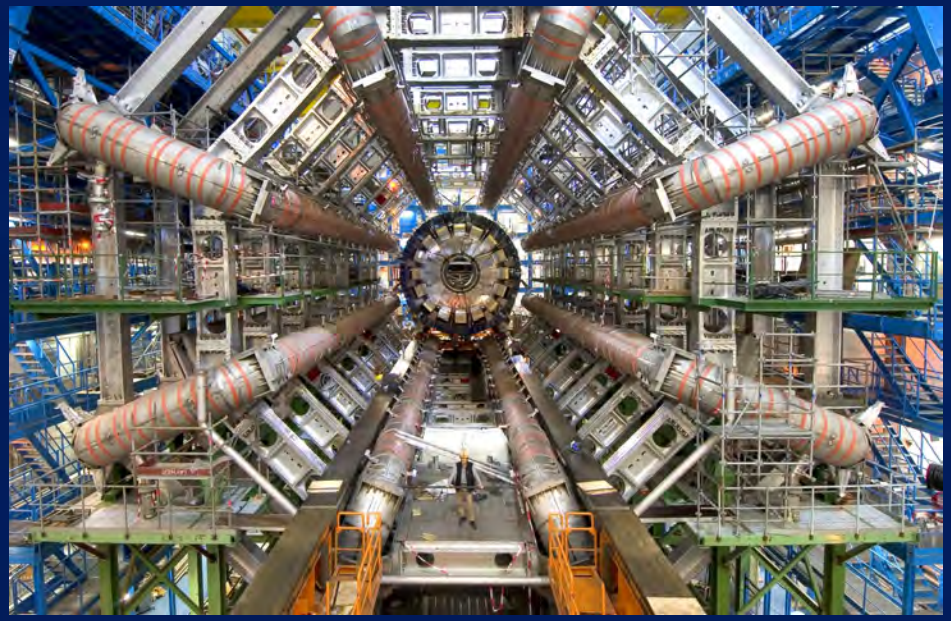
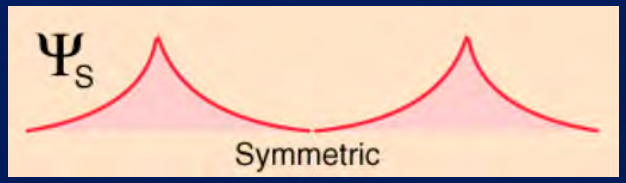
The ATLAS Experiment, the Large Hadron Collider, and the Discovery of a Higgs Boson



Joseph M. Izen
joe@utdallas.edu

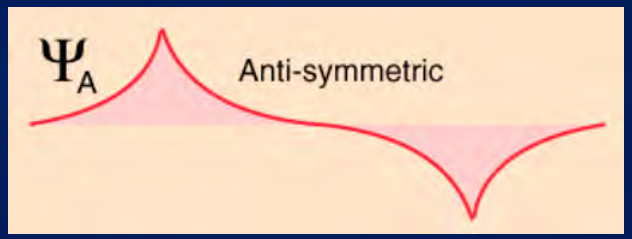
What is a Boson (or a Fermion)?

- Boson
- Particle or Composite with Angular Momentum 0$\hbar$, 1$\hbar$, 2$\hbar$, 3$\hbar$, …
- Totally symmetric wave function



Angular Momentum	Boson Examples
0$\hbar$	^{4}He nuclei, Higgs
1$\hbar$	g, W, Z, gluon, ^{6}Li nuclei
2$\hbar$	Graviton, ^{8}Li nuclei

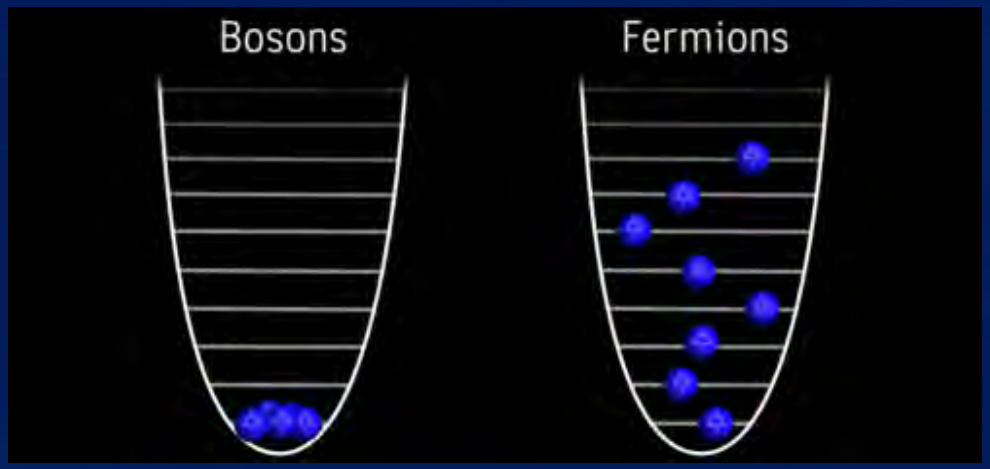
- Fermion
- Particle or Composite with Angular Momentum 1/2$\hbar$, 3/2$\hbar$, 5/2$\hbar$, …
- Totally anti-symmetric wave function

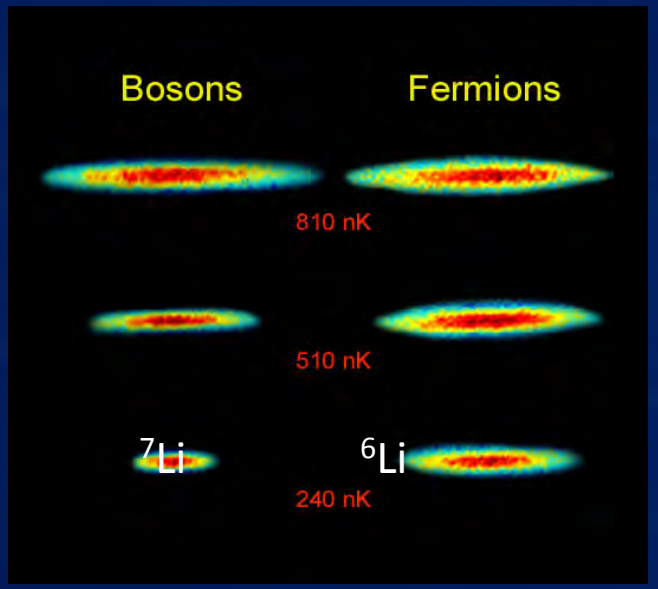


Angular Momentum	Fermion Examples
1/2 $\hbar$	e^-, ν, p, n, quarks, ^{3}He
3/2 $\hbar$	^{5}Li, ^{9}Li nuclei, N(1520)
5/2 $\hbar$	^{17}O nuclei, N(1675)

Pauli Exclusion Principle

- No 2 identical Fermions can not exist in the same quantum state.
- Any number of Bosons can.





R. Hulet *et al.* Rice University

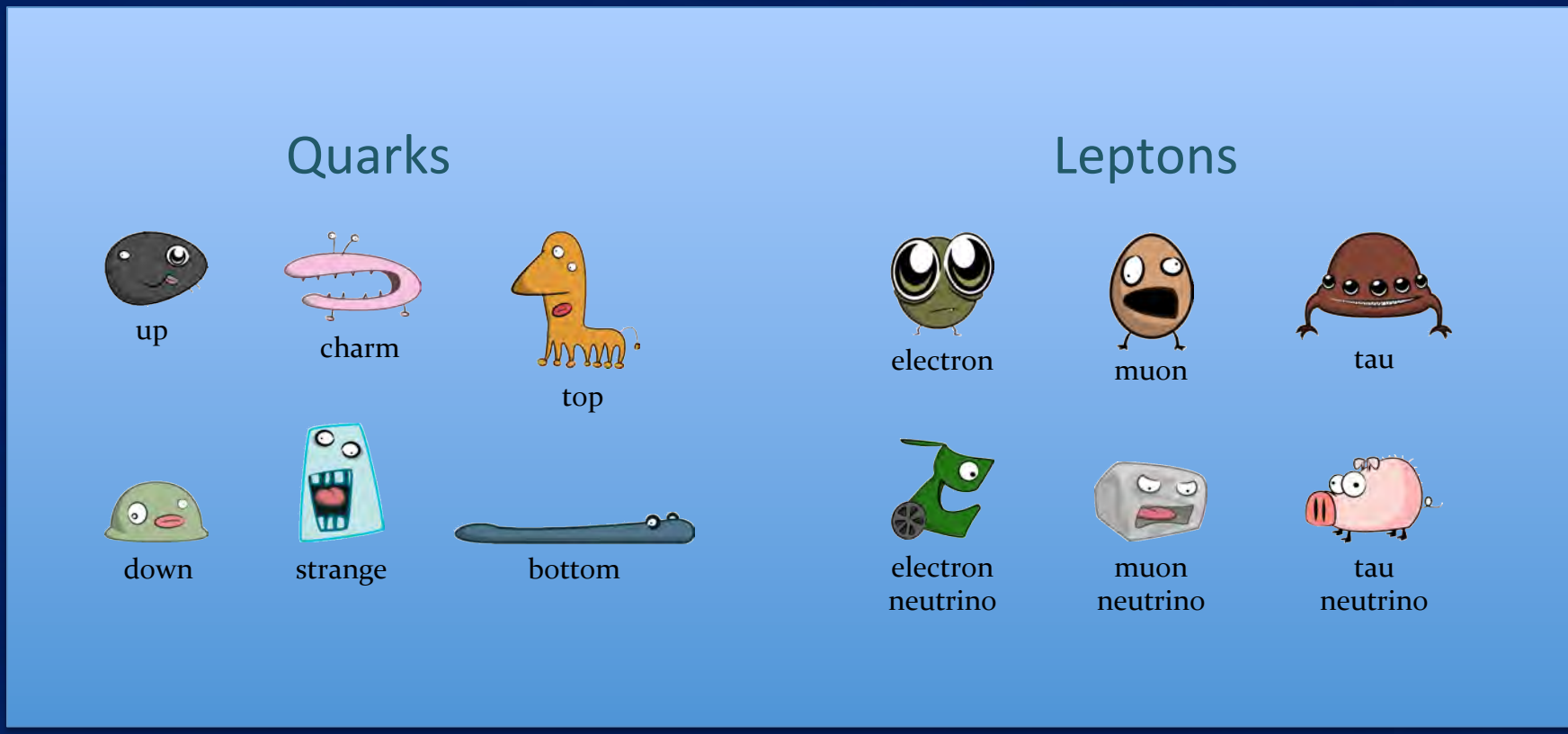
Lithium Atoms (nucleus + electrons)
Ultracold clouds of atoms called "condensates"

What is the Standard Model?

A theory that describes:

- The fundamental particle building blocks of the Universe
- All the known forces (except Gravity)
  - Electromagnetism
  - Strong nuclear force
  - Weak nuclear force

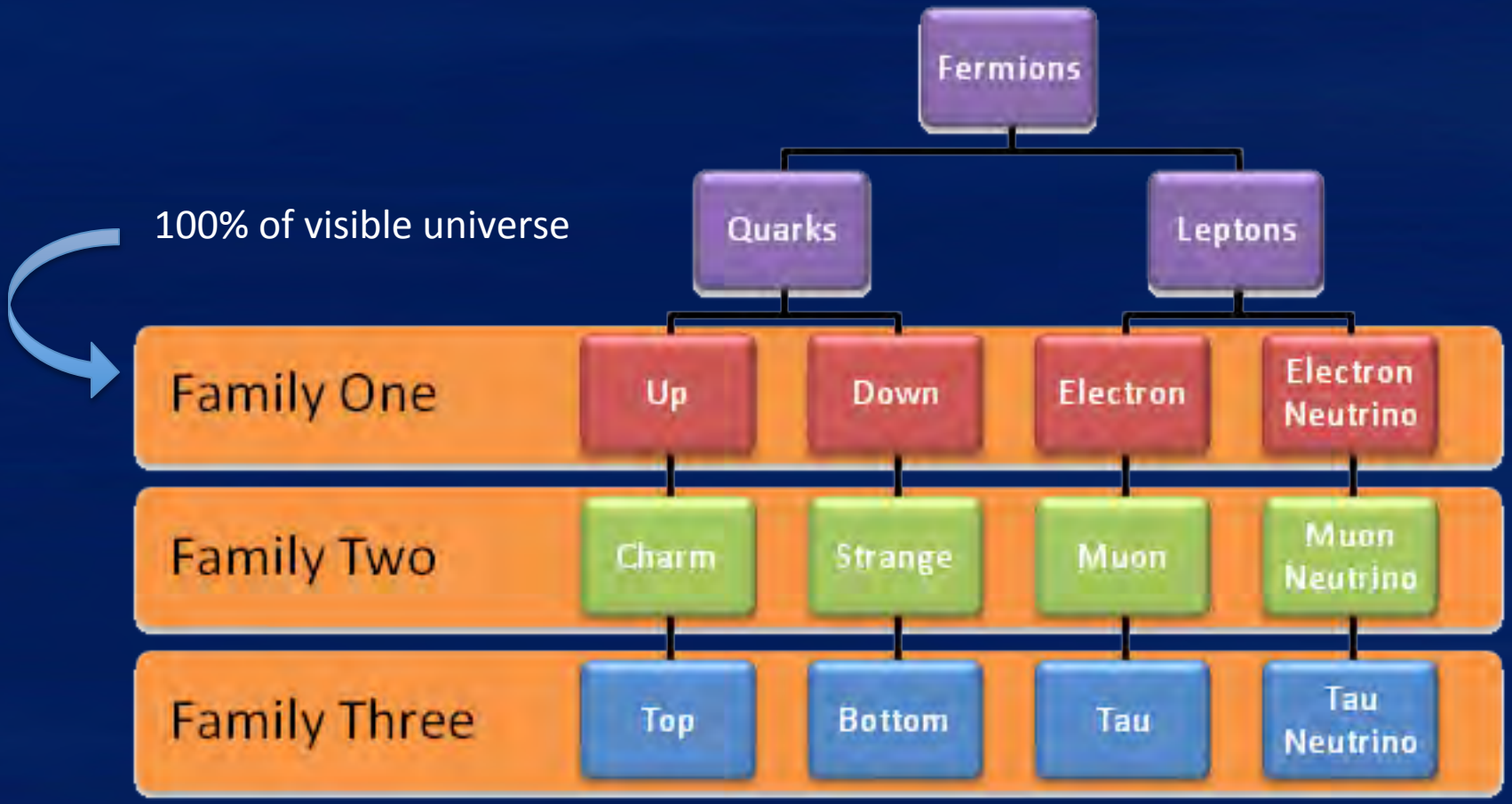
Quarks and Leptons



"Feel" Strong, Electromagnetic , Weak force

"Feel" Electromagnetic , Weak force
Leptons don't feel the Strong force

Quarks and Leptons

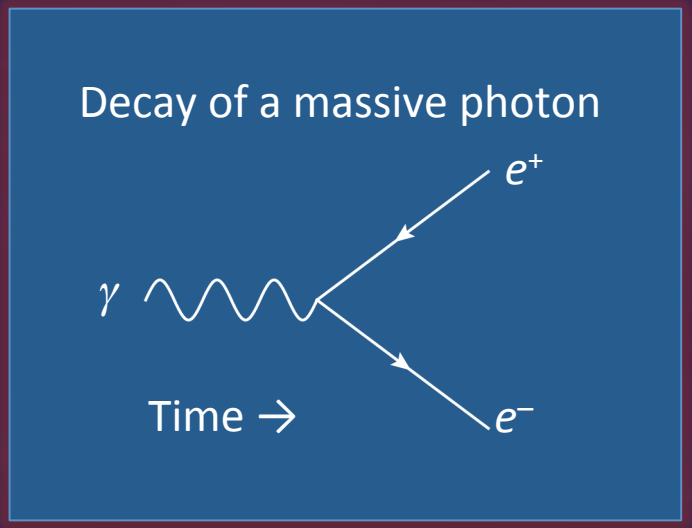


http://www.physicsforidiots.com/particlesandforces.html

All quarks and leptons have and intrinsic angular momentum (spin) of $\frac{1}{2}\hbar$
They are fermions and obey the Pauli exclusion principle

Photons: Are We Lucky, or What?

