

The Standard Model and Beyond

*Paris Sphicas
CERN & NKUA (Athens)
CERN Accelerator School
May 2022*

- **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**

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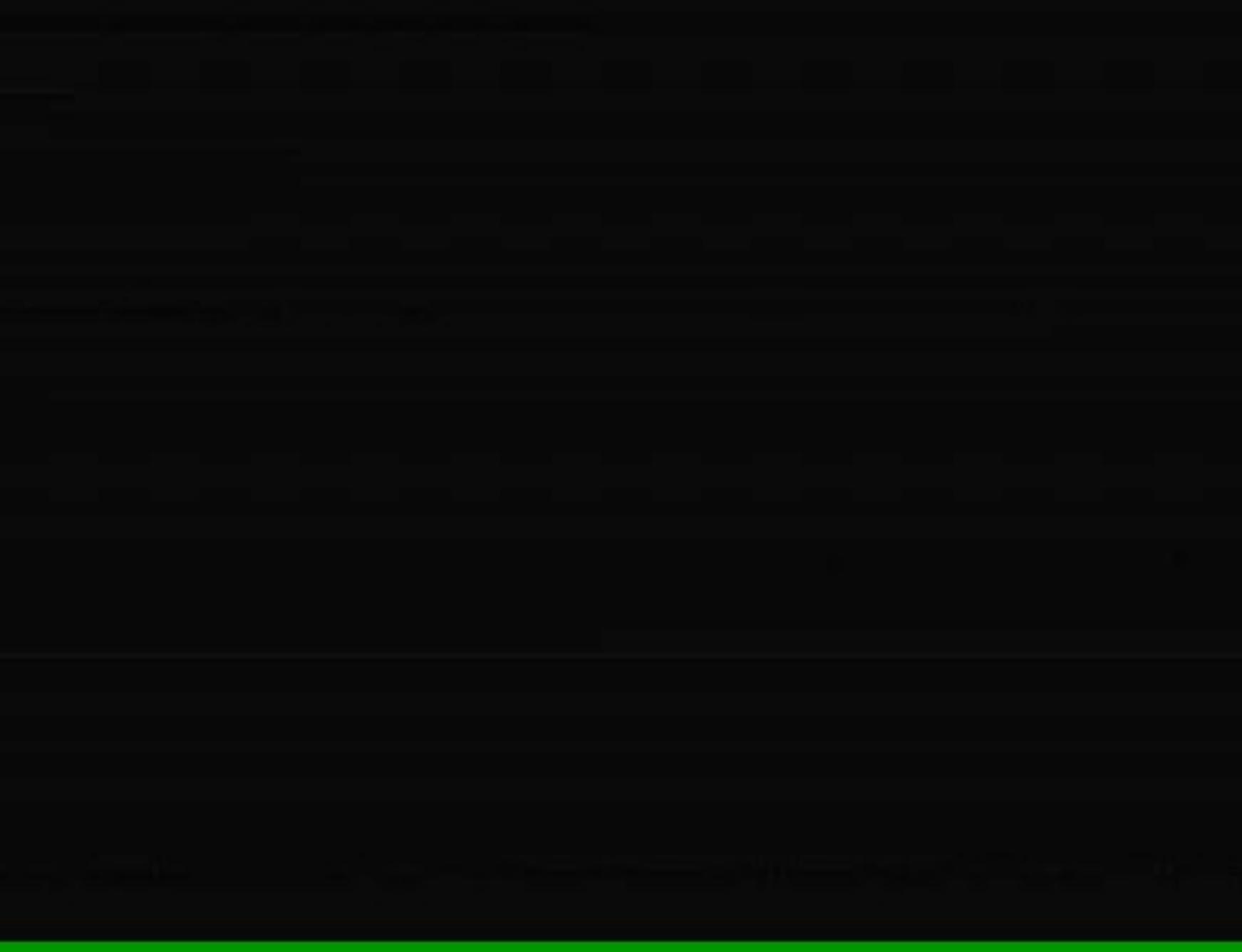
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Nature...

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

["Zoom into a tooth"](#)



What everything is made of

IA		IIA																0																					
1	H	3	Be															2	He																				
2	Li	11	Mg	IIIIB		IVB		VB		VIB		VIIIB		VII		IB		IB		VIIA																			
3		12		19	K	20	Ca	21	Sc	22	Ti	23	Y	24	Cr	25	Mn	26	Fe	27	Co	28	Ni	29	Cu	30	Zn	31	Ga	32	Ge	33	As	34	Se	35	Br	36	Kr
4				37	Rb	38	Sr	39	Y	40	Zr	41	Nb	42	Mo	43	Tc	44	Ru	45	Rh	46	Pd	47	Ag	48	Cd	49	In	50	Sn	51	Sb	52	Te	53	I	54	Xe
5				55	Cs	56	Ba	57	*La	72	Hf	73	Ta	74	W	75	Re	76	Os	77	Ir	78	Pt	79	Au	80	Hg	81	Tl	82	Pb	83	Bi	84	Po	85	At	86	Rn
6				87	Fr	88	+Ac	89	104	Rf	105	Ha	106	107	108	109	109	110	110	111	111	112	112																
Naming conventions of new elements																																							

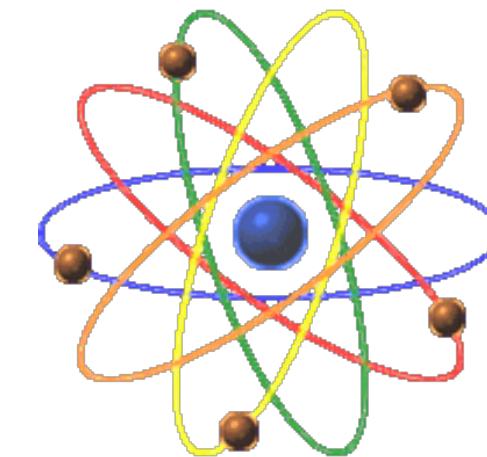
* Lanthanide Series

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

+ Actinide Series

90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

All elements are made of a-toms



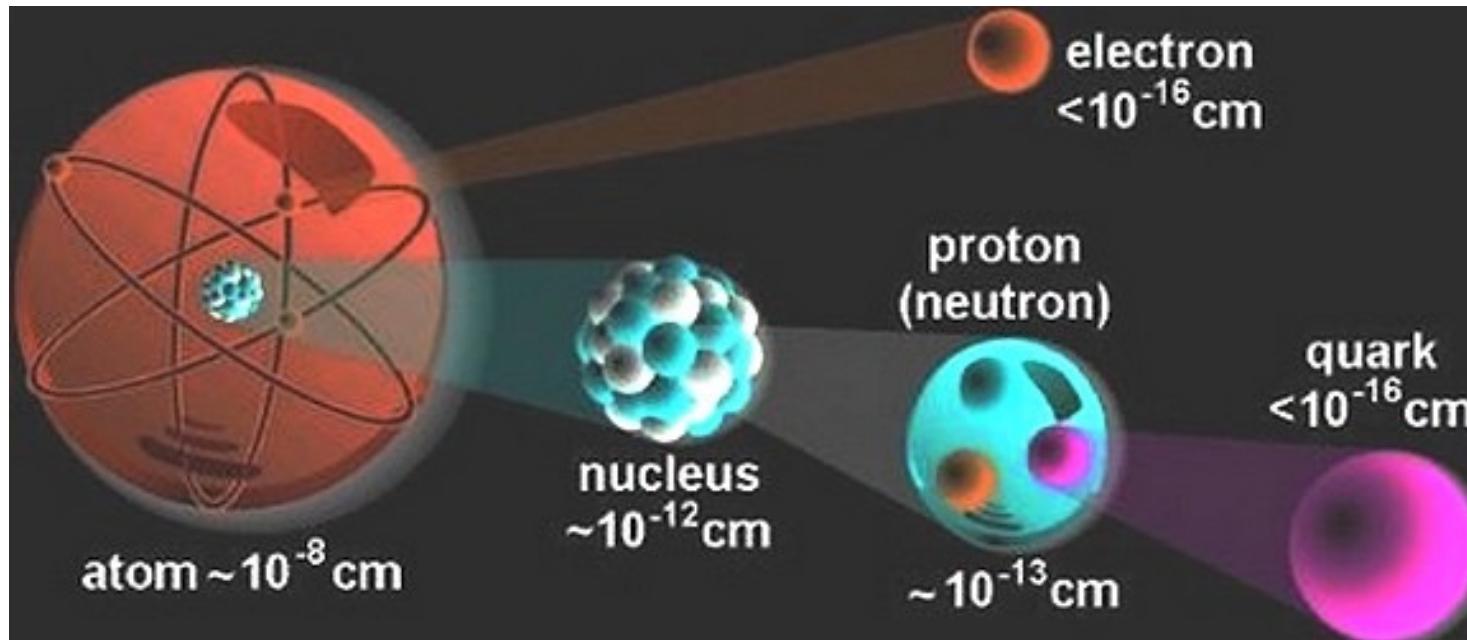
Complexity of behavior: one parameter: the number of electrons!

Zooming (entering) into the atom

Excerpt from “Powers of Ten”



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



These are **pointlike!**

* Plus two copies...

Forces...

