The Standard Model and Beyond

Paris Sphicas
CERN & NKUA (Athens)

CERN Accelerator School
May 2021

- **The Standard Model of Particle Physics**
  - **What is everything made of?**
  - **And how do these things interact?**
  - **And how do they get their substance – mass?**
- **Looking for the Higgs**
  - **A new boson at ≈ 125 GeV!**
  - **Studying its properties**
- **Is this all there is to Nature?**
  - **Searching for New Physics; e.g. Supersymmetry, extra dimensions…**
- **Outlook**

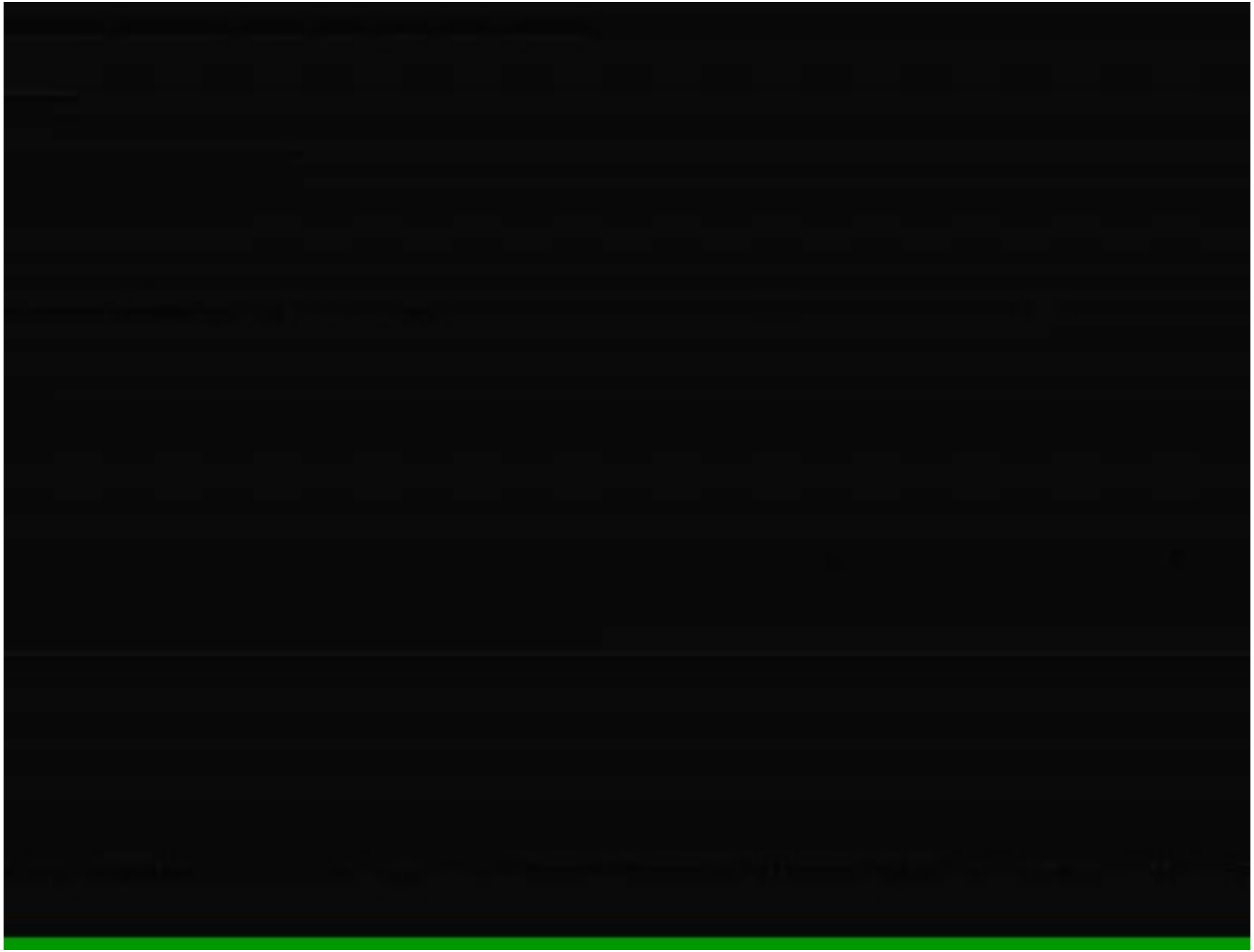
Copyright statement and speaker's release for video publishing

The CERN Accelerator School

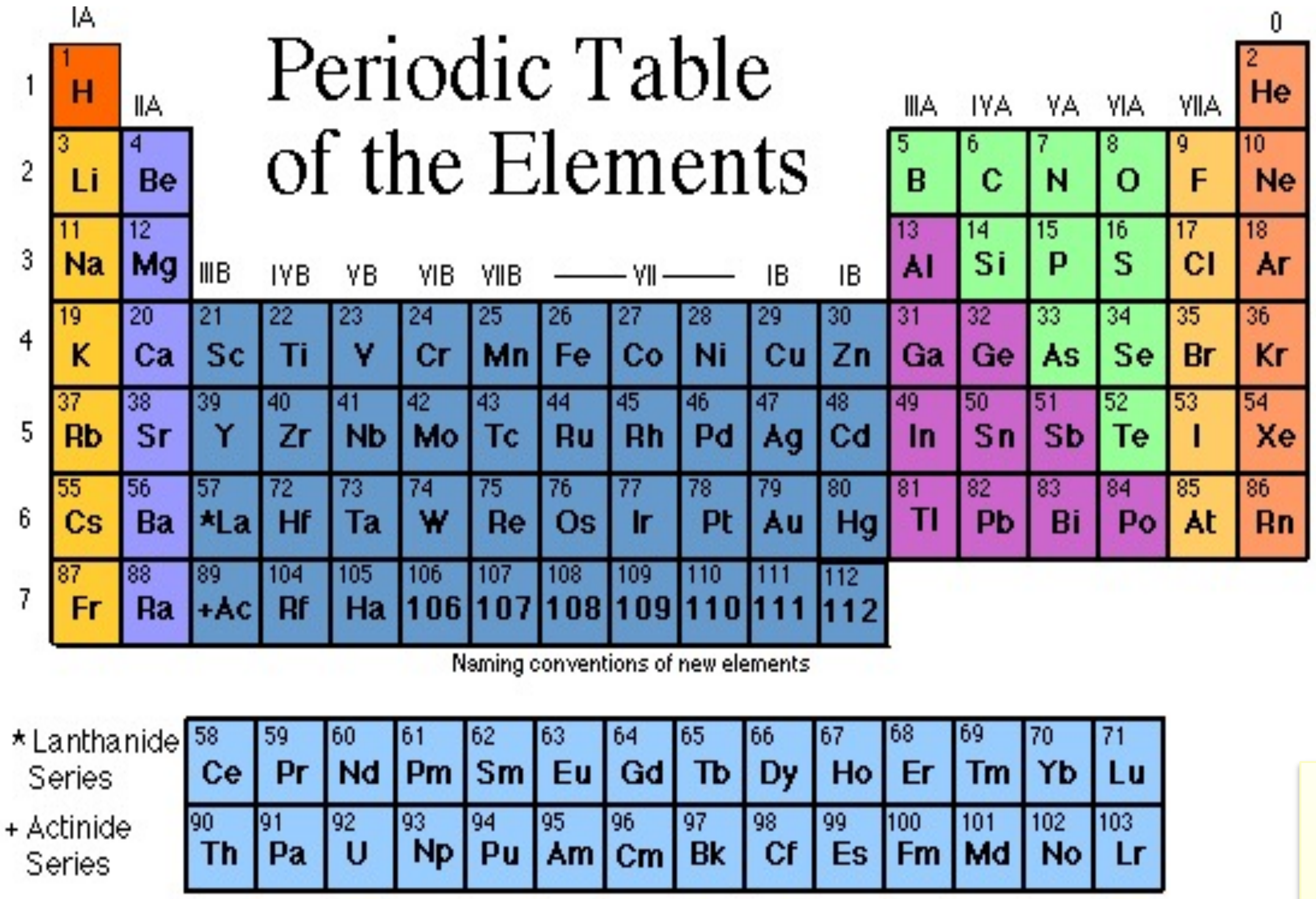
Nature...

What is everything made of?
And what is there in between?

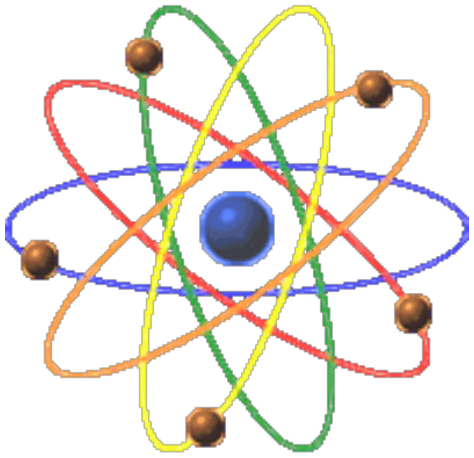
https://www.dailymotion.com/video/x4muob



What everything is made of



All elements are made of a-toms

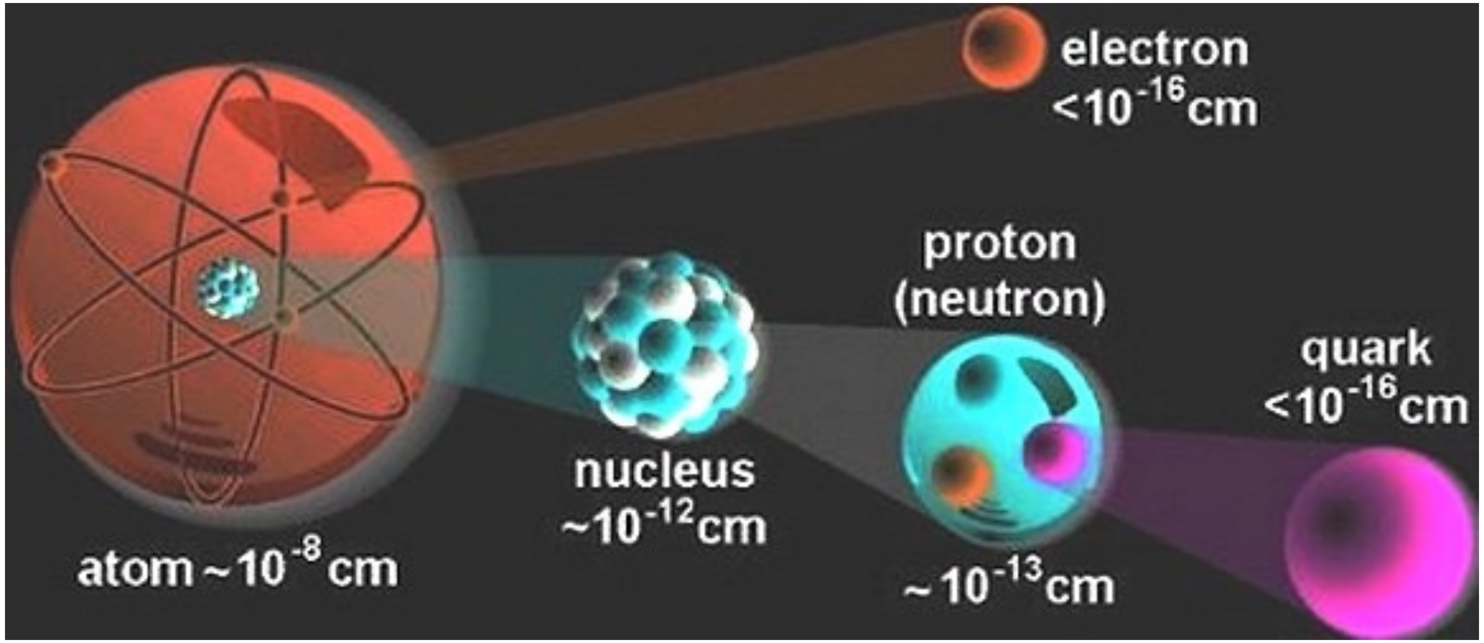


Complexity of behavior: one parameter: the number of electrons!

