low energy scales, the running is altered and Grand Unification is possible

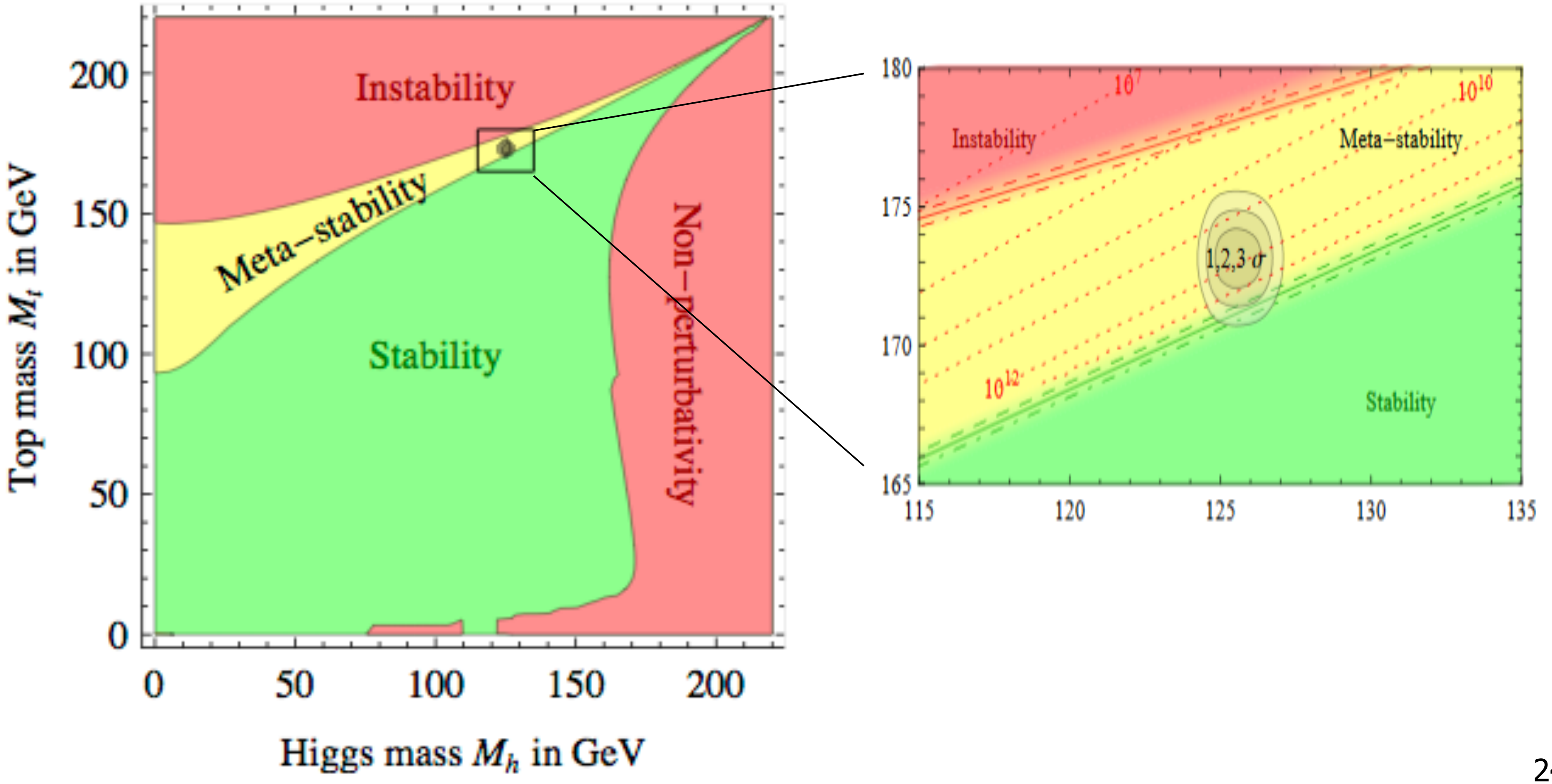
Yukawa coupling for top quark also changes

Most astonishingly, the λ parameter in the Higgs potential becomes negative!

Vacuum becomes unstable!

Living on the edge

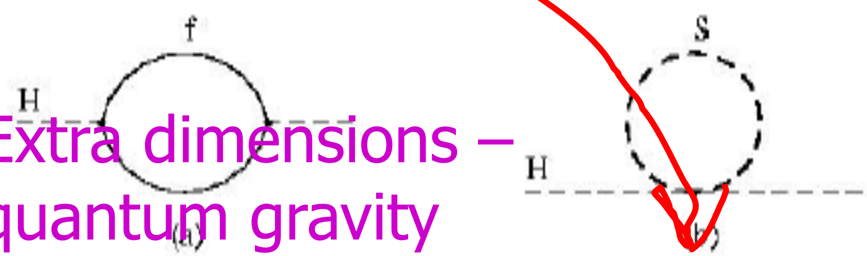
- The top and Higgs masses are arranged so that we live just on the edge of stability
  - Anthropic factor at work?! What is the physics that determines it??



The Naturalness Problem

We want theory that can be unified with gravity (energies $\sim M_P$)

Quantum correction to fundamental scalar mass are order of $M_P \sim 10^{19}$ GeV, and are obviously very unlikely to cancel to give $m_h \sim 10^2$ GeV



Extra dimensions – quantum gravity scale is at 10^3 GeV

Supersymmetry - corrections have to cancel

Technicolor type models – composite Higgs

$$(a)\quad \Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f)\right]$$

$$(b)\quad \Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[+2\Lambda_{UV}^2 - 2m_S^2 \ln(\Lambda_{UV}/m_S)\right]$$

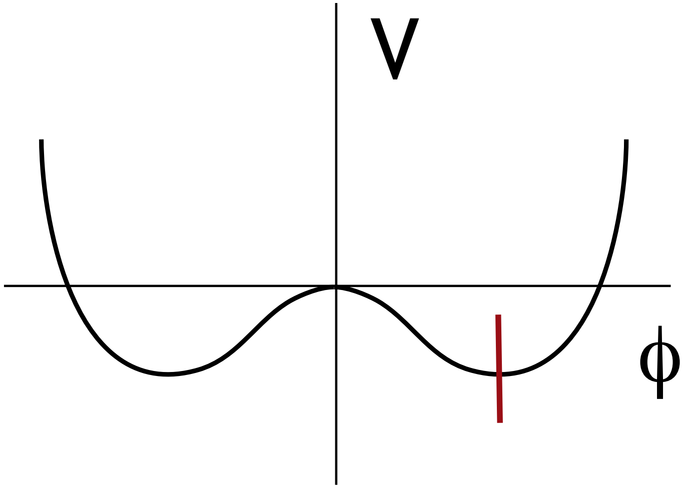
$$\Lambda_{UV}^2 \sim M_{\rm Planck}^2 \sim (2.4\times 10^{18}\ {\rm GeV})^2.$$

To achieve EWSB Higgs mass should be O(100 GeV), not O(10000000000000000000 GeV)

What is the probability that corrections $\sim M_{planck}$ will accidentally cancel each other?

All predict new particles, that can be looked for directly or in loop effects

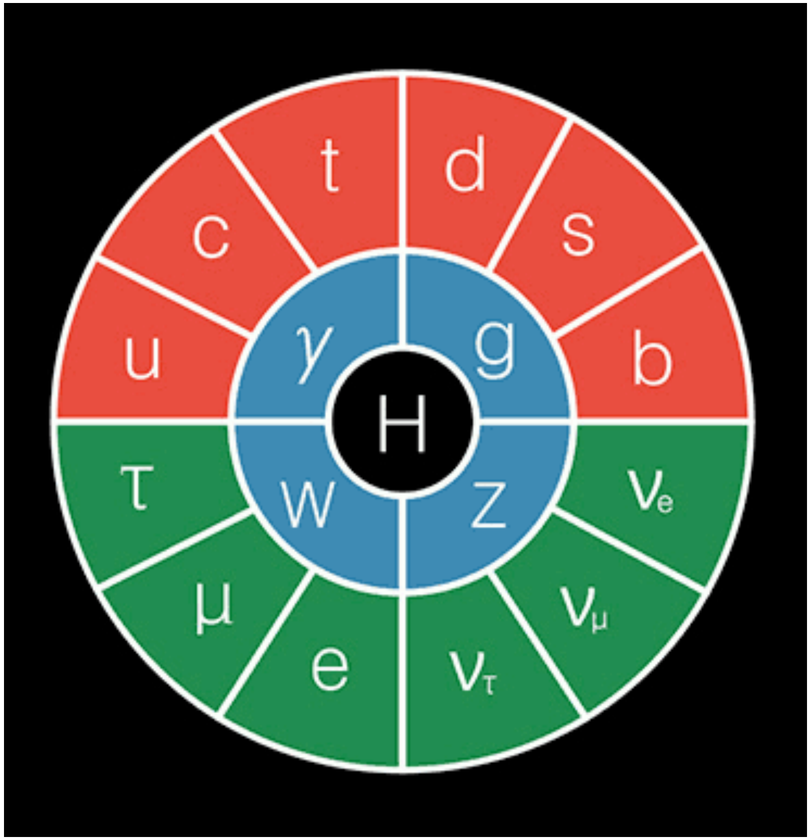
Why Electroweak Symmetry is Spontaneously broken?



$$V(\phi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$$

- The Standard Model "explanation" is that $\mu^2<0$
- That is similar to saying that Ginzburg-Landau superconductivity model explains superconductivity
  - but then we'd be missing the microscopic explanation of electron-phonon interactions

Any real explanation of SSB requires new forces between SM particles – and, therefore, new particles