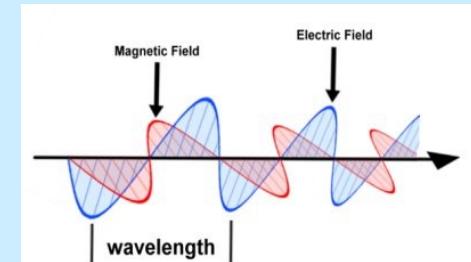
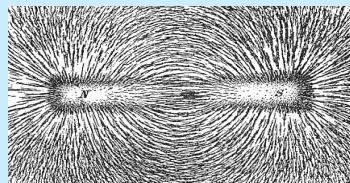
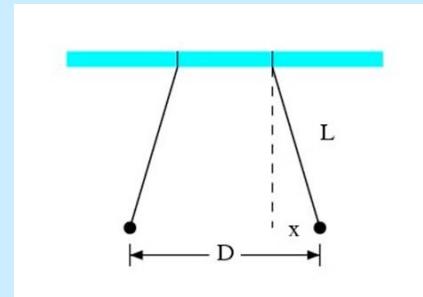
**How does one particle
“act” on another?**

**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



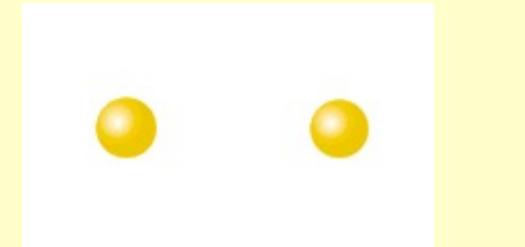
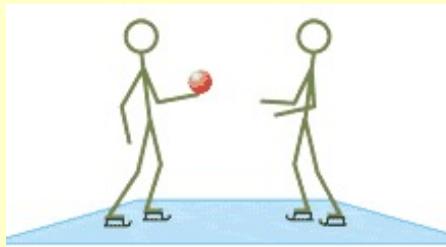
With electromagnetism we could “see” that empty space was filled with fields
Which can propagate in empty space!

20th century: two scientific revolutions:

Quantum mechanics → discretization

Relativity → no instantaneous interactions

New picture: Force == particle exchange.



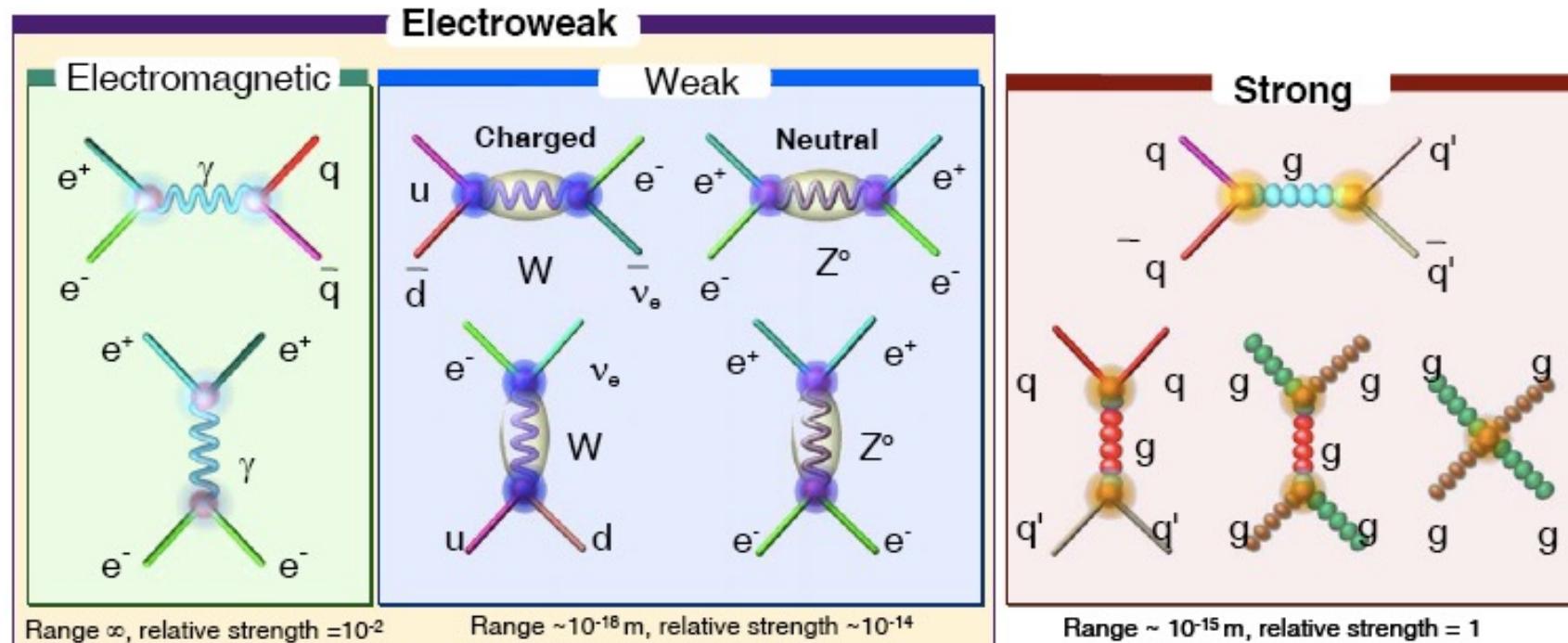
Applying these ideas to two other forces (weak and strong interaction) yields an excellent description

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

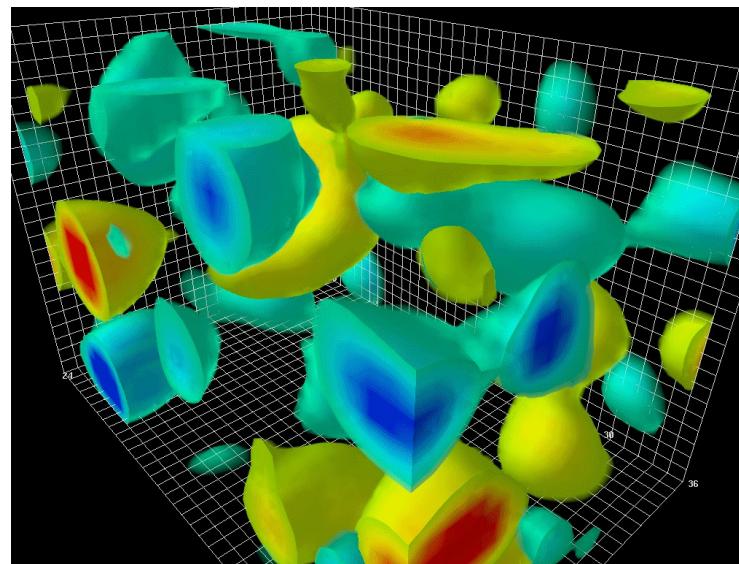
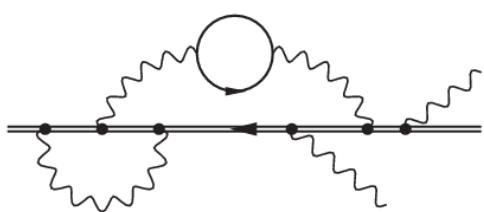
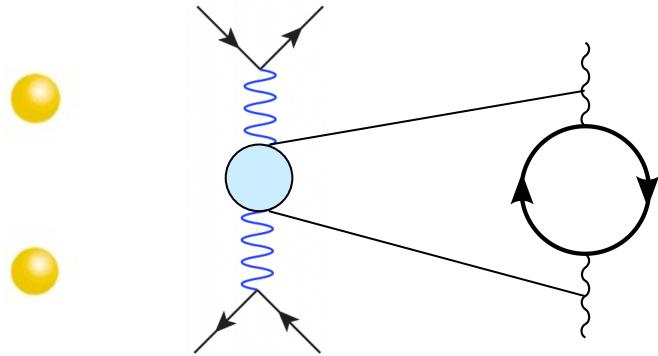
- Quantum Field theory: matter particles (spin-1/2) interact via the exchange of force particles (spin-1)



- Interactions → need charges. Which should be conserved. Implies some new symmetry...
 - Internal symmetry ($SU(3) \times SU(2) \times U(1)$) → massless bosons

Standard Model of Particle Physics

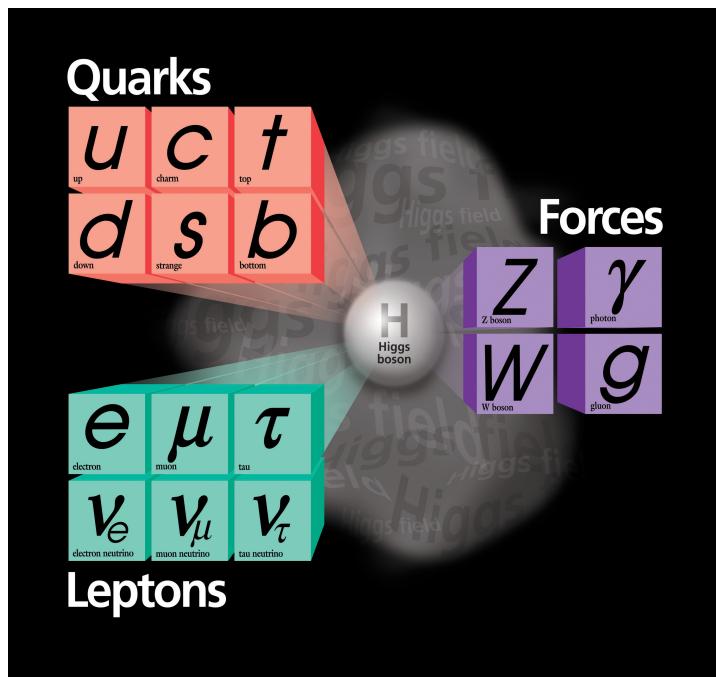
The vacuum is not empty – again



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

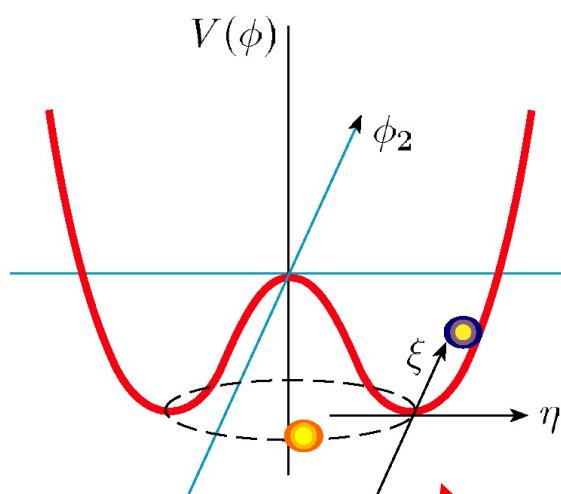
One on the plane; “massless” mode that is lost (once a direction is chosen). Each degree of freedom appears as additional degree of freedom of a gauge boson