- If the Photon had mass
  - Flashlight filaments couldn't get hot enough to glow
  - Kiss $1/r^2$ force goodbye
    - Atoms and chemistry would be very different, if even possible
  - Photons would decay
    - No astronomy, or even vision



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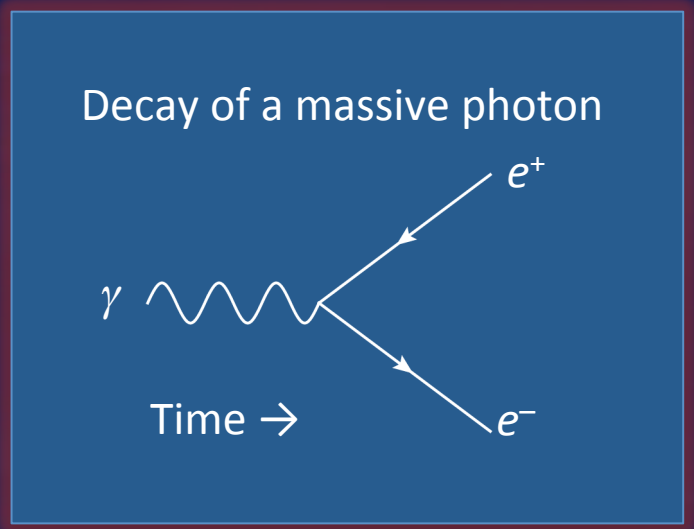

- What a stupid idea! Why would there be such a force?

Photons: Are We Lucky, or What?

- If the Photon had mass
  - Flashlight filaments couldn't get hot enough to glow
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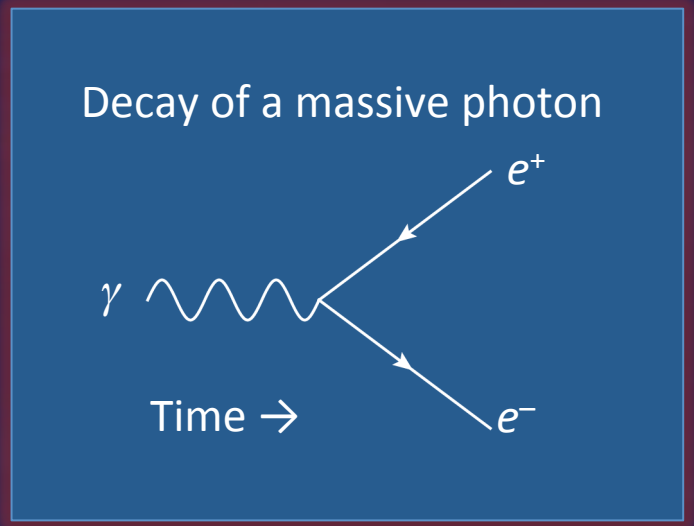


- The universe does have such a force!
- Direct complaints to your deity of choice.

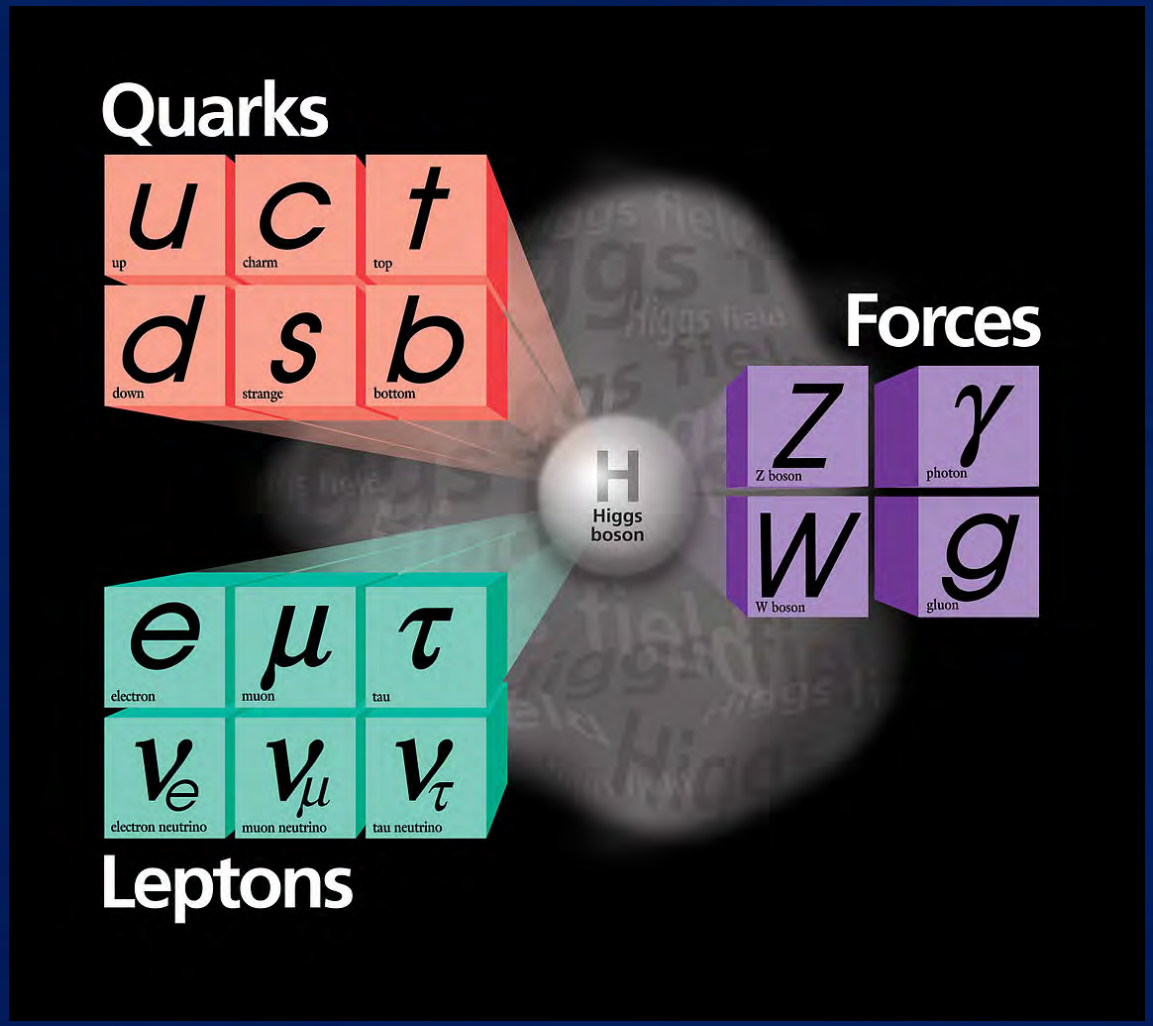
Force Carriers

Force	Electromagnetism	Gravity	Strong Nuclear	Weak Nuclear
Number of Bosons	1	1	X 8	3
Bosons	Photon	Graviton**	Gluon (8 of 'em)	W^+, W^-, Z^0
Boson Mass*	0	0	0	80/91 GeV
Boson Charge	0	0	0	±1, 0
Acts on	Anything With Charge	Anything With Mass	Anything With Colour quarks+gluons	Left Handed particle or Right Handed anti-particle with Flavour

http://www.physicsforidiots.com/particlesandforces.html

Photons, W, Z, and gluons have and intrinsic angular momentum (spin) of $\hbar$
That makes them Bosons, so they are not restricted by the Pauli exclusion principle.

Fundamental Particles of the Standard Model



The Higgs has NO intrinsic angular momentum (spin).

That makes it a Boson too.

What is the Higgs boson?
(…and who is Peter Higgs?)

- Tale of Quantum Field Theory and Three Forces
- An underlying symmetry leads to a "gauge boson(s)" and a force
- Gauge theories predict massless "gauge bosons" like the Photon

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  Example 1: Quantum Electro Dynamics (QED)

  Local quantum phase symmetry -> Electric Force and the Photon

  Photon has no Mass

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(…and who is Peter Higgs?)

- Tale of Quantum Field Theory and Three Forces
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Example 2: Quantum Chromo Dynamics (QCD)

Quark color-charge symmetry -> Strong Force and the 8 gluons

Gluons have no mass

What is the Higgs boson?
(…and who is Peter Higgs?)

- Tale of Quantum Field Theory and Three Forces
- An underlying symmetry leads to a "gauge boson(s)" and a force
- Gauge theories predict massless "gauge bosons" like the Photon

Example 3: Weak Force

Glashow: Weak-flavor symmetry -> Weak Force and W^+, W^-, Z^0

Very massive W^+, W^- expected from properties of
neutrino -> electron scattering and radioactive decays, but…

Gauge theories predict massless bosons, not bosons with mass

No evidence for Z^0 or "neutral current" neutrino -> neutrino scattering

What is the Higgs boson?
(…and who is Peter Higgs?)

- A (spinless) field throughout space can break the underlying symmetry, letting gauge bosons acquire mass.
- Three groups work out details for relativistic gauge theories independently:

L to R (Kibble, Guralnik, Hagen), (Englert and Brout), Higgs
All winners of the 2010 APS Sakurai prize

Should the Nobel Prize for Physics be changed to include groups as well as individuals?

Yes!

L to R (Kibble, Guralnik, Hagen), (Englert and Brout), Higgs
All winners of the 2010 APS Sakurai prize

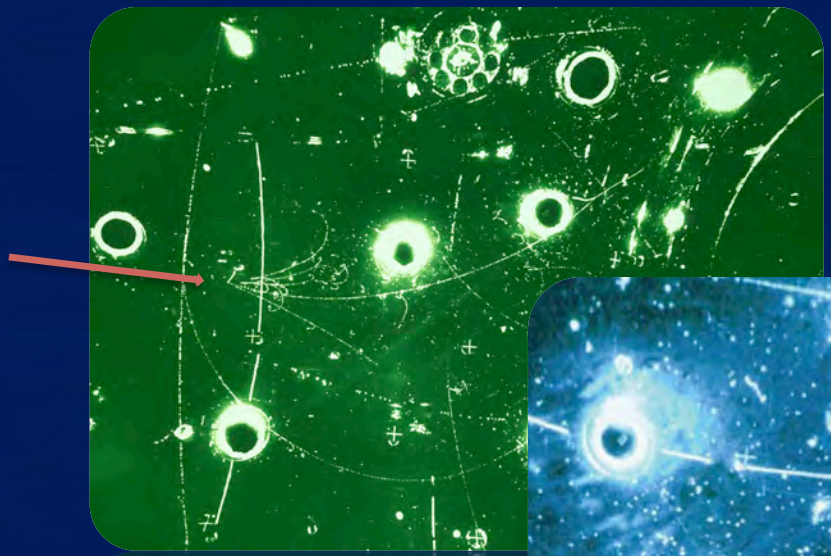
The Higgs Mechanism and ElectroWeak Unification

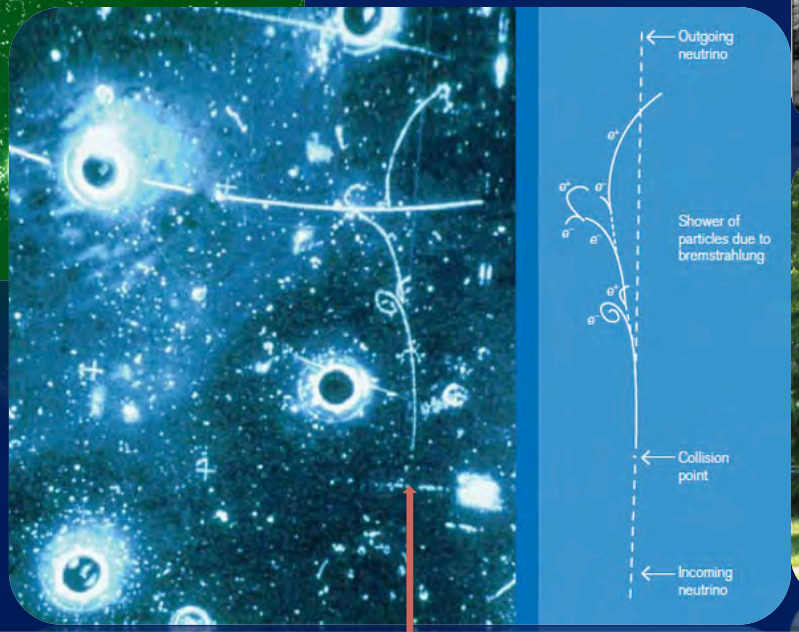
- Weinberg and Salaam connect the dots
  - Incorporate the Higgs Mechanism into Glashow's ElectroWeak theory
- 't Hooft and Veltman demonstrate the renormalizability (cancelation of infinities) of theories like that of Glashow, Weinberg, and Salaam
- Predictions:

1. Neutrinos can scatter without turning into an electron or muon (Weak Neutral Current)
2. There exists a massive neutral, weak boson, the Z^0
3. The relative strength of Charged and Neutral Current neutrino scattering predicts the mass ratio for W and Z
4. A 4^{th} quark exists with a mass ~1 GeV
5. The Higgs field's coupling to fermions determines their mass – The meaning of fermion mass!
6. The Higgs field's leads to a Higgs spinless (scalar) particle of unknown mass but specified mass-dependent decays – the Higgs Boson! (at least one, but possibly more)