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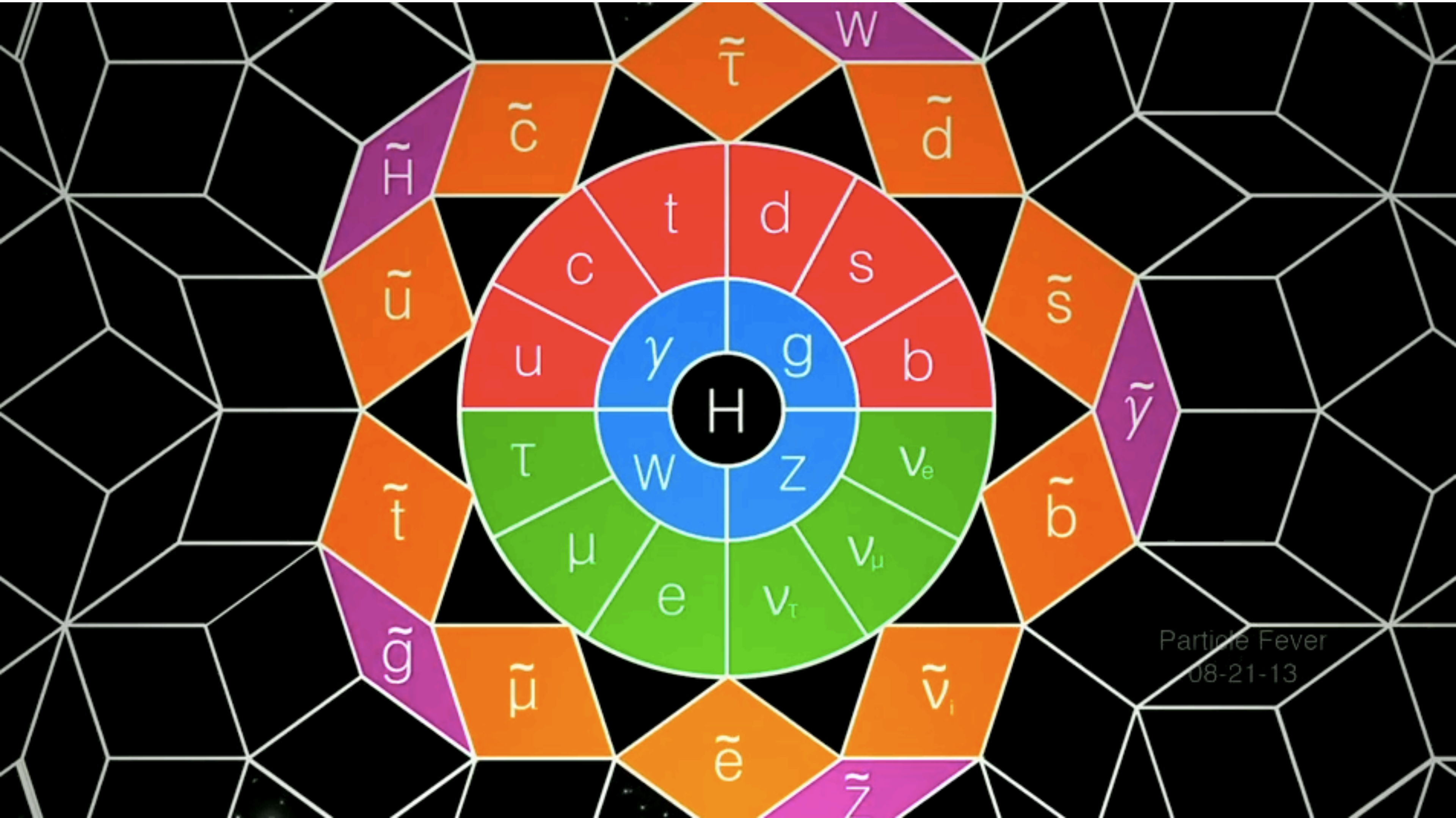
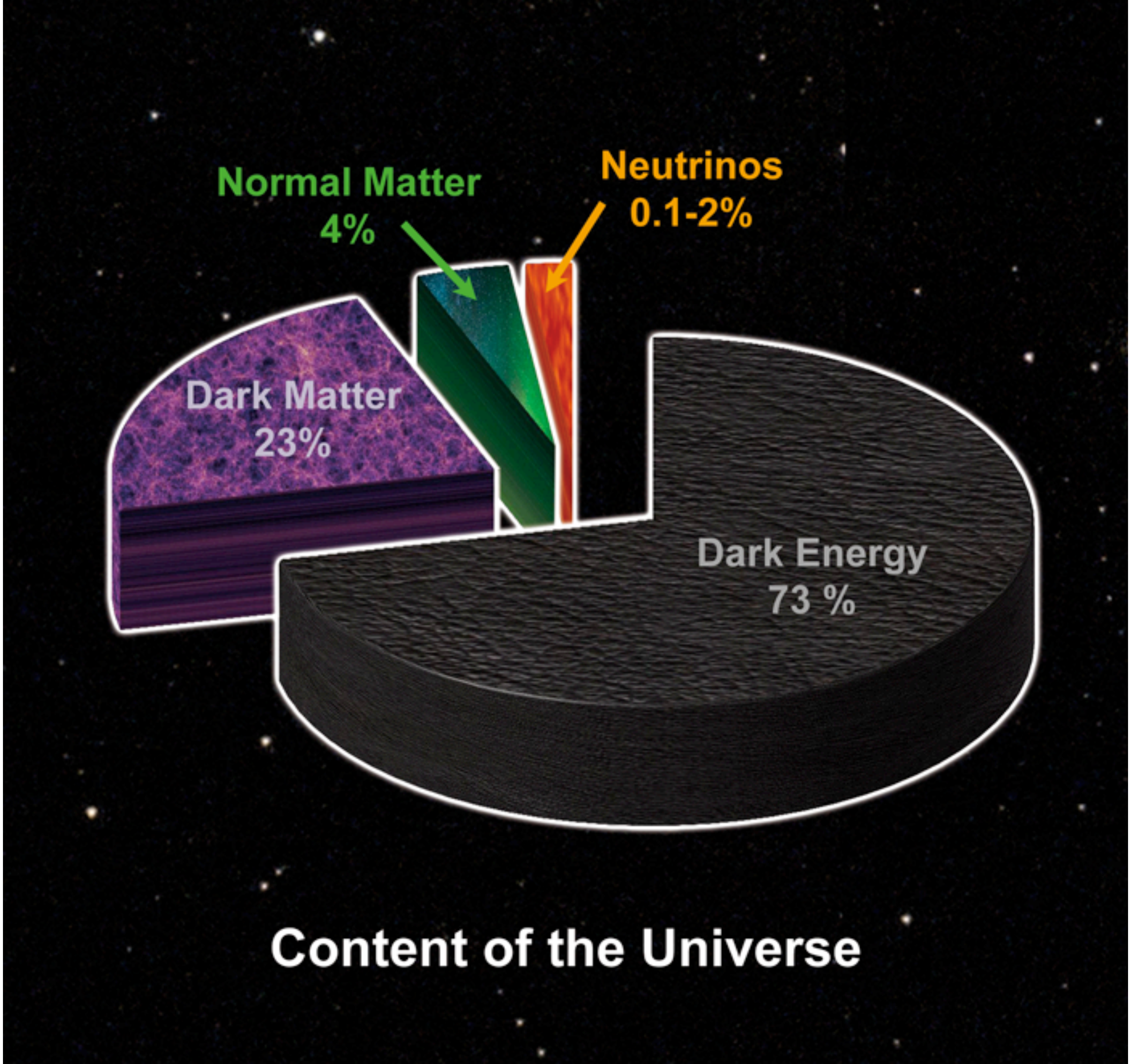



Normal Matter
4%
Neutrinos
0.1-2%
Dark Matter
23%
Dark Energy
73 %
Content of the Universe