Extra polarization state

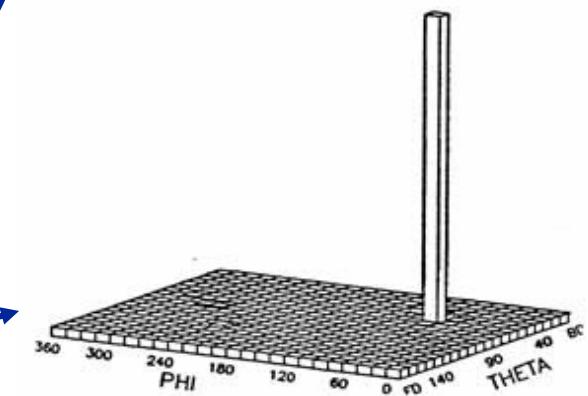
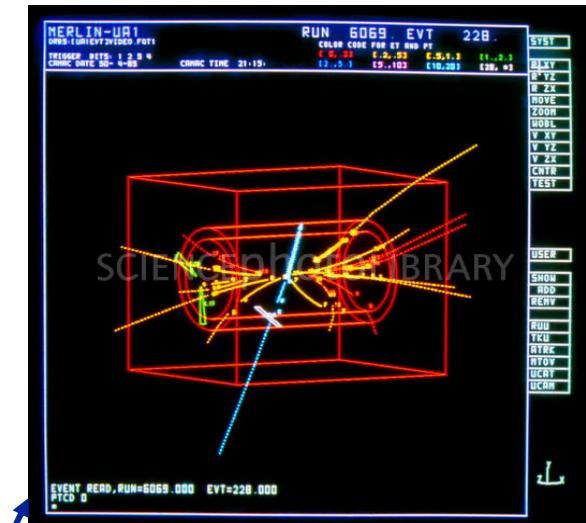
The boson becomes massive!

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.



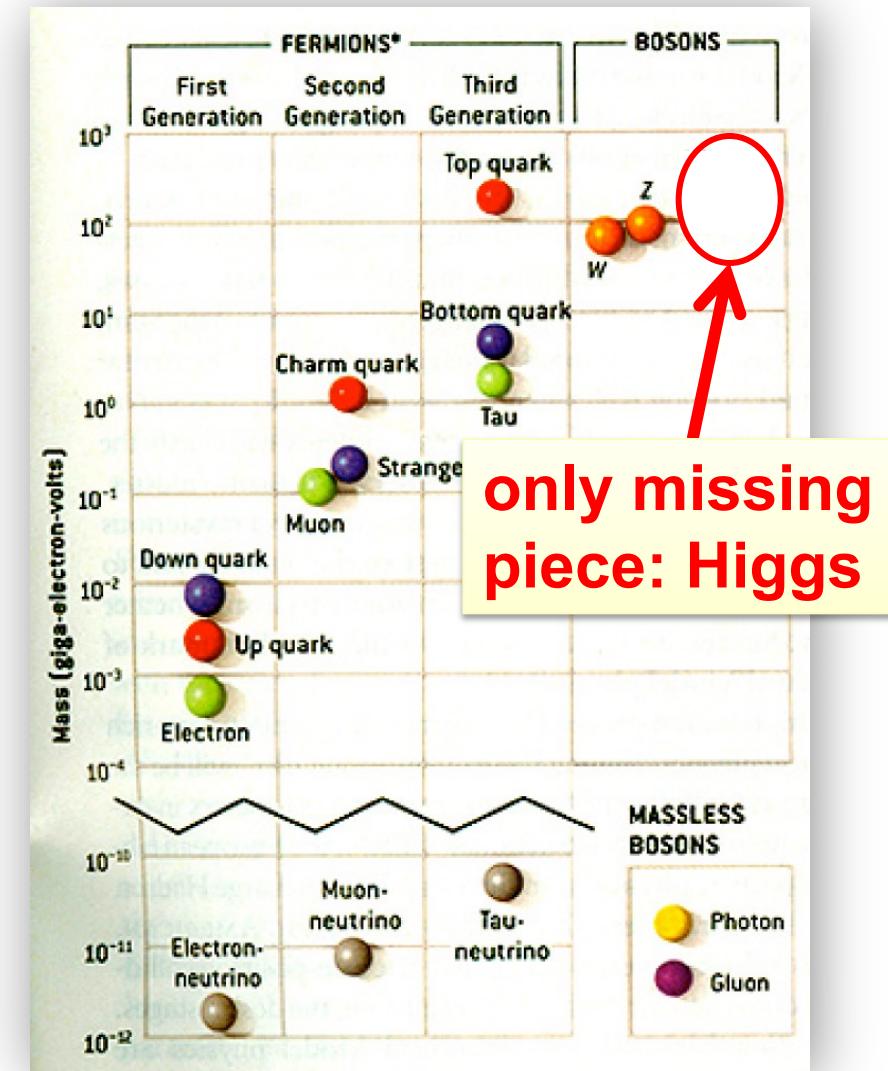
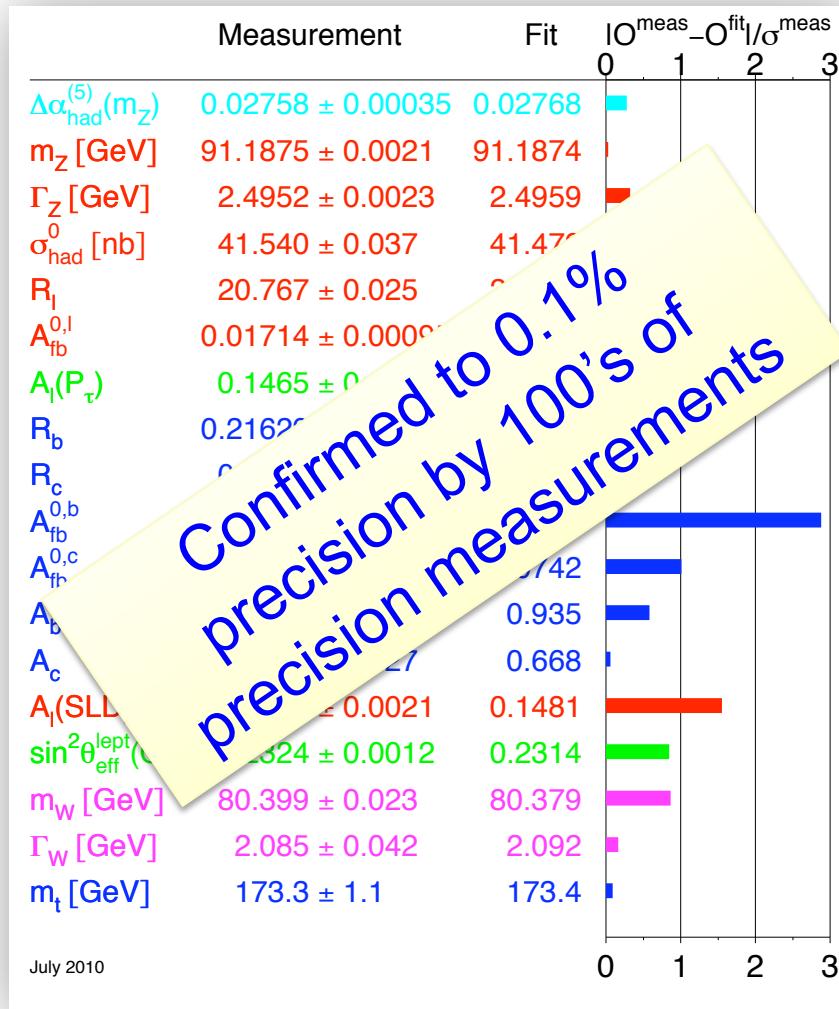
There is, actually, a full theory behind this

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}\mathbf{W}_{\mu\nu} \cdot \mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}}_{\text{kinetic energies and self-interactions of the gauge bosons}} + \underbrace{\bar{L}\gamma^\mu(i\partial_\mu - \frac{1}{2}g\tau \cdot \mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)L + \bar{R}\gamma^\mu(i\partial_\mu - \frac{1}{2}g'YB_\mu)R}_{\text{kinetic energies and electroweak interactions of fermions}} + \underbrace{\frac{1}{2}|(i\partial_\mu - \frac{1}{2}g\tau \cdot \mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)\phi|^2 - V(\phi)}_{W^\pm, Z, \gamma, \text{and Higgs masses and couplings}} + \underbrace{g''(q\gamma^\mu T_a q) G_\mu^a}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$