Zooming (entering) into the atom

Excerpt from “Powers of Ten” https://www.youtube.com/watch?v=0fKBhvDjuy0

20^{st} century: everything is made of four particles (u, d, e, ν_e)*



These are pointlike!

* Plus two copies…

Forces...

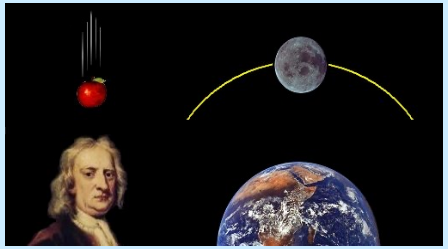
How does one particle "act" on another?

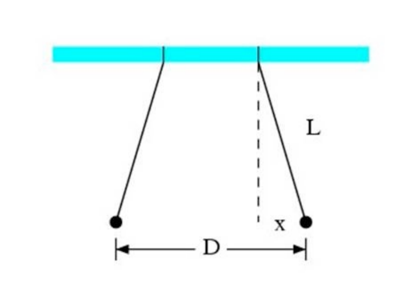
Do they have to "touch" each other, or can they act at a distance?

Nature and forces

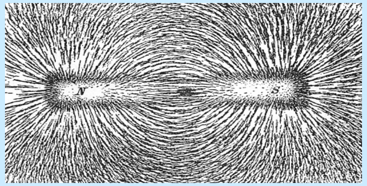
Action at a distance!? Bodies in the vacuum acting on each other !?!

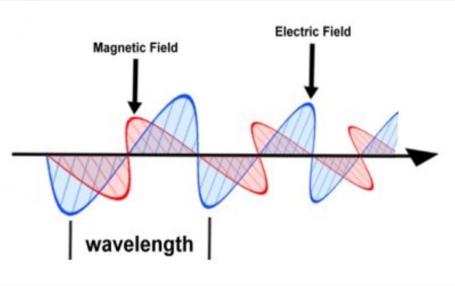
Gravity, then electricity and magnetism





With electromagnetism we could "see" that empty space was filled with fields





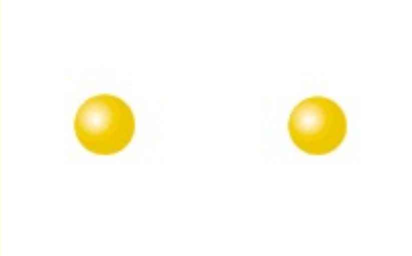
Which can propagate in empty space!

20^{th} century: two scientific revolutions:

Quantum mechanics → discretization

Relativity → no instantaneous interactions

New picture: Force == particle exchange.



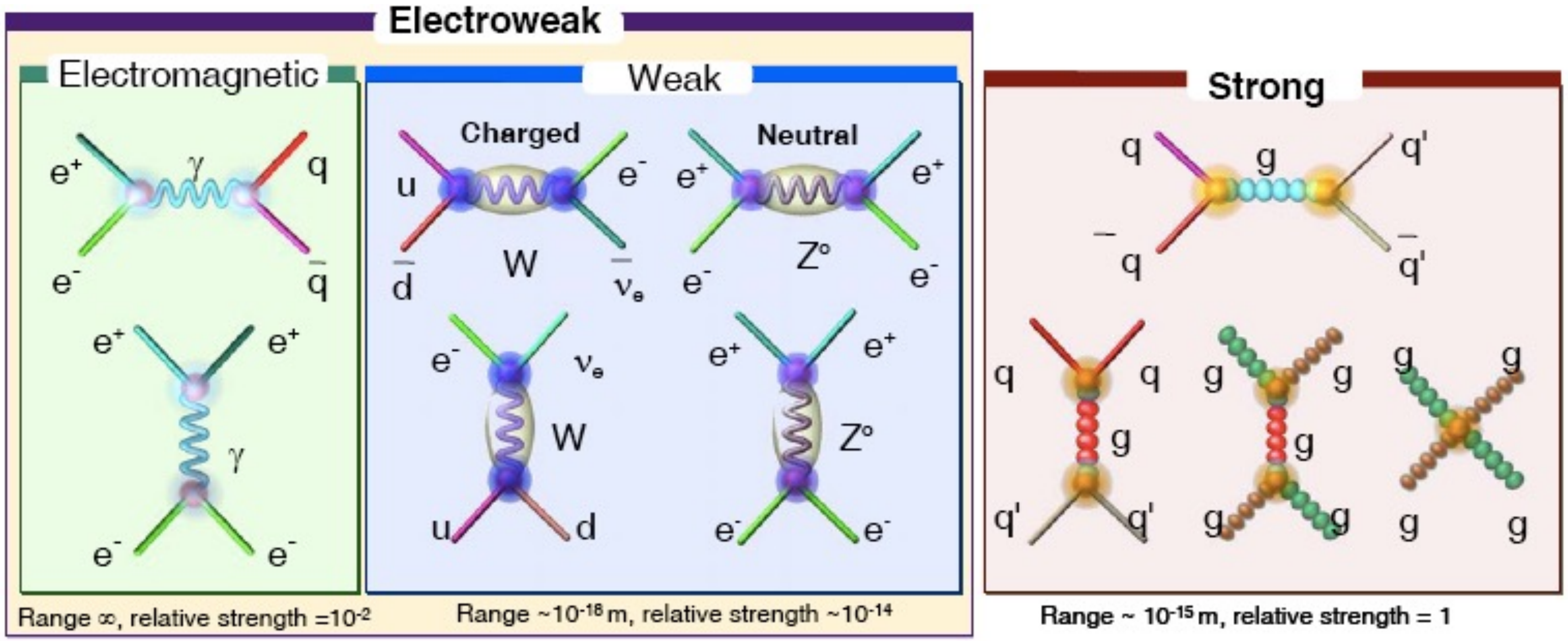
Applying these ideas to two other forces (weak and strong interaction) yields an excellent description

Except for their relative strength: e.g. the weak force is weak – and short range.

Property that decides these: the MASS of the particle that mediates the force

Standard Model of Particle Physics

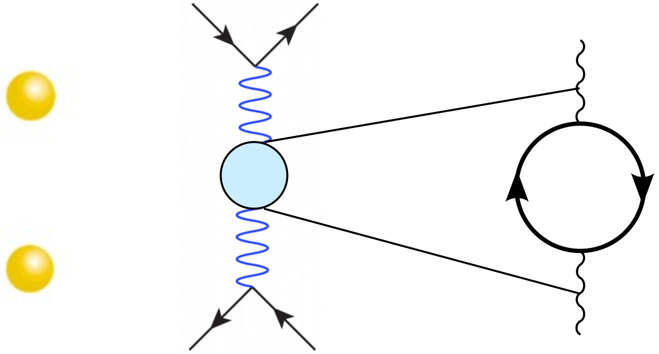
- Quantum Field theory: matter particles (spin-1/2) interact via the exchange of force particles (spin-1)

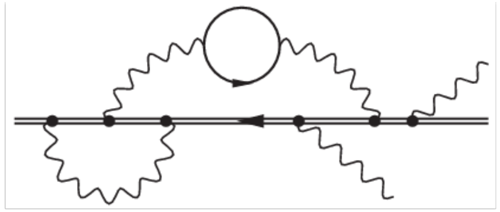


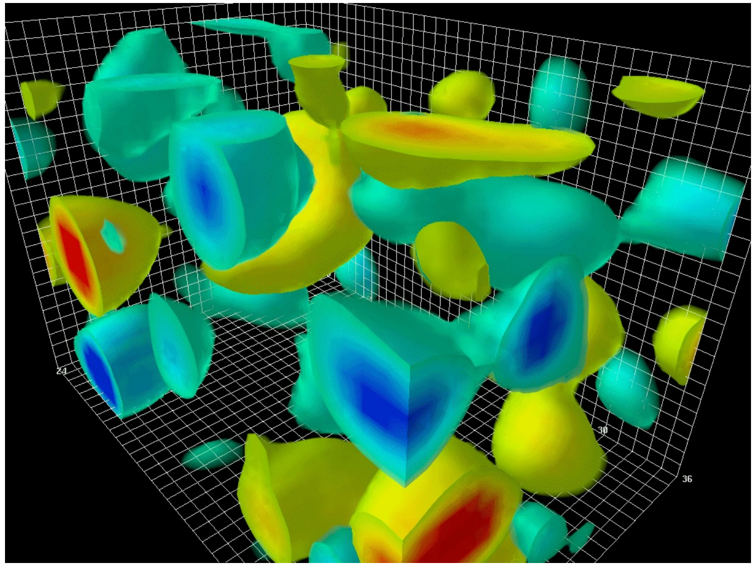
- Interactions → need charges. Which should be conserved. Implies some new symmetry…
  - Internal symmetry (SU(3)xSU(2)xU(1)) → massless bosons