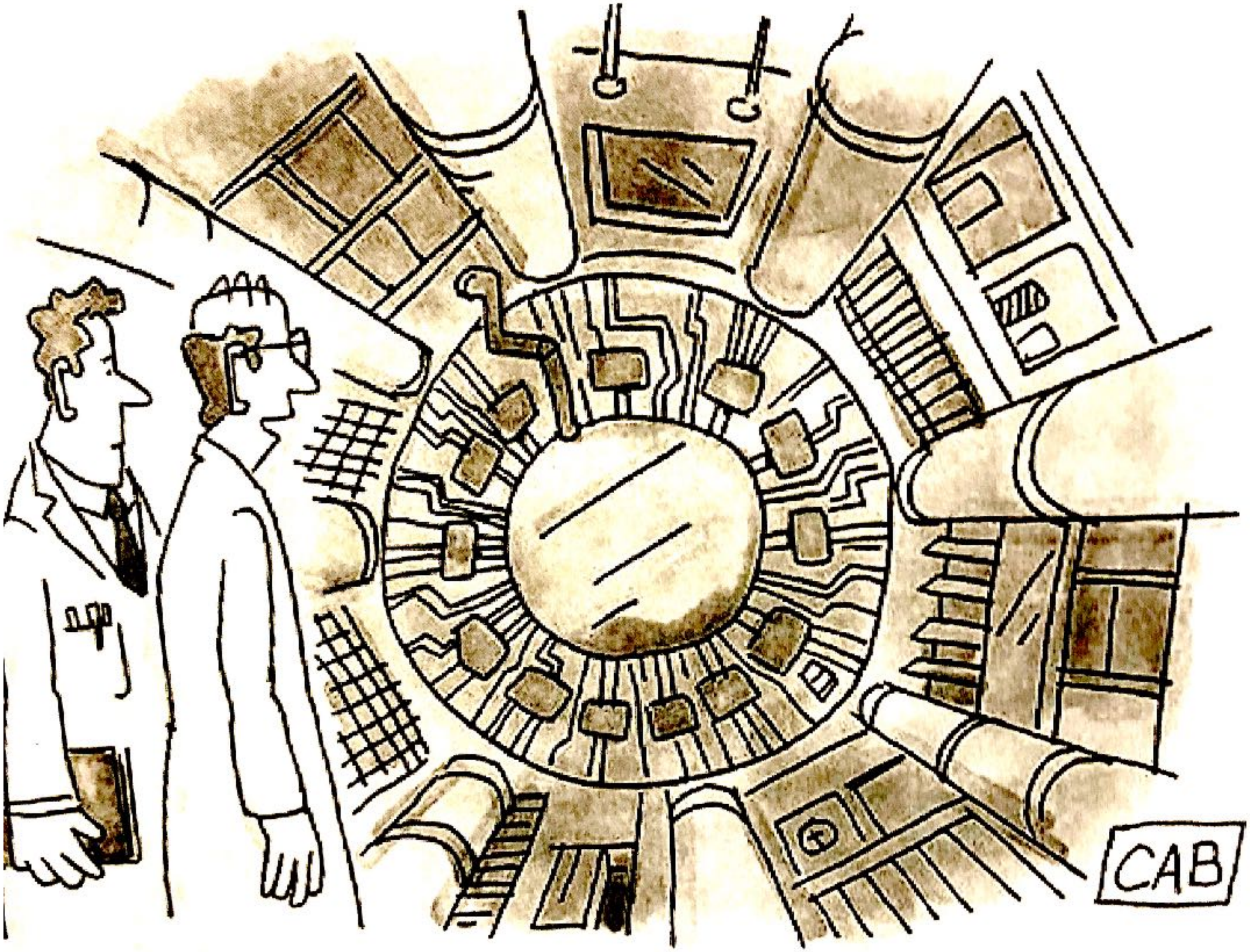
Cosmological problems probably related to particle physics

- Dark Matter
  - new kind of matter, not baryons
- Inflation
  - is it physics related to GUT?
  - typically, models include a new scalar field
- Baryogenesis
  - Electroweak baryogenesis requires extra scalar fields
- Dark Energy
- Quantum gravity

You may have noticed the common thread in my recitation of the shortcomings of the Standard Model:

- New particles are involved
- In scenarios of new physics where Higgs is a fundamental scalar, other fundamental scalars are present

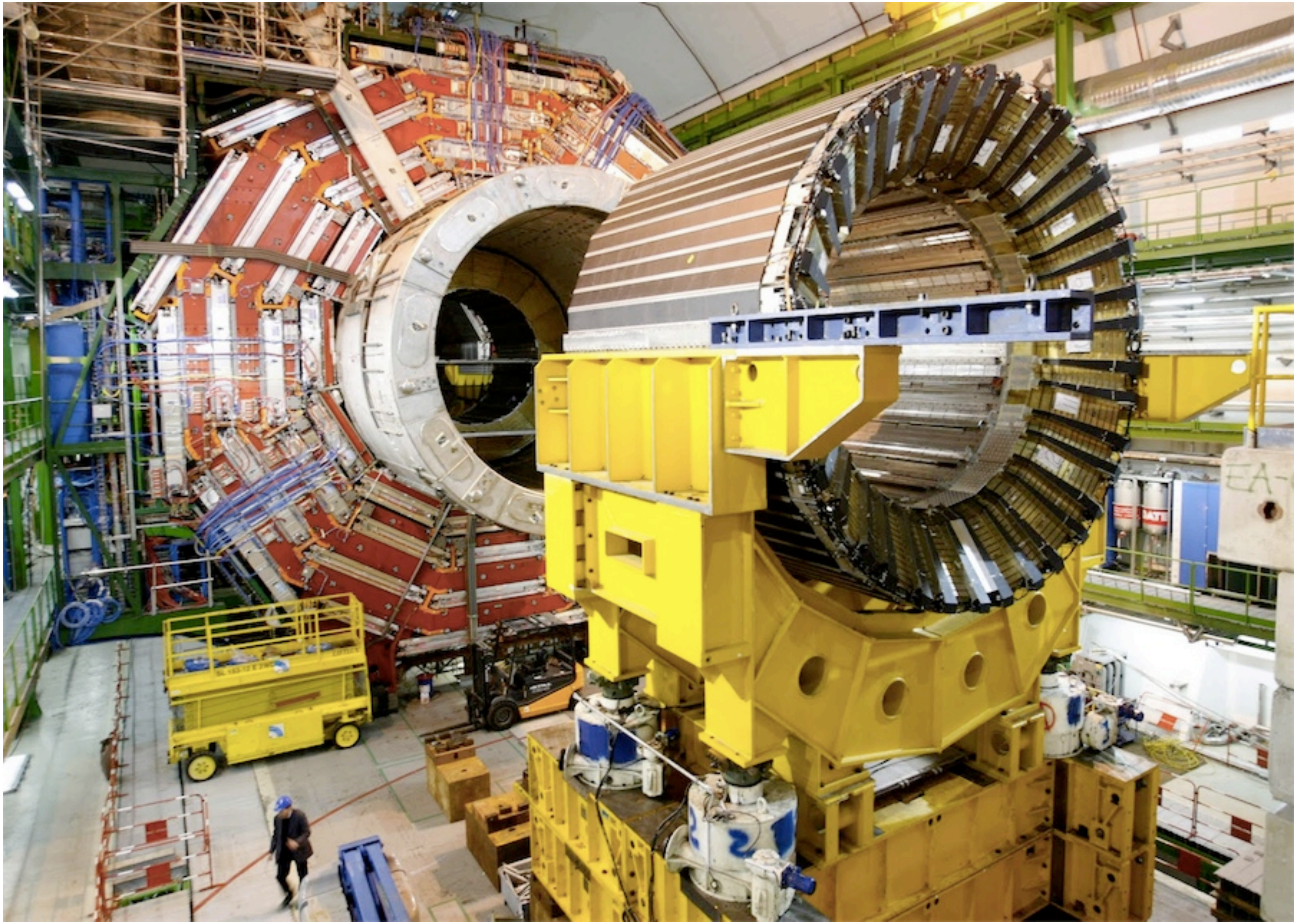
In other words…



"Once you have a collider, every problem starts to look like a particle."

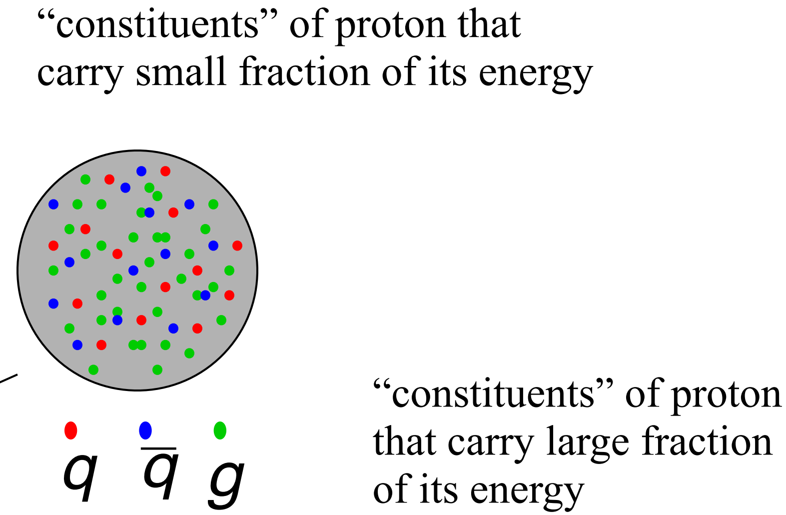
And what a collider we have!