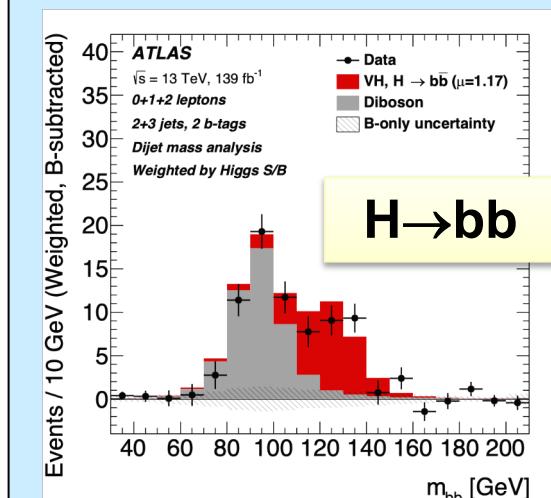
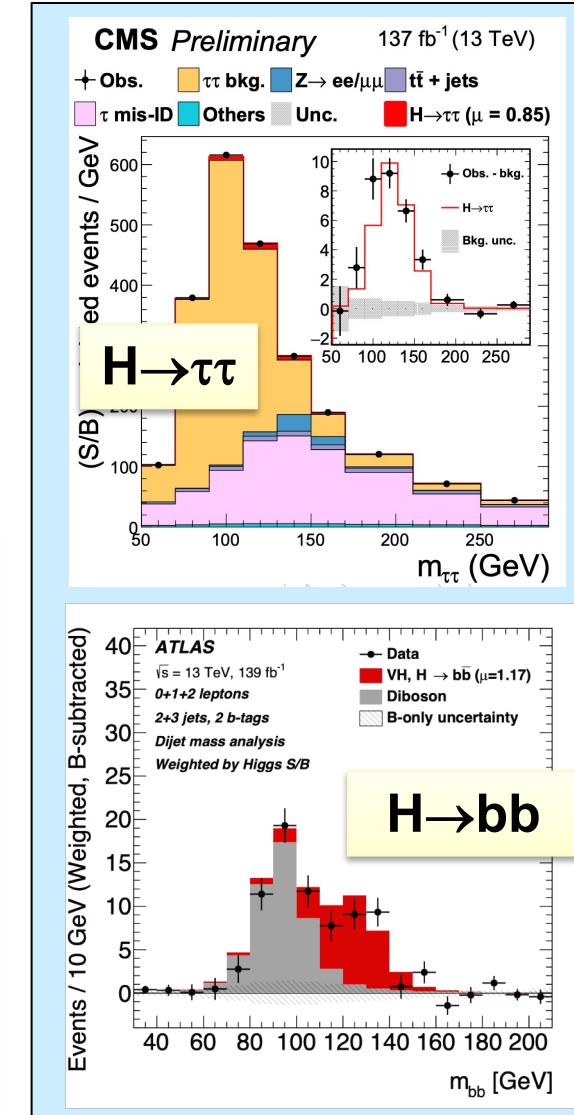
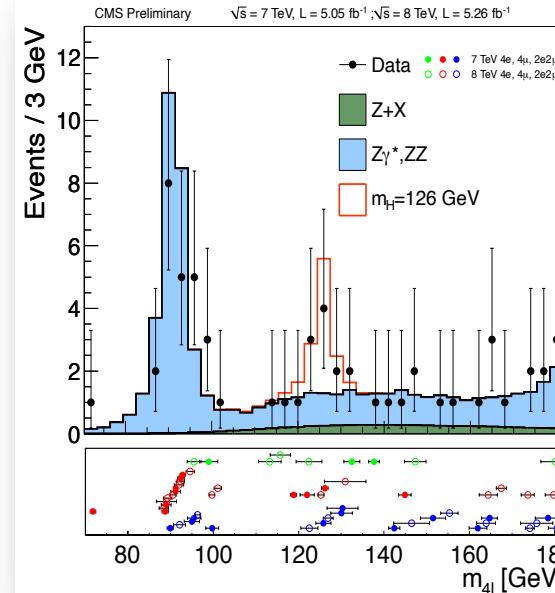
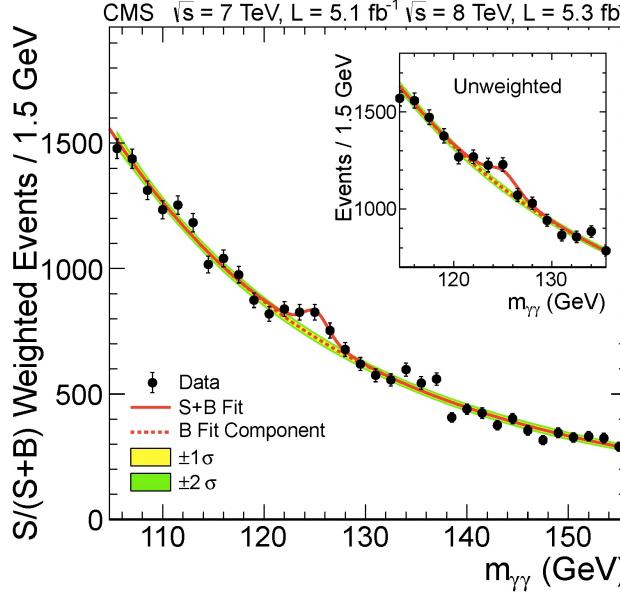
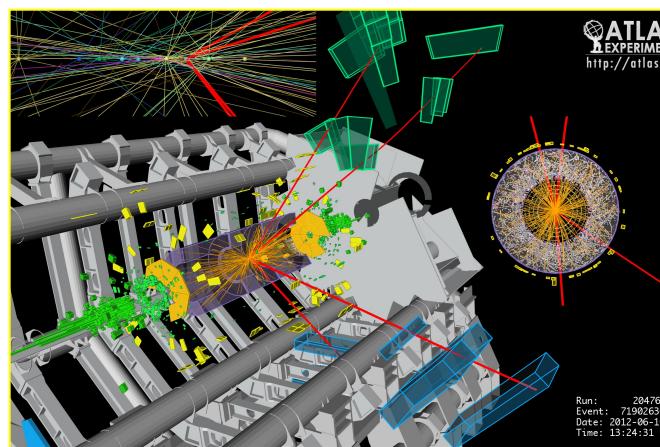
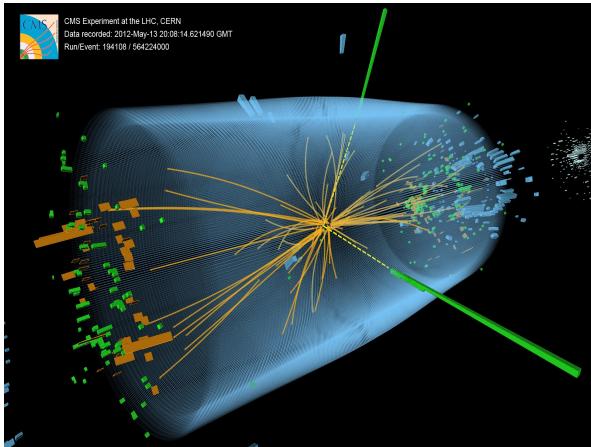
$1/3 \rightarrow$

$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{a'bc'} g_\mu^a g_\nu^b g_\mu^{c'} g_\nu^{c'} + \\
& \frac{1}{2}ig_s^2 (q_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + G^a \partial^2 G^a + g_w f^{abc} \partial_\mu G^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
& \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
& \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
& W_\nu^- \partial_\nu W_\mu^+)] - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
& W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
& \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + \\
& g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
& \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
& g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
& W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
& \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+)) + \\
& ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^- \partial_\mu \phi^- - \phi^+ \partial_\mu \phi^+) + \\
& ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
& \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) + \frac{1}{4}ig^2 \frac{s_w^2}{c_w} H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \frac{2s_w^2}{c_w} (2s_w^2 - 1) Z_\mu^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+)
\end{aligned}$$

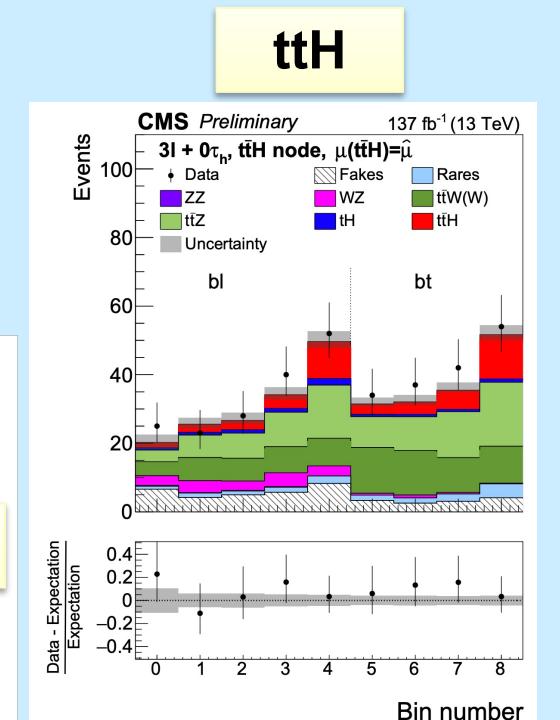
The Standard Model up until 2012



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



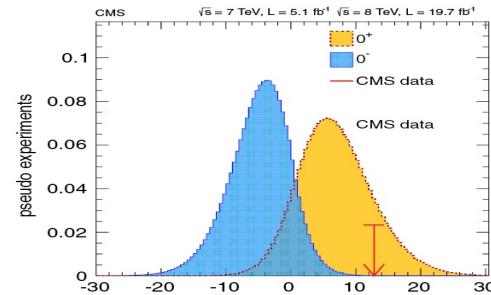
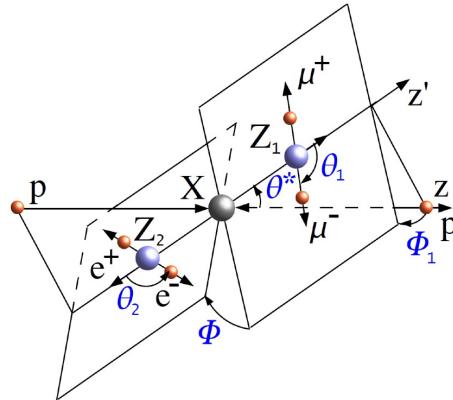
Clear observation
of couplings to
3rd-gen fermions