Standard Model of Particle Physics

The vacuum is not empty – again



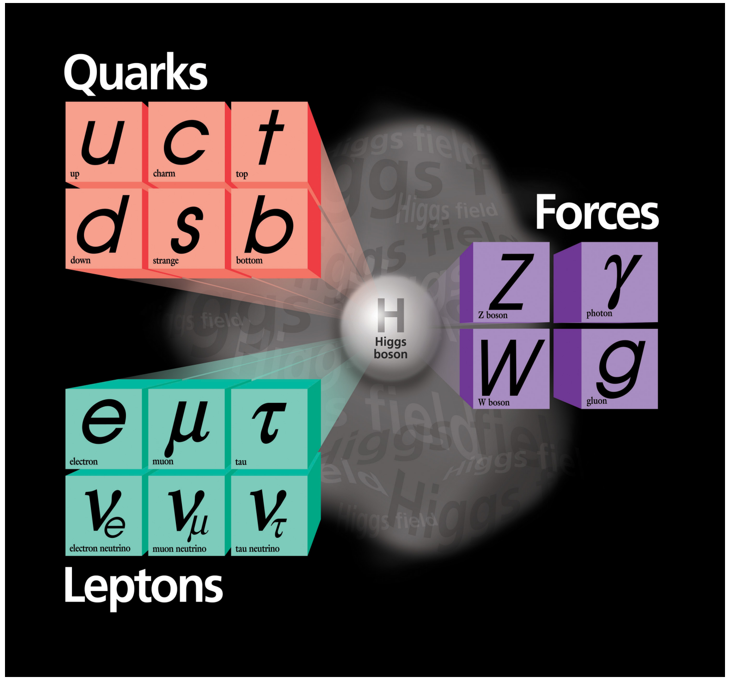




Brout-Englert-Higgs mechanism:

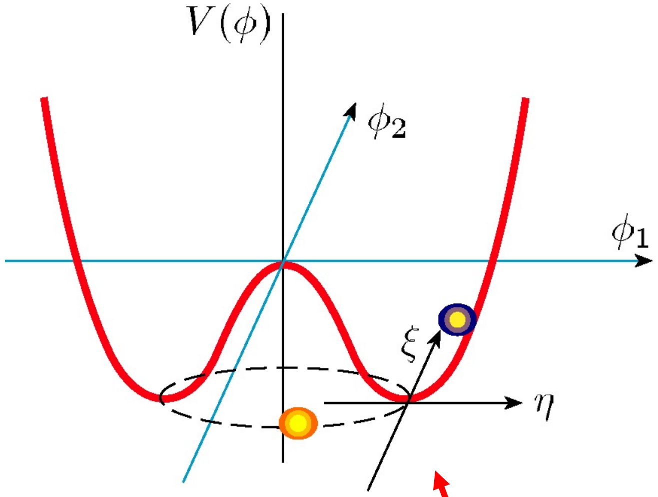
there is a new field that permeates all of space.
It fills up the "vacuum"
Particles travel ("swim") through it – so they feel resistance
Inertia...
They acquire mass!

Matter particles



Force particles

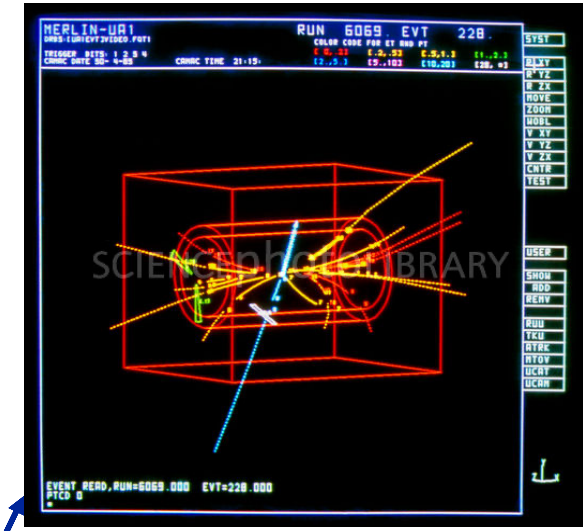
The Higgs Mechanism: mathematics

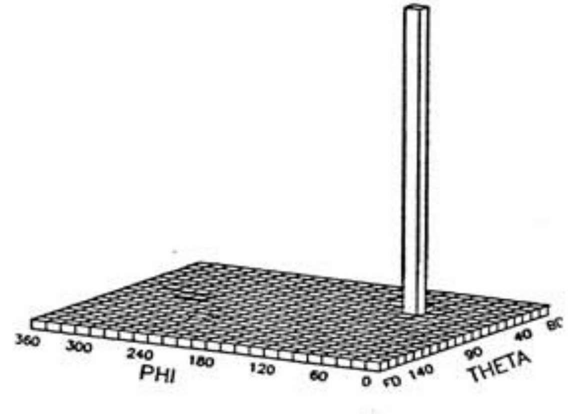


Two (complex) fields (4 DoFs)

Two “motions” in the potential

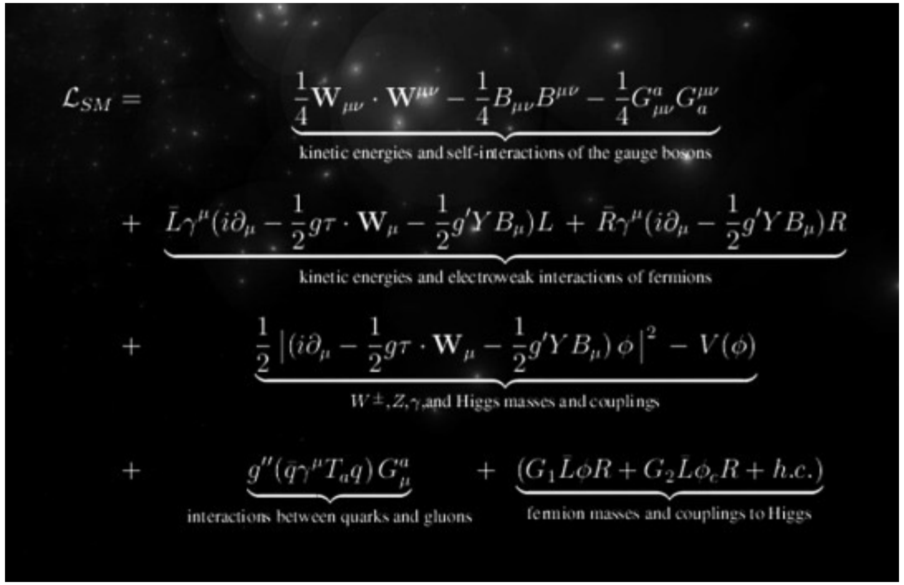
- One on the plane; “massless” mode that is lost (once a direction is chosen). Each degree of freedom appears as additional degree of freedom of a gauge boson
  - Extra polarization state
  - The boson becomes massive!
- One up/down on potential; massive
  - Higgs boson; for which theory predicts everything, except one parameter: its mass!



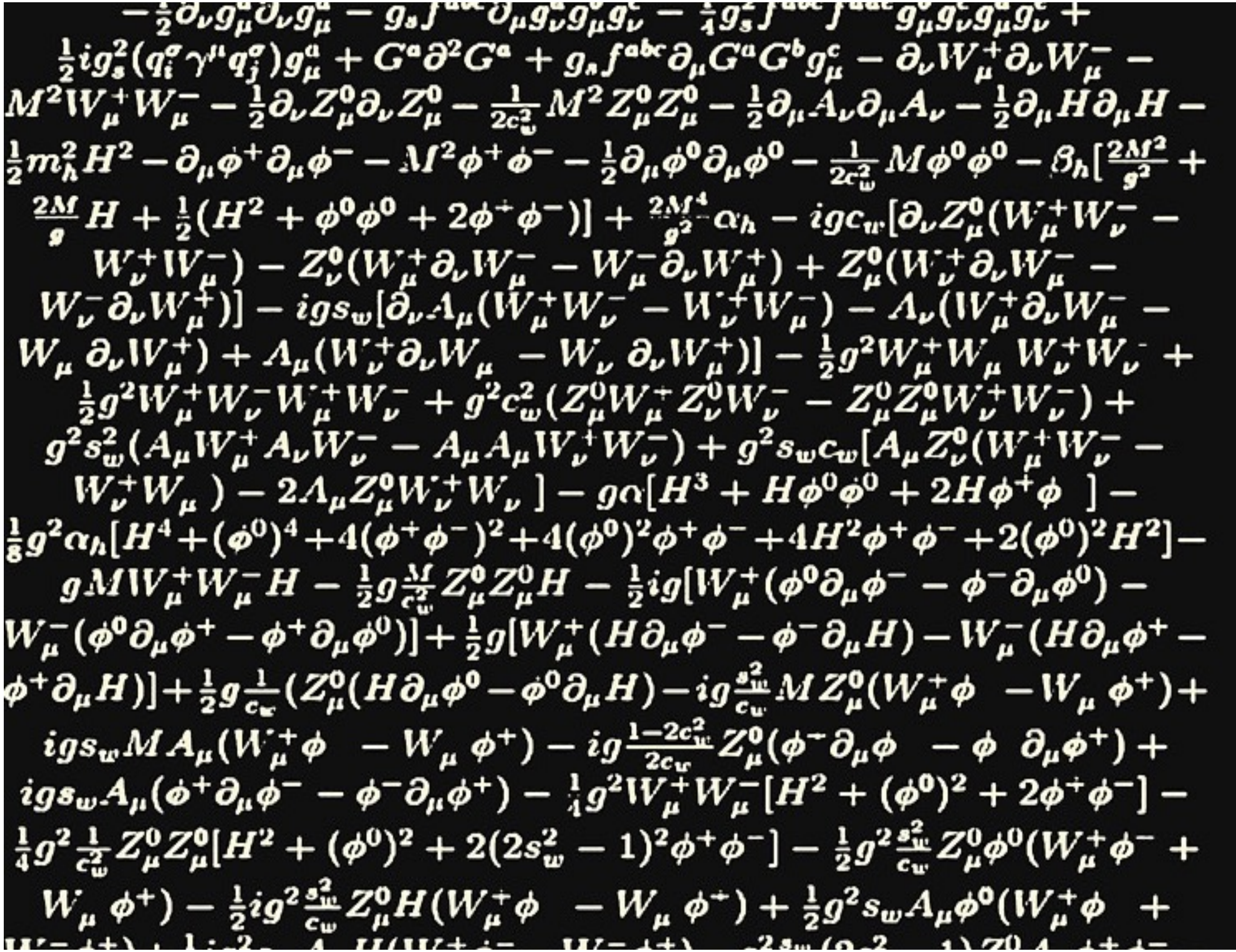


Thus were the W/Z masses born in theory; and discovered (at the right value) @ CERN in 1984.