ElectroWeak Unification Experiment 1973: Round 1

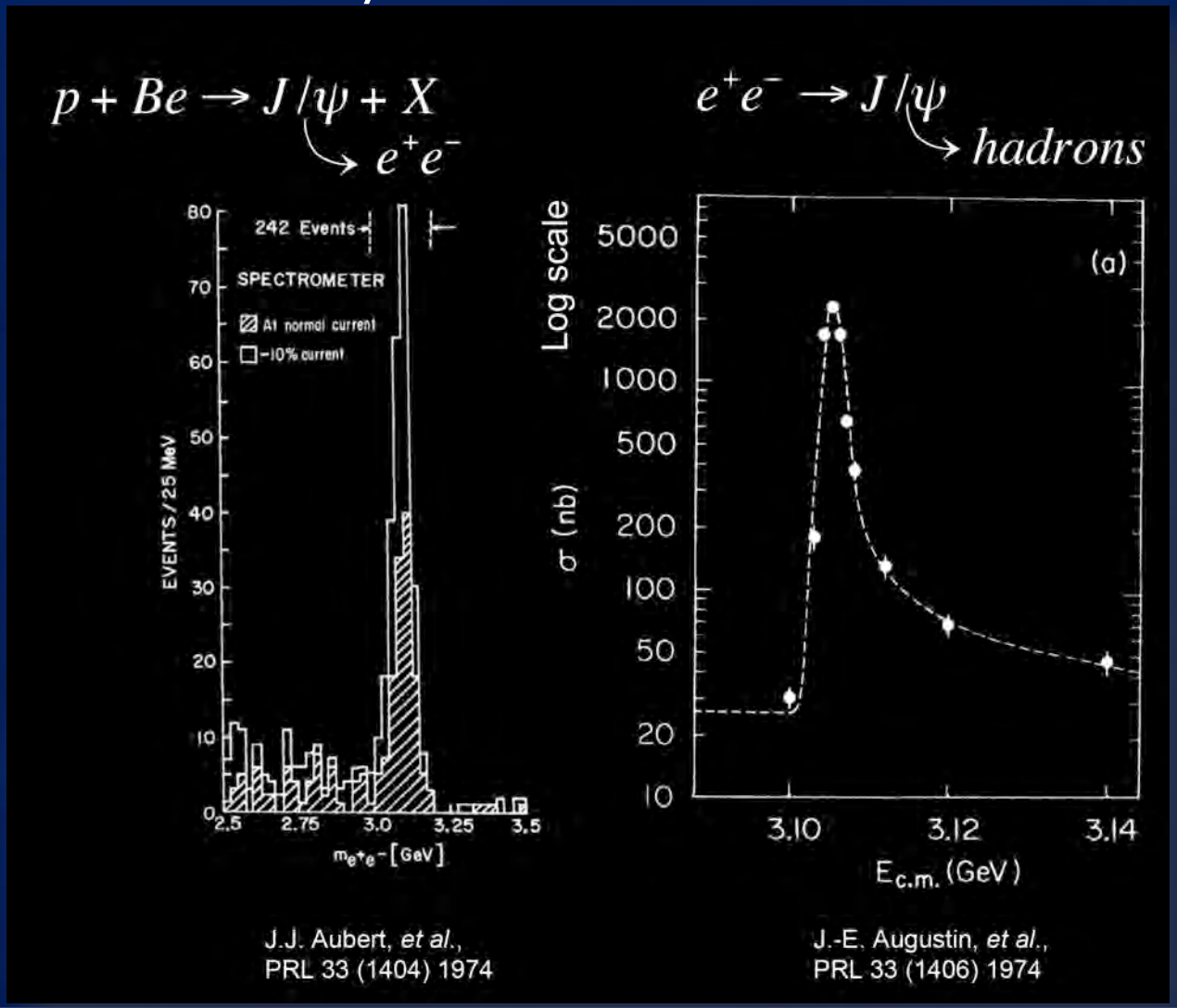
- Gargamelle (CF_3Br) Bubble Chamber: Weak Neutral Current

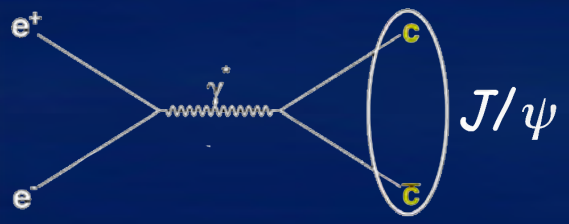




ElectroWeak Unification Experiment 1974: Round 2

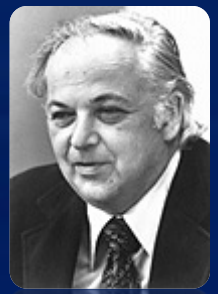
Discovery of Charm Quark: Charmonium (J/ψ)





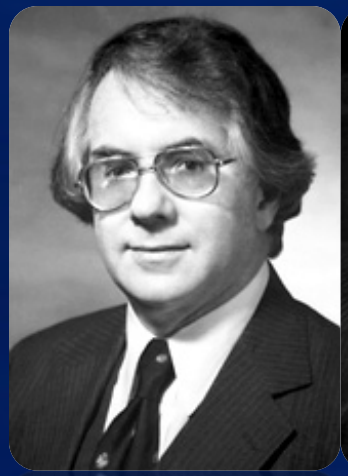
1976

S.C.C. Ting



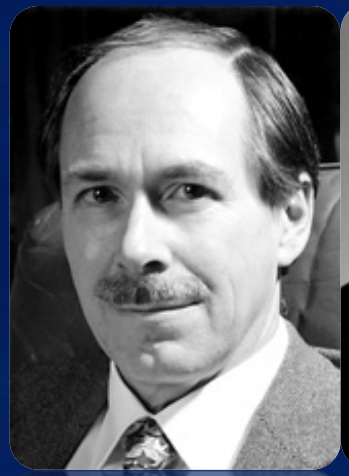
B. Richter

Interlude: Theoretical Nobel Prizes


S.L. Glashow


A. Salaam


S. Weinberg


G. 't Hooft


M.J.G. Veltman


1979

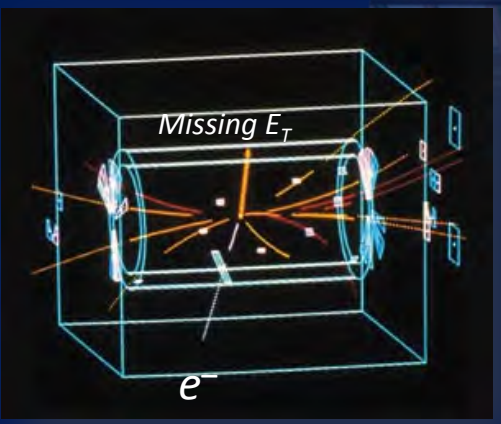

1999

ElectroWeak Unification Experiment 1982: Rounds 3+4

CERN UA1 and UA2 experiments discover *W* and *Z*, confirmation of mass ratio

UA1

UA2



$pp \rightarrow W+X,\ W \rightarrow e\nu$

$pp \rightarrow Z+X,\ Z \rightarrow e^+e^-$

C. Rubbia

S. Van der Meer

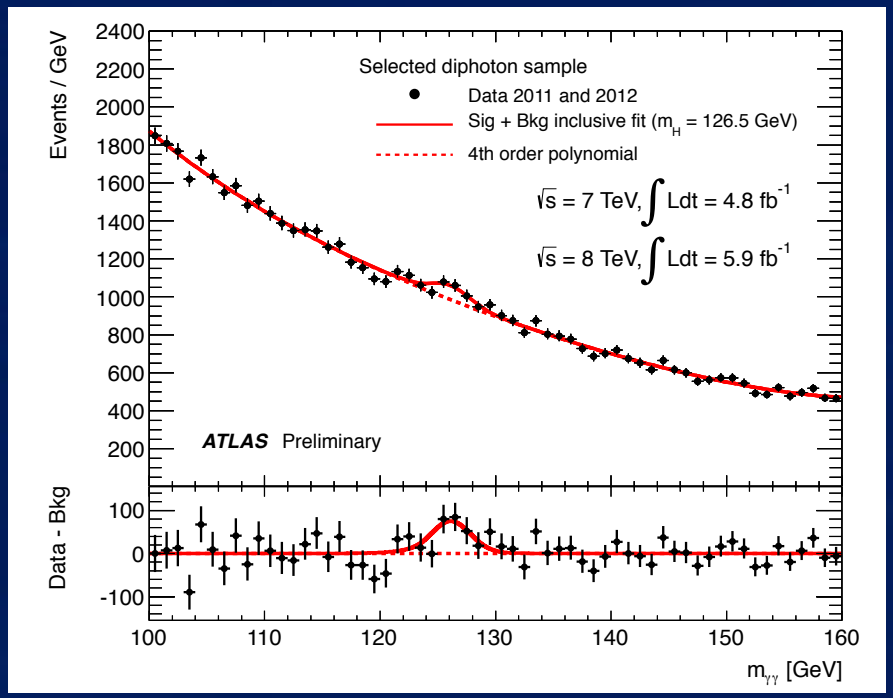
1984

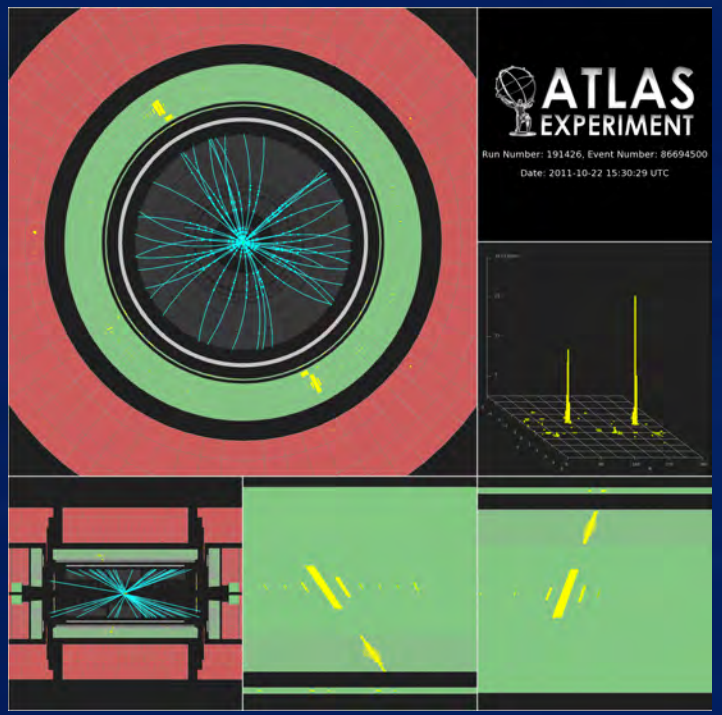
- Which particles constitute the product of the decay of a Higgs boson particle directly after its production?

- How do you see the Higgs boson? How do you know what you see is actually the Higgs particle?

- Which particles constitute the product of the decay of a Higgs boson particle directly after its production?

$H \rightarrow \gamma\gamma$





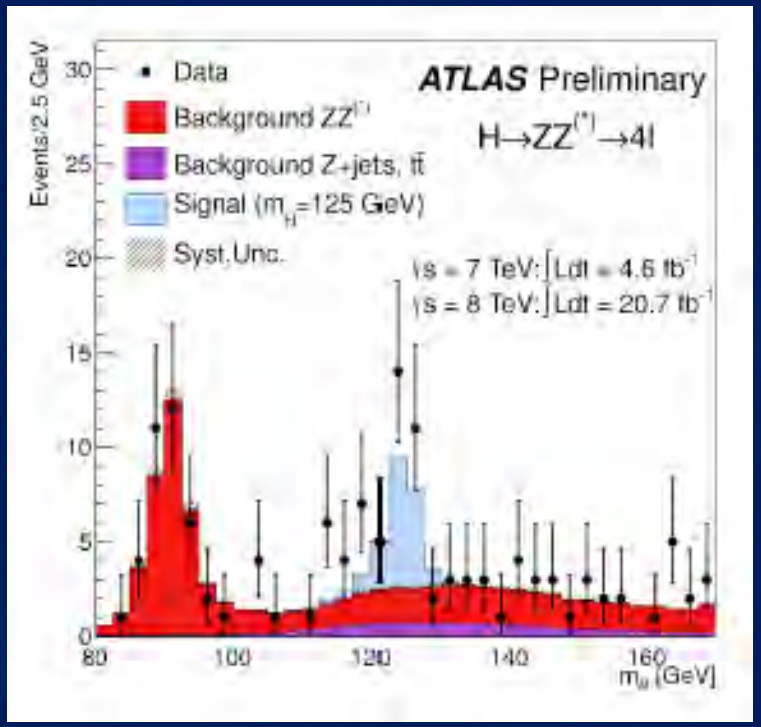
Observed significance 7.4σ (expected 4.1σ)

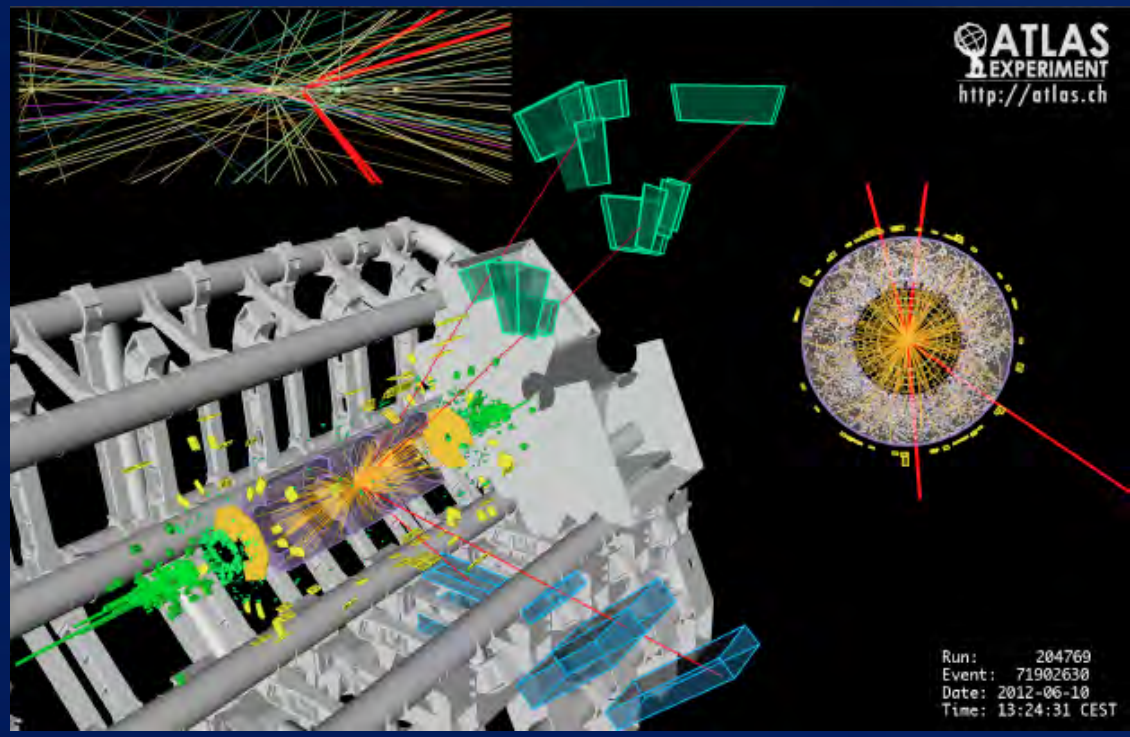
Mass: m_H =126.8 ± 0.2(stat) ± 0.7(syst) GeV

Signal strength: μ = 1.65 ± 0.24(stat) ± 0.22(syst) [2.3σ compatibility with SM]

- Which particles constitute the product of the decay of a Higgs boson particle directly after its production?

$H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$



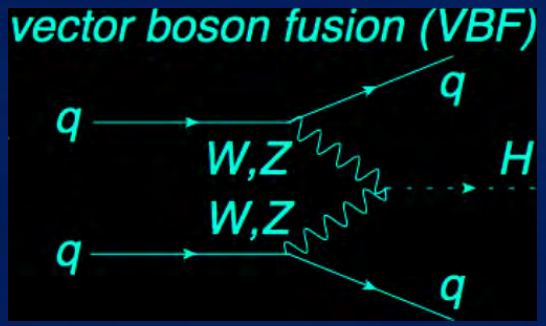


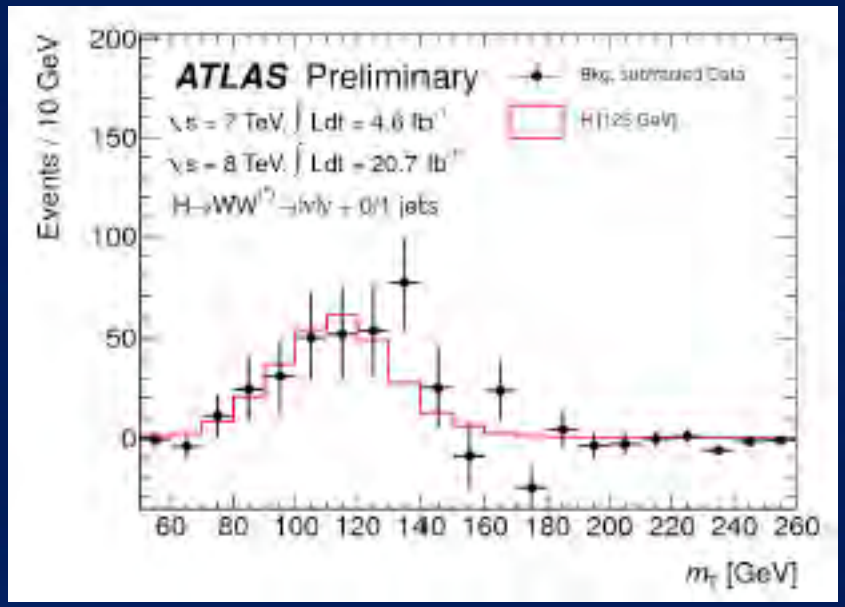
Observed significance 6.6σ (expected from SM Higgs 4.4σ)

m_H = 124.3 ± 0.6 (stat) ± 0.4 (syst) GeV μ (124.3 GeV) = 1.7 ± 0.4

- Which particles constitute the product of the decay of a Higgs boson particle directly after its production?