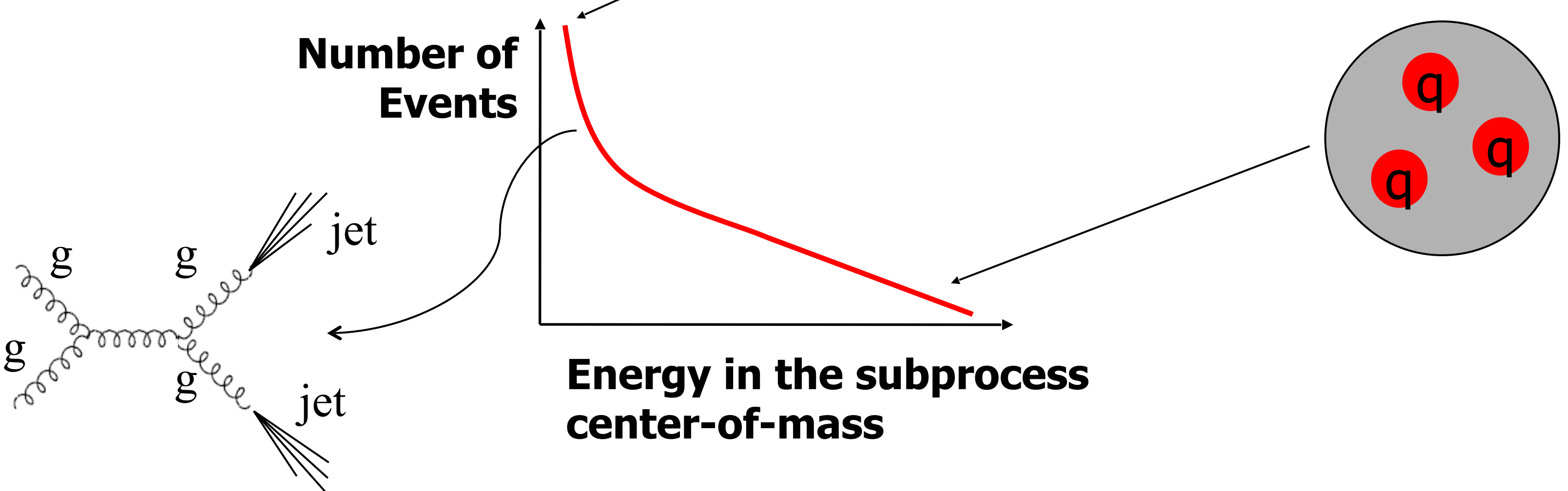
CMS Detector Construction



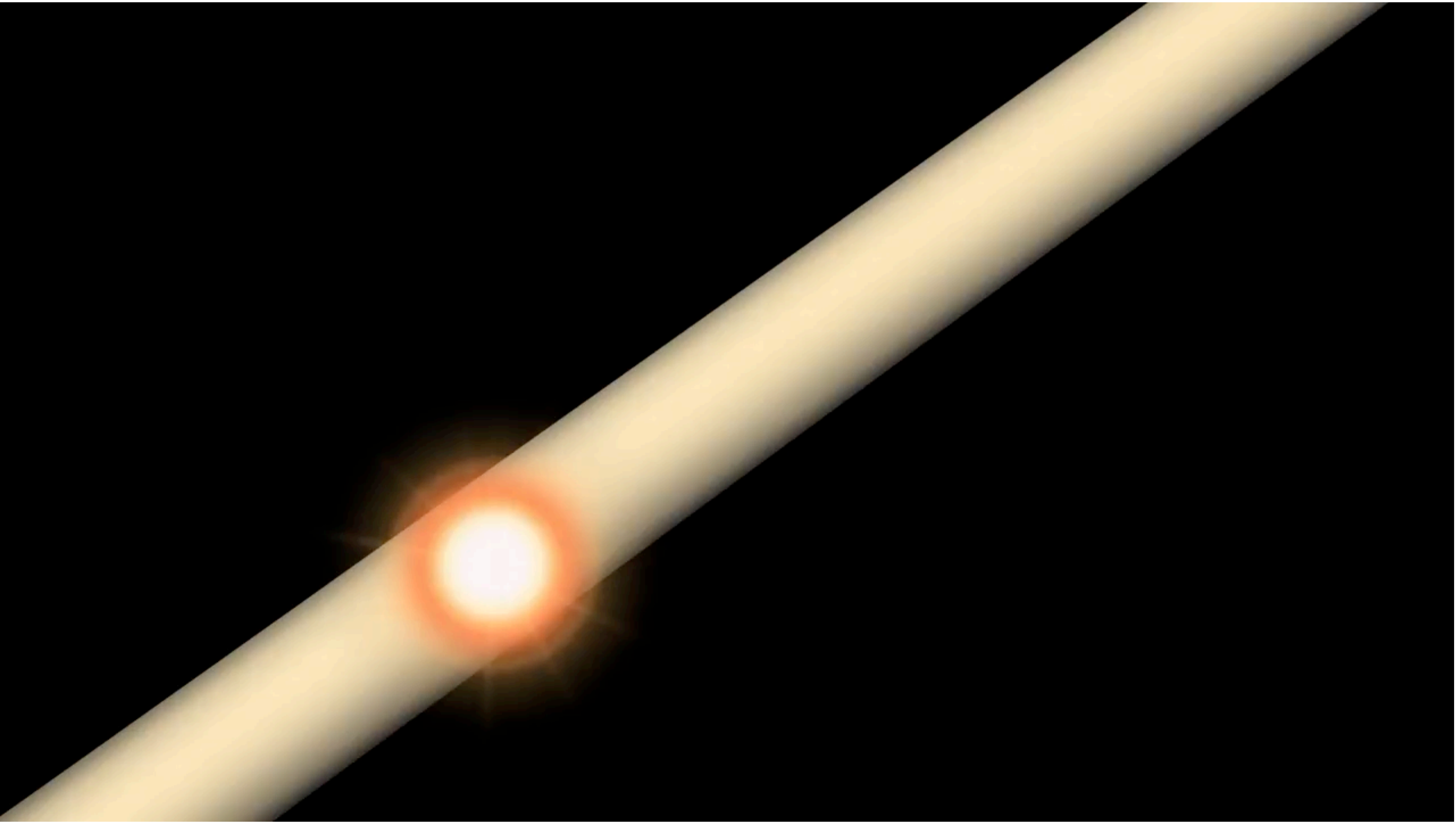
Hadron Colliders

- The new particles are heavy – need a lot of energy
- Easiest way to achieve high center-of-mass energy is colliding beams of protons or anti-protons
  - heavy, so no synchrotron radiation
  - stable, so can take time accelerating
- But: messy!
  - quark/gluon colliders
  - remnants of the proton get in the way
  - multiple **pp** collisions in the same event