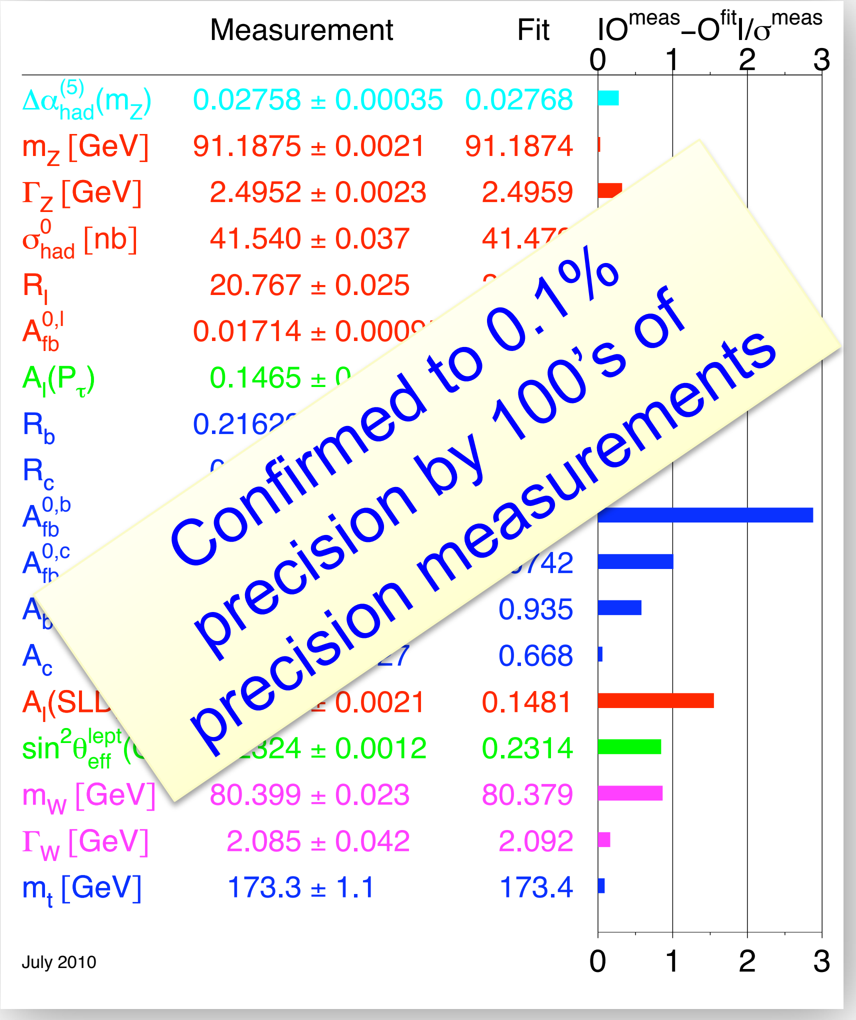
There is, actually, a full theory behind this

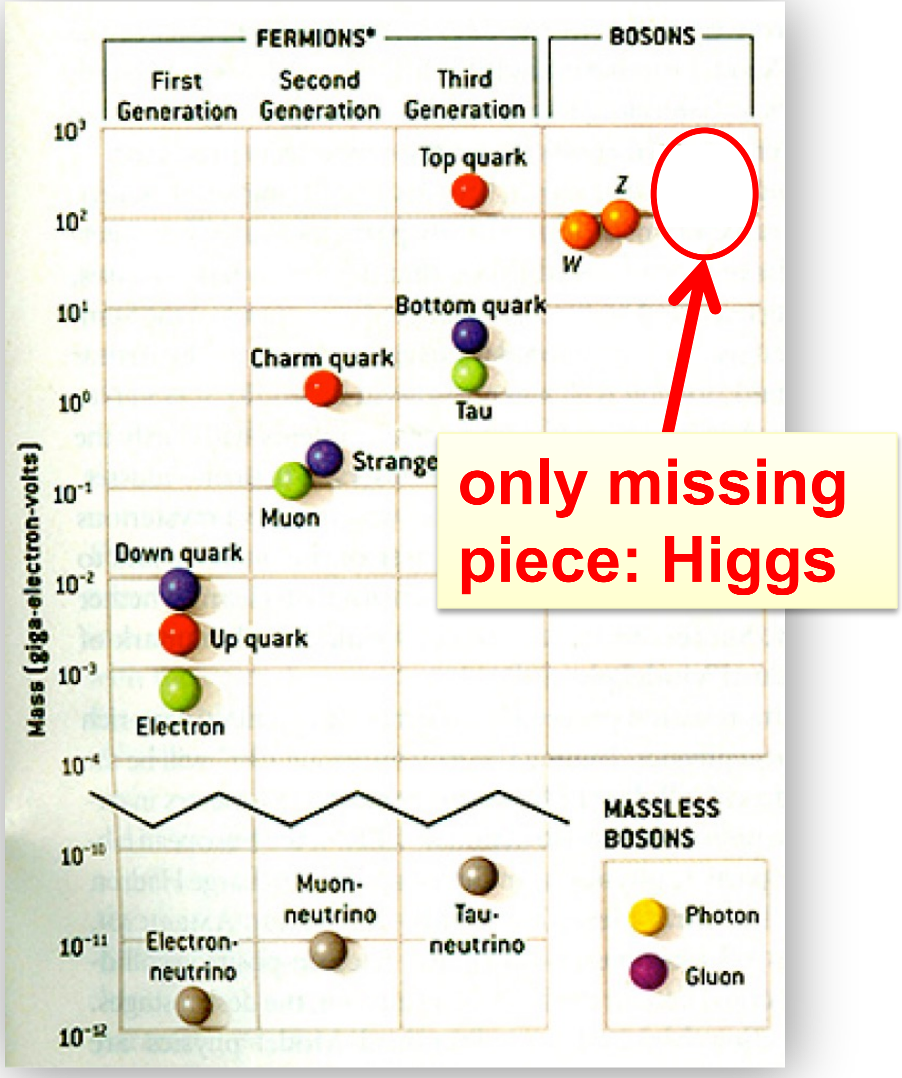


1/3 →

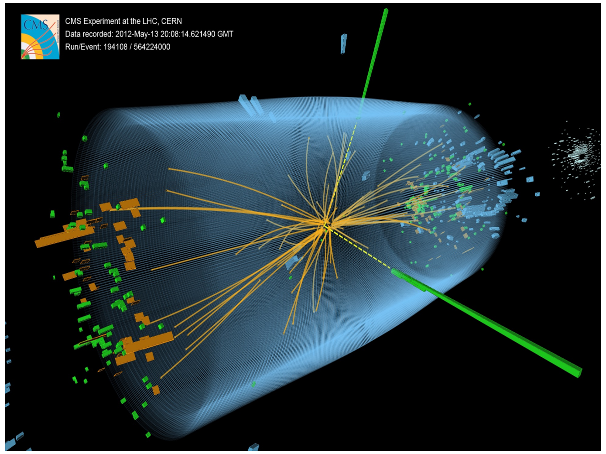


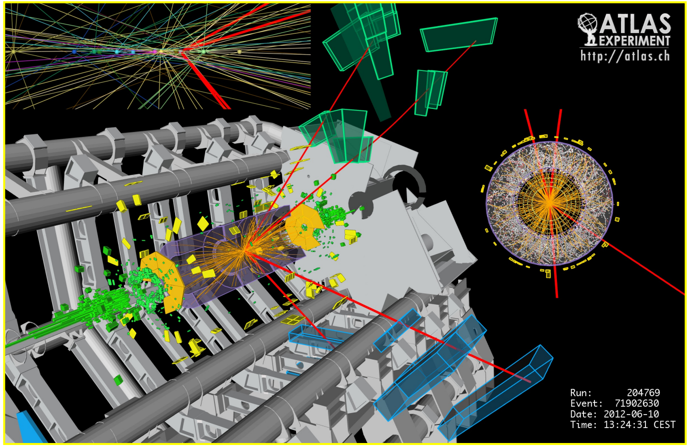
The Standard Model up until 2012

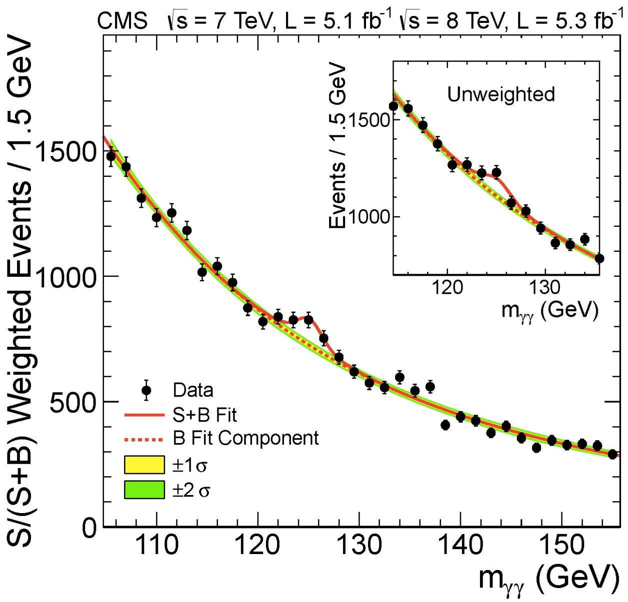


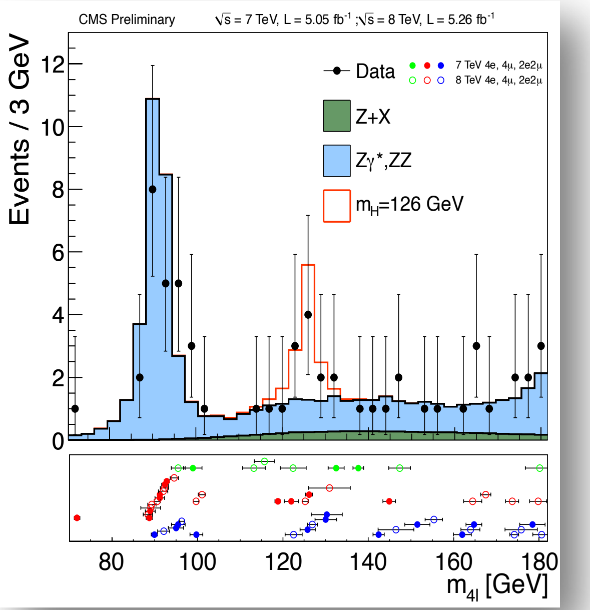


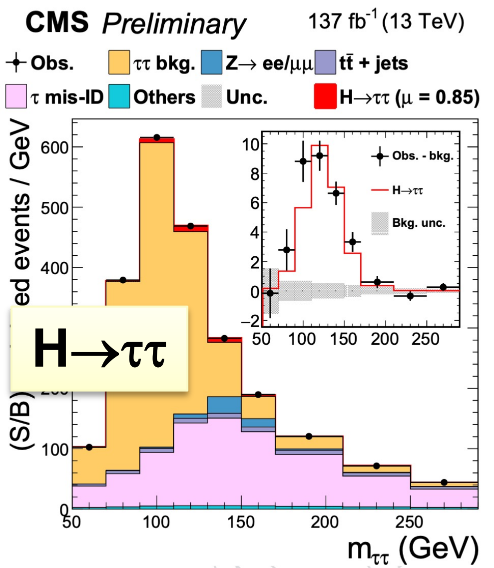
Then came 2012, and a boson at 125 GeV was discovered; we have been studying it ever since…