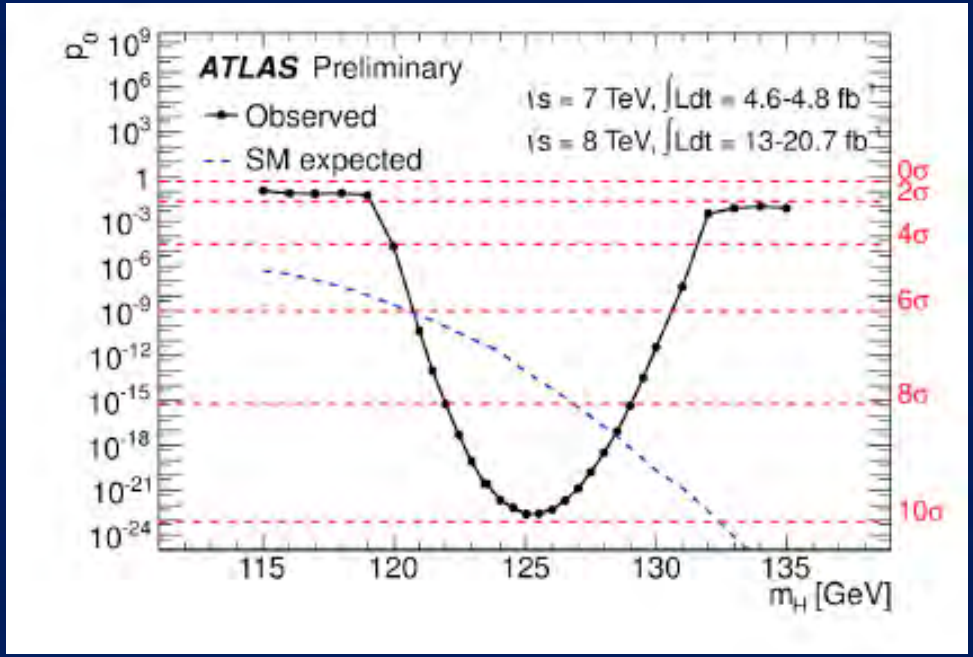
$$H \rightarrow WW \rightarrow l\nu\, l\nu$$

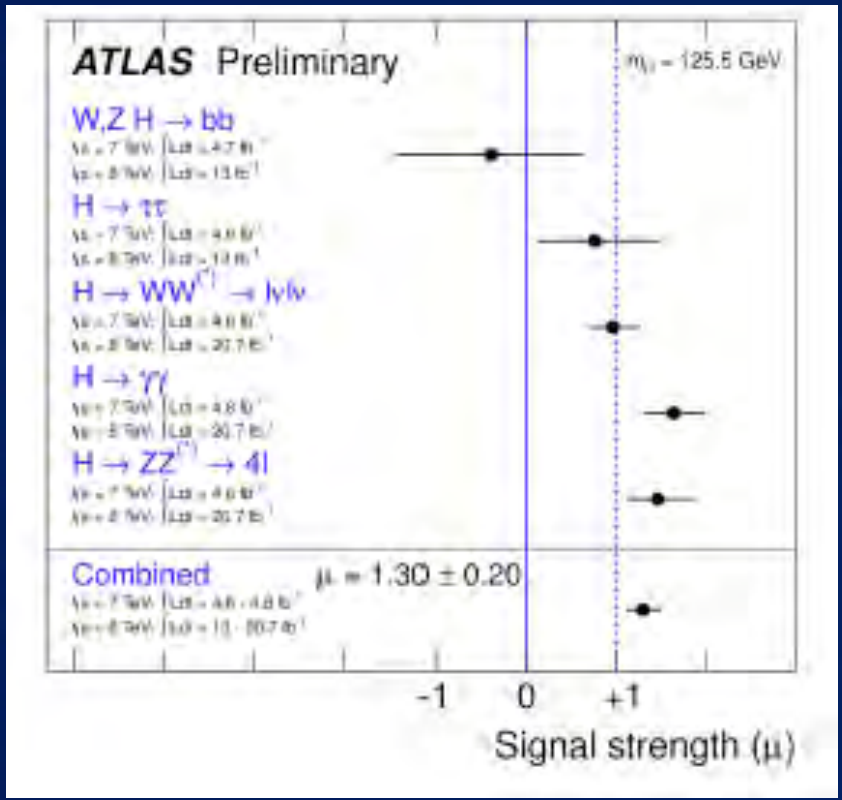




Observed sig. (125 GeV) 3.8σ (3.7σ expected)
Signal strength at 125 GeV μ = 1.01 ± 0.31

- How do you see the Higgs boson? How do you know what you see is actually the Higgs particle?



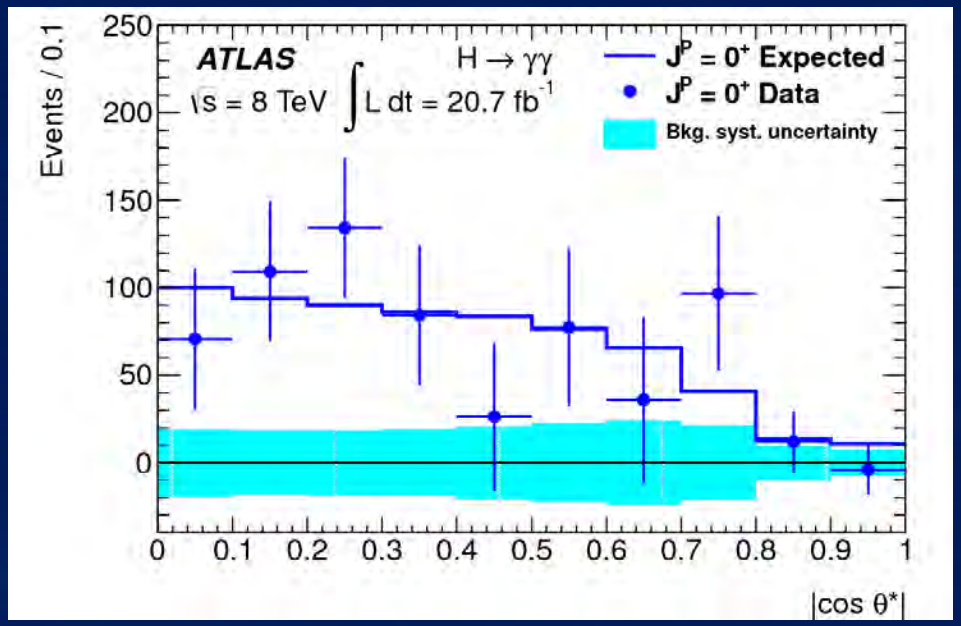


Combined signal strength
$\mu = 1.30 \pm 0.13\ (stat) \pm 0.14\ (syst)$

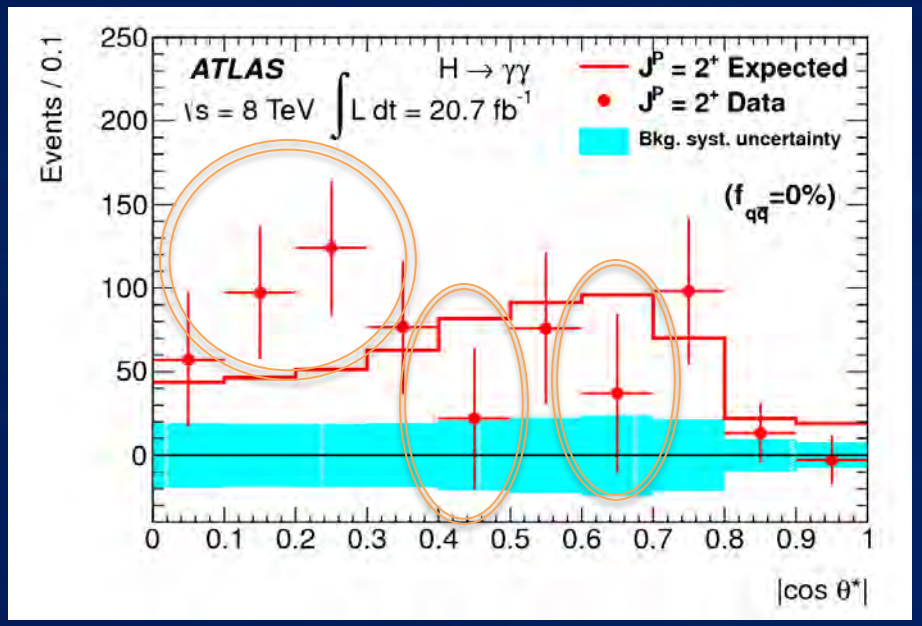
- How do you measure the Higgs "spin" (*J*) ?

Study angular orientation of H → γγ decays

Spin 0 Hypothesis
(Standard Model)



Spin 2 Hypothesis
(100% gg production)



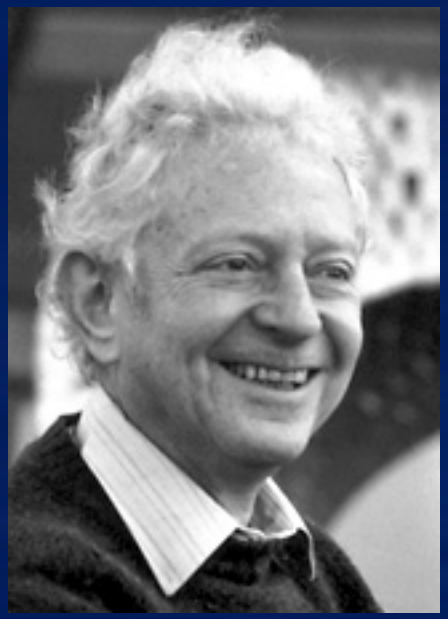
Spin 2 strongly disfavored

- Why is the Higgs boson nicknamed "the God particle"? Who named it?

According to The Economist: The Higgs Boson was dubbed the “Goddamn Particle” by Leon Lederman since it was seemingly impossible to isolate.

Lederman, wanted to title his book

“The Goddamn Particle:
If the Universe is the Answer,
What is the Question?”



1988

But his editor decided that the title was too controversial and convinced Lederman to change the title to

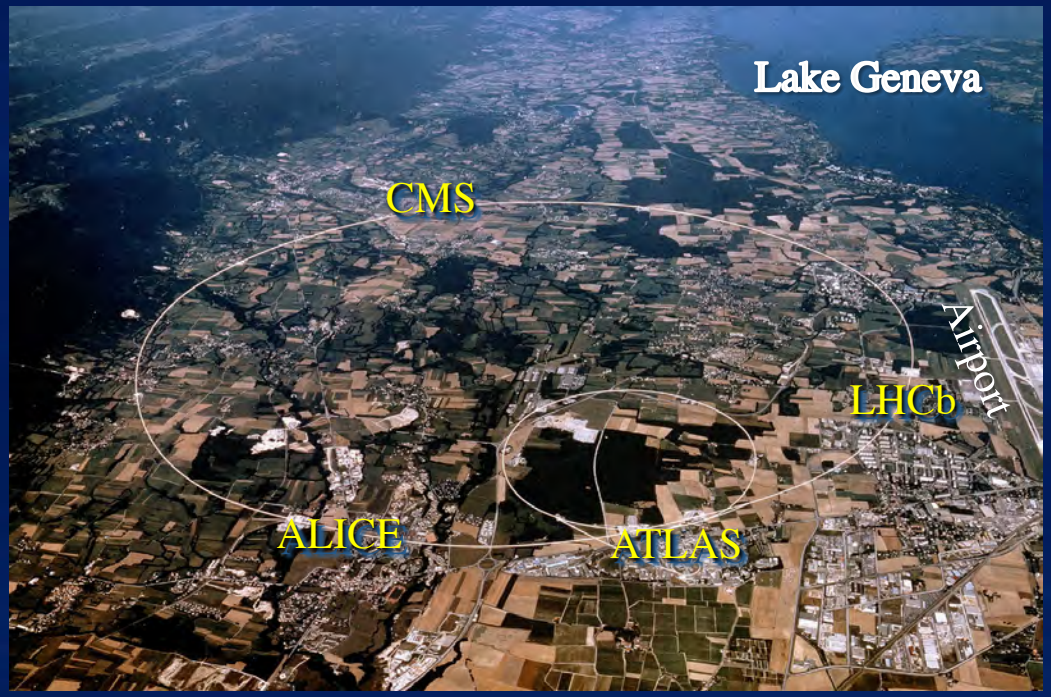
“The God Particle:
If the Universe is the Answer, What is the Question?”

http://www.inquisitr.com/267872/the-god-particle-the-goddamn-particle-and-the-higgs-boson/

- How long did it take to build the Atlas?
- About 5 years to assemble in its cavern

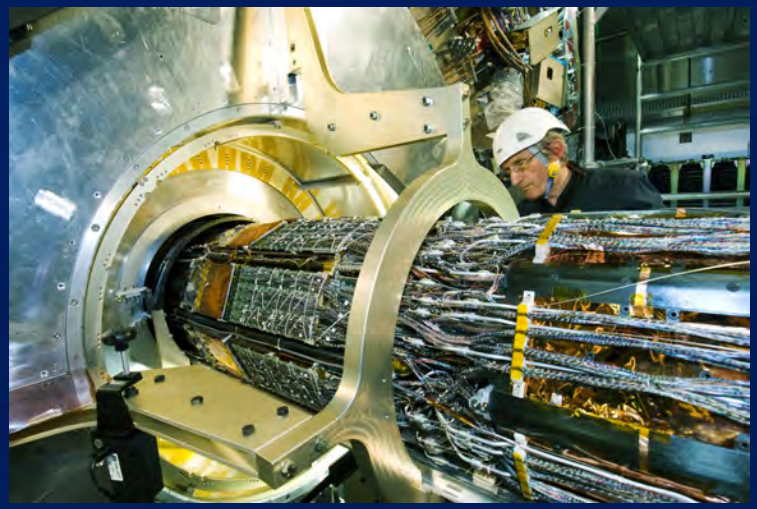
UTD physicists were involved during the final ~1.5 years of construction.