C. Palmer ICHEP2020
K. Jakobs ICHEP2020

Studying the properties of the new boson @ 125 GeV

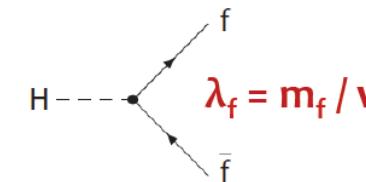
Amazingly enough (a):
It has no spin



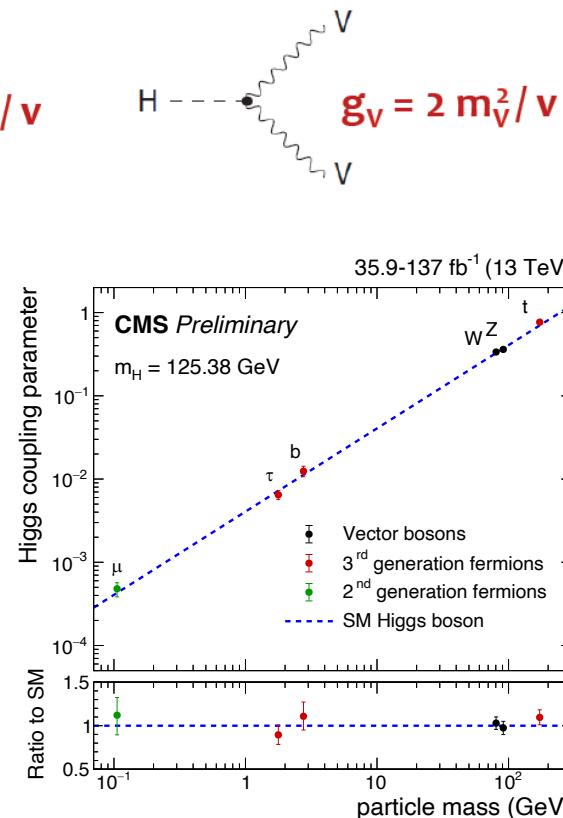
It is, indeed, the Vacuum Particle

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);
2021: evidence for μ point (2nd gen!)

Amazingly enough (b):
It couples to the MASS of the other
particles



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



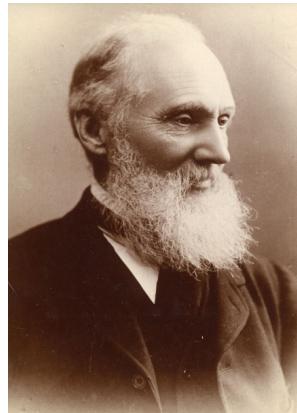
Beyond All Reasonable Doubt:
The “125 GeV boson” is a Higgs boson

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 $\sim O(100)$ 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

$$m^2(p^2) = m_0^2 + \frac{J=1}{p \phi} + \frac{J=1/2}{\text{circle}} + \underline{\text{O}}^{J=0}$$

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



P.A.M Dirac

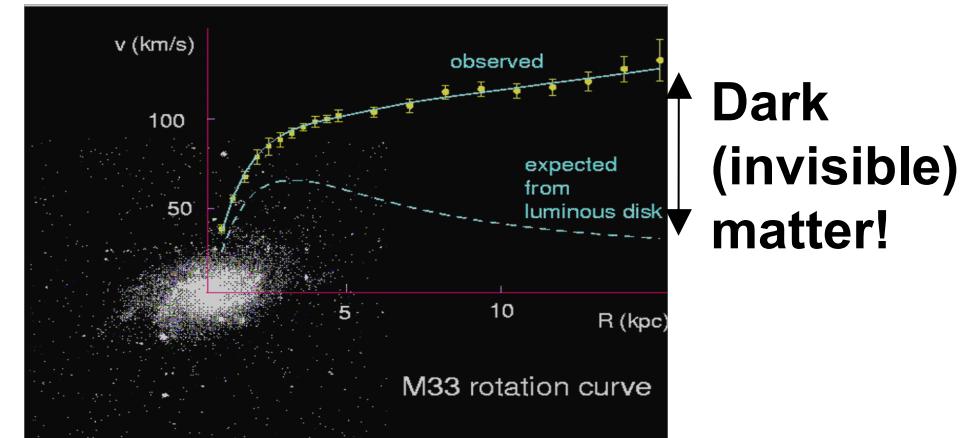
M(H) with corrections all the way up to the Planck scale: for $\Lambda \sim 10^{19}$ GeV

$$\begin{aligned} m^2 &= 1234567890123456789012345675432189012 - \\ &\quad 1234567890123456789012345675432173387 = \\ &\quad 15625 \text{ GeV}^2 \end{aligned}$$

An immense coincidence of googlic sizes?

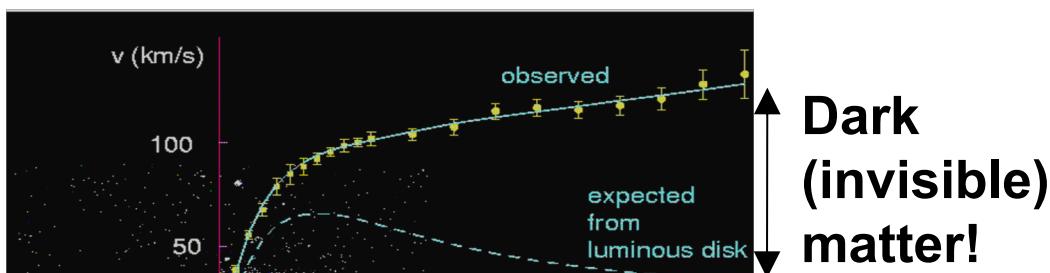
Probably, simply some additional (i.e. New) physics on the way to 10^{19} GeV

We know there is new physics already



Plus neutrinos and their masses!

Dark matter

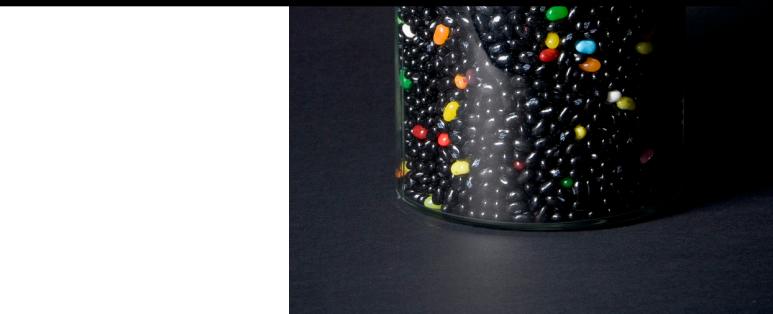


Probably the biggest mystery in nature (as we speak)

New type of matter?

New forces?

New dimensions?



There are many options for this new physics

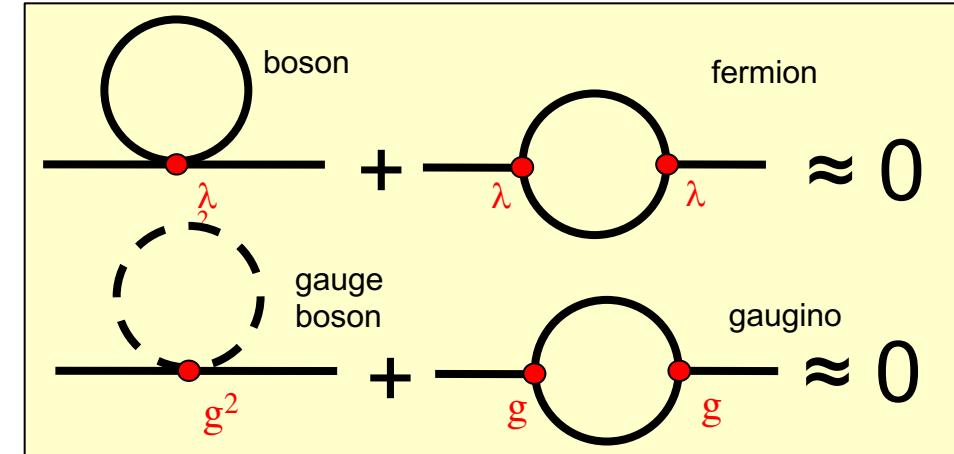
Solution #1: a composite Higgs?

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

Solution #2: supersymmetry?

Partners for ALL SM particles,
spin different by $\frac{1}{2}$

Presumably broken symmetry
(since partners unseen)



Solution #3: “little Higgs”?