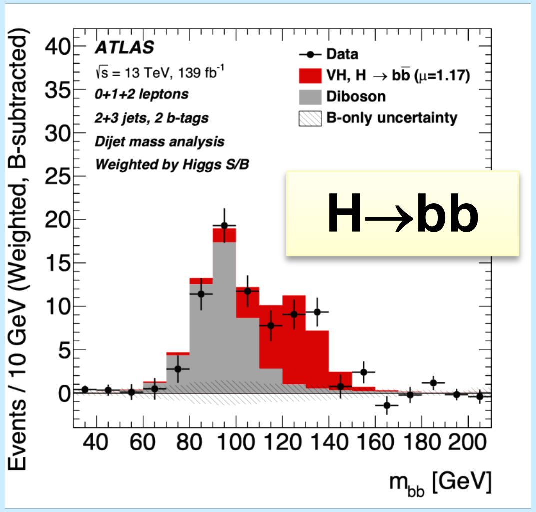






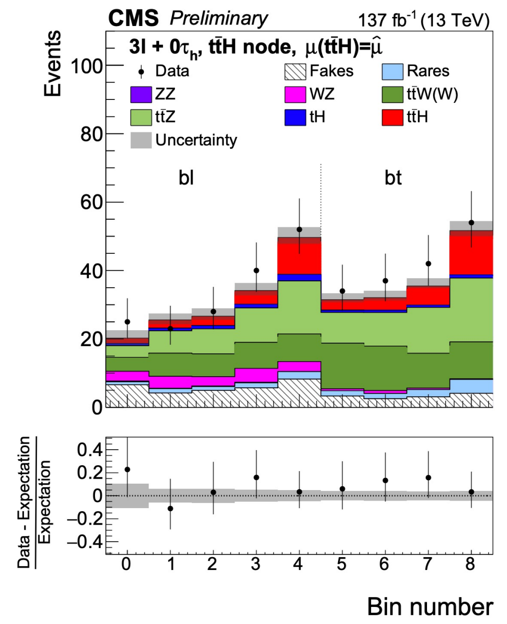






Clear observation of couplings to 3rd-gen fermions

ttH

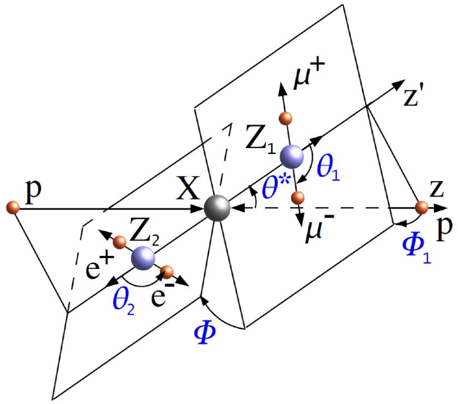


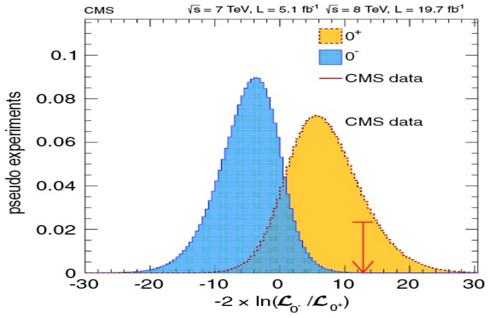
C. Palmer ICHEP2020
K. Jakobs ICHEP2020

Studying the properties of the new boson @ 125 GeV

Amazingly enough (a):

It has no spin



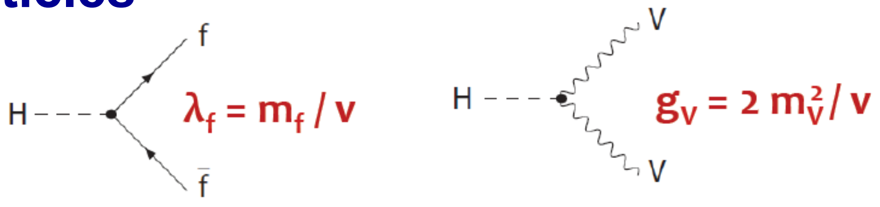


It is, indeed, the Vacuum Particle

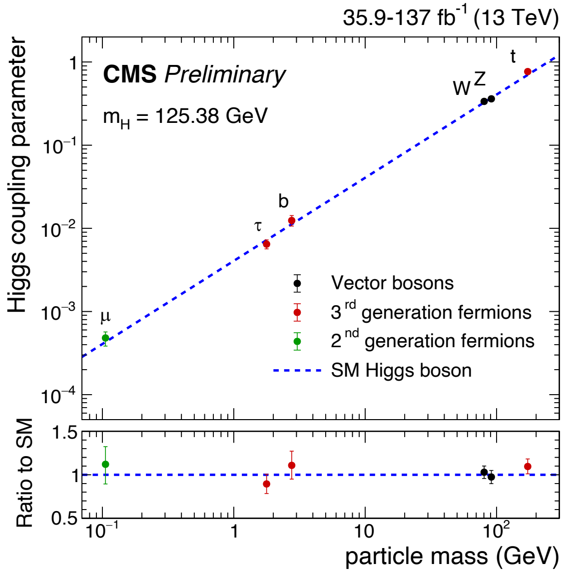
First three years gave us W, Z, points; (plus indirect info on t point) then τ…
Some evidence for b point
Last ~three years: the b and t points (this time, directly);
2020: evidence for μ point (2^{nd} gen!)

Amazingly enough (b):

It couples to the MASS of the other particles



$J^P=0^+$
+
Ultimate non-universal coupling: to mass (!)



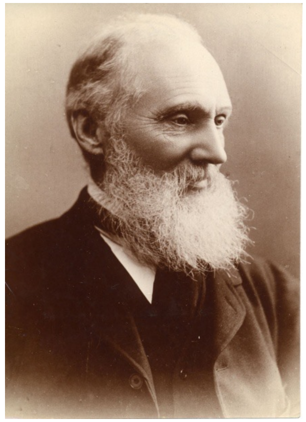
Beyond All Reasonable Doubt:
The "125 GeV boson" is a Higgs boson

The discovery of the Higgs boson was the ultimate crown on the Standard Model of Particle Physics

With the discovery of the Higgs boson, the Standard Model (SM) is now "complete": its full particle content has been observed

The SM provides a remarkably accurate description of experiments with and without high-energy accelerators. At the cost of 26 parameters determined by experiment…

With the physics of the very small [thought to be] understood at energy scales of ~O(100) GeV, the situation is reminiscent of previous times in history when our knowledge of nature was deemed to be "complete"



Lord Kelvin (1900):
There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

1905-1920: Relativity, Quantum mechanics

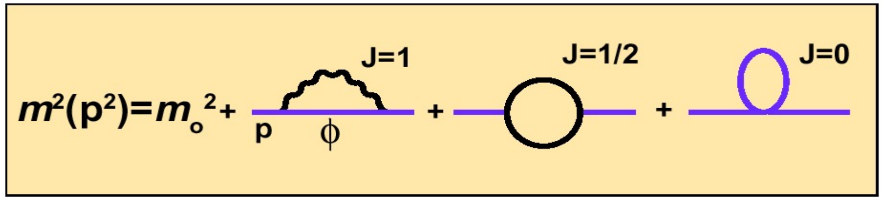
So is this it?

In a world of an SM Higgs, is there any room for new physics?

The magic of the Higgs boson mass

Quantum Mechanics: ultimate destructor of small numbers (in nature) not protected by some symmetry (thus "law")

Higgs boson: the ultimate example; spinless → zero cost from mass correction



$$m^2\left(p^2\right)=m^2\left(\Lambda^2\right)+Cg^2\int_{p^2}^{\Lambda^2}dk^2$$

P.A.M Dirac

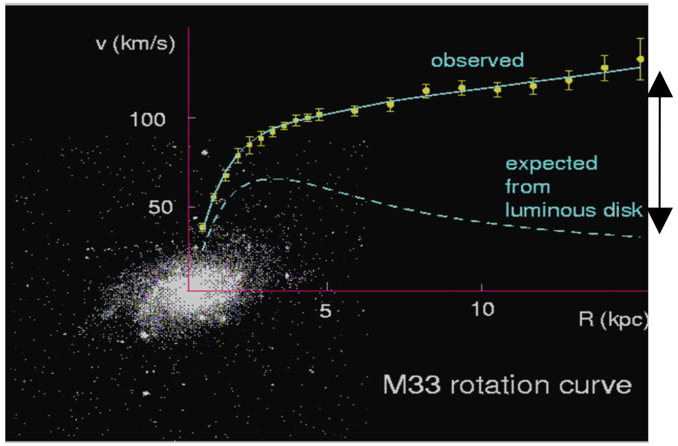
M(H) with corrections all the way up to the Planck scale: for $\Lambda \sim 10^{19}$ GeV

m^2 = 123456789012345678901234567543218901 –
123456789012345678901234567543217387 =
15625 GeV²

An immense coincidence of googlic sizes?

Probably, simply some additional (i.e. New) physics on the way to 10^{19} GeV

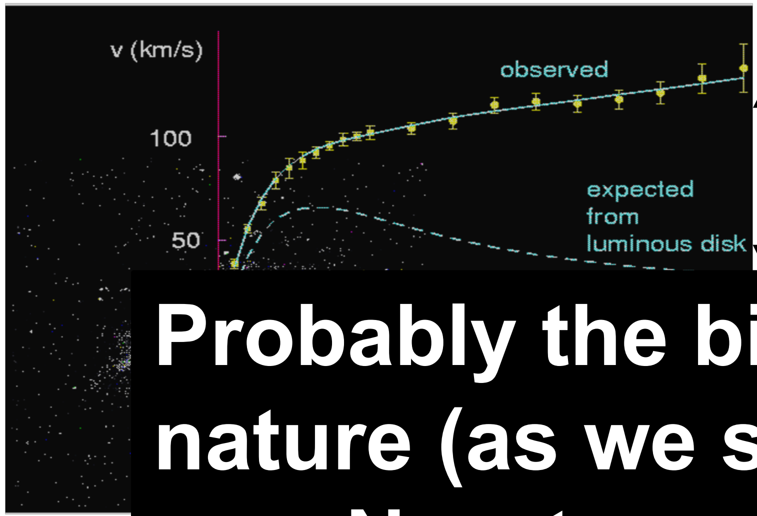
We know there is new physics already



Dark (invisible) matter!

