Journey to the Heart of Matter

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Trinity College Dublin
July 4, 2019

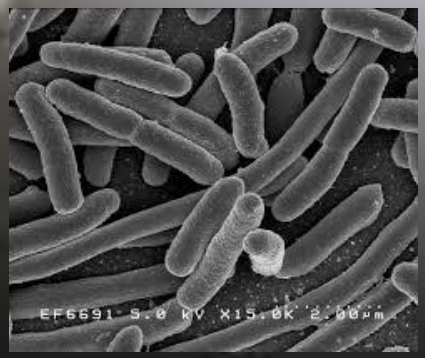
SAGEX
Scattering Amplitudes from Geometry to Experiment

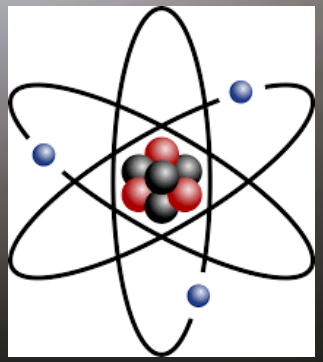
IOP Institute of Physics In Ireland

CERN

SLAC NATIONAL ACCELERATOR LABORATORY

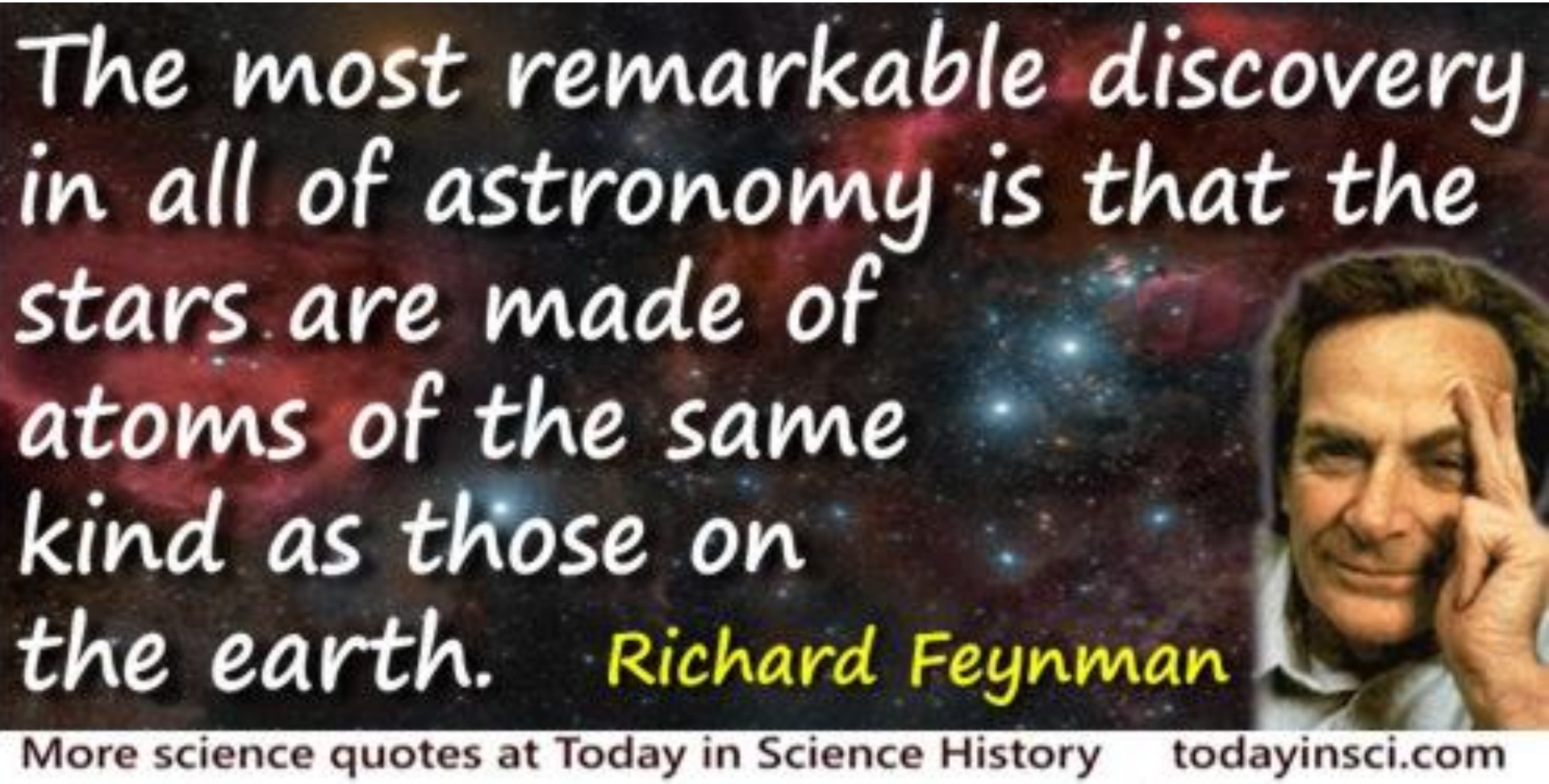
What laws govern the universe and all the matter in it?