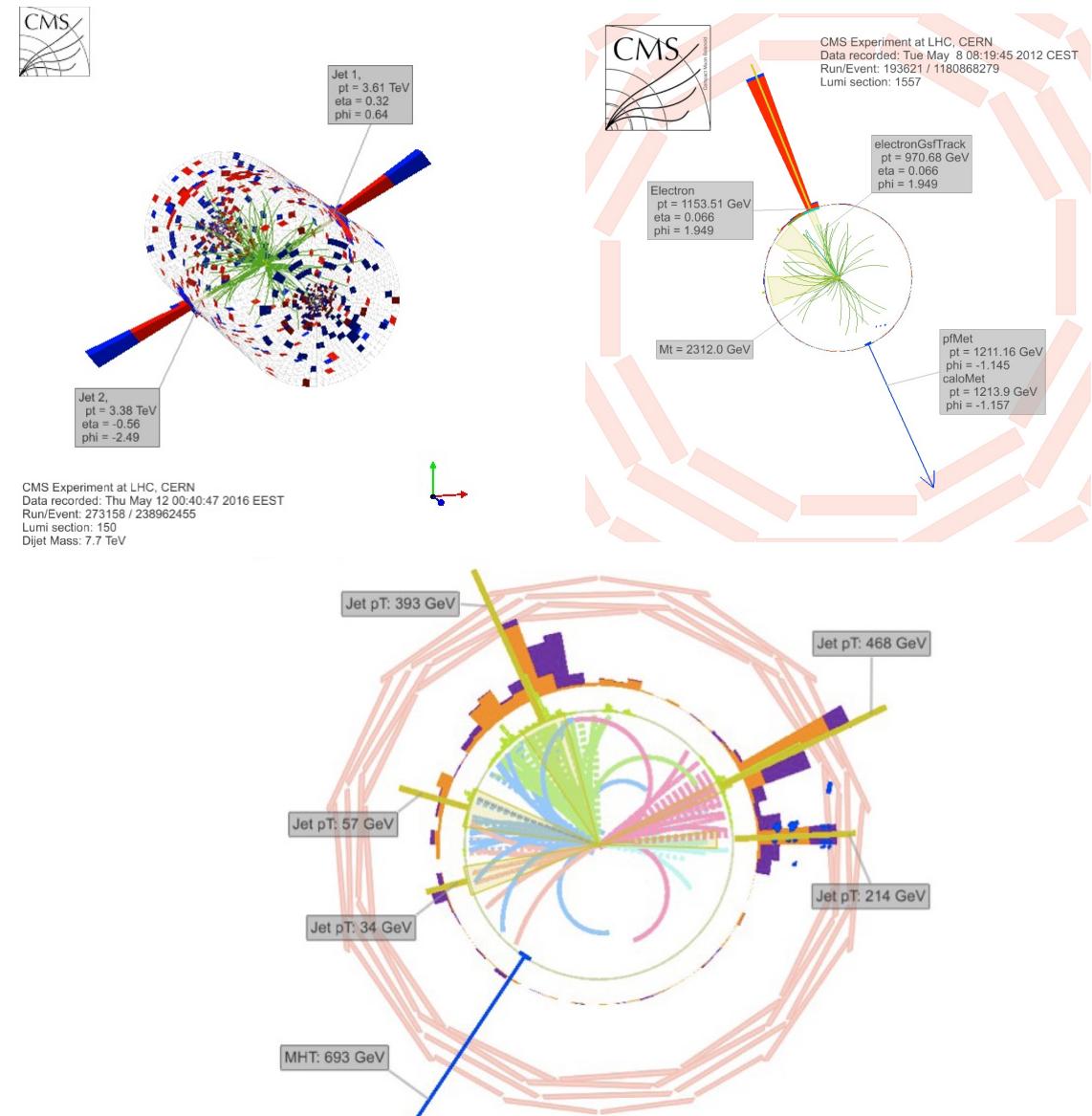
H: pseudo-Goldstone boson of Ultimate Theory; just another effective theory, e.g. valid to ~ 10 TeV. Loops cancel by particles of same spin (so need to introduce these particles)

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

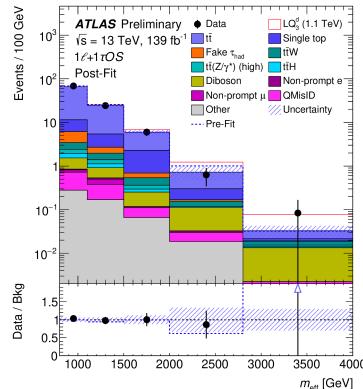
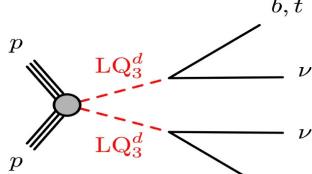
- All solutions demand the presence of new particles
 - More Higgs bosons;
 - SUSY partners;
 - New W/Z bosons;
 - New quarks;
 - ...
- Searches for new physics: main path has been the search for these (higher-mass) states
 - In the beginning inclusively; as time goes by and searches come in empty-handed,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



Non-SUSY BSM: vast, simply vast...

V. Cavaliere ICHEP2020

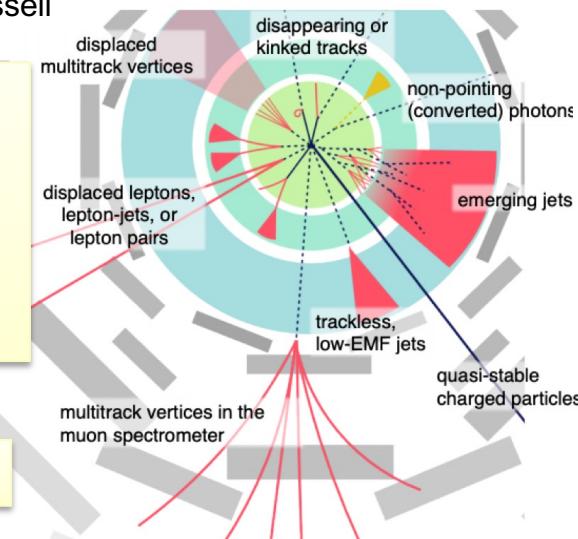
Leptoquarks



Credit: H. Russell

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

+FASER

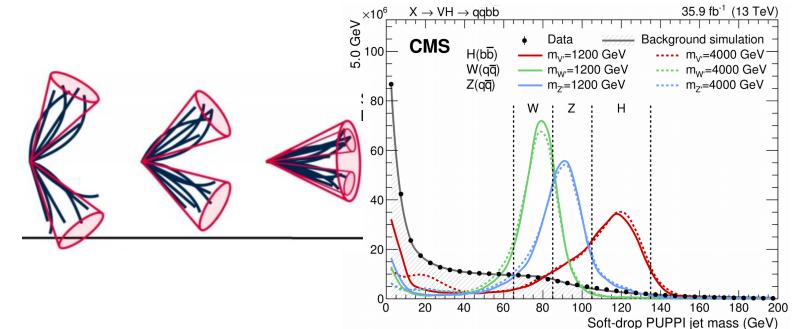


"In many places, able to increase the sensitivity beyond the expectation from the increased dataset owing to important work on analysis techniques, on object performance or unconventional signatures"

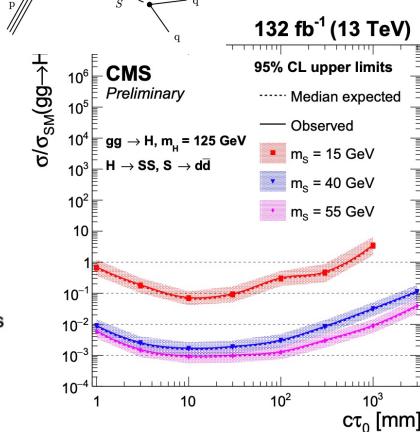
LFV

	ATLAS	LEP
$B(Z \rightarrow e \tau)$	8.1×10^{-6}	9.8×10^{-6} [OPAL]
$B(Z \rightarrow \mu \tau)$	9.5×10^{-6}	12×10^{-6} [DELPHI]

Boosted Objects (VV, VH, HH)

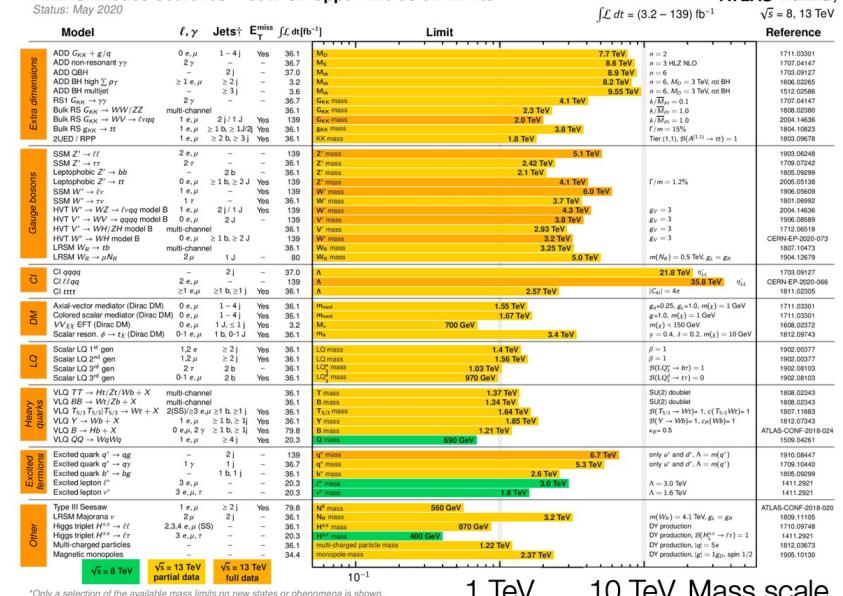


Displaced jets



V. Cavaliere
ICHEP2020

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

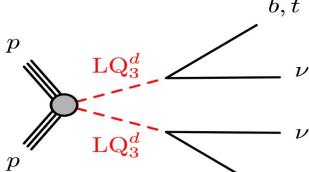


*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter (j).

Non-SUSY BSM: vast, simply vast...