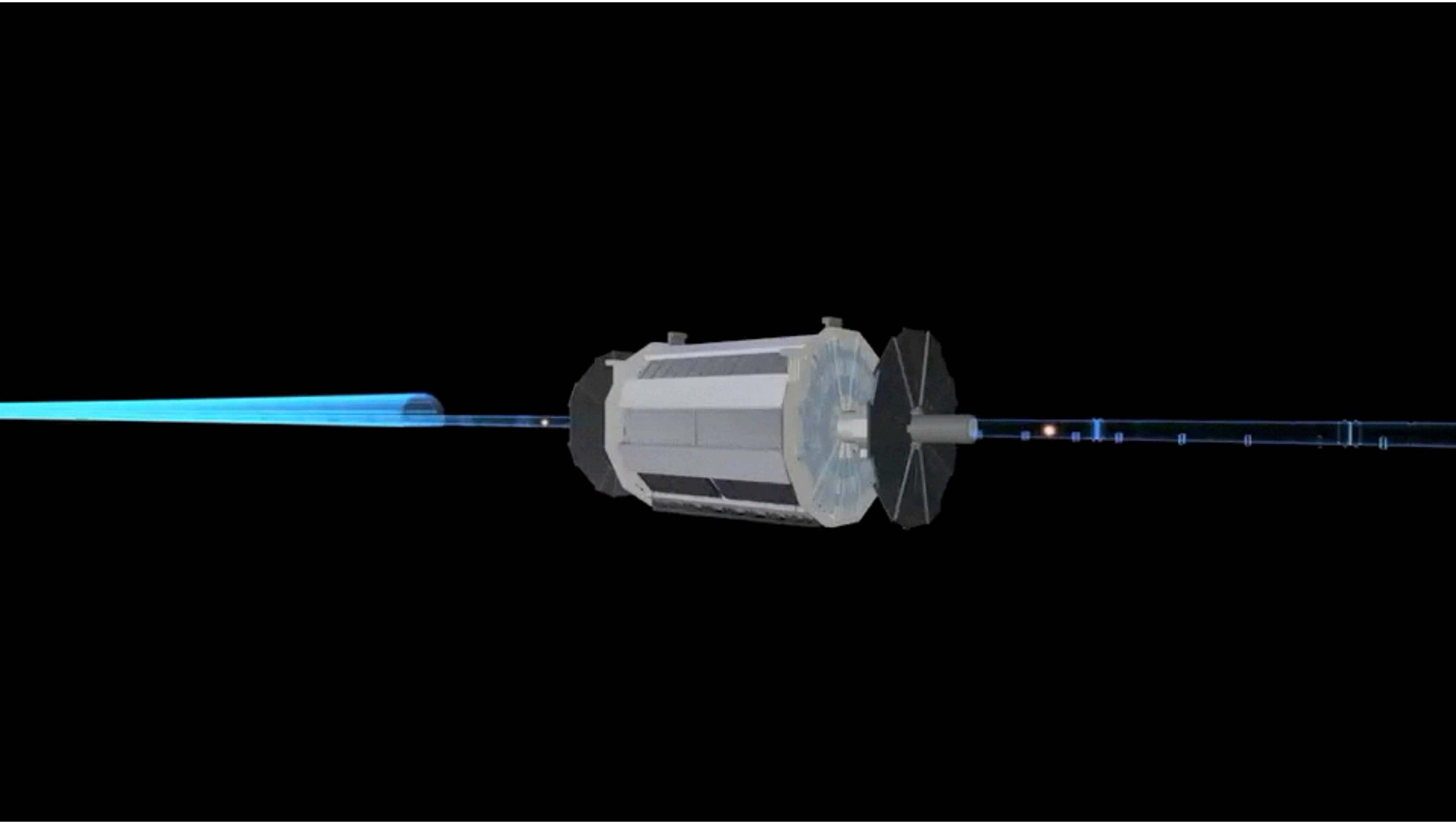


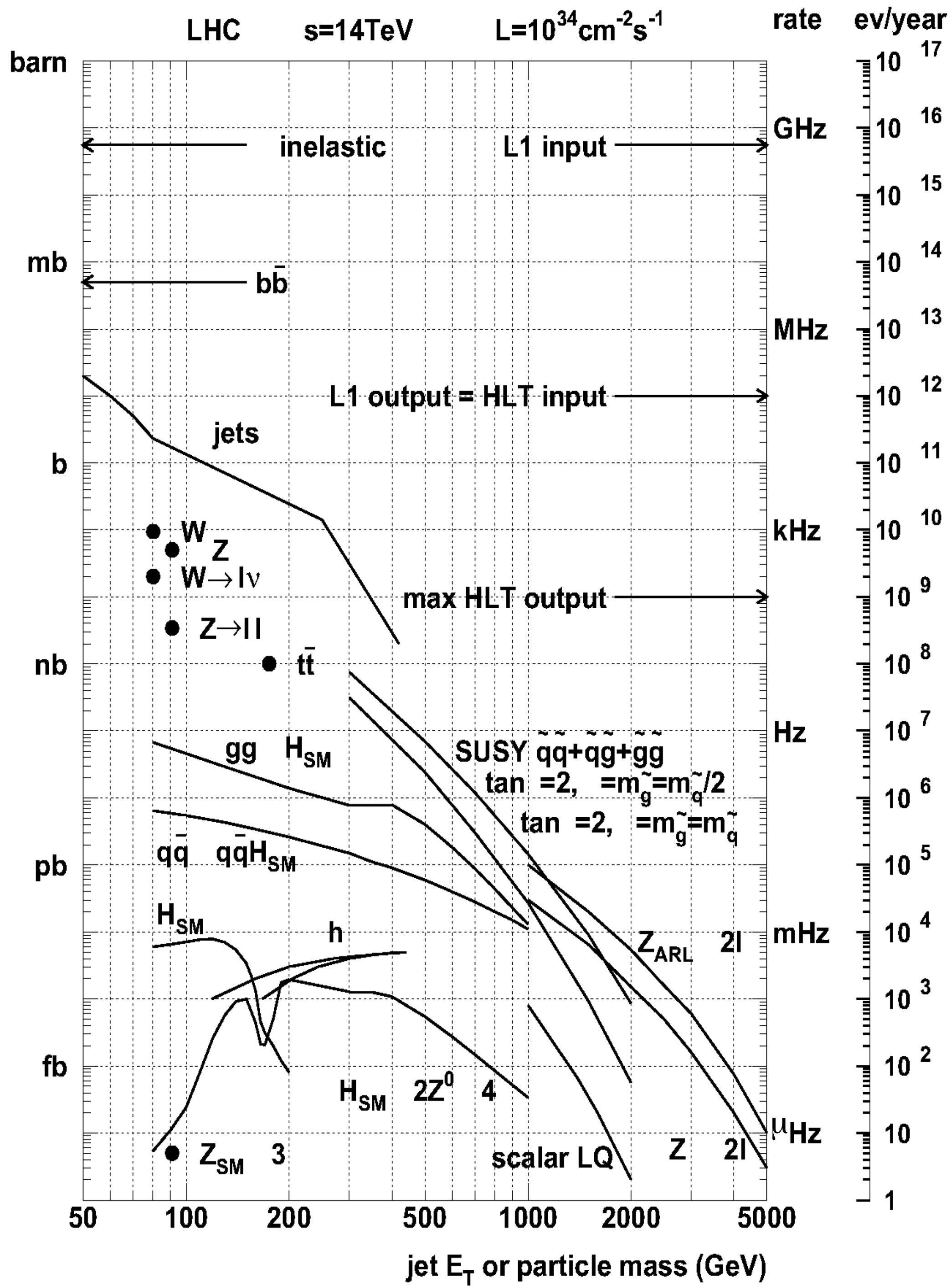


Most common LHC event



H->ZZ->ee μμ





Such poor signal to background ratio has its consequences: have to decide on the fly which events to write to tape for closer examination

- 40 million beam crossings per second
- only 1000/second can be saved
- job for custom electronics and very smart algorithms…

To get enough interesting events one chooses to focus the beams such that to have multiple overlapping events for every beam crossing

~ 50 for the current run

~ 200 or more for the next one

LHC Physics Program

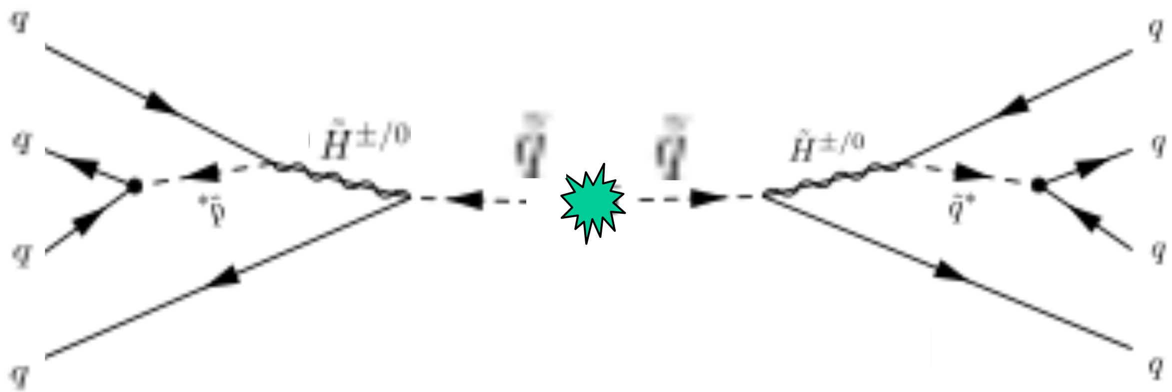
- Higgs couplings
  - new physics may change those
  - Higgs couples so weakly to the SM particles that even tiny coupling to BSM could be noticeable
- New physics searches
  - a lot of “natural” favorites are excluded
    - but far from conclusively! One need to get more data and be patient
  - A lot of room for thinking out of the box
    - new physics in unusual places…

A few examples

done by Rutgers group

- New physics hides in plain sight
  - jets with substructure
- New physics is very hard to trigger on
  - “Hidden Valley” new physics scenarios
  - weakly coupled particles
  - long-lived particles
- Rare Higgs decays
- High Luminosity LHC detector upgrades

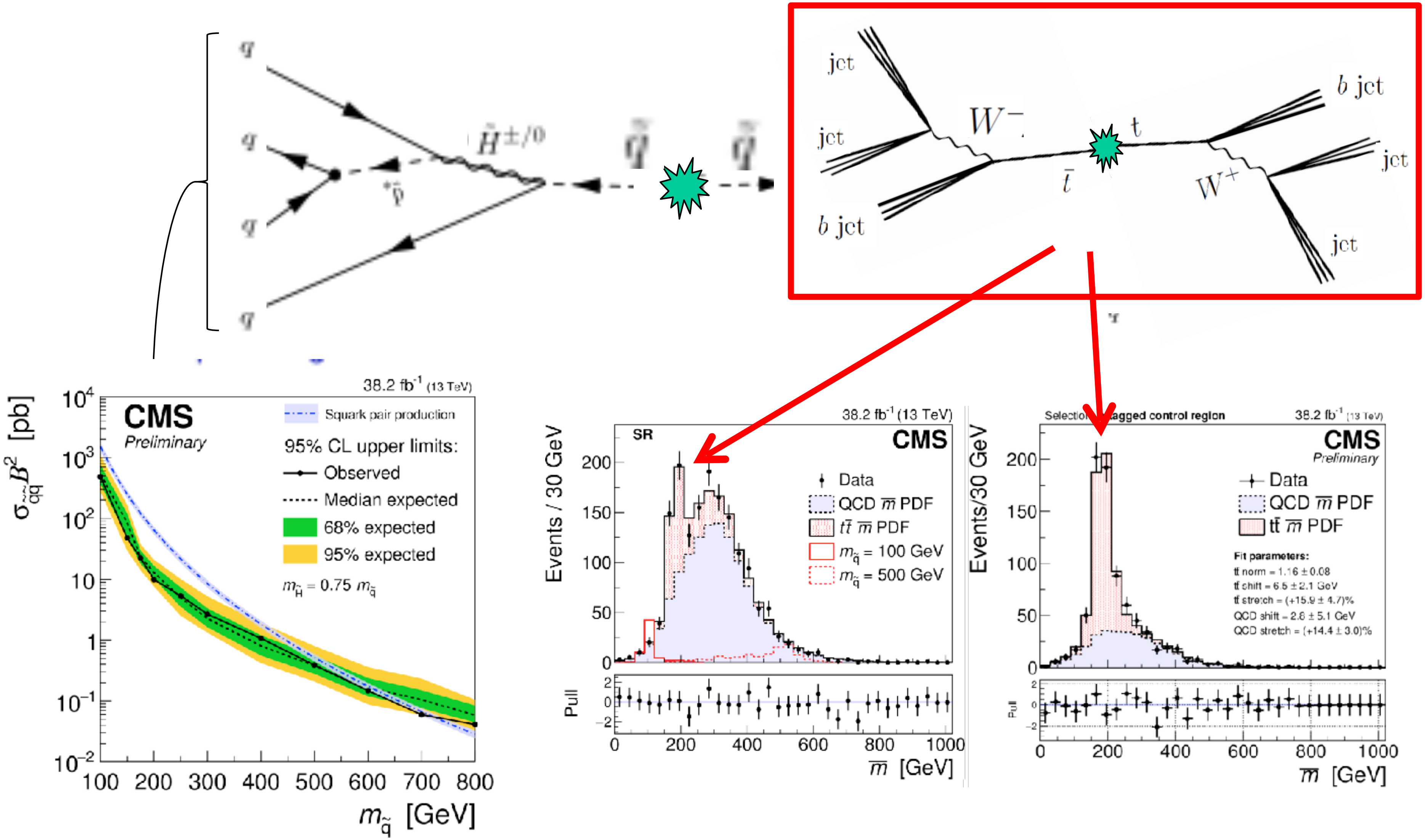
Light scalar quarks



- Events energy release in squark decay can be small: all decay products are boosted close to each other
  - Events look like dijet events!