All the same stuff

(apart from dark matter)



All ordinary matter made of atoms

zoom in by another 100,000:
proton made of smaller objects

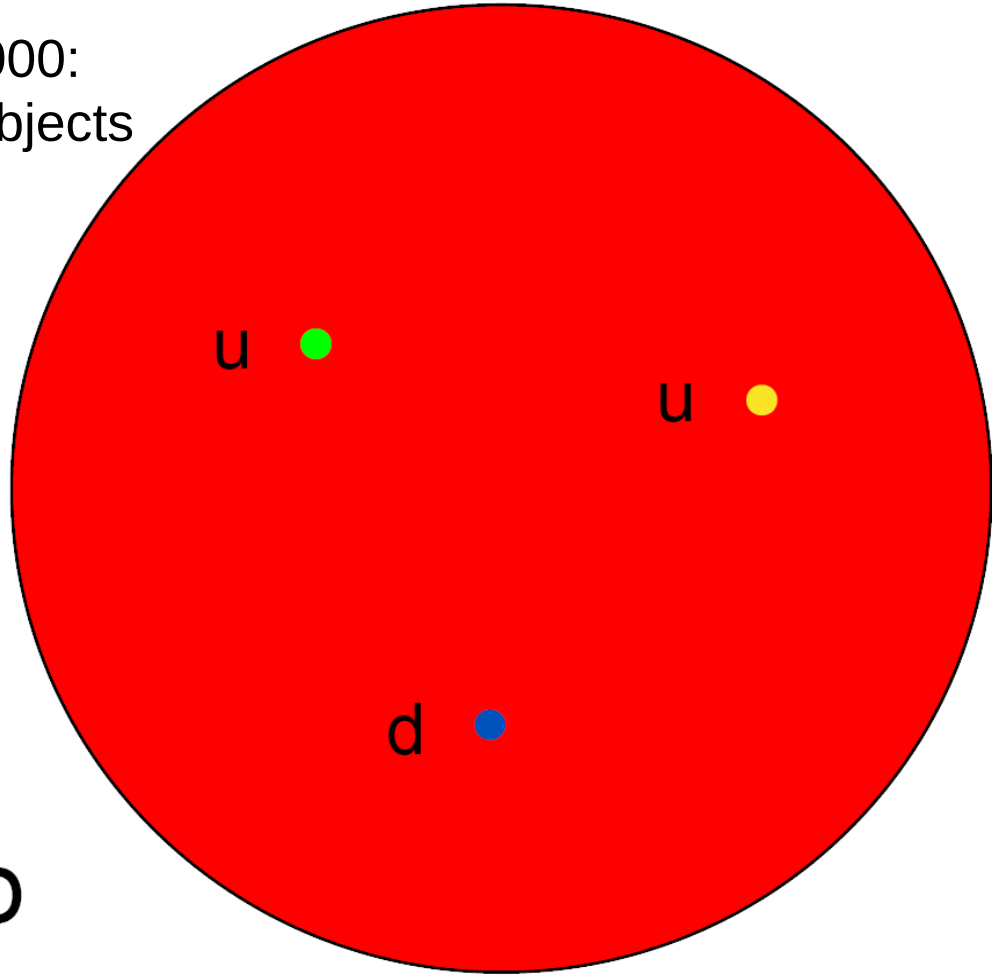
what are these things?

what holds them inside?

can we knock them out?

what other kinds of subatomic particles are there?

how do they help explain our universe?



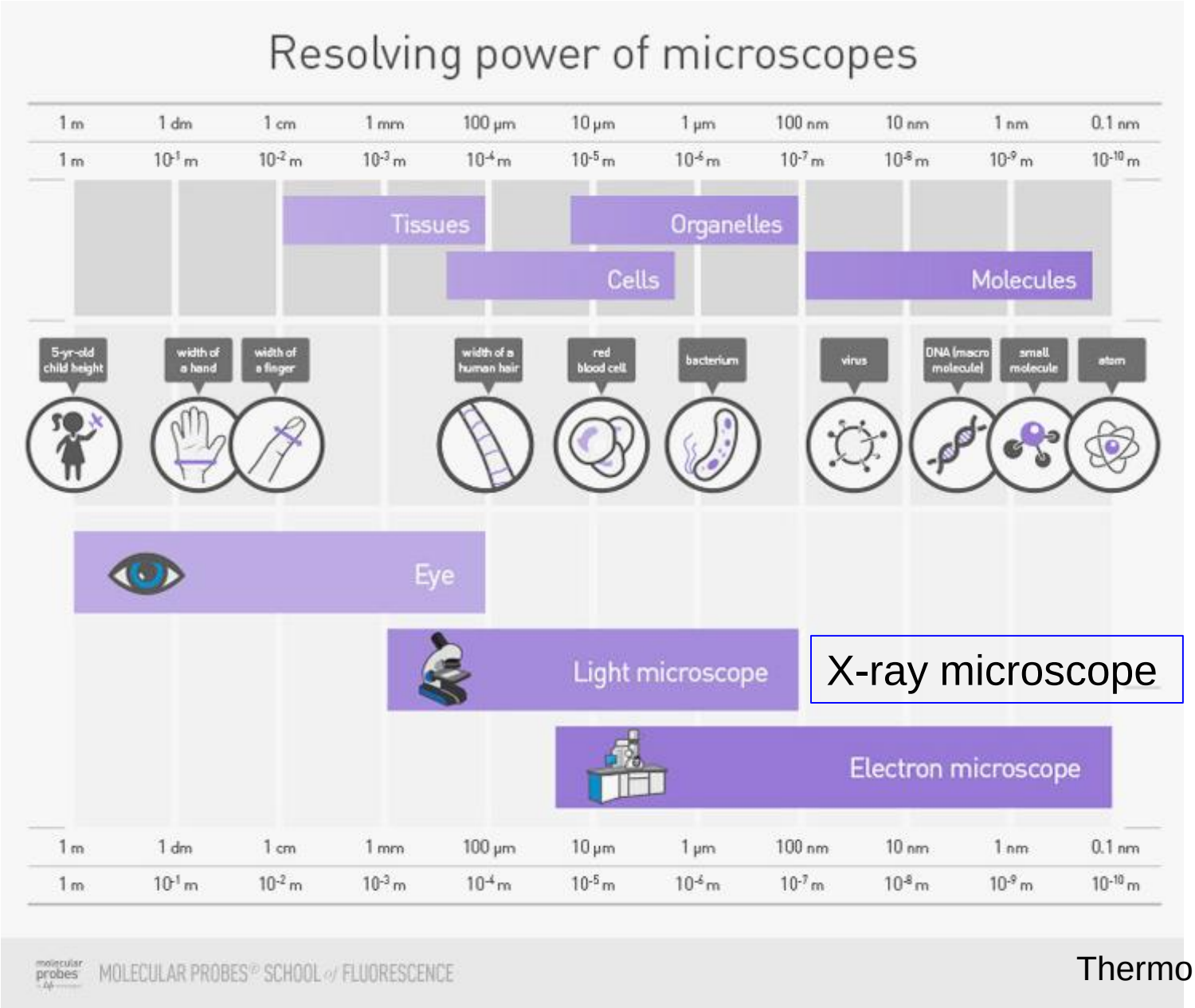
Journey to a Quantum Realm

Quantum Realm as viewed by Ant Man

Ant-Man and the Wasp, Marvel Studios, 2018

In real world, we'll go to Geneva, Switzerland

Why such a big machine to see such tiny things?