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Leptoquarks

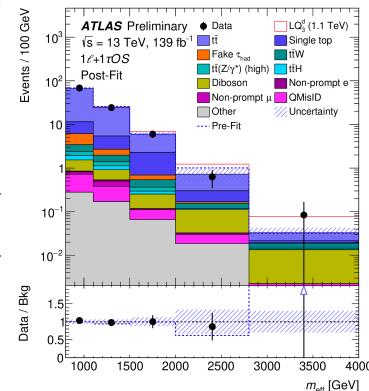


Credit: H. Russell

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

+FASER

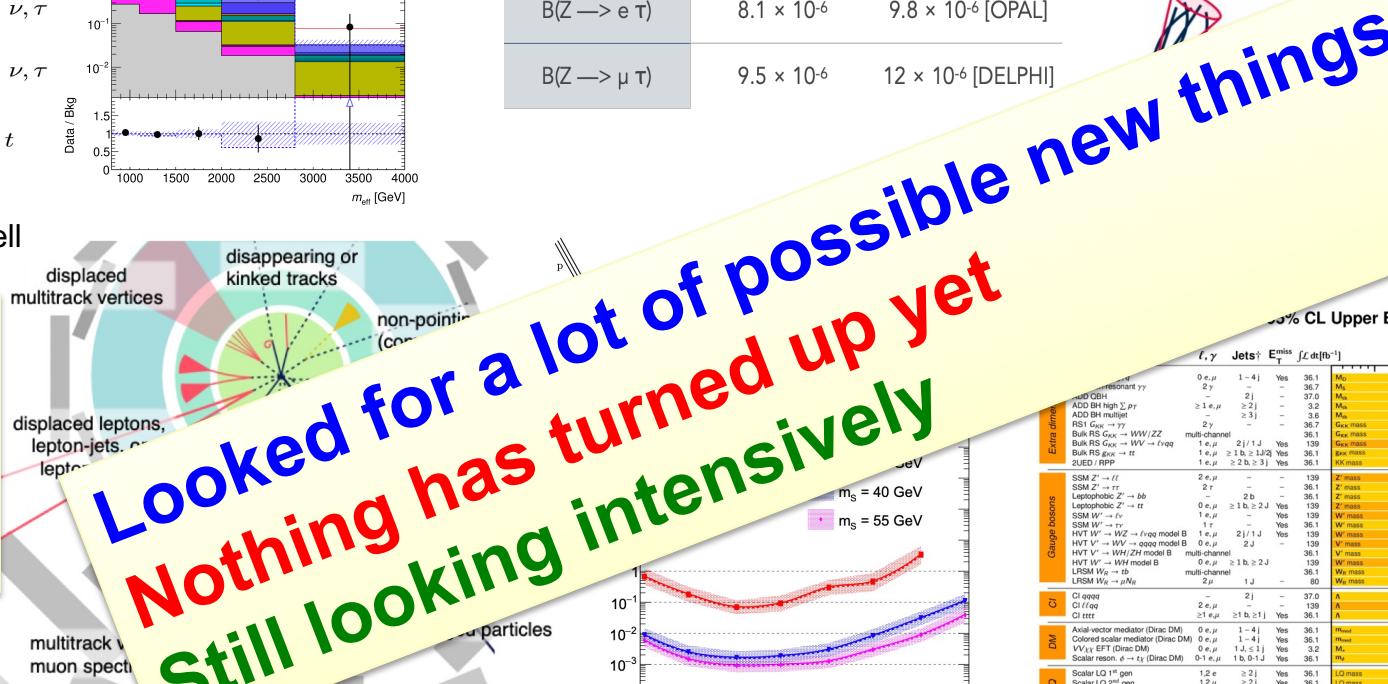
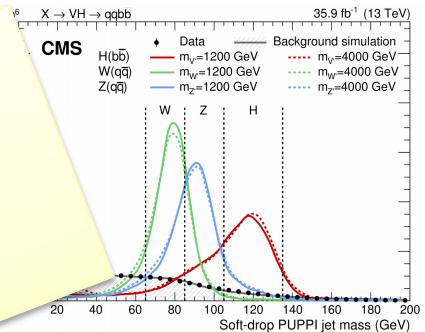
"In many places, able to increase the sensitivity beyond the expectation from the increased dataset owing to important work on analysis techniques, on object performance or unconventional signatures"



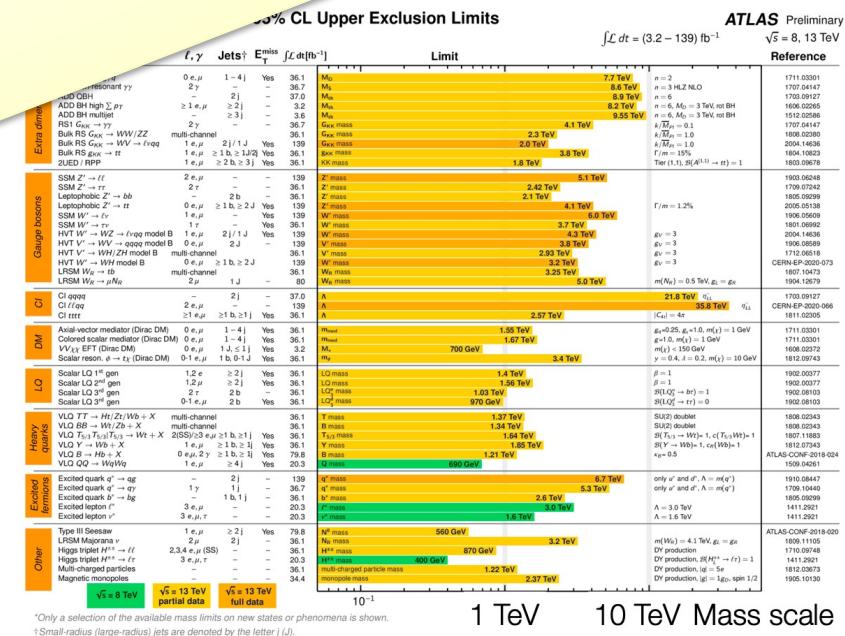
LFV

	Upper 95% CL limits	ATLAS	LEP
$B(Z \rightarrow e \tau)$	8.1×10^{-6}	9.8×10^{-6} [OPAL]	
$B(Z \rightarrow \mu \tau)$	9.5×10^{-6}	12×10^{-6} [DELPHI]	

Boosted Objects (VV, VH, HH)



V. Cavaliere
ICHEP2020



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

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?

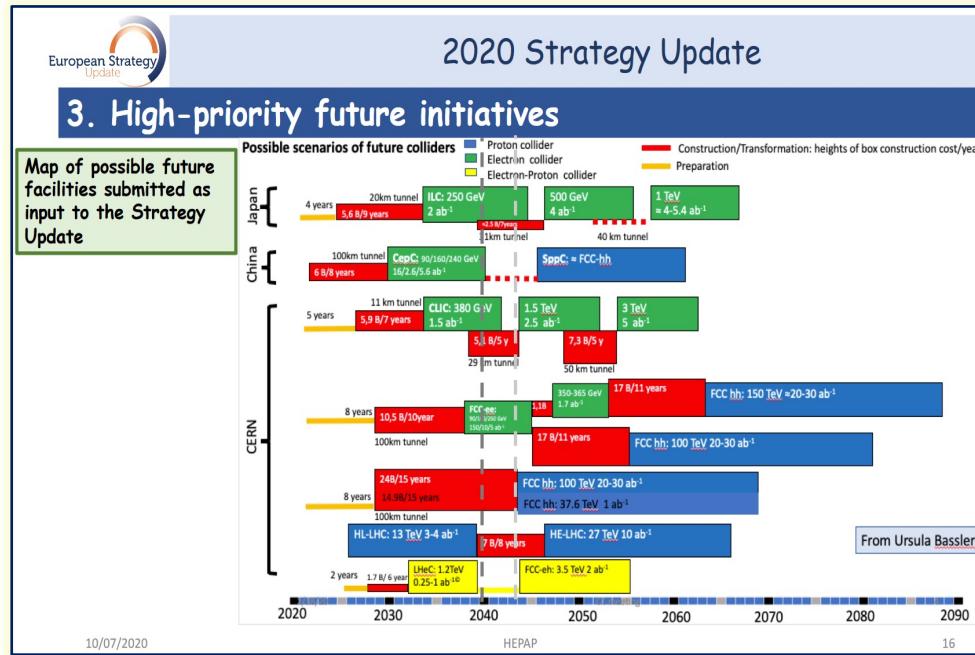
Does the Higgs boson “see” dark matter? Is it a “portal” to an entire new sector?

Plus, several unsolved/unanswered issues remain unsolved/unanswered
Matter-antimatter asymmetry? Simply not enough CP violation to explain the current
universe (baryon-antibaryon asymmetry).

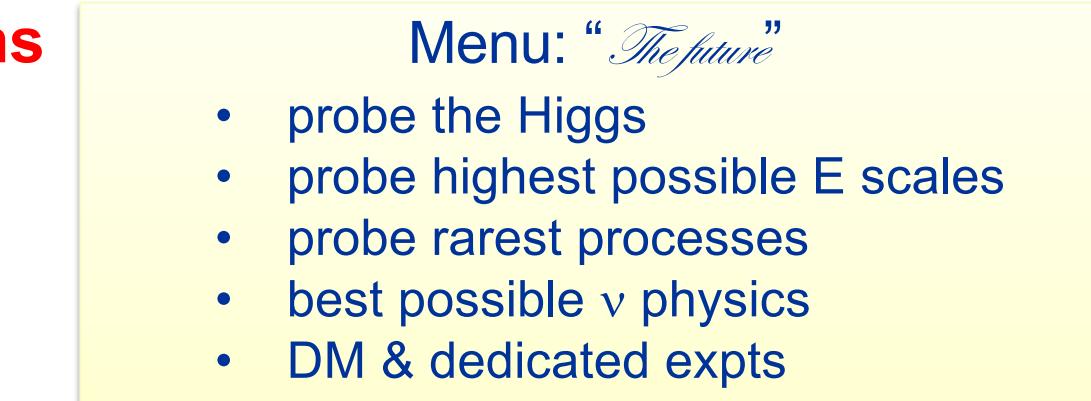
Need to go a bit more backwards in time in the evolution of the universe.

Future machines

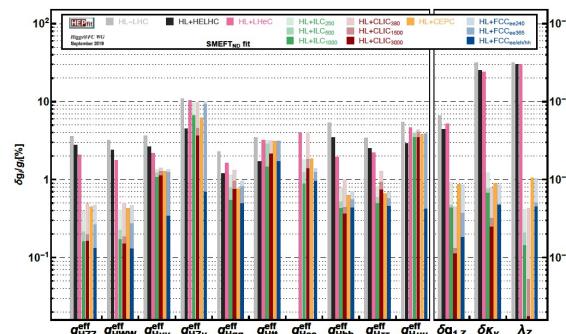
Definitely no lack of ideas/options



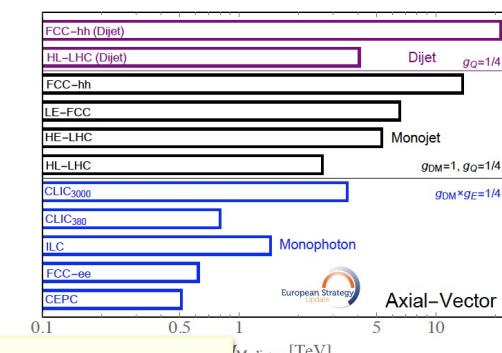
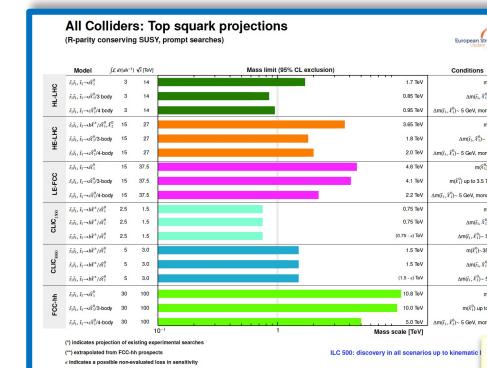
M. Shiltsev (ICHEP2020 plen)
Long list of new colliders; but also neutrino beams, and blue-sky R&D on novel accelerator methods



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



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



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”

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

V. Shiltsev ICHEP2020



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.