- Special methods have been developed to differentiate "ordinary" quark or gluon jets from many-core jets like these
  - After the clean-up, one can measure the invariant mass of the squark by adding up all components of the jet together

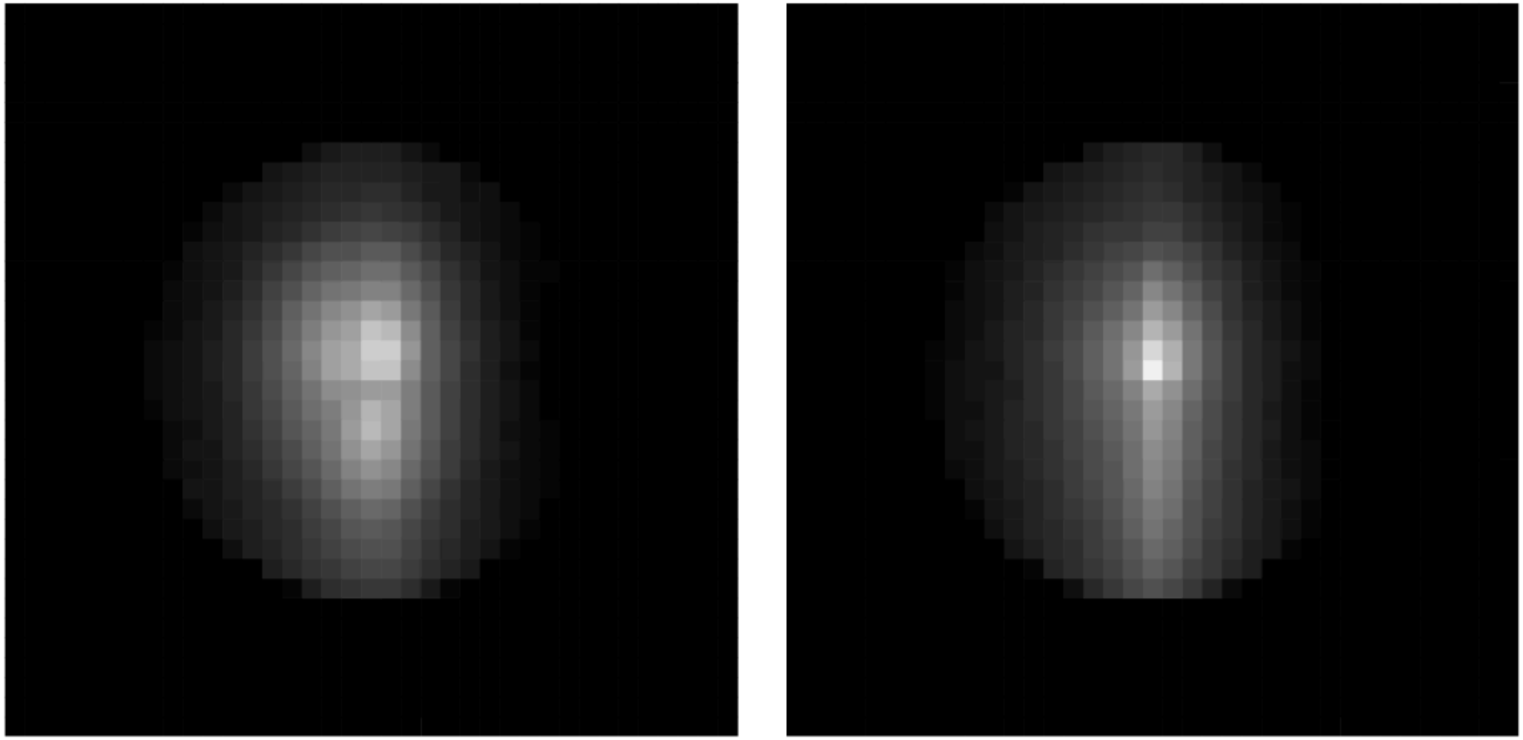
Light scalar quarks



Next in jet substructure

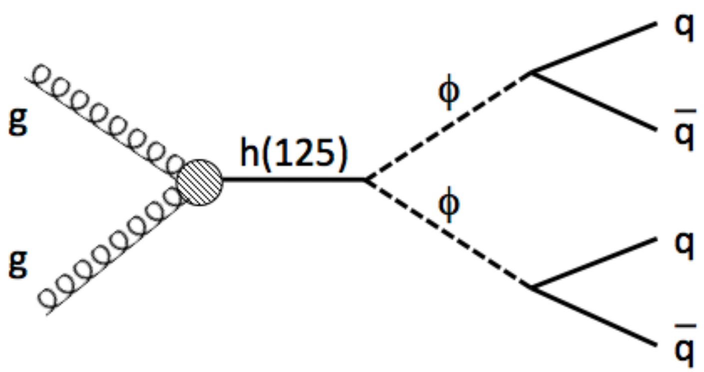
- Machine learning
  - picking out thin cores in jets is very similar to computer vision
    - except one has to be very inventive with what “see”, “color”, etc means

ArXiv 1803.00107



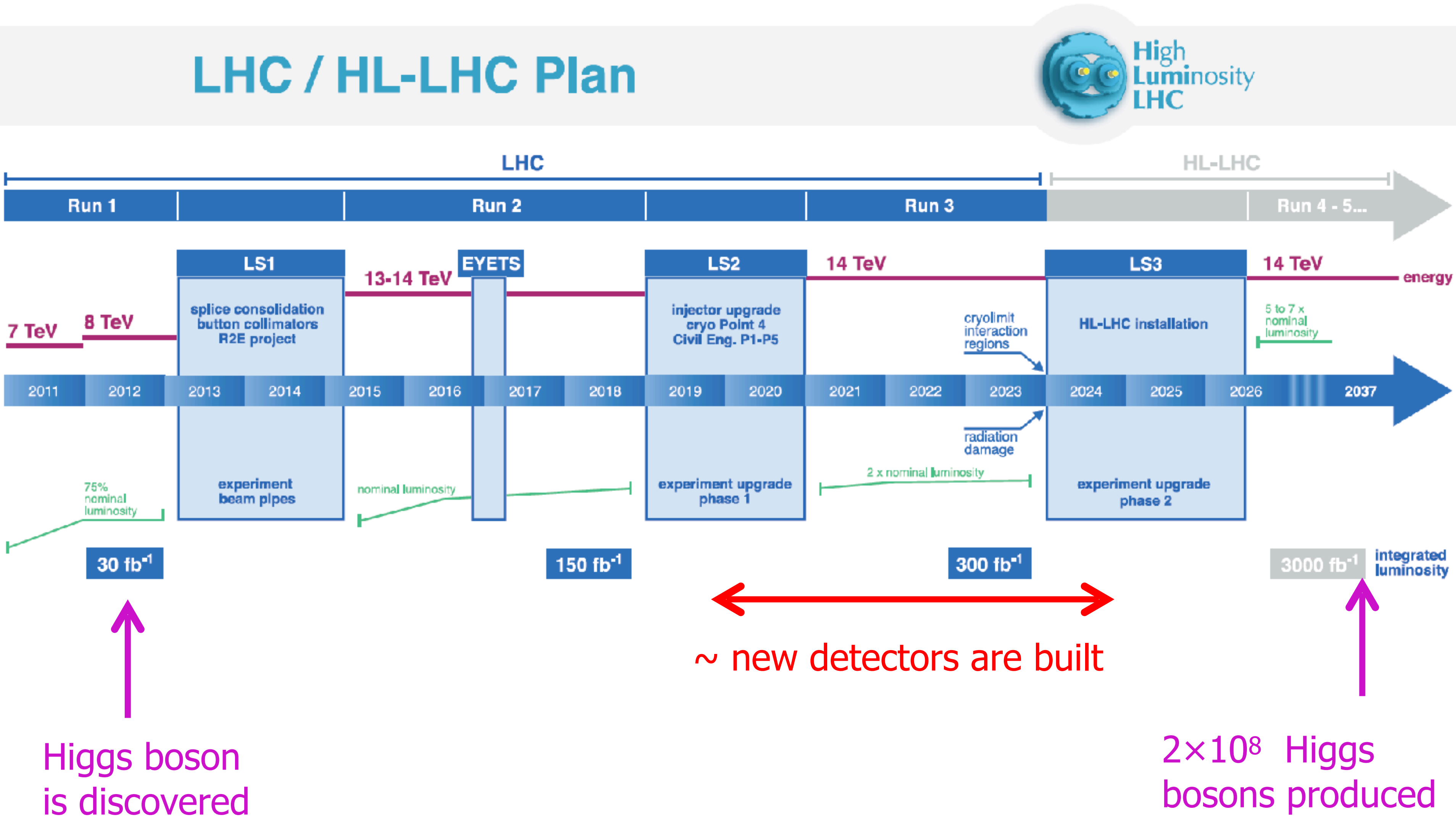
Rare Higgs decays

- Since we share the vacuum with new physics (i.e. dark matter?), it's very unlikely to completely not couple to Higgs. It could show up as exotic Higgs decays
  - Branching fractions as small as 10^{-5-6}
- Very well theoretically motivated & studied (arXiv:1312.4992, Curtin, Strassler, et al)



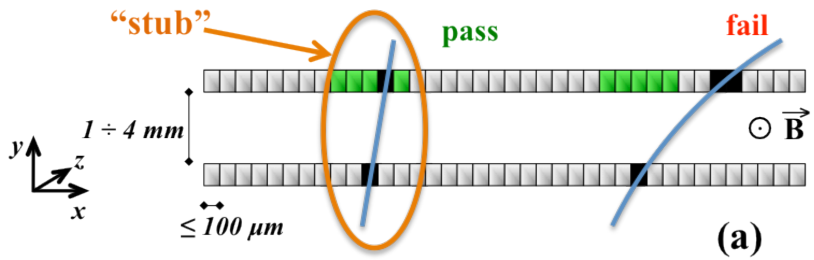
- Small couplings to our sector also make macroscopic decay lengths generic
- If ϕ is long-lived, then if we had events on tape, the background is almost zero
  - New trigger possibilities in HL-LHC