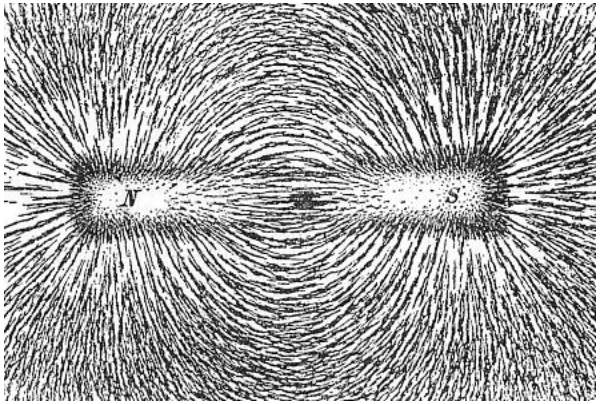


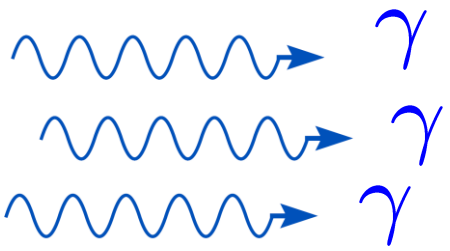
ThermoFisher

Electromagnetism

- Force holding atoms together
- Electricity, magnetism, light, radio waves, ...
- All “carried” by photon, a packet of light

γ





Quantum Mechanics: wave-particle duality

phys.org

Photon energy proportional to light frequency

$$E = h\nu$$

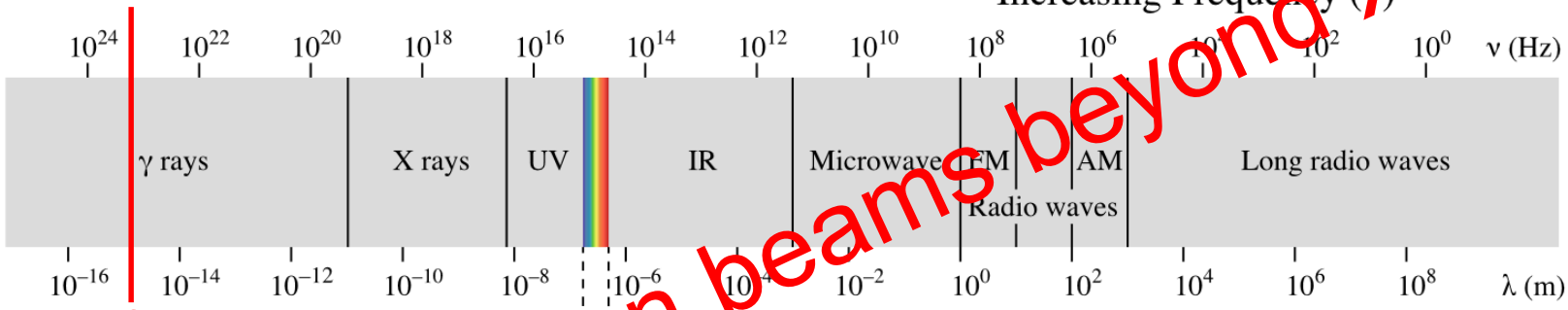
h = Planck's constant = 6.6 x 10^{-34} kgm^2/s = 4.1 x 10^{-15} eV/Hz

E = 10^9 eV = 1 GeV

1 eV

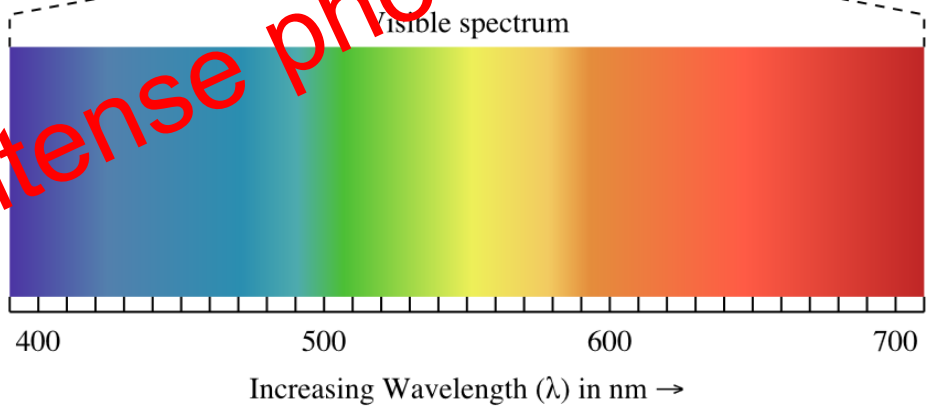
← Increasing Energy

← Increasing Frequency (ν)



size of proton

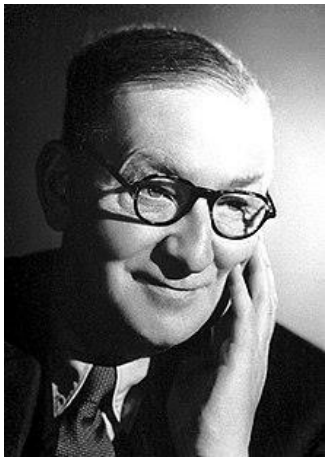
Increasing Wavelength (λ) →



No intense photon beams beyond X-rays!