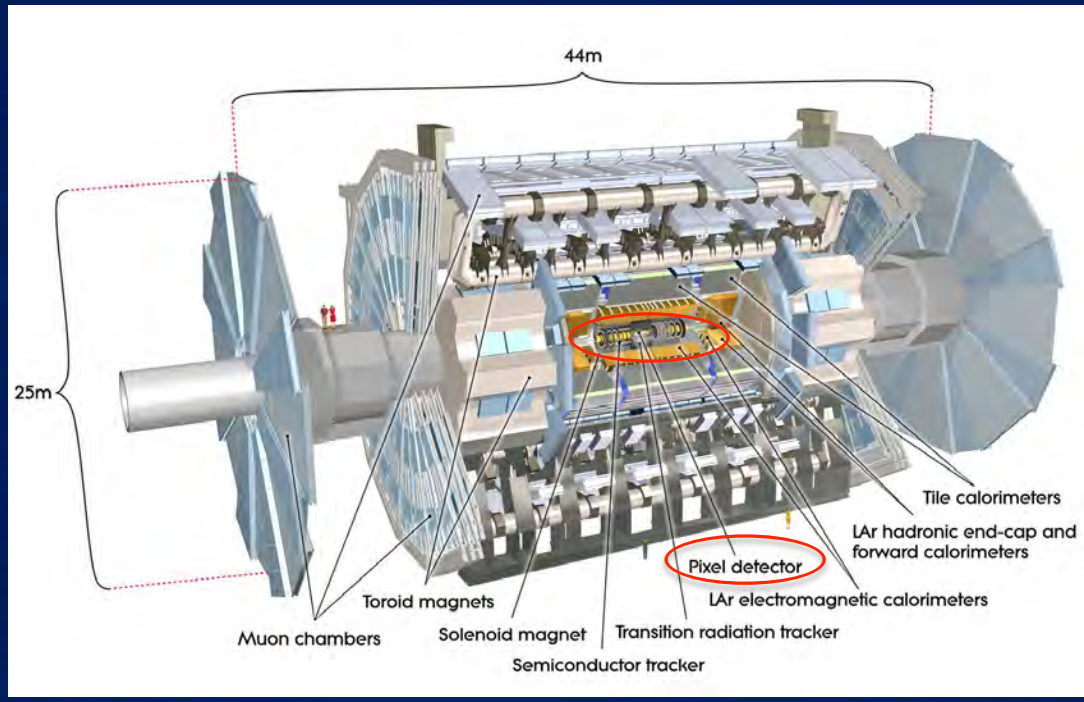
- Why was the LHC built underground?



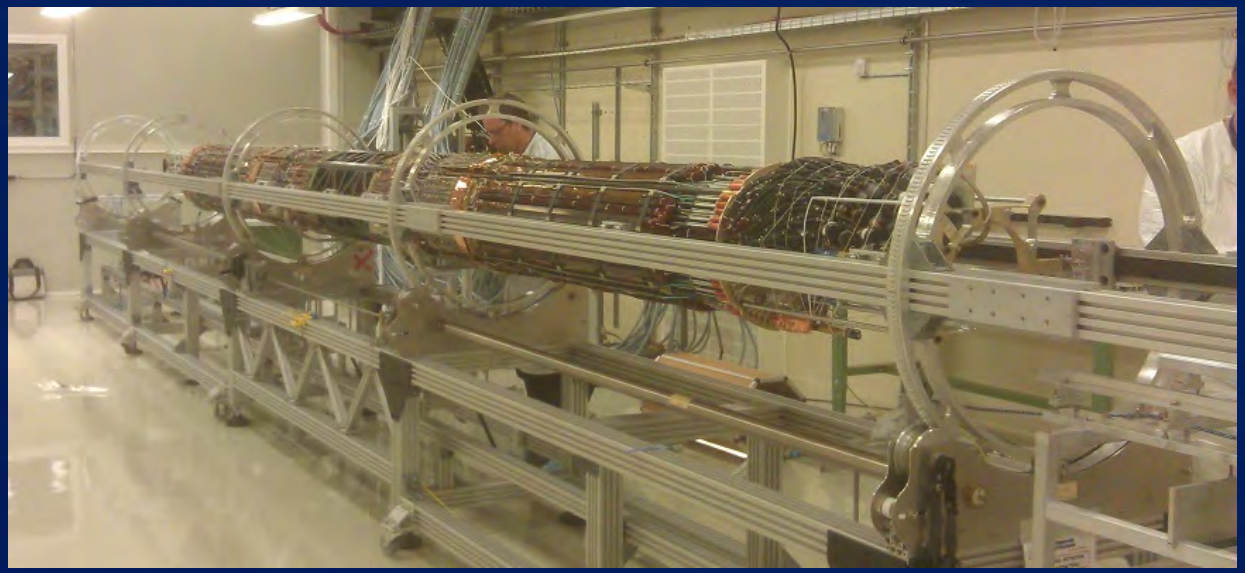
- Underground advantages
  - Radiation shielding
  - Temperature stability
  - Security
- Above ground disadvantages
  - Angry homeowners, businesses, farmers

- What part of the Atlas do you work on?





The "Pixel" Subdetector



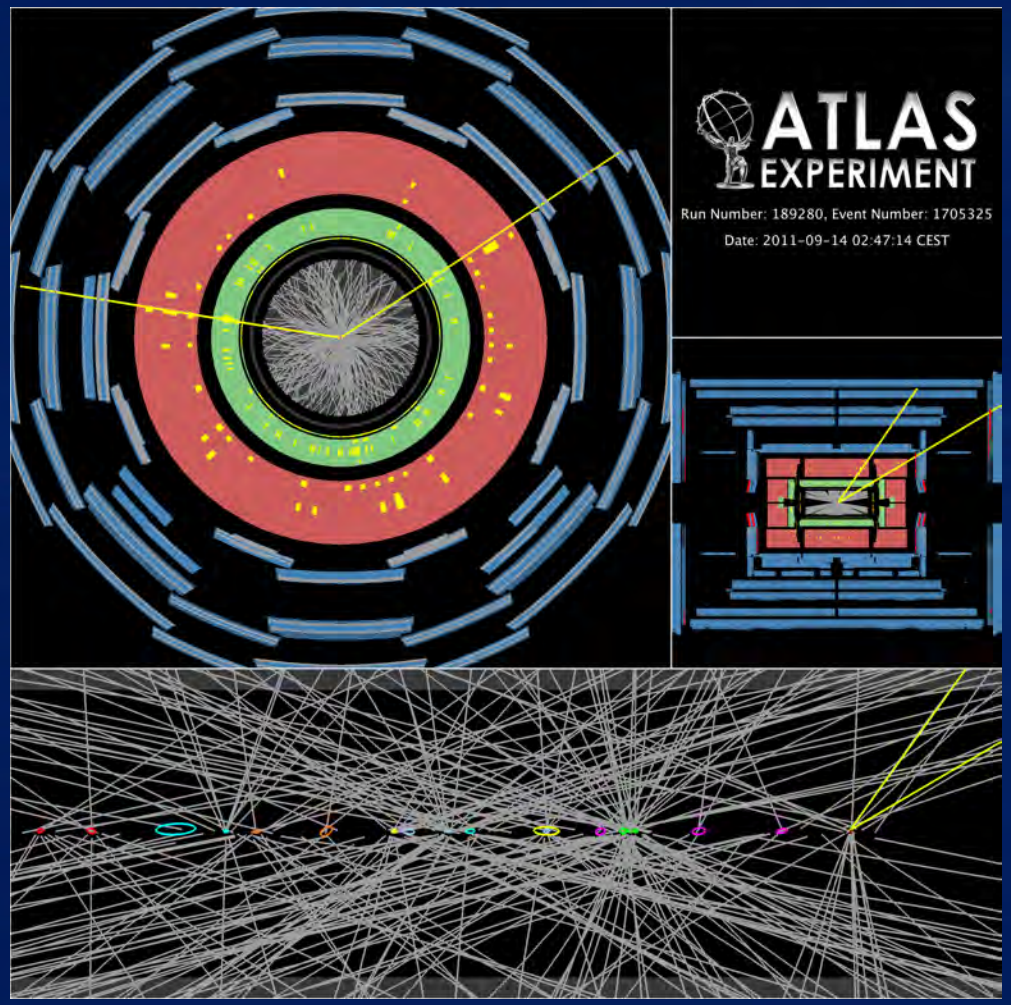
- What part of the Atlas do you work on?

We can sort out “pile-up” thanks to the Pixel subdetector

Bunches of ~10^{11} protons collide every 50 ns (200 MHz).

Of those, ~30 “bump” per bunch crossing

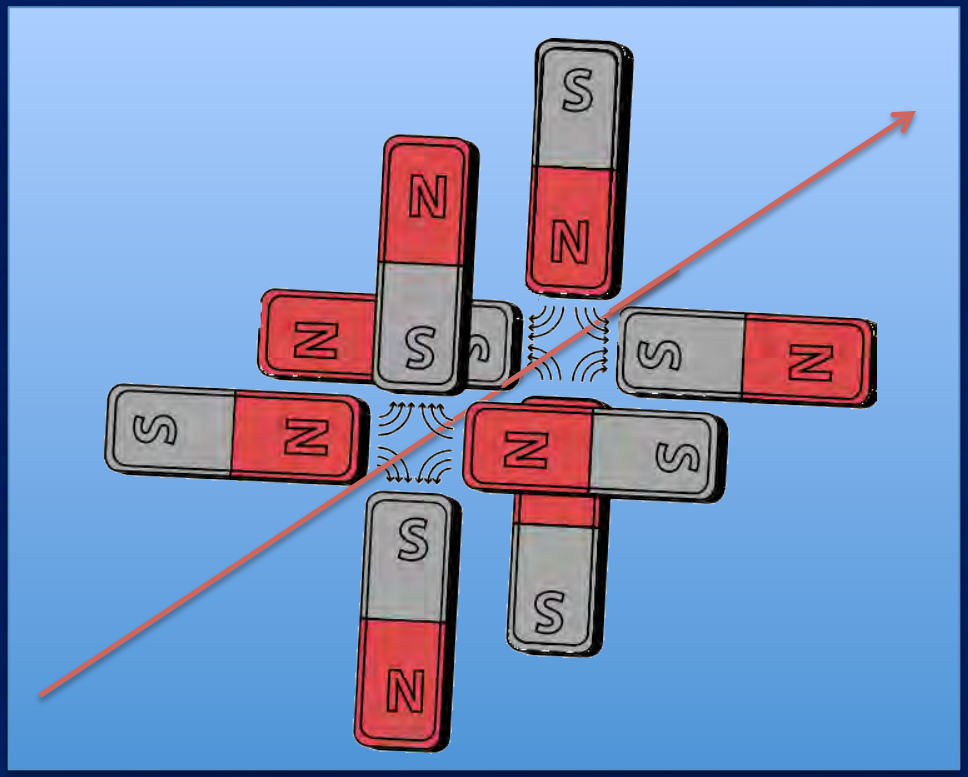
ATLAS records 500 Hz



A crossing with 20 reconstructed collisions, including a $Z \rightarrow e^+e^-$

How does one ensure that the particles will actually collide with one another and not just zip right past each other?

- How does one ensure that the particles will actually collide with one another and not just zip right past each other?



Magnetic Lenses: Quadrupole Magnets

LHC Super Conducting Quadrupole

The protons you allow to collide are from what element?

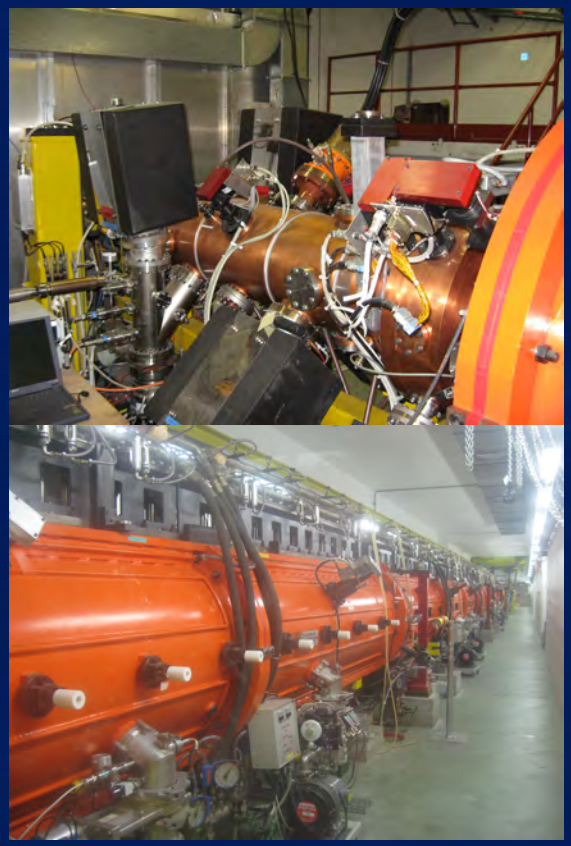
Hydrogen

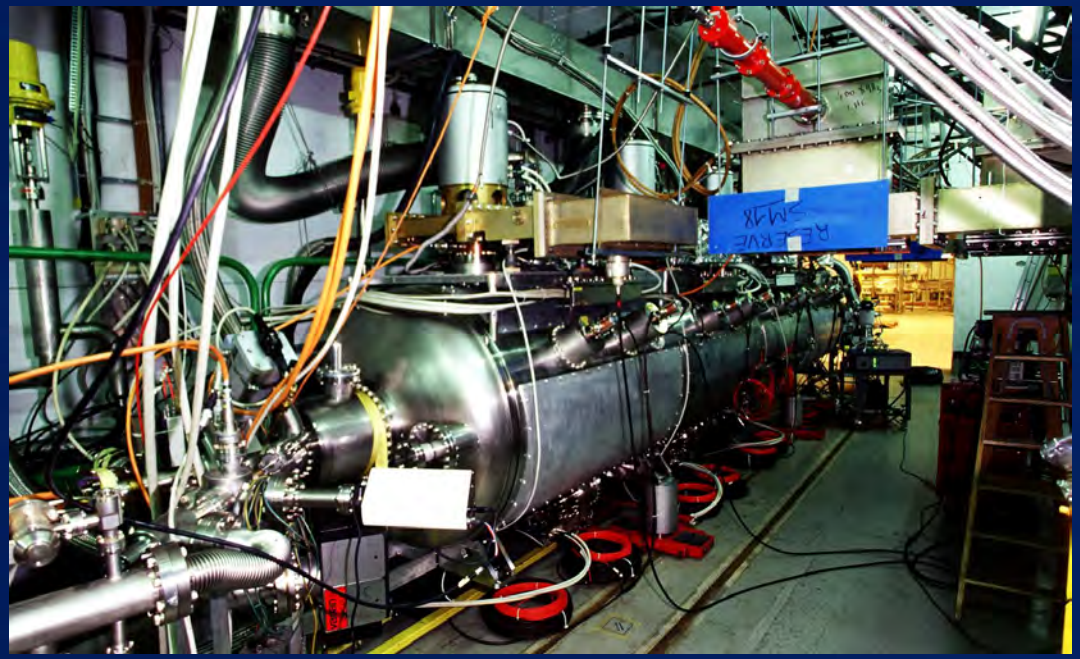
H_2 bottle

What force is used to accelerate the particles in the LHC?

Electric fields produce a force on protons and Pb nuclei

Linear Accelerator





LHC Superconducting Cavity

- I'd like to know about the working conditions you had at the LHC -- what were the hours? With how many colleagues did you work at a time? Did you spend more time in an office-type setting or was it more of a laboratory-type setting?
- What is a typical work day like for an ATLAS experiment member? Are there new responsibilities every day as mechanical issues or new discoveries come up, or is it more of a routine?
- What were the working relationships like there?

UTD Office

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- What were the working relationships like there?