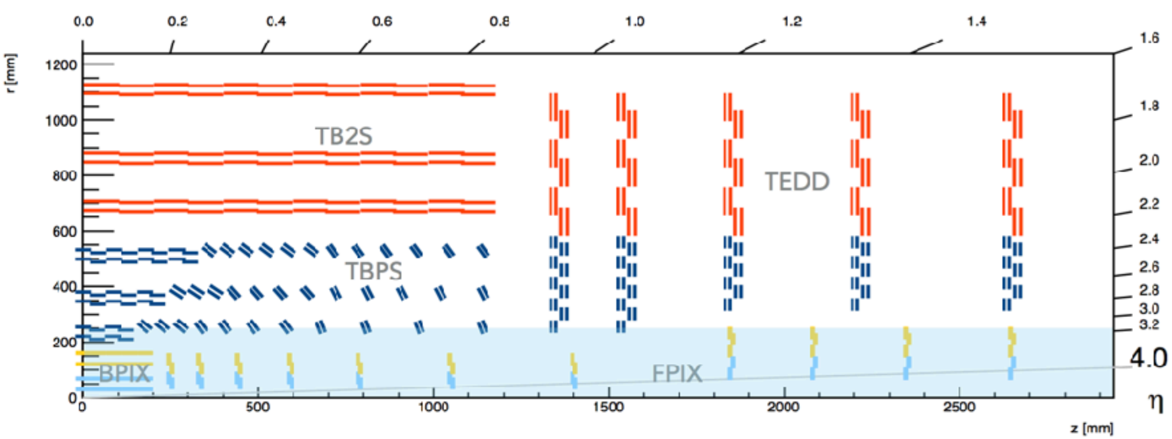
LHC / HL-LHC Plan

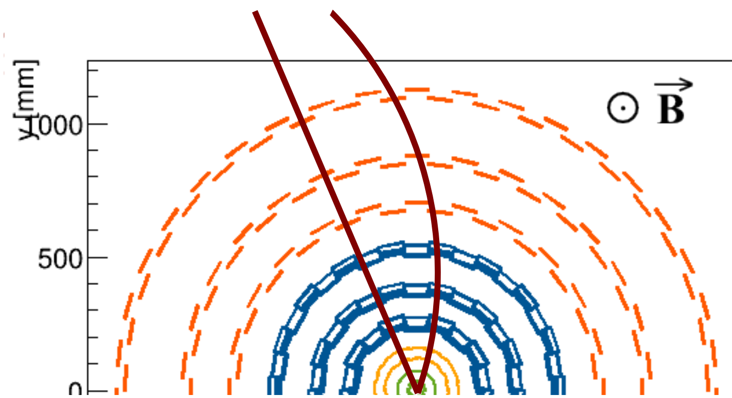


Track Reconstruction @40 MHz

- Huge number of hits drives the readout time – not feasible at 40 MHz even for binary readout
- Solution: stack of two sensors that both run strips along the beam
  - The pair of hits (stub) measures pT of the track that left them
  - The electronics that measures that pT lives on the module – a factor of order 100 in the occupancy, sufficient to make readout of the high pT hits possible
- Sensor separation is optimized based on position



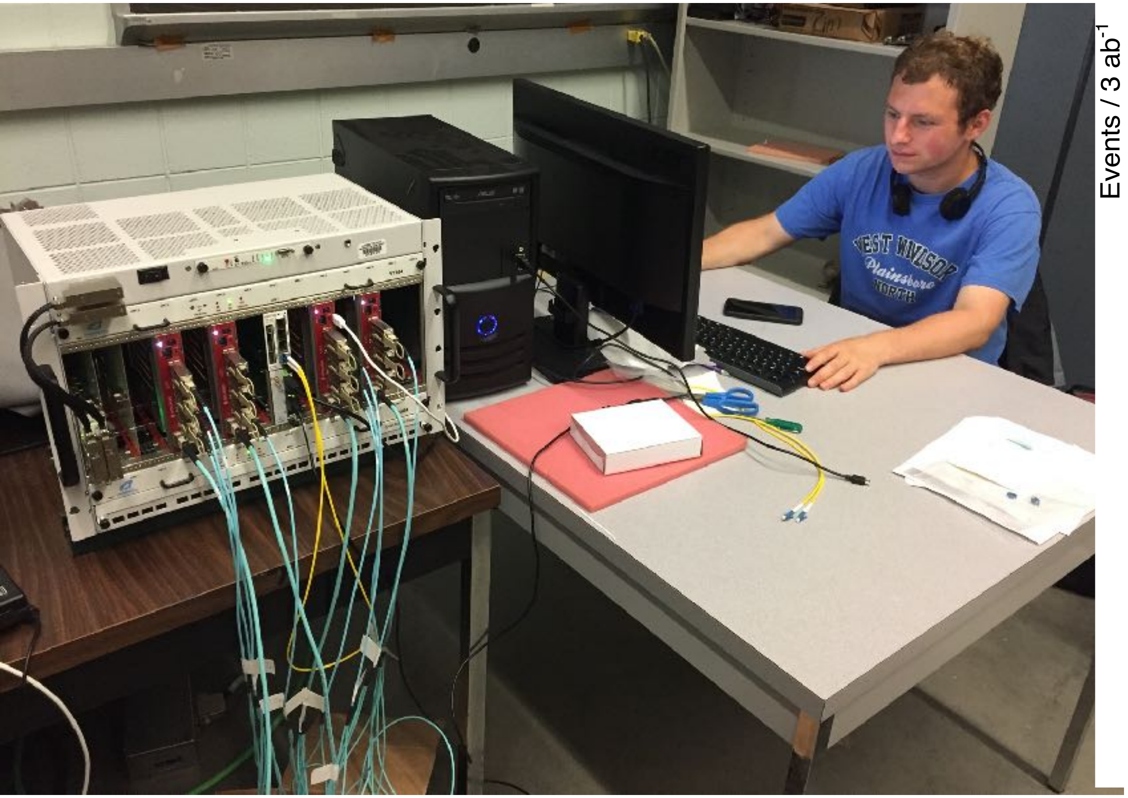




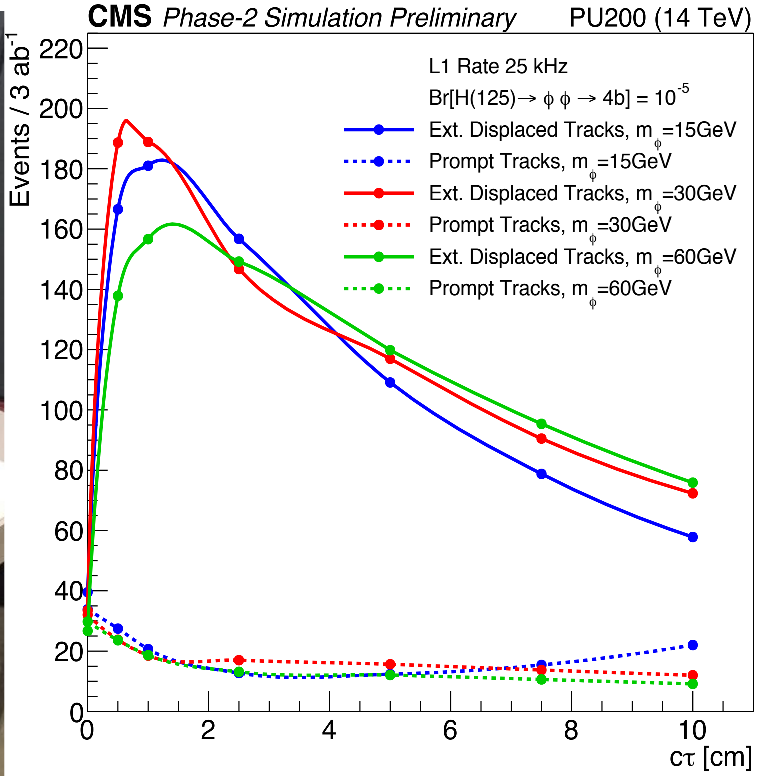
Tracking @ 40 MHz

- ~200 pp collisions every 25 ns
- Every track in every collision is reconstructed!
- A feat of data routing (~5Tbps) and parallelized calculations in FPGAs