1 eV = 1 electron-Volt

Solution: Accelerate charged particles, electrons, protons



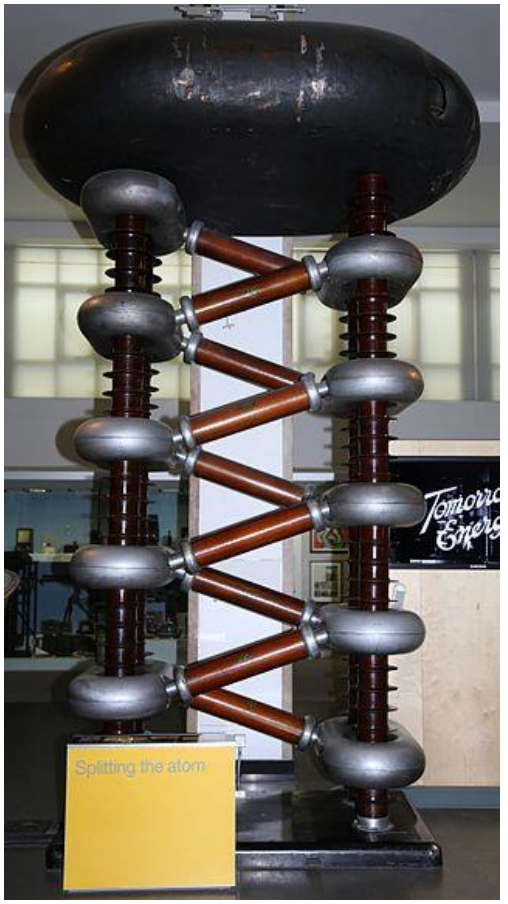
John Cockcroft

Ernest Walton
Trinity College
undergraduate
and TCD professor

Nobel Prize 1951

Importance of being Ernest!