Plus neutrinos and their masses!

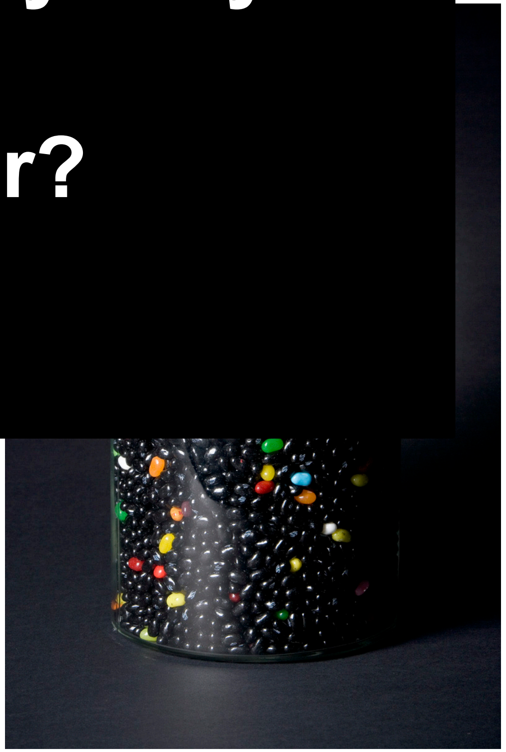
Dark matter



Dark (invisible) matter!

Probably the biggest mystery in nature (as we speak)

- **New type of matter?**
- **New forces?**
- **New dimensions?**



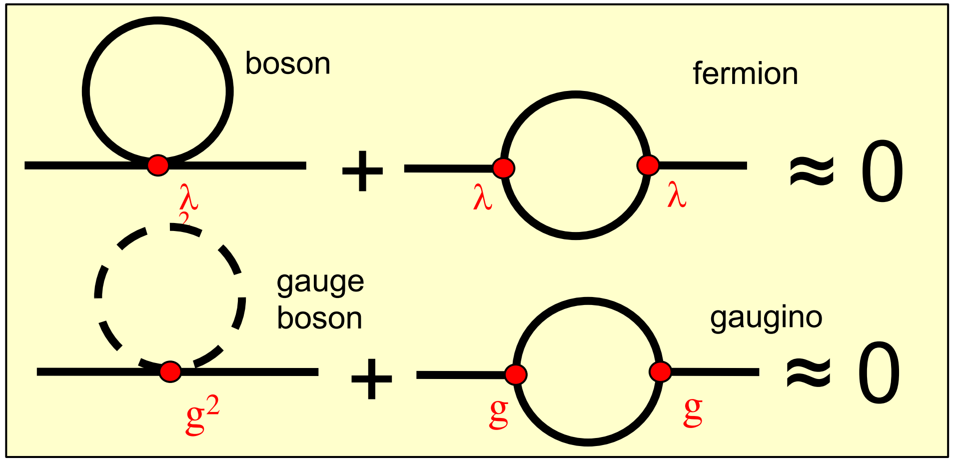
There are many options for this new physics

Solution #1: a composite Higgs?

H: bound state (e.g. due to some new strong interaction)

Solution #2: supersymmetry?

Partners for ALL SM particles,
spin different by ½
Presumably broken symmetry
(since partners unseen)



Solution #3: "little Higgs"?

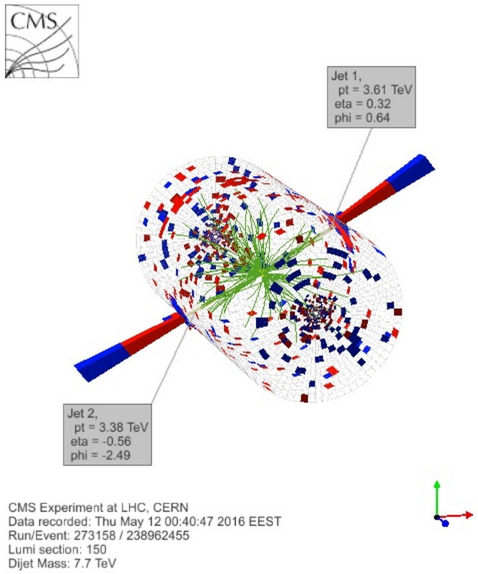
H: pseudo-Goldstone boson of Ultimate Theory; just another effective theory, e.g. valid to ~10 TeV. Loops cancel by particles of same spin (so need to introduce these particles)

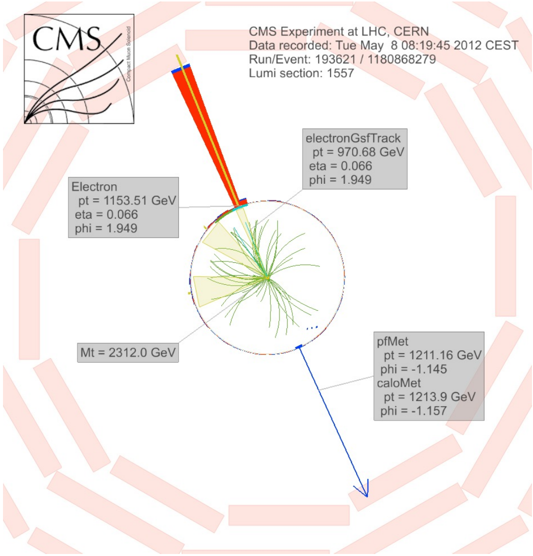
Solution #4: extra dimensions?

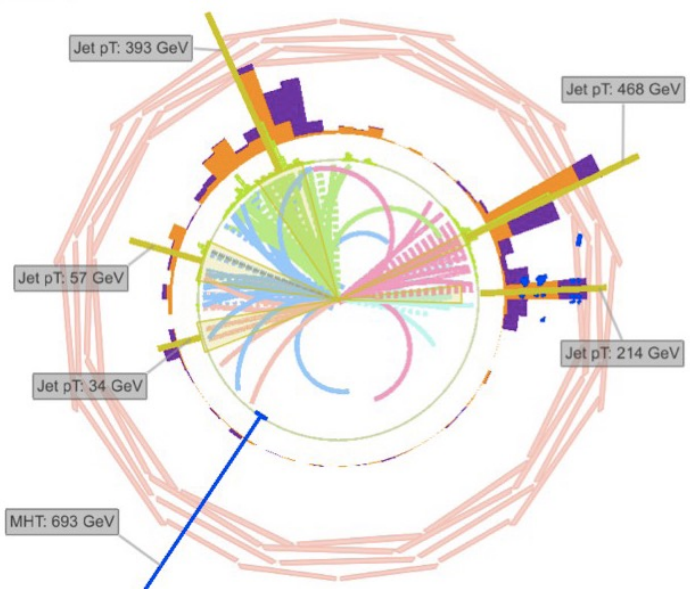
N-dim space; gravity propagates in all dims, SM only in "our" 3 dims; e.g. warped extra dimension can explain weakness of G

And there has been an intense effort to find it at the highest energies – e.g. at the CERN Large Hadron Collider

- **All solutions demand the presence of new particles**
  - More Higgs bosons;
  - SUSY partners;
  - New W/Z bosons;
  - New quarks;
  - …
- **Searches for new physics: main path has been the search for these (higher-mass) states**
  - In the beginning inclusively; as time goes by and searches come in empty-handed, ask "what/how" would have escaped?
    - And then tune analyses and go after specific signatures



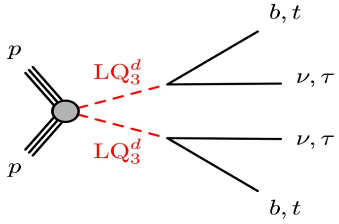


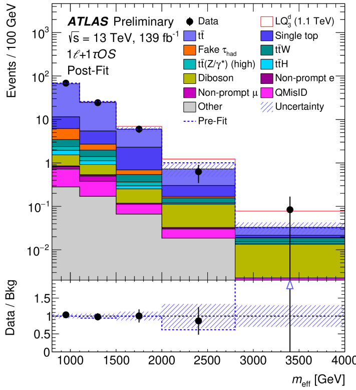


Non-SUSY BSM: vast, simply vast…

V. Cavaliere ICHEP2020

Leptoquarks



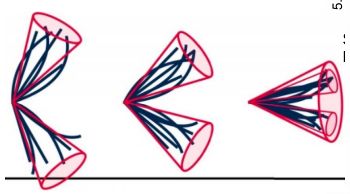


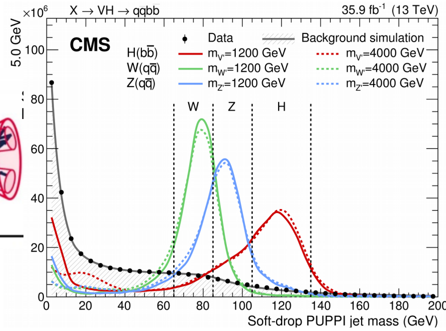
Credit: H. Russell

LFV

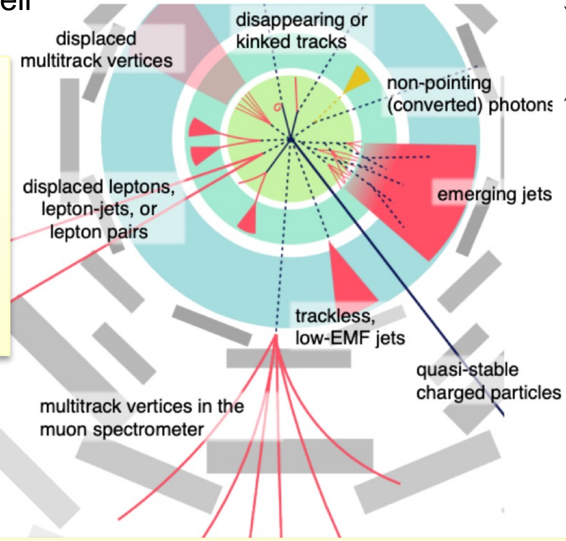
Upper 95% CL limits	ATLAS	LEP
B(Z —> e τ)	8.1 × 10⁻⁶	9.8 × 10⁻⁶ [OPAL]
B(Z —> μ τ)	9.5 × 10⁻⁶	12 × 10⁻⁶ [DELPHI]

Boosted Objects (VV, VH, HH)





Unconventional Signatures… e.g. Long-lived particle searchs: still early days; ~unthinkable back in 2000-2004