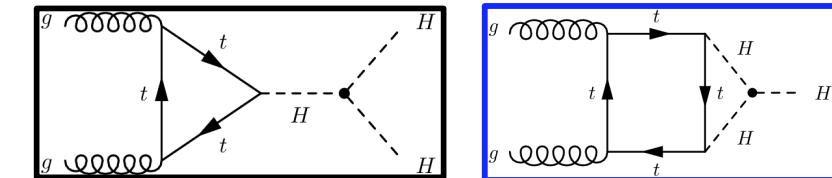
Cooperation/Collaboration will be the key

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

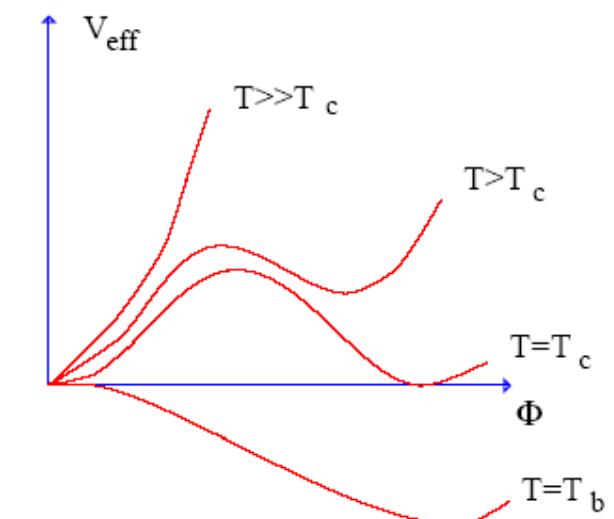


En route to the new physics, we will establish how the symmetry of the Higgs field is broken.

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

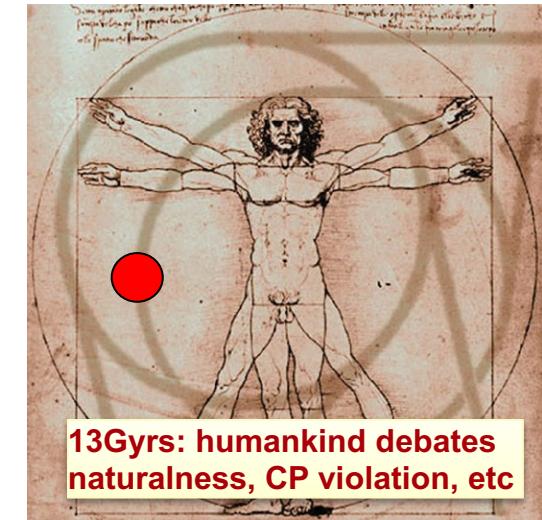
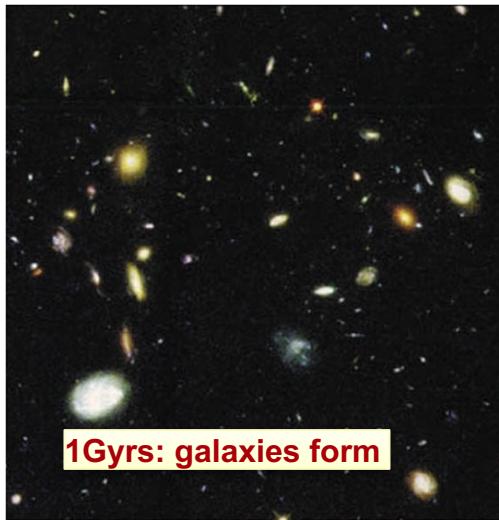
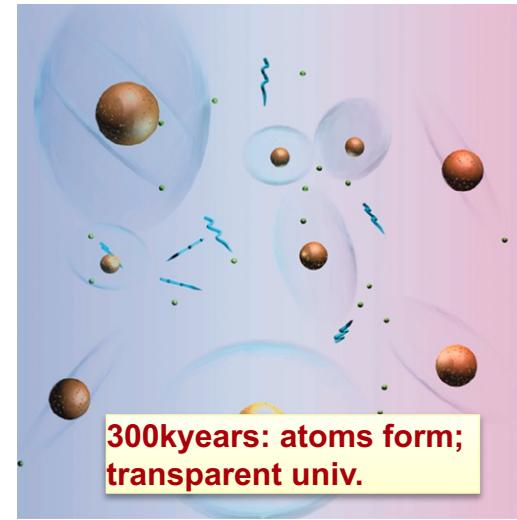
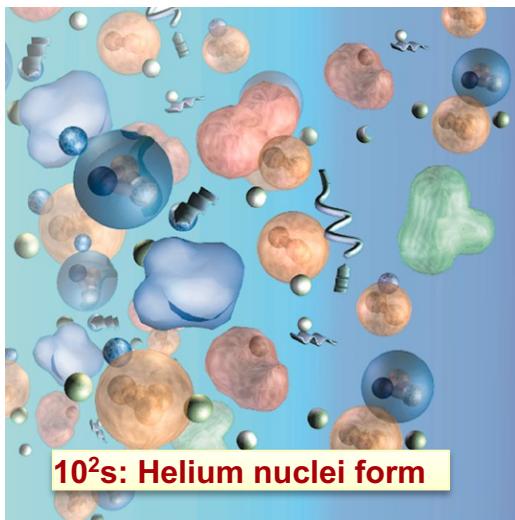
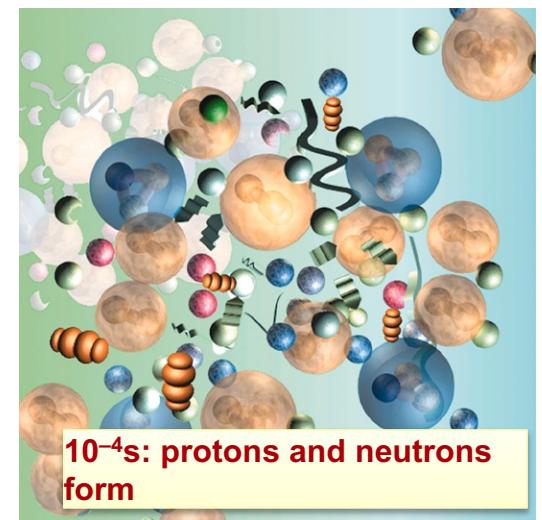
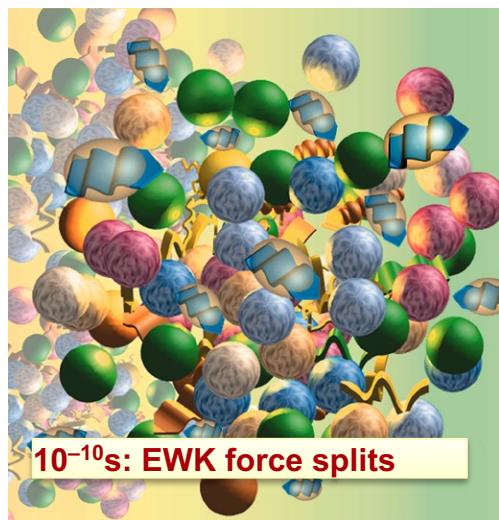
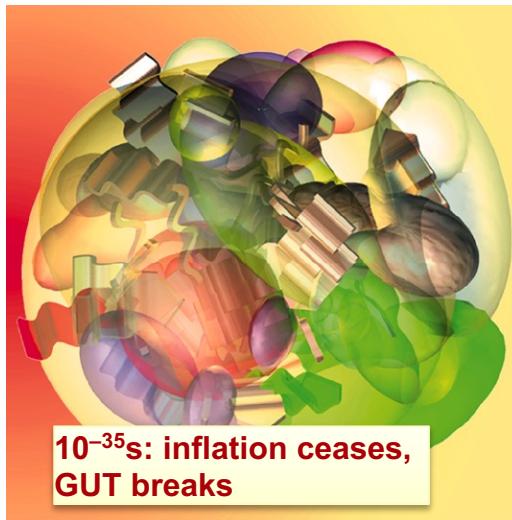
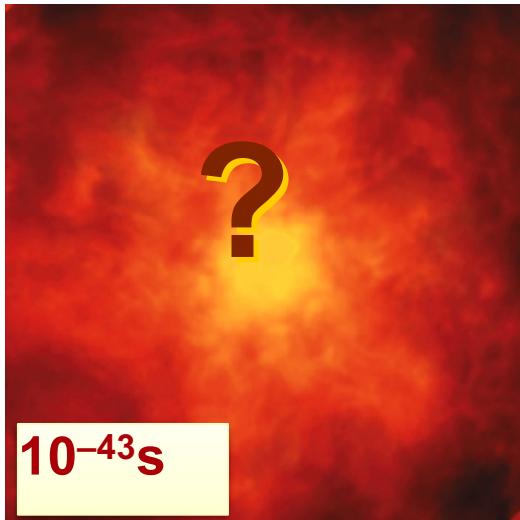
We will obtain information on the ultimate phase transition – the one through which the Higgs acquired its strange vacuum properties;

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



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

Summary and Outlook



Credit: S. Cittolin/CMS