Electronics “Counting Room”, 90 m below the surface

- I'd like to know about the working conditions you had at the LHC -- what were the hours? With how many colleagues did you work at a time? Did you spend more time in an office-type setting or was it more of a laboratory-type setting?
- What is a typical work day like for an ATLAS experiment member? Are there new responsibilities every day as mechanical issues or new discoveries come up, or is it more of a routine?
- What were the working relationships like there?

The UTD Group 2012: Away From and Towards the ATLAS Control Room

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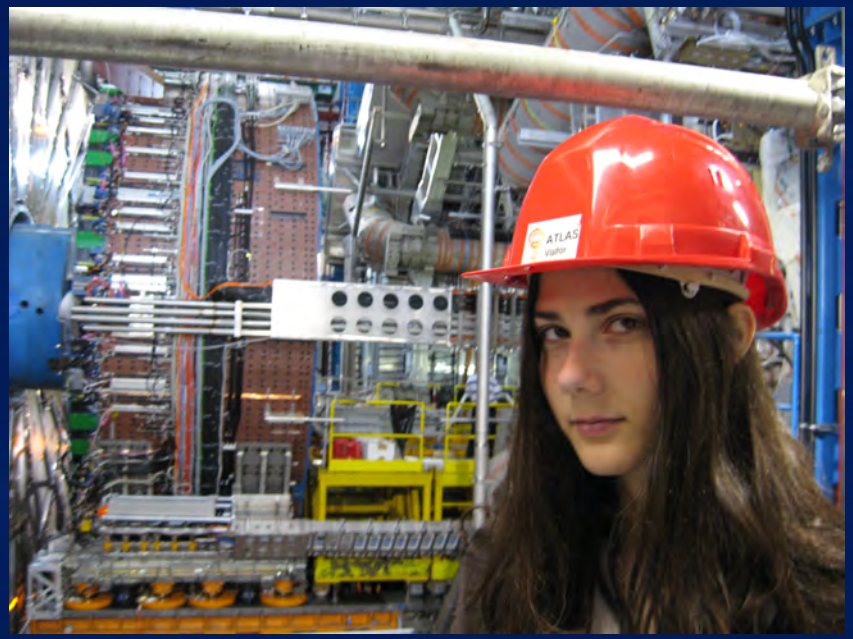

ATLAS Cavern

- Hello, I'd like to know about the working conditions you had at the LHC -- what were the hours? With how many colleagues did you work at a time? Did you spend more time in an office-type setting or was it more of a laboratory-type setting?
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ATLAS Control Room

- The LHC is obviously a very expensive piece of equipment. Did you ever fear that someone (or yourself) would make a mistake that could cause millions or billions of dollars in damage?

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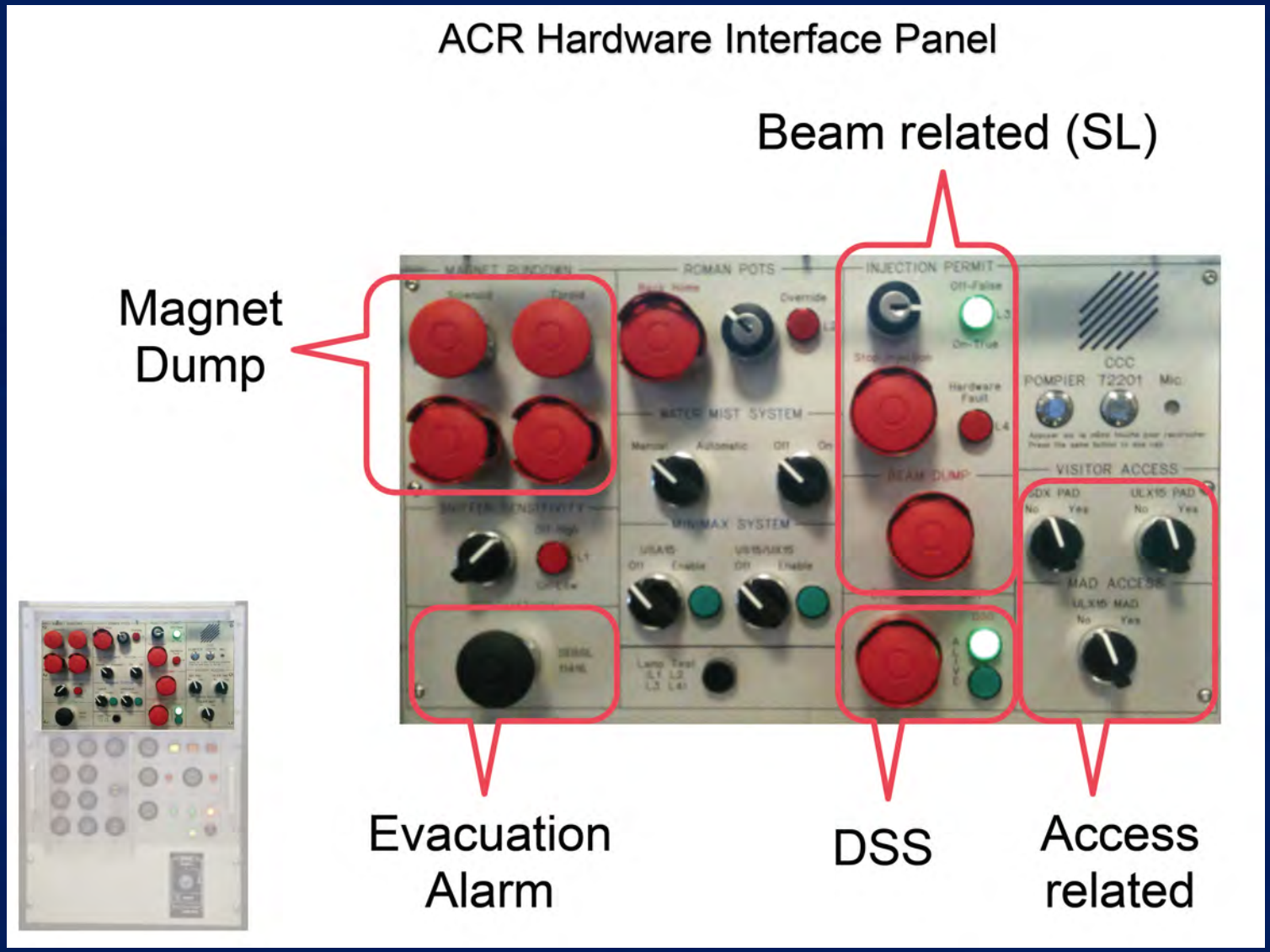

- What are some of the possible negative consequences of the LHC. Such as the worst case scenario of experiments taking place. Such as is a 'spontaneous black hole' or the like possible or plausible?

The Lawsuit

Luis Sancho
Walter L. Wagner
PO Box 411
Honomu, HI 96728
808-964-5535
pro se

IN THE UNITED STATES DISTRICT COURT

DISTRICT OF HAWAII

--oo0oo--

LUIS SANCHO, et al., Plaintiffs, vs. US DEPARTMENT OF ENERGY, et al., Defendants.	Civil No. CV08-00136 HG **AFFIDAVIT OF WALTER L. WAGNER IN SUPPORT OF REPLY MEMORANDUM** Date: October 14, 2008 Time: 10:00 A.M. Court: Hon. Kevin S.C. Chang

AFFIDAVIT OF WALTER L. WAGNER
IN SUPPORT OF REPLY MEMORANDUM

LHC violates
Environmental Protection Act

The Lawsuit

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AFFIDAVIT OF WALTER L. WAGNER
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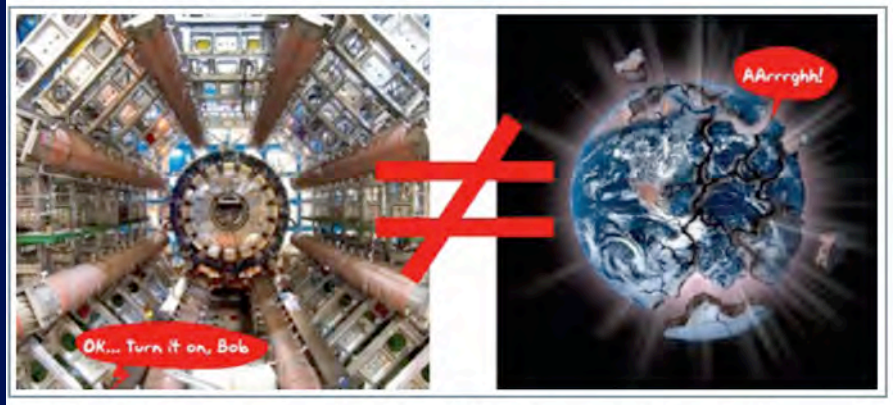
LHC violates Environmental Protection Act

Gizmodo Coverage

SCIENCE

CERN to Morons: Large Hadron Collider Won't Destroy Earth. Morons.

Posted by Gizmodo US Edition at 2:28 AM on April 1, 2008

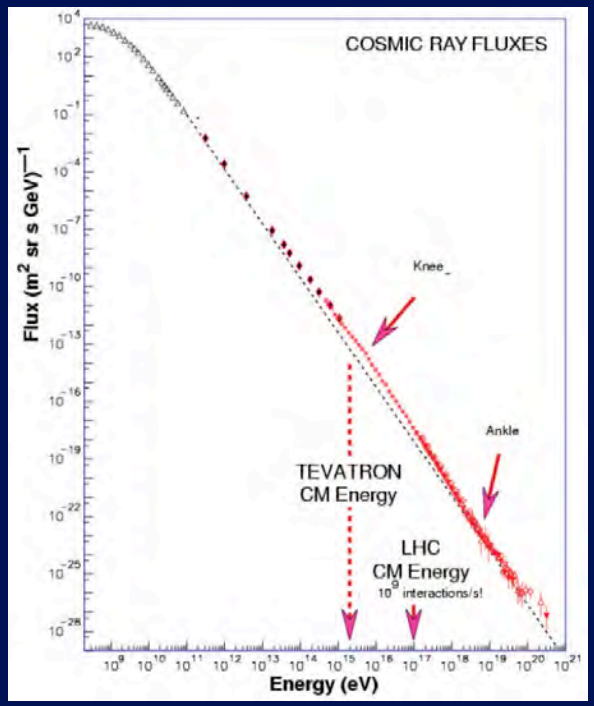


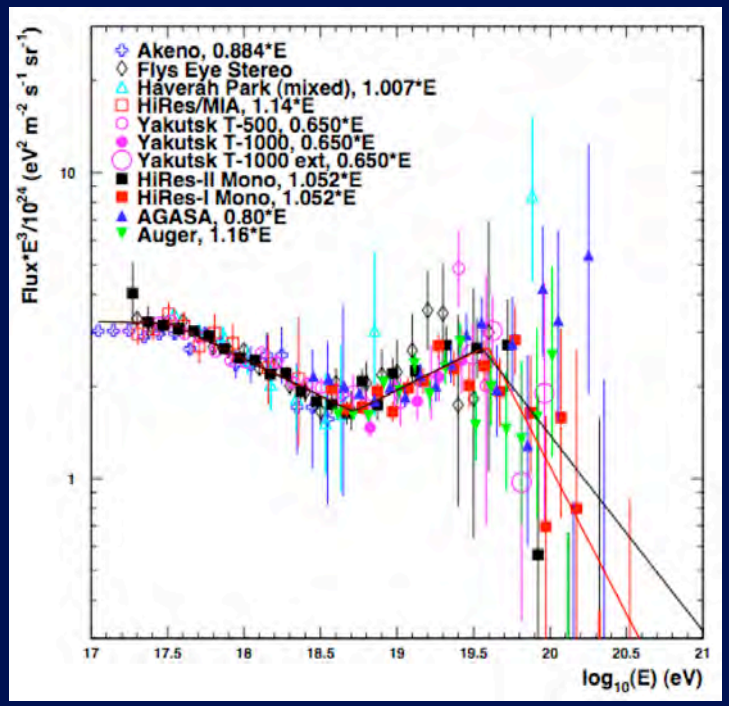
Contrary to the somewhat feverish claims laid out in an recent lawsuit, when our favourite particle-smashing, Force-finding Large Hadron Collider is switched on soon it *will not* result in the destruction of life as we know it. Such claims are "complete nonsense" say the scientists at CERN (and everywhere else,) in response to the suit. They should know: it's their machine, they designed it and they've been telling everyone for a while that their research shows it's safe.

A new (or old) particle is discovered!

See http://public.web.cern.ch/public/en/LHc/Safety-en.html for a summary of CERN's actual response.

Cosmic Ray Flux





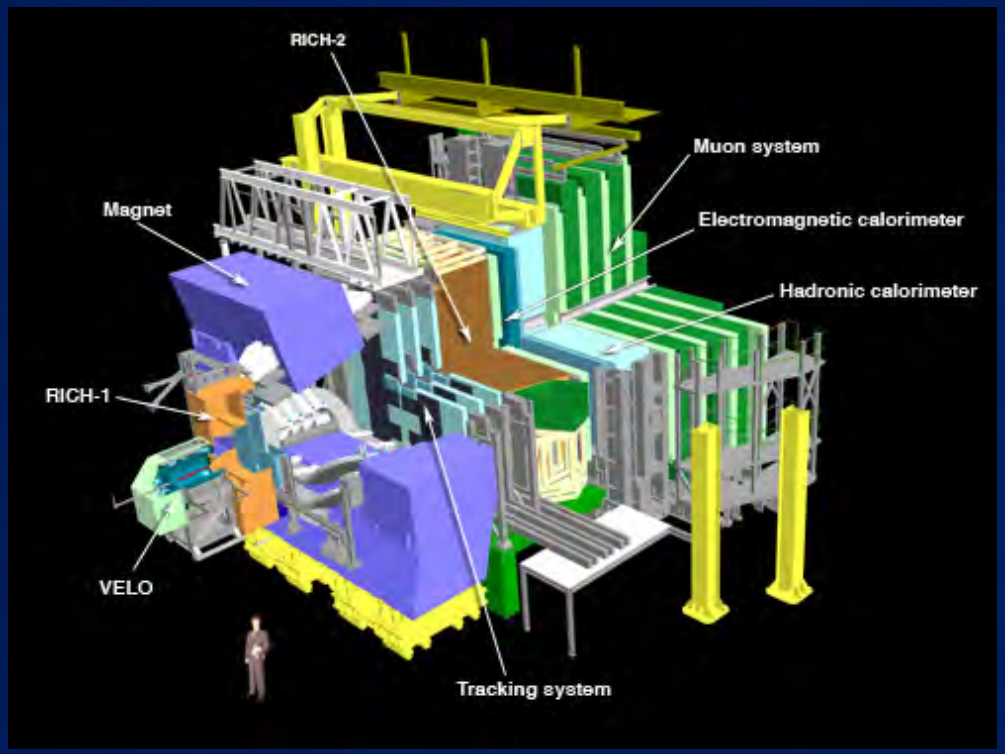
Produces collisions with E > the LHC

"…over 3×10^{22} cosmic rays with energies of 10^{17} eV or more, equal to or greater than the LHC energy, have struck the Earth's surface since its formation. This means that Nature has already conducted the equivalent of about a hundred thousand LHC experimental programmes on Earth already – and the planet still exists."

Sun: 10^9 x LHC programmes. Milky Way - 10^{11} stars, Visible Universe – 10^{11} galaxies…

- I'm curious as to how this experiment [*ATLAS*], as well as the more recent HEP data [http://pdg.lbl.gov/2012/reviews/ sheds light on the question of the anti-matter and matter asymmetry found in nature.
- Answer: It doesn't yet

  LHC Rap: "LHCb looks for where the antimatter's gone"



- I gather that fermions are the actual particles that make up the world, such as electrons, and bosons are force-carrying particles like gravitons. However, those rules seem to be very basic, as Helium-4 is not a force carrying particle. So what are bosons and fermions and what are the differences between the two?