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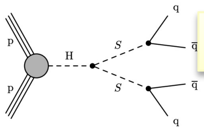
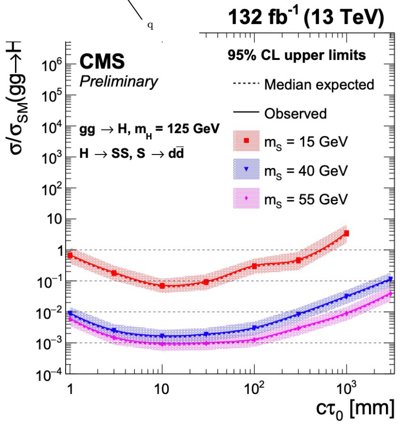
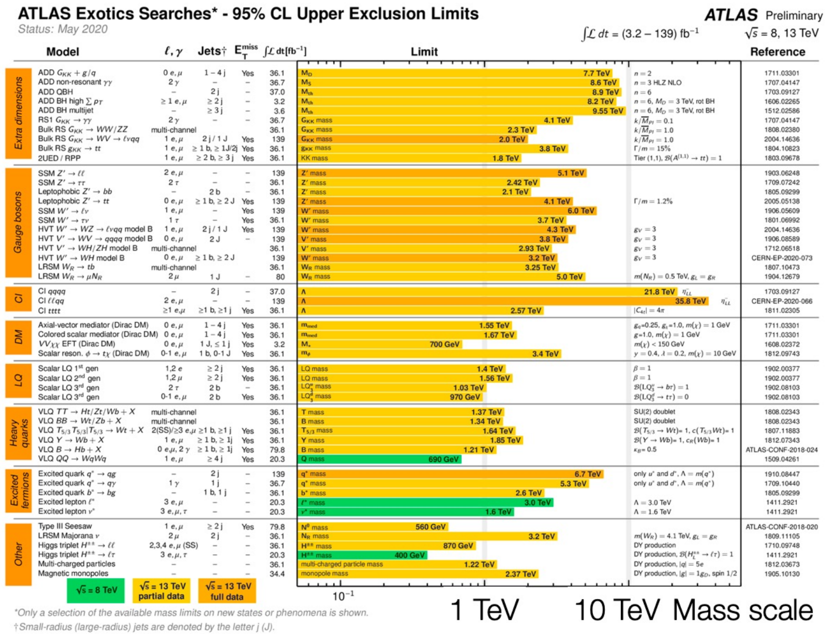
Displaced jets







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V. Cavaliere ICHEP2020

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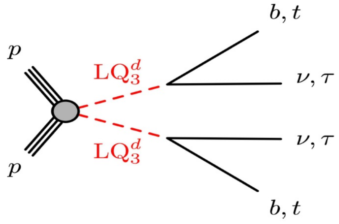

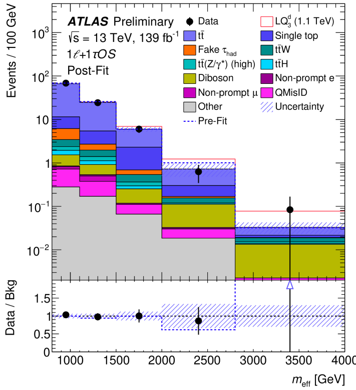

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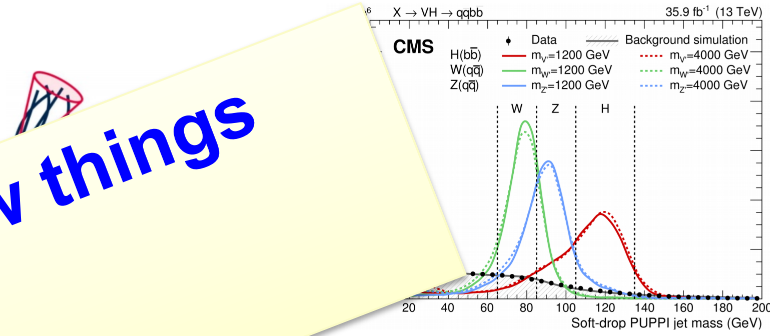

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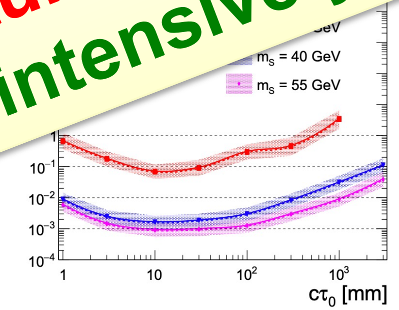
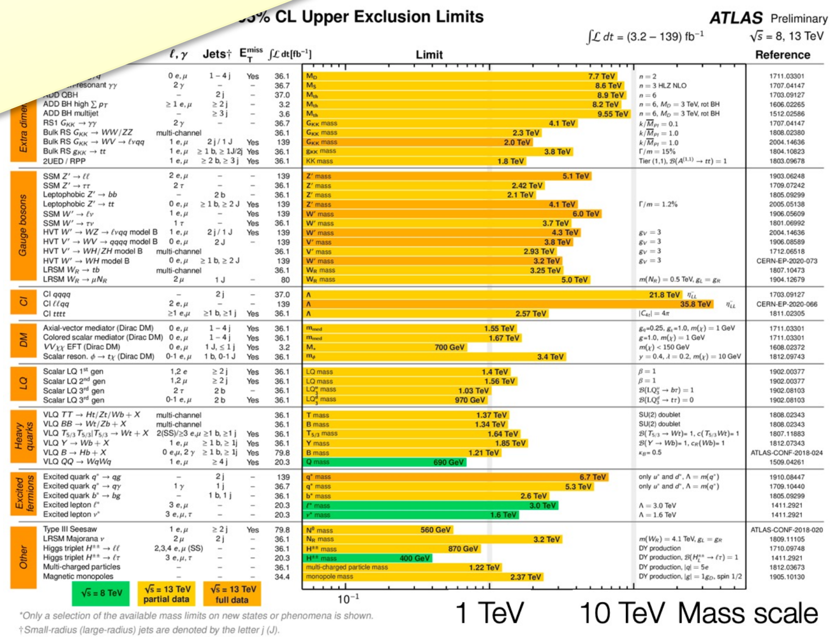


+FASER

Looked for a lot of possible new things

Nothing has turned up yet

Still looking intensively



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Is a null result exciting? And what next?

Actually, it is (as history teaches us; e.g. recall Michelson-Morley experiment)

For, with each null search, the mystery deepens.

Incredibly enough: we simply do not really understand the vacuum – yet!

- **How is the Higgs stabilized against itself?**

Does the Higgs couple to all mass out there?

- **Does the Higgs boson “see” dark matter? Is it a “portal” to an entire new sector?**

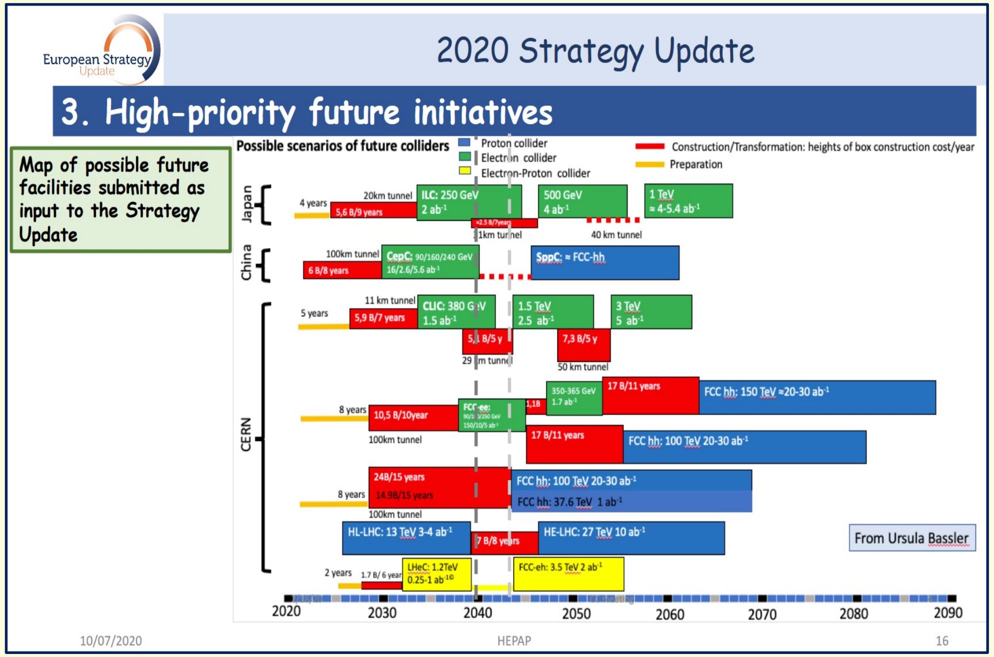
Plus, several unsolved/unanswered issues remain unsolved/unanswered

- **Matter-antimatter asymmetry? Simply not enough CP violation to explain the current universe (baryon-antibaryon asymmetry).**

Need to go a bit more backwards in time in the evolution of the universe.

Future machines

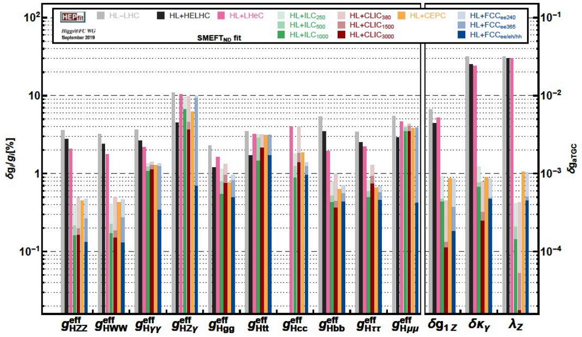
Definitely no lack of ideas/options



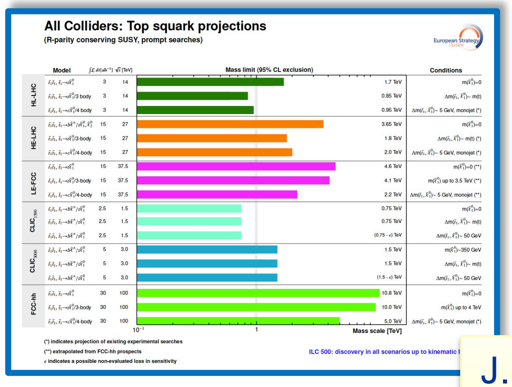
M. Shiltsev (ICHEP2020 plen)
Long list of new colliders; but also neutrino beams, and blue-sky R&D on novel accelerator methods