Demonstration in hardware



Expected improvement for rare Higgs decays



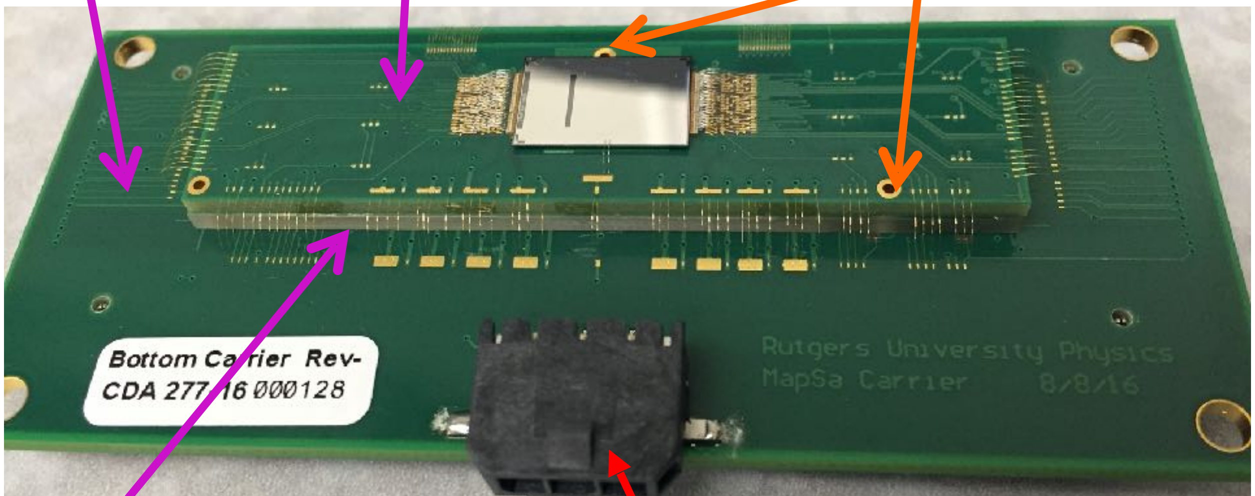
R&D Prototypes

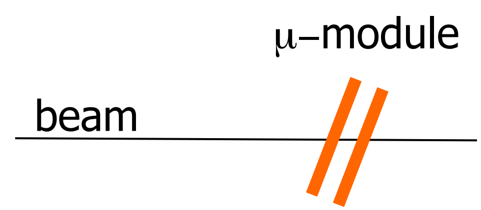
- Starting from smaller then a thumbnail size

Top carrier

Bottom carrier

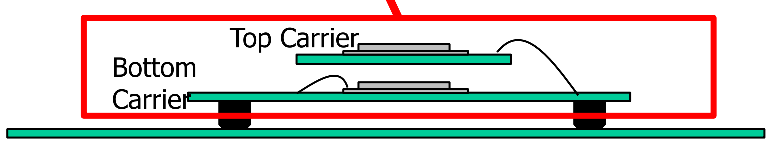
Alignment holes



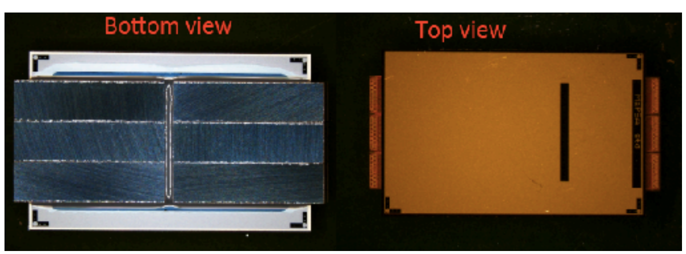


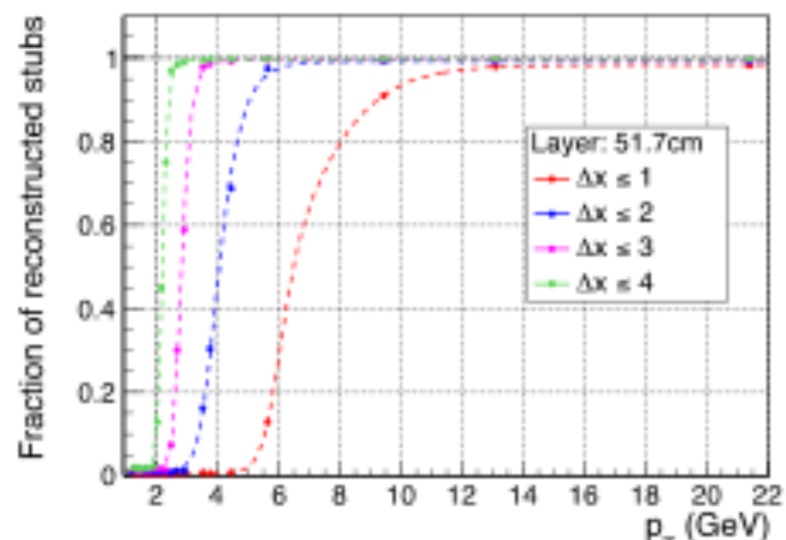
angle simulates bend in magnetic field

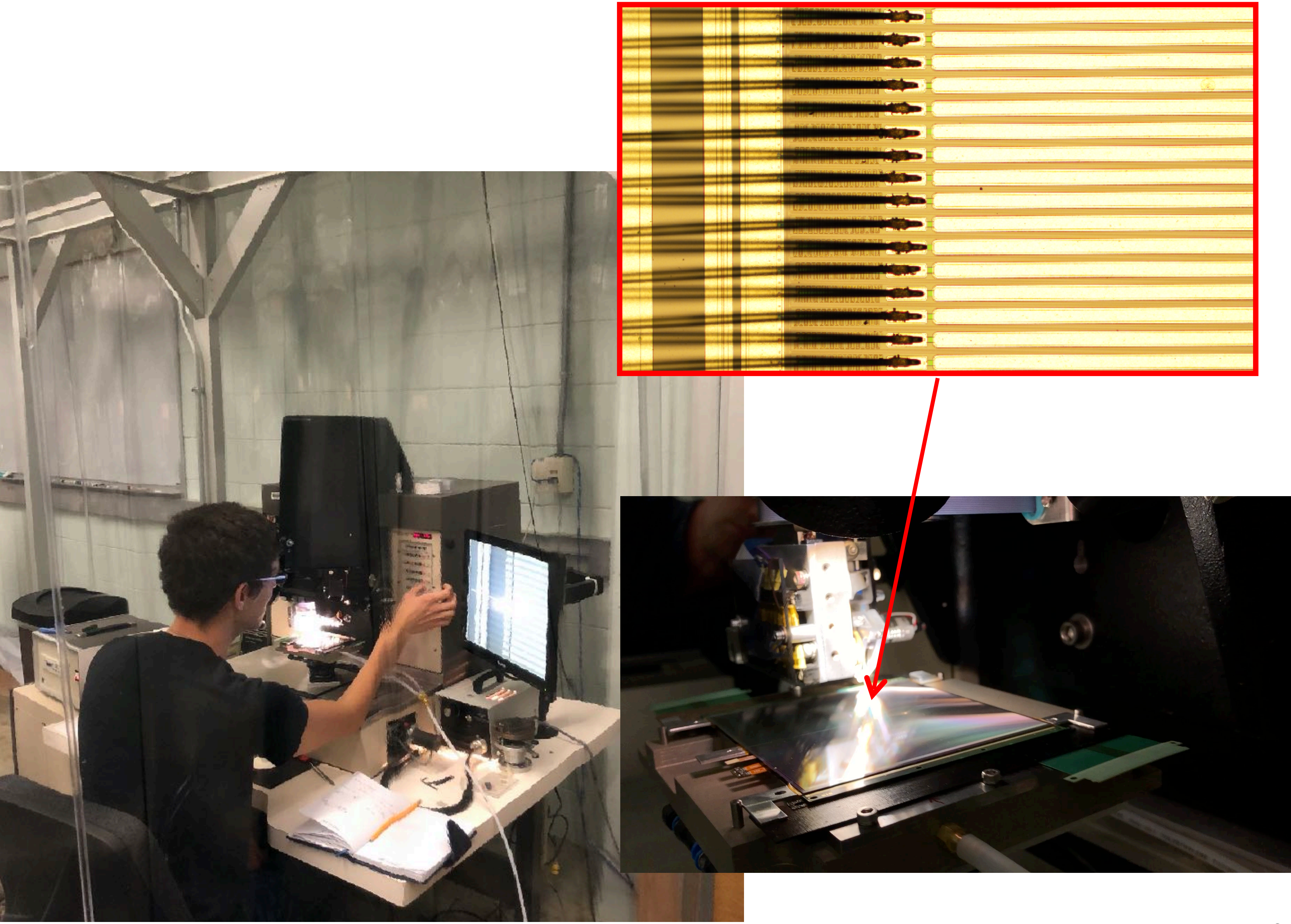
G10 spacer



Macro-pixel ROC prototype







Plan of attack

- main areas that Rutgers group is involved in
  - Analysis of 13 TeV data
    - study 125 GeV boson properties
    - look for new particles that can explain the hierarchy problem and Dark Matter
      - some may be heavy – like Supersymmetric partners
      - some may be light – but only very weakly interact with us
  - Building the upgrades
    - new tracker
    - FPGA-based track trigger

What Will You Do

- Two types of activity:
  - Service (taking care of the detector and its operations)
  - Physics (analysis of data leading to publications and a doctorate degree)
  - Code C++/python, high speed electronics and FPGA programming, work with your hands (building detector modules)

- Service:
  - building detectors
  - shifts
  - calibration of detectors
  - finding and fixing problems

- Physics:
  - work on particle identification algorithms
  - optimize event selection
  - measure SM process or discover new physics
  - talk about it
  - publish papers

Where Will You Be

- Depends on exact project you'd get involved in
  - Some detector and electronics work is here at Rutgers
  - CMS is at CERN - you probably would spend significant time there or at the physics center in the US: at Fermilab, near Chicago

Summary

- The experiment tells us that a fundamental scalar field with non-zero vacuum expectation value, responsible for electroweak symmetry breaking and particle masses exist
  - modern version of aether
- Flavor, Dark Matter, Baryogenesis, Inflation all require some kind of new physics
  - And there are still valid arguments for new physics at the unification scale of Electromagnetic and Weak forces
  - That is the energy scale of the LHC
  - LHC made a good dent in excluding “natural” models, but is far away from making a definitive statement about new physics at EWK scale

The best results from the LHC are still to come!
New, paradigm-shifting detector technologies, new analysis methods, plus **200 million Higgs bosons** produced:

Exciting and fun times ahead!