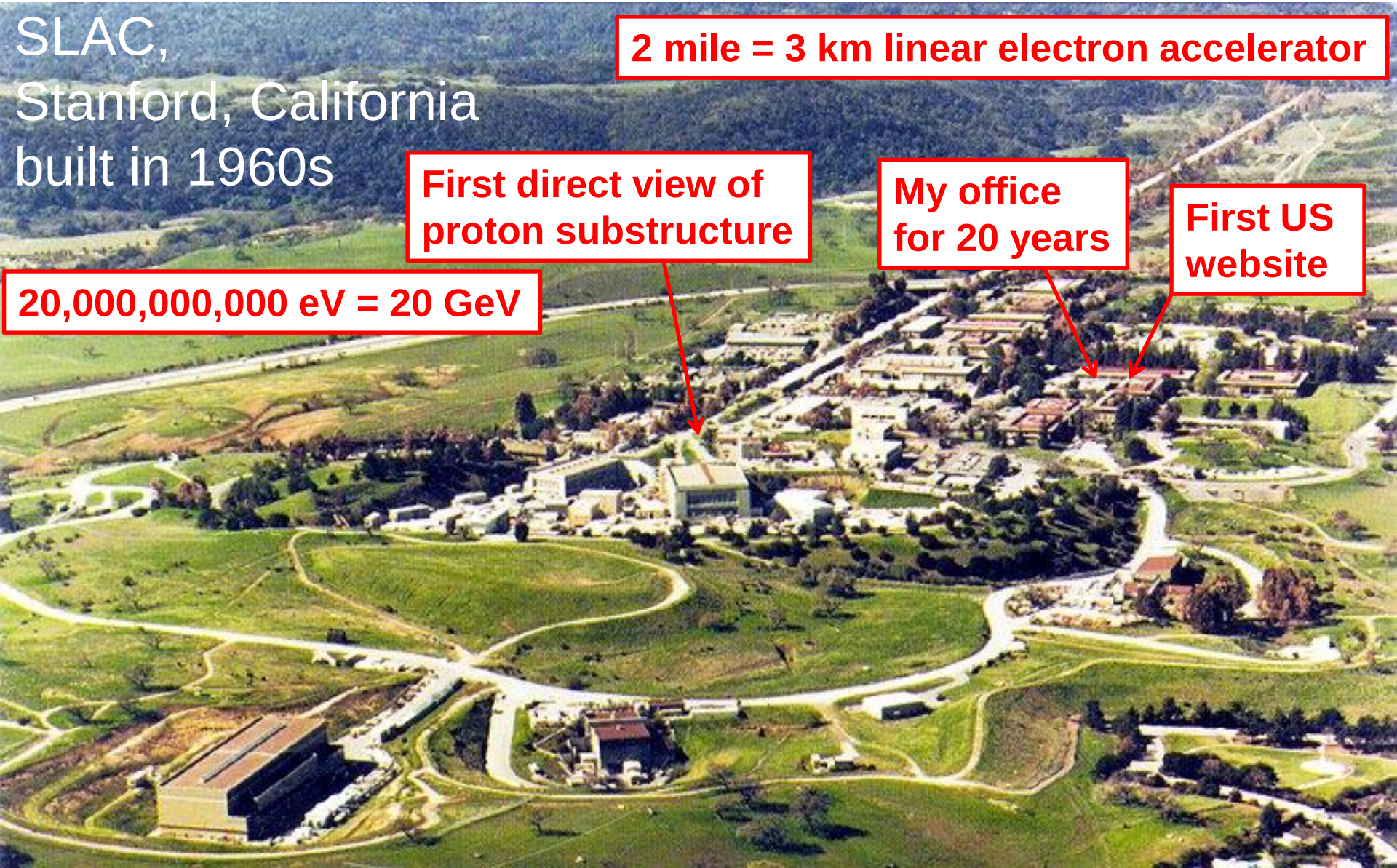
Cockcroft-Walton accelerator, 1932



100,000 to
1 million eV

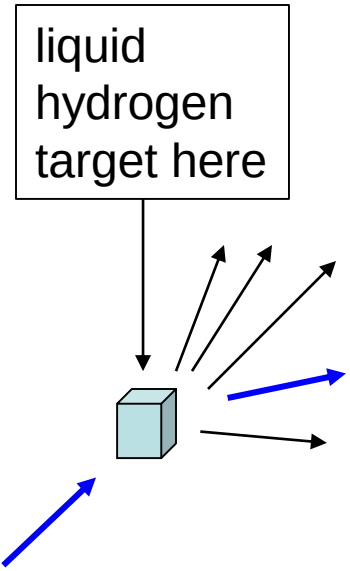
Wikimedia, Geni

Electron microscope on steroids

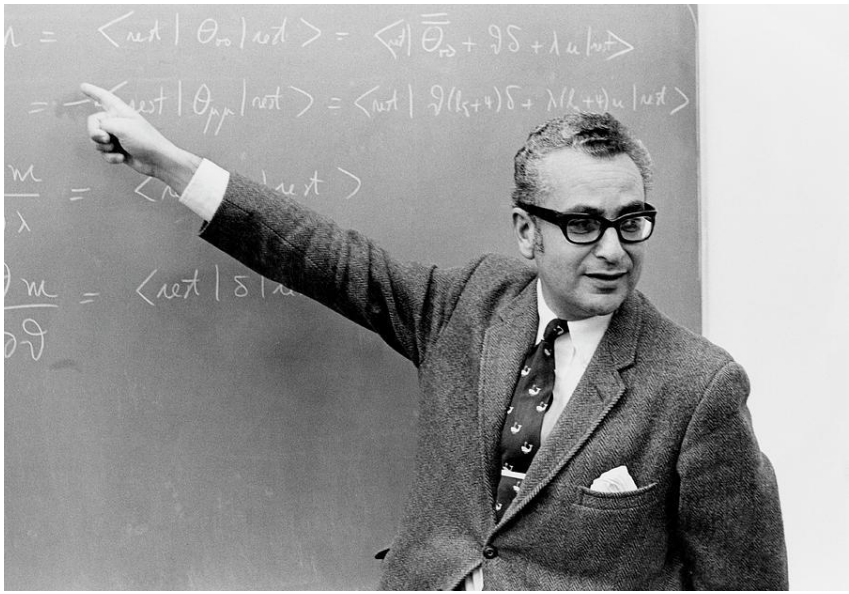


20 GeV electrons scattered off protons

Measured only the electron, saw “hard” scattering



Hard objects inside anticipated ~1963…



Physics Today

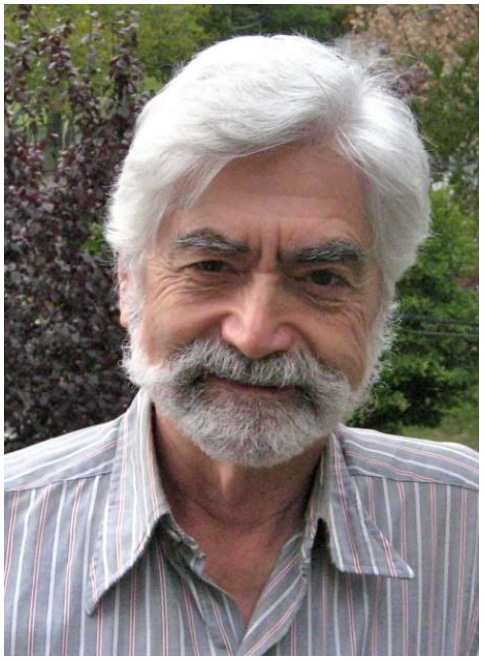
Murray Gell-Mann, 1929 – May 24, 2019

“Three quarks for Muster Mark”

- James Joyce, *Finnegans Wake*

Zürich, Switzerland

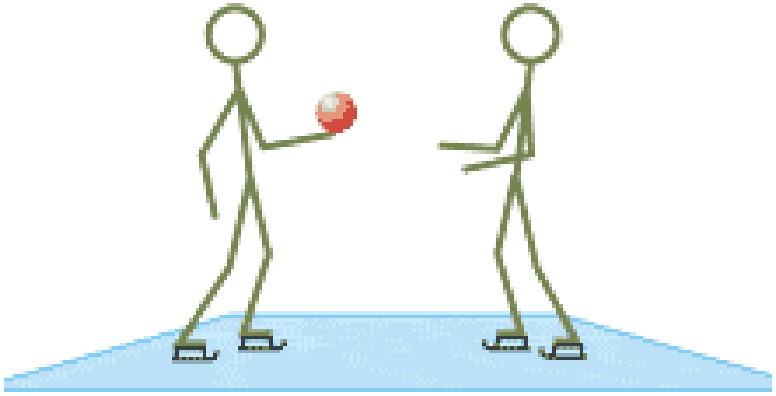
Quarks also invented as “aces”



George Zweig

But “aces” never caught on…

Exchanging particles makes forces



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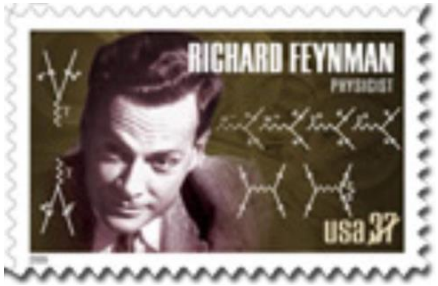
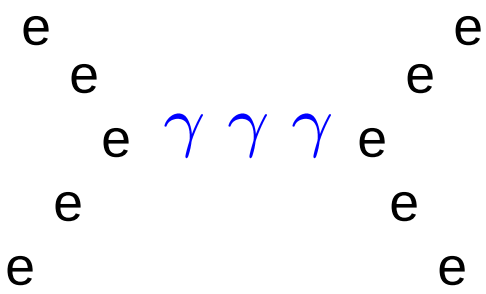
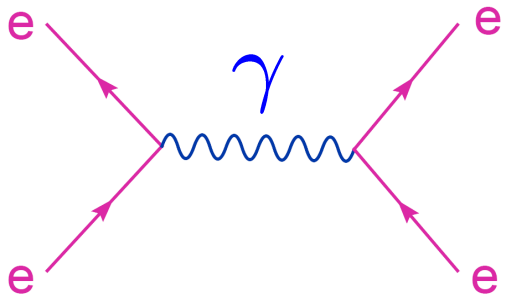