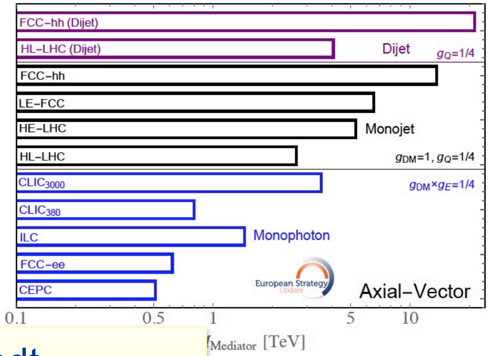
Menu: "*The future*"

- probe the Higgs
- probe highest possible E scales
- probe rarest processes
- best possible ν physics
- DM & dedicated expts



per detector in e^+e^-	# Z	# B	# τ	#c	#WW
LEP	4x 10^6	1x10^6	3x10^5	10^6	2x 10^4
SuperKE KB	-	10^{11}	10^{11}	10^{11}	-
FCC-ee	2.5x 10^{12}	7.5x 10^{11}	2x 10^{11}	6x 10^{11}	1.5x 10^8





J. D'Hondt (ICHEP2020 plen)

Towards a/new machine(s)

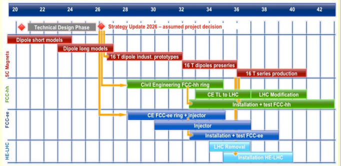
European Particle Phys Strategy
"... An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology…
... the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors"

Common denominator: need for R&D

Even for machines (e.g. linear colliders/ ILC) where things are more "ready"

V. Shiltsev ICHEP2020

- Positron production (>20x SLC)
- Luminosity and commissioning time: Ground motion, focusing, etc
- CLIC two-beam scheme is novel



As for next step in pp energy

- Driven by magnets… begs for more investment
- Muon collider: "R&D required on: μ production and cooling, fast acceleration (magnets, RF), MDI, large aperture 12 T magnets, ν-radiation"
- And of course on new acceleration methods.

Cooperation/Collaboration will be the key

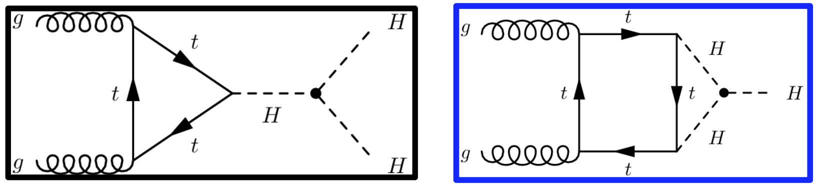
Next steps on the energy frontier

There are several ways in which low-scale (humanly accessible) new physics could have escaped.

The ongoing hunt for new physics is as intense as ever.

Highest priority: precision understanding of the Higgs

Couplings; Ultimate target: λ

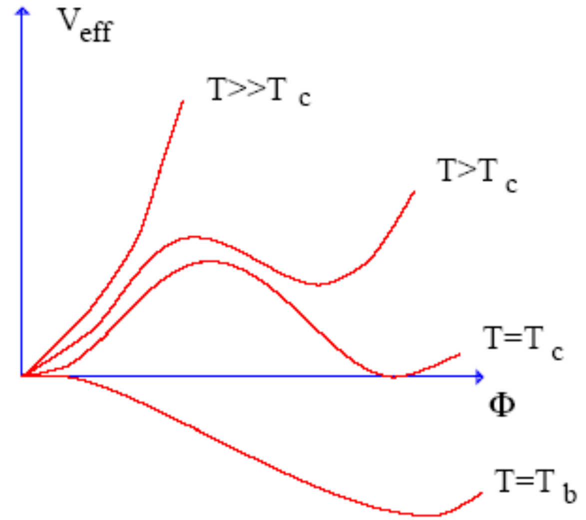


$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

En route to the new physics, we will establish how the symmetry of the Higgs field is broken.

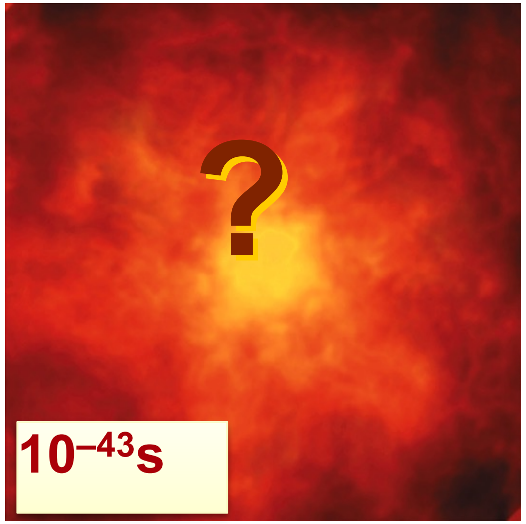
This we know can be done at future colliders/experiments.
(By measuring the Higgs potential)

We will obtain information on the ultimate phase transition – the one through which the Higgs acquired its strange vacuum properties;

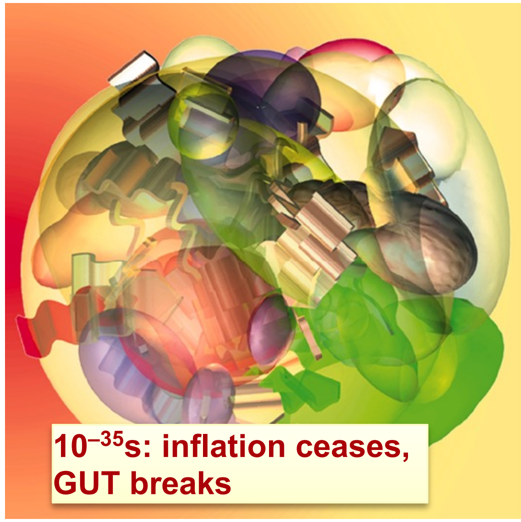


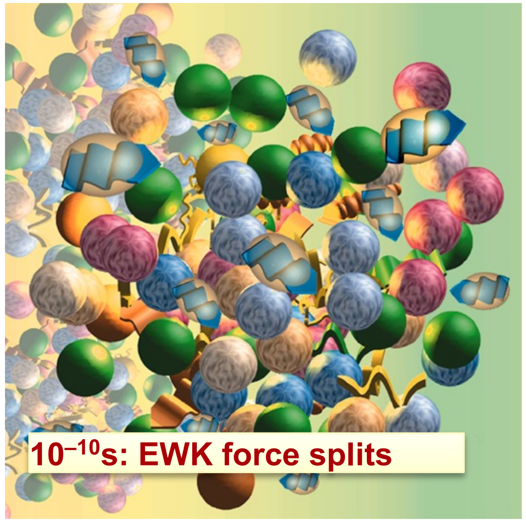
Is this what is responsible for the universe as we know it?

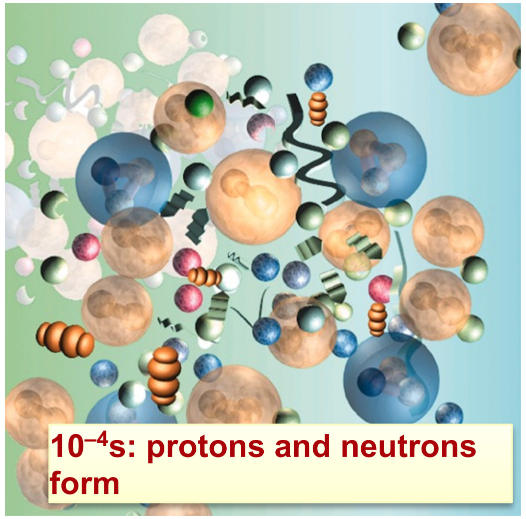
Summary and Outlook

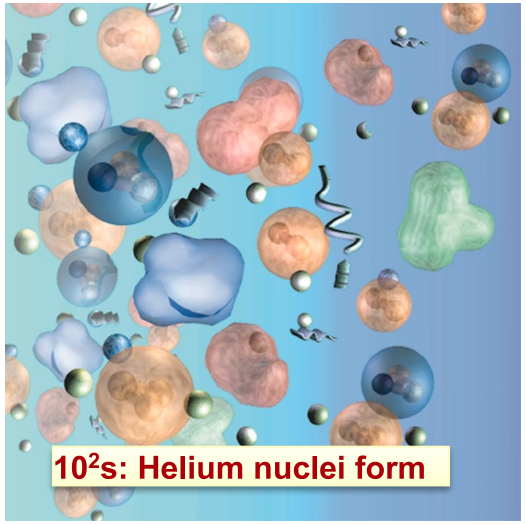


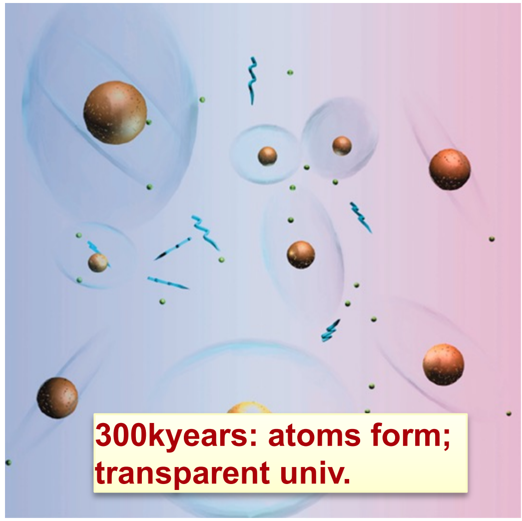
10^{-43}s


10^{-35}s: inflation ceases, GUT breaks

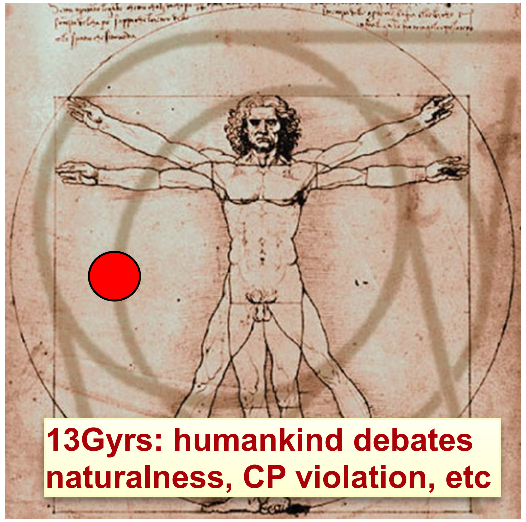

10^{-10}s: EWK force splits


10^{-4}s: protons and neutrons form


10^{2}s: Helium nuclei form


300kyears: atoms form; transparent univ.


1Gyrs: galaxies form


13Gyrs: humankind debates naturalness, CP violation, etc

Credit: S. Cittolin/CMS

We are here