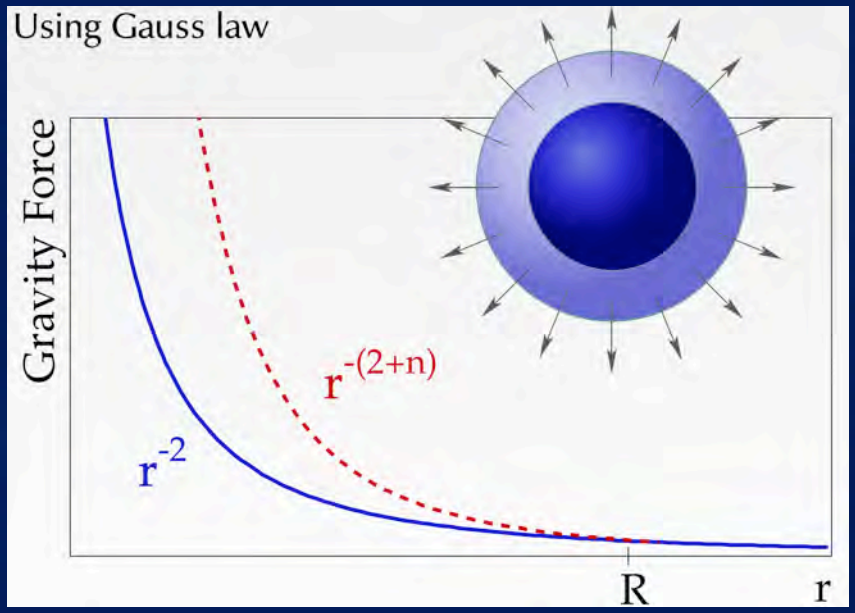
All Force Carriers are Bosons ≠ All Bosons are Force Carriers

All atoms are either fermions or bosons:

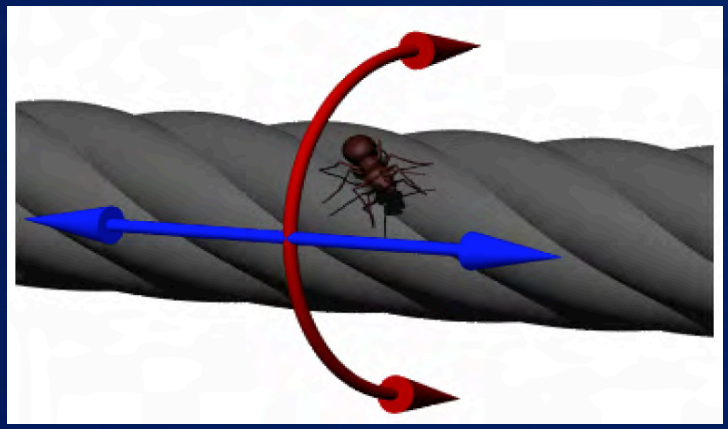
Boson angular momenta: $0\hbar, 1\hbar, 2\hbar, 3\hbar, \ldots$
Fermion angular momenta: $1/2\ \hbar, 3/2\ \hbar, 5/2\ \hbar \ldots$

- I heard Brian Greene mention that a difference in energy before and after the collision may indicate that the energy went into a different dimension. Do you expect any evidence at all for string theory will come from the LHC?

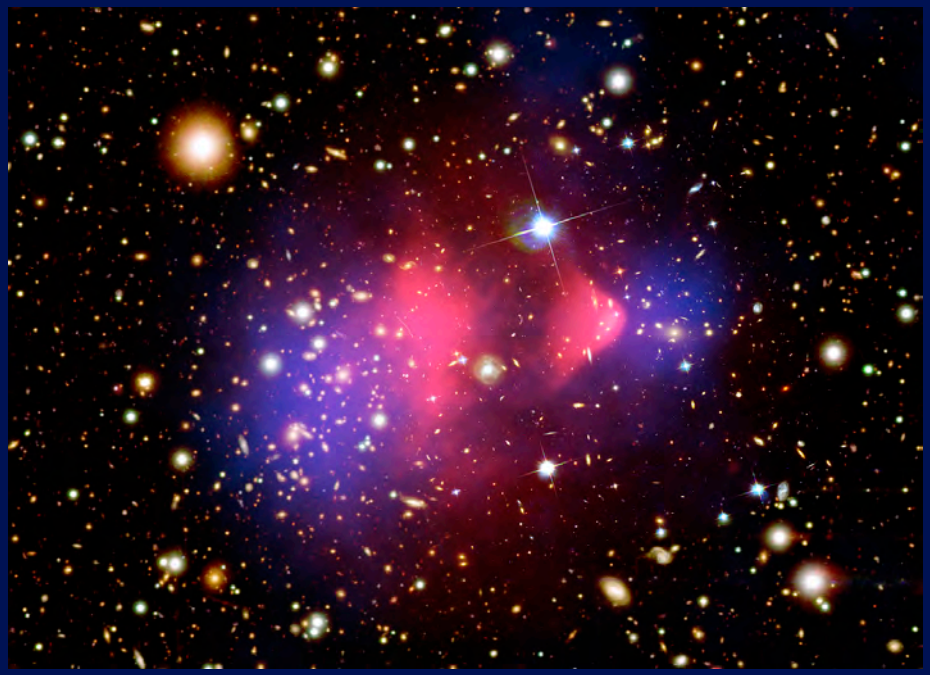
Black Holes from Particle Collisions



Extra dimensions if real would enhance micro black hole production.



Separating Dark Matter from Gas/Luminous Matter

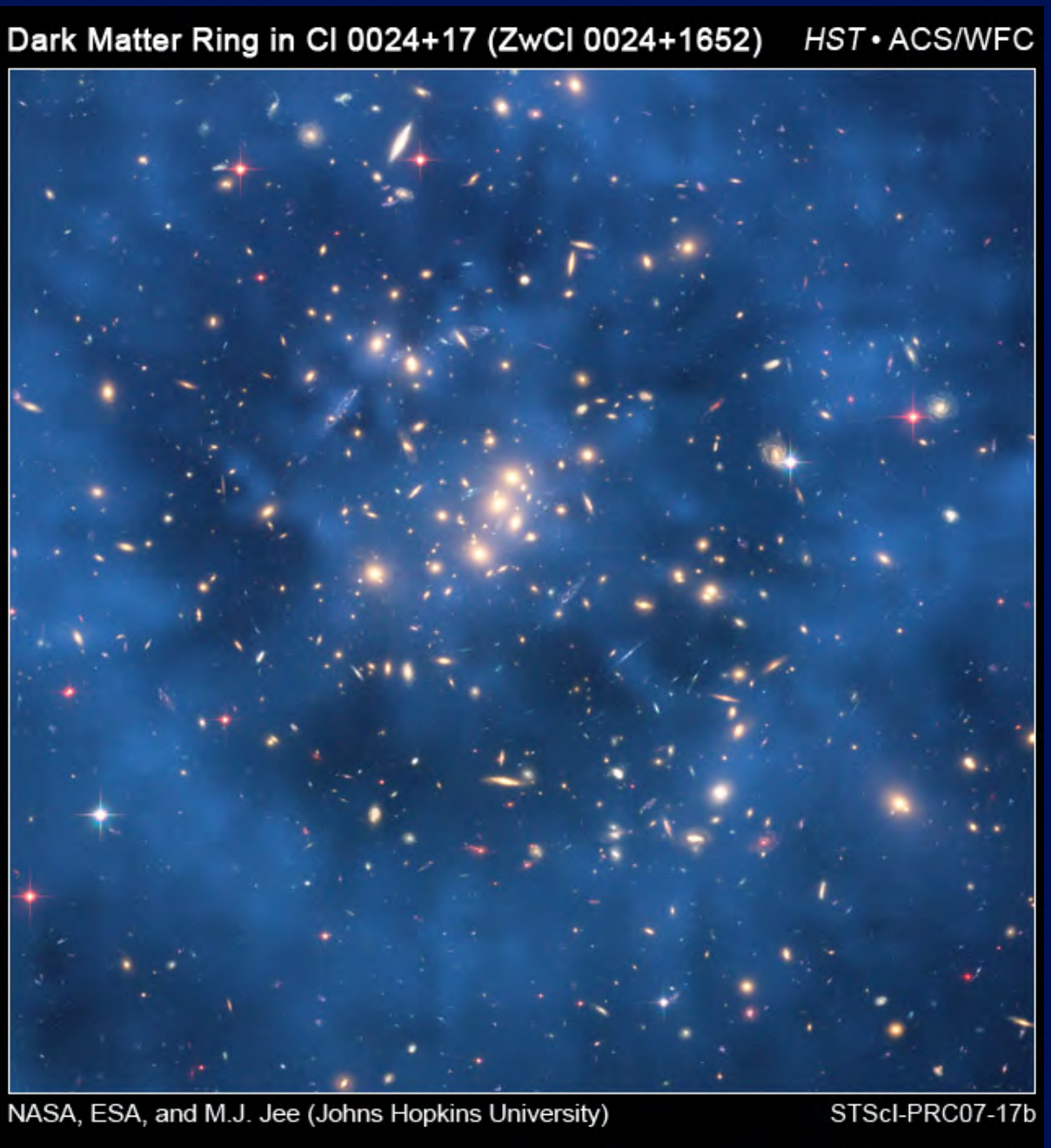


Galaxy Cluster 1E 0657-556 "Bullet Cluster"

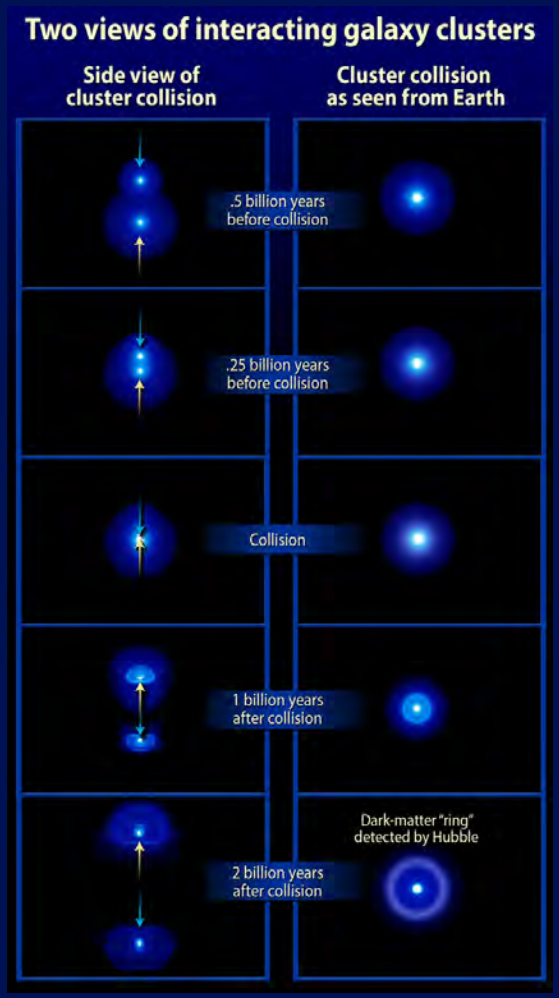
Optical: Hubble and Magellan
X-Ray: Chandra (Magenta)
Dark Matter: inferred from lensing of background (Blue)

X-ray: NASA/CXC/M.Markevitch et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

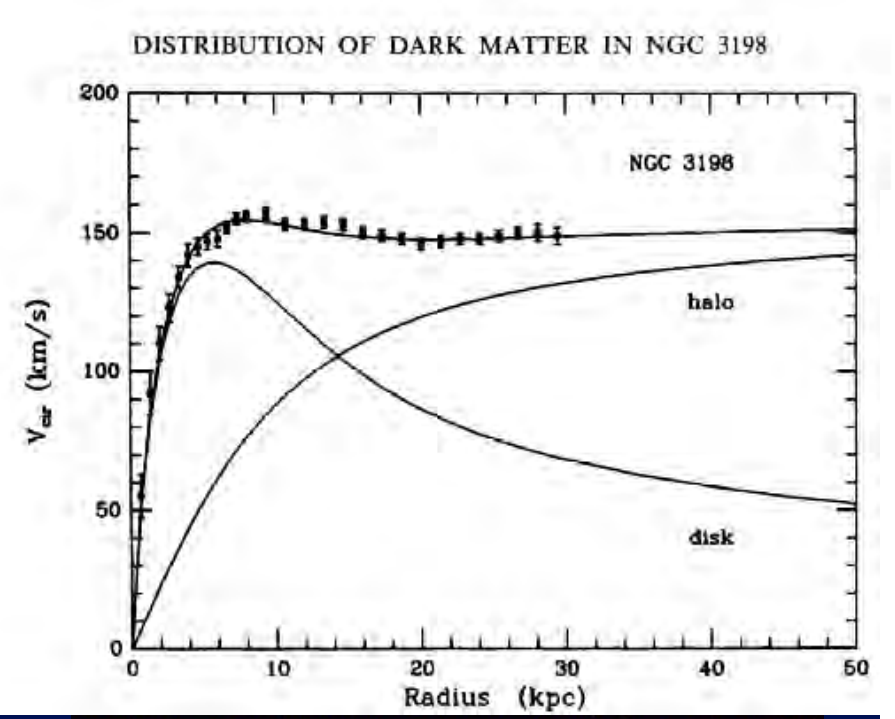
Line of Sight Collision



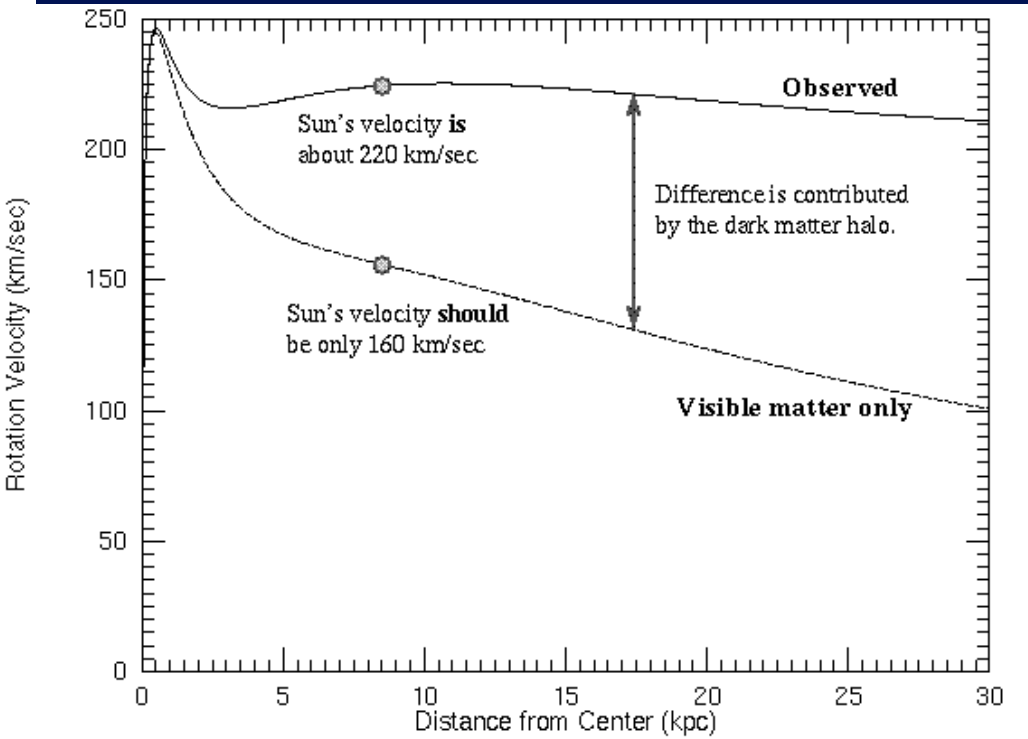
Dark Matter (blue) inferred from lensing of distant galaxies.