diagrams invented by Richard Feynman, Nobel 1965

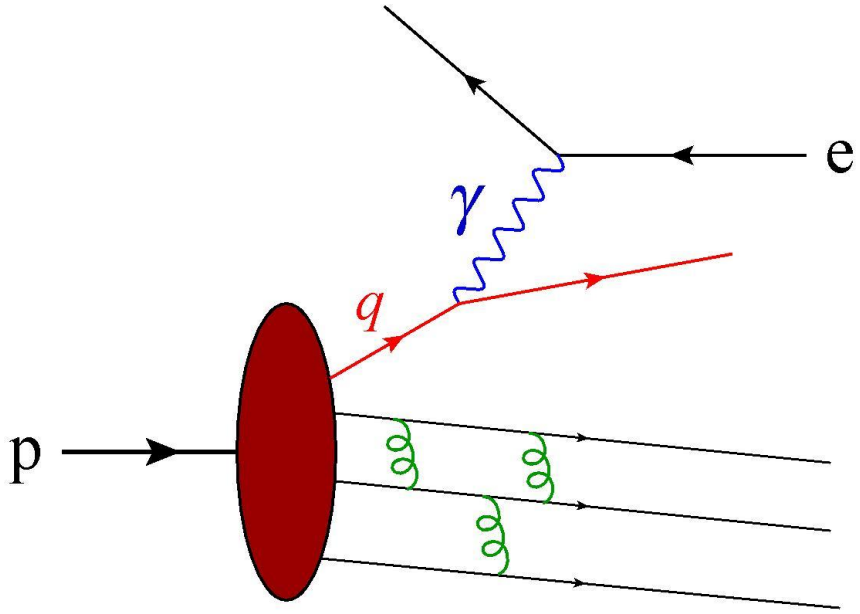




Photons are massless, force is very long range

Force carriers for weak interactions are heavy, force is very short range

Picture of electron proton collision



"Virtual" photon sends electromagnetic force from electron to proton

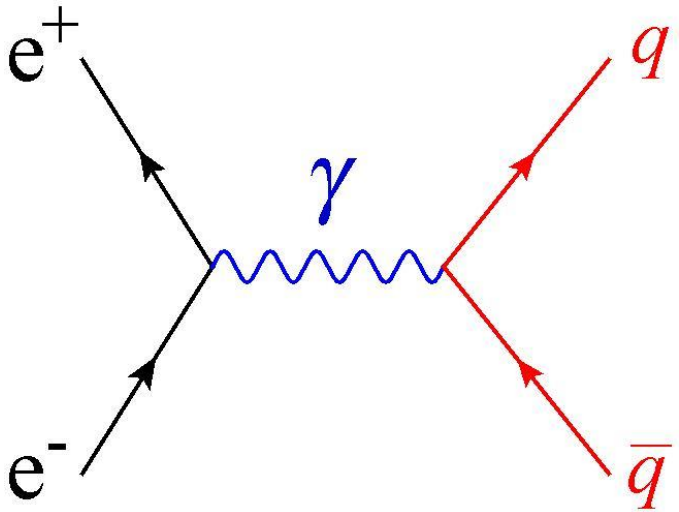
High energy → happens extremely fast
- electron can strike only one quark at a time
- quark doesn't realize that it's bound (at first)

→ **"See" quarks within the proton as if they were free!**

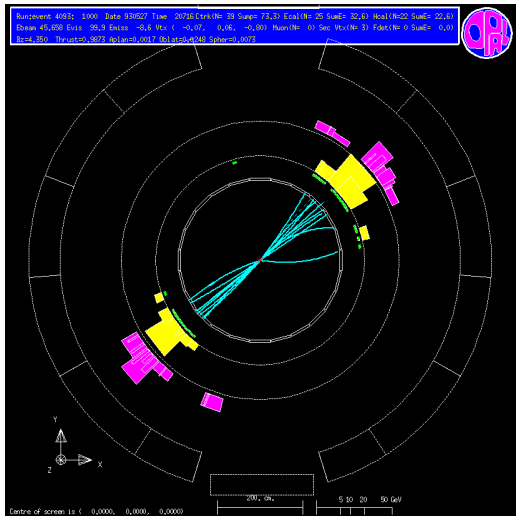
What happens to the quark?

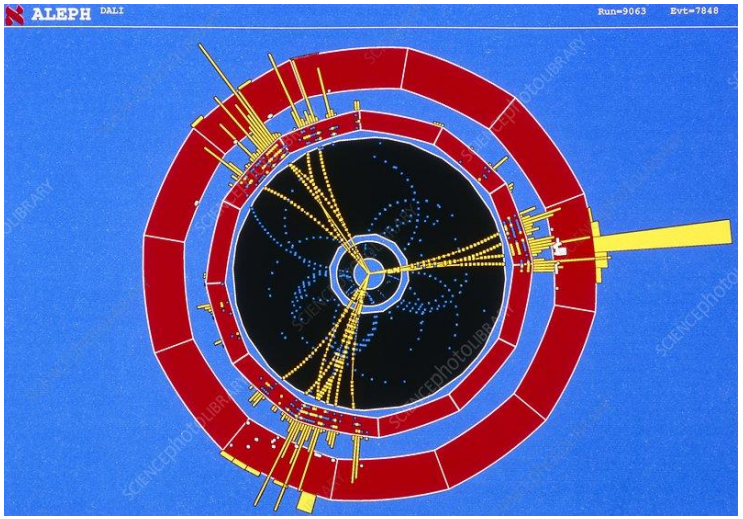
- Easiest to see when one makes quarks out of “nothing”
- Instead of colliding electrons with protons,
  collide electrons with positrons.
- Positrons = anti-electrons. First predicted by P.A.M. Dirac
- Like electron moving back in time.
- Much simpler than a proton!
- Electron + positron annihilate into a virtual photon (or Z boson), which can materialize into a quark and it’s anti-quark.