Dark Matter Halos in All Galaxies



…including the Milky Way



The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

John Vickery and Jim Matthes/Adam Block/NOAO/AURA/NSF

- How can the finding of Higgs Boson benefit our world?

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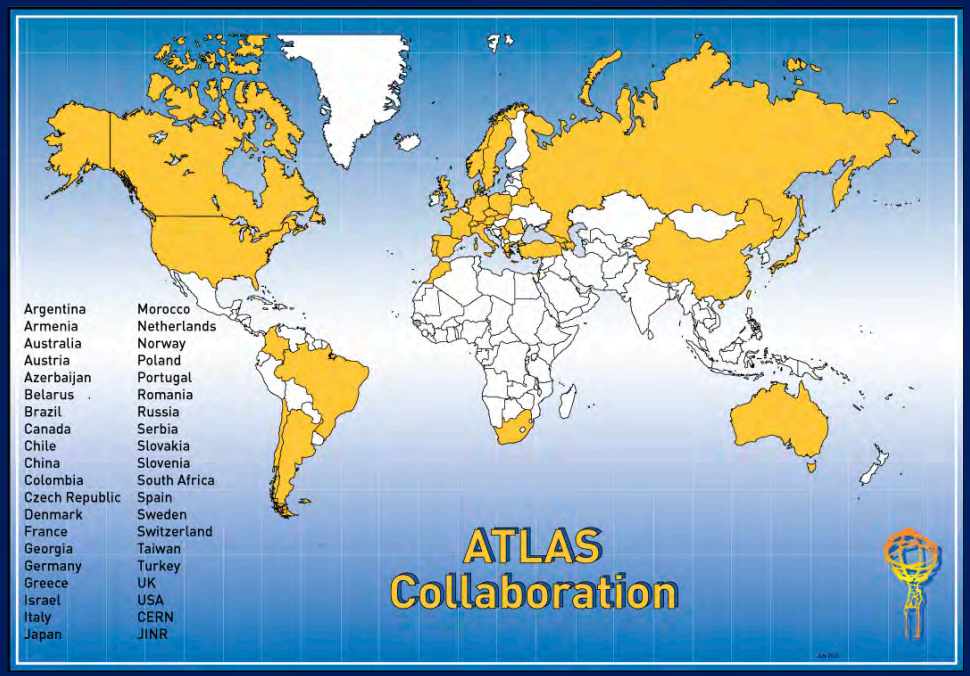
- CERN: European Laboratory for Particle Physics
- Founded in 1954
- 20 member countries
- More than 10,000 scientists



- I would like to know your opinion on universal theories and other such theories attempting to combine many physics laws into a simple, mathematical explanation. Do you think that there is such an equation on explanation, or do you think humans are blinded by the desire for the laws to be beautiful and simple? I have always wondered if we are too quick to try and assume that the physical laws are nice, when they could very well be way more complicated and not as perfect as we tend to believe them to be.

- I gather that fermions are the actual particles that make up the world, such as electrons, and bosons are force-carrying particles like gravitons. However, those rules seem to be very basic, as Helium-4 is not a force carrying particle. So what are bosons and fermions and what are the differences between the two?

Boson angular momenta: $0\hbar, 1\hbar, 2\hbar, 3\hbar, \ldots$
Fermion angular momenta: $1/2\ \hbar, 3/2\ \hbar, 5/2\ \hbar \ldots$

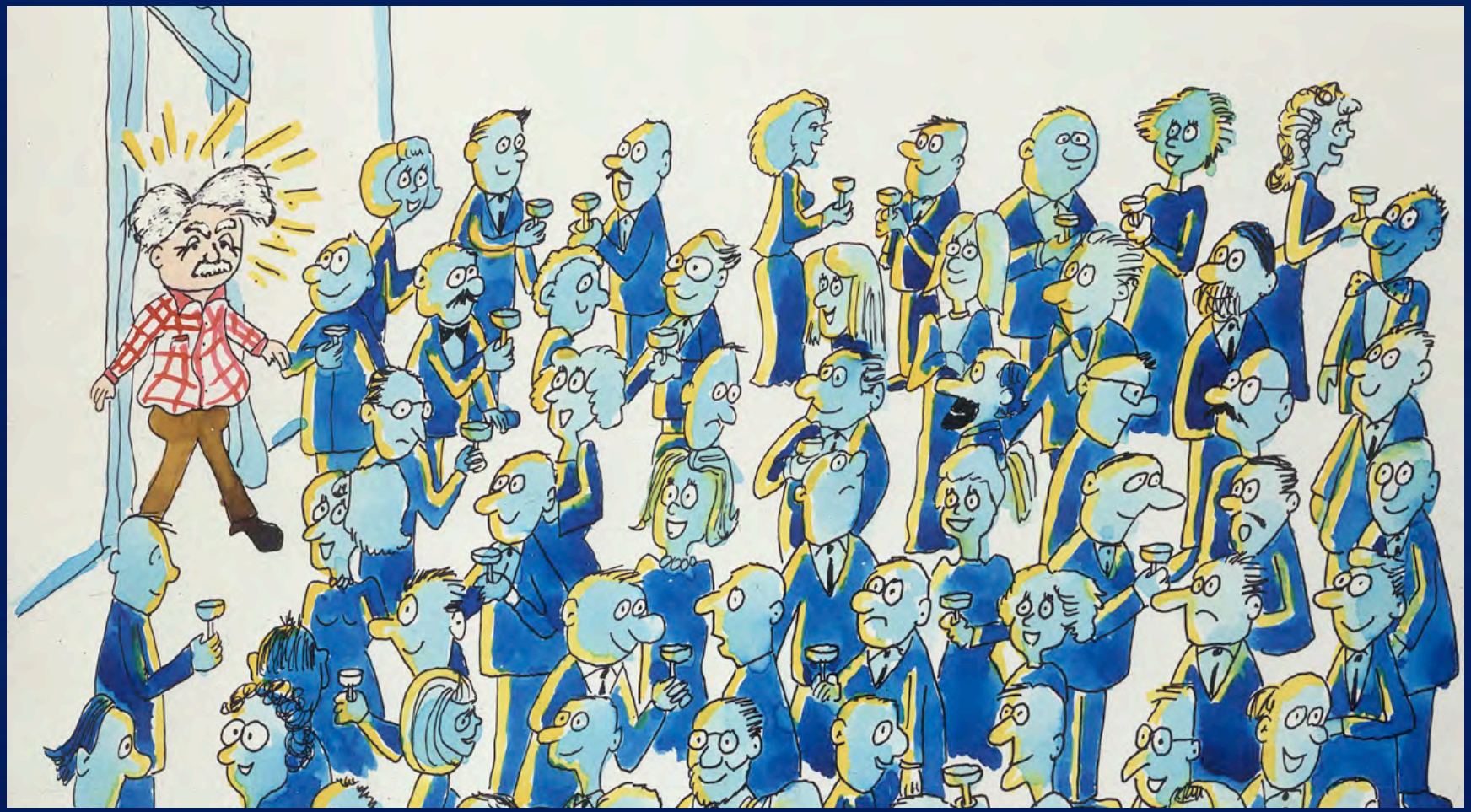
^{4}He has 2 protons, 2 neutrons, and 2 electrons
The protons (neutrons/electrons) have "spins" in opposite directions that cancel.
Total angular momentum = $0\ \hbar$ $\longrightarrow$ boson

^{3}He has 2 protons, 1 neutrons, and 2 electrons
Lone neutron has no partner
Total angular momentum = $\hbar/2$ $\longrightarrow$ fermion

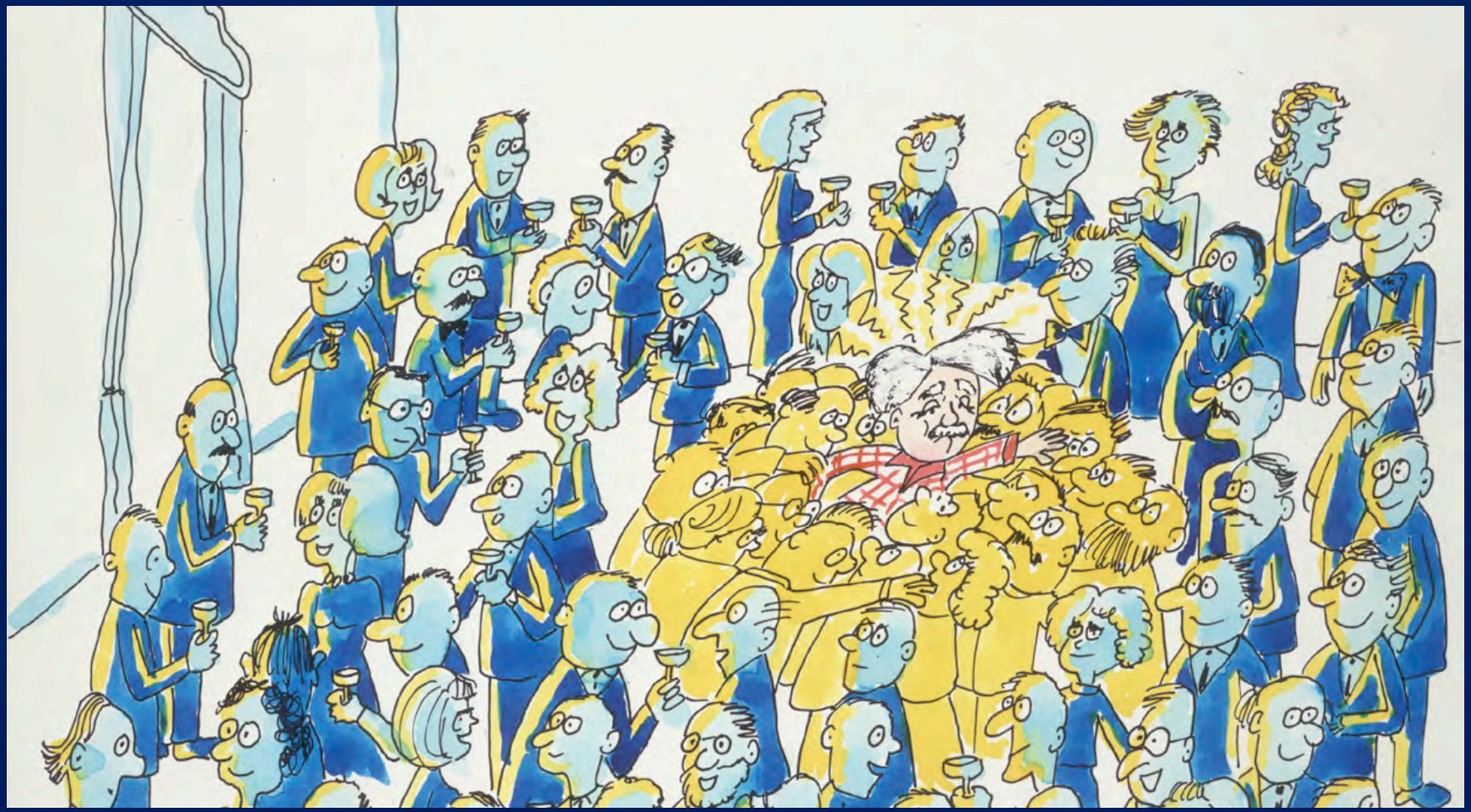
Application: ^{4}He becomes a superfluid at a warmer temperature than ^{3}He.

What's a Higgs Boson

What's a Higgs Boson



What's a Higgs Boson



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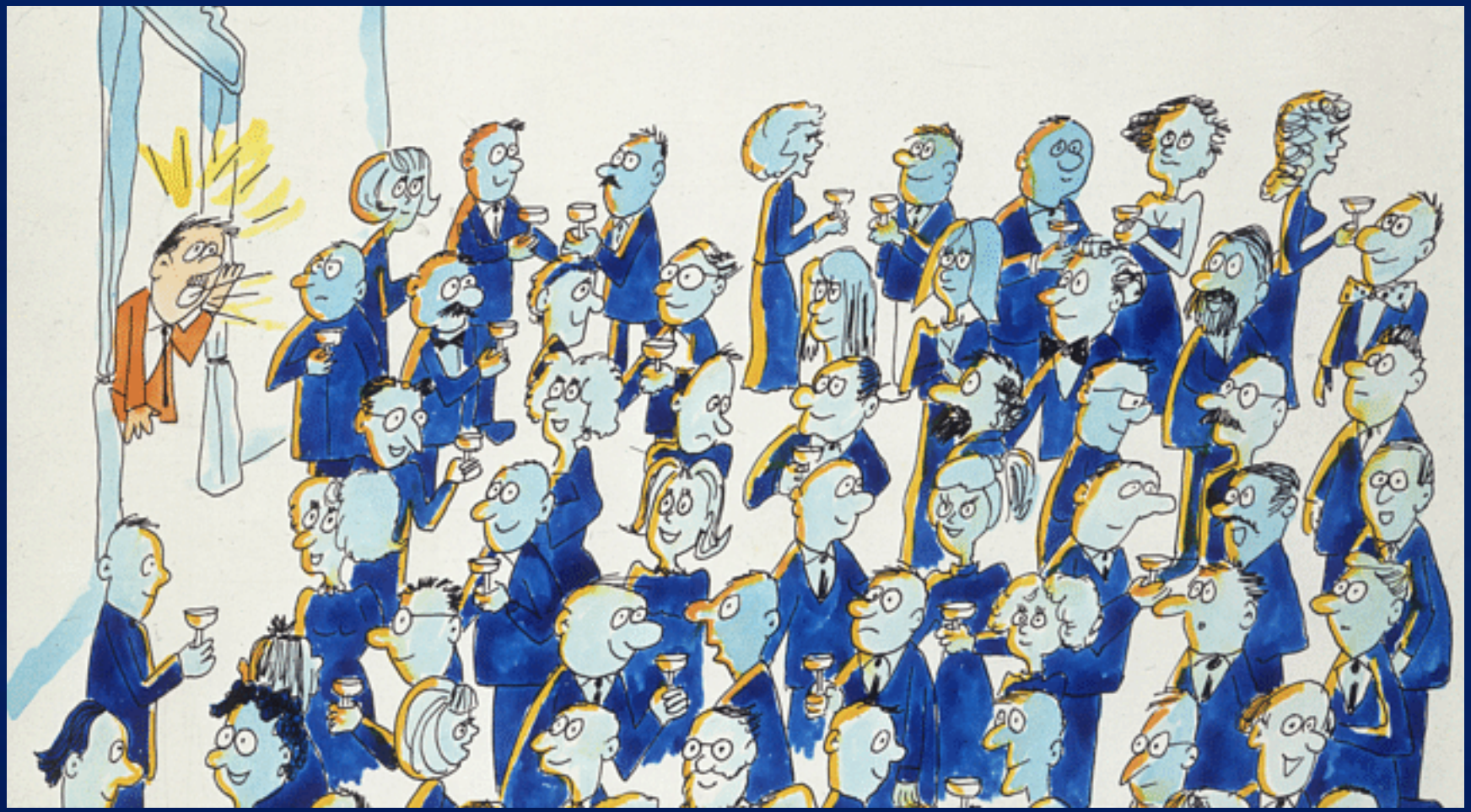

What's a Higgs Boson