Time →

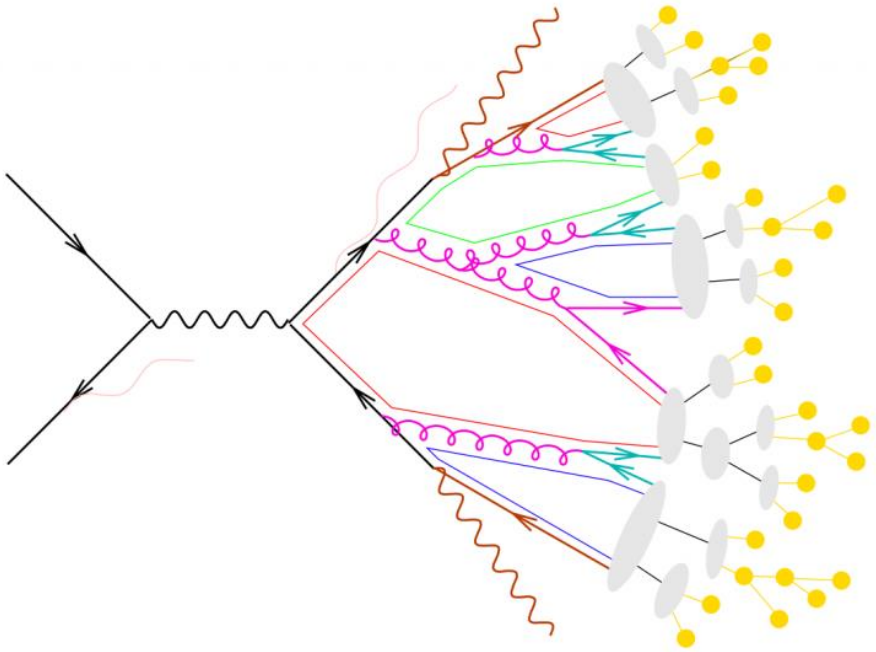


“Jets” of strongly interacting particles





LEP
CERN
1990s



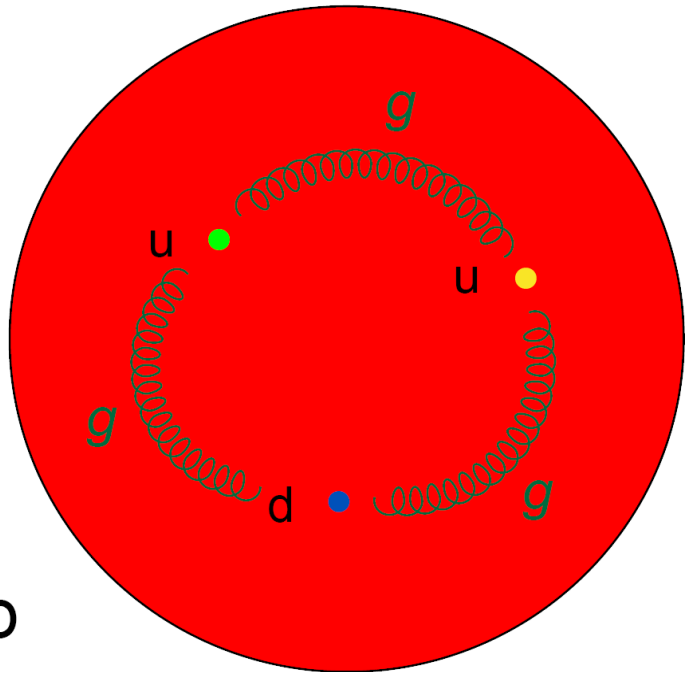
Third jet is from gluon, force carrier of the strong interactions

At long distances gluons bind quarks into protons and other hadrons: confinement

At short distances, quarks and gluons act almost like free particles

The Strong Force or QCD

- Holds quarks together tightly inside proton,
- Also holds protons & neutrons together inside nuclei
- Carried by gluon *g*



gluon named by Harald Fritzsch, Gell-Mann, Heinrich Leutwyler, 1971-73

quarks have flavor (u, d, …)
but also color which gluons "see"
like photons see electric charge.

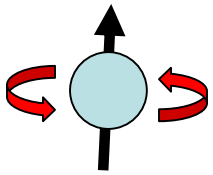
Theory of electron-photon interactions:
Quantum ElectroDynamics (QED)

Theory of quark-gluon interactions:
Quantum ChromoDynamics (QCD)

More from Finnegan’s Wake

- p. 26, "such pivotal ancestors as the Glues, the Gravys, the Northeasts"
- p. 85, "dieting against glues and gra-vies"
- p. 118, "can be built with glue and clippings"
- p. 204, "his smile likequid glue (the suessiest sourir ever weanling wore)"
- p. 286, "his mother was a gluepot"
- p. 329, "Glue on to him, Greevy!"
- p. 360, "Like glue. Be through."
- p. 470, "His lapper and libbers was glue goulewed"
- p. 476, "pretty decent trade price for my glueglue gluecose"
- p. 528, "the gren, woid and glue been broking"

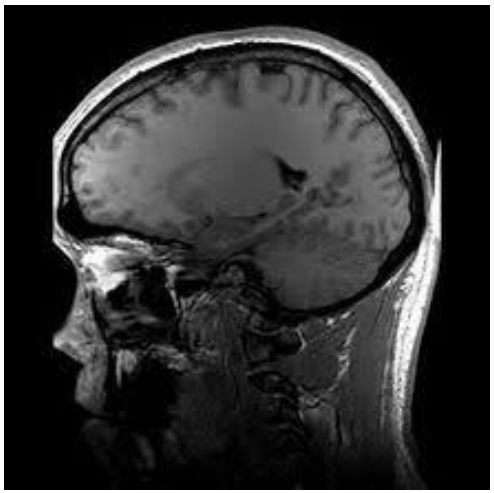
A little spin



- Particles, like little tops, carry a small amount of angular momentum: $\vec{J} = \hbar\vec{S}$

$$S = 0, \frac{1}{2}, 1, \frac{3}{2}, 2, \ldots$$

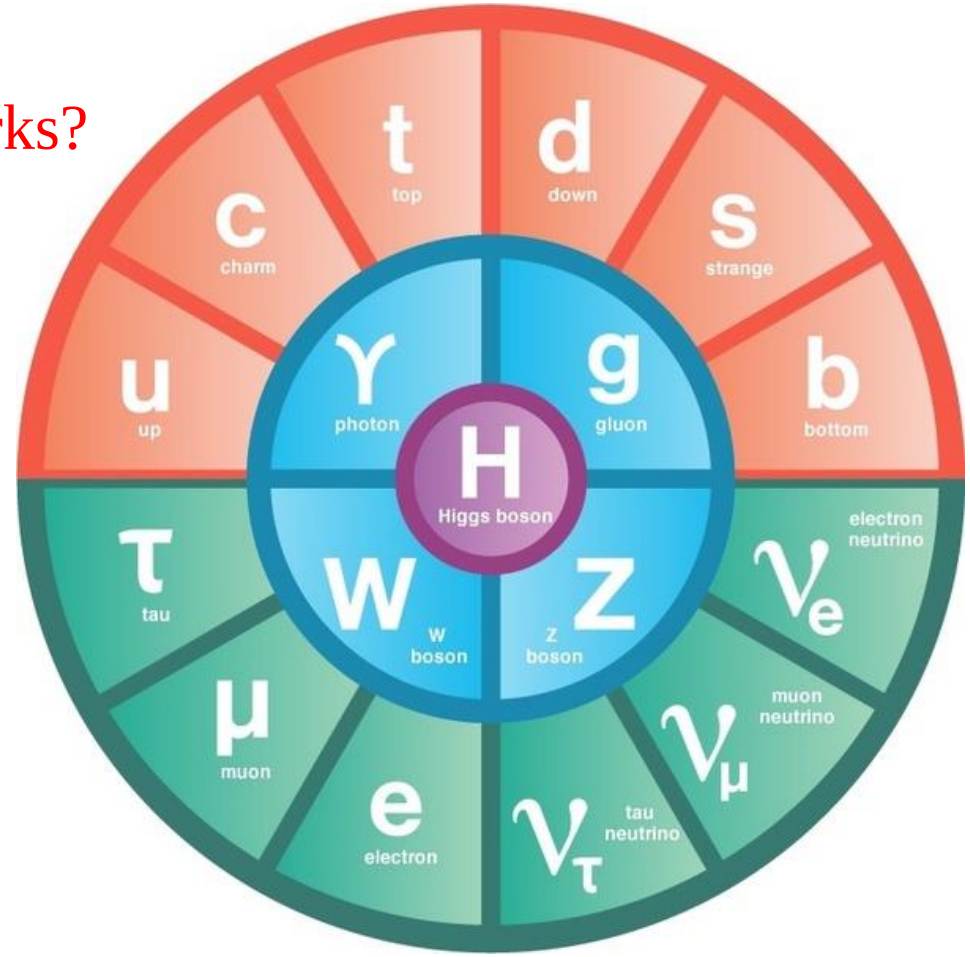
- Proton spin used everyday for MRI



All known elementary particles

6 quarks
for 2 Muster Marks?

$S = \frac{1}{2}$



4 force
carriers

$S = 1$

6 leptons
(light ones)

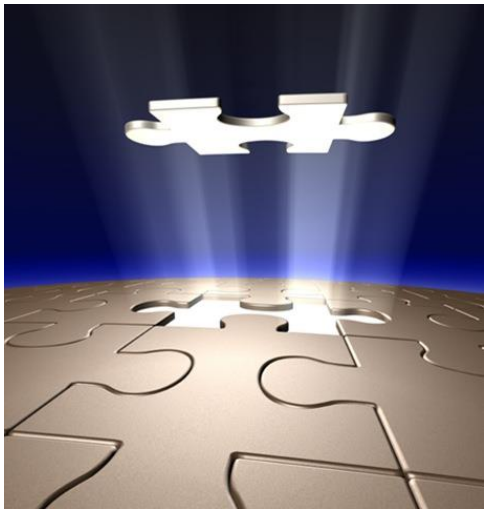
$S = \frac{1}{2}$

1 Higgs
boson

$S = 0$

The elusive Higgs boson

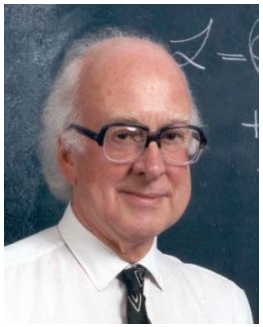
Last missing piece in
a theory of matter and
subatomic forces,
five decades in the making



- Conceived in 1964
- Experimental searches began around 1980
- More seriously in 1990s and 2000s
- Took thousands of clever physicists

working at increasingly powerful
particle accelerators around the world

An explanation for "origin of mass" given 55 years ago



Peter Higgs

idea came to Higgs in 1964 while walking in the Cairngorms, Scotland

Required a new particle – the Higgs boson

Many similar ideas percolating at same time

→ Higgs boson sometimes known as

"Anderson-Brout-Englert-Guralnik-Hagen-Higgs-Kibble boson"

Mass

- Ability to resist being accelerated by a force:

$$F = m\,a$$

or

$$a = F/m$$

A World Without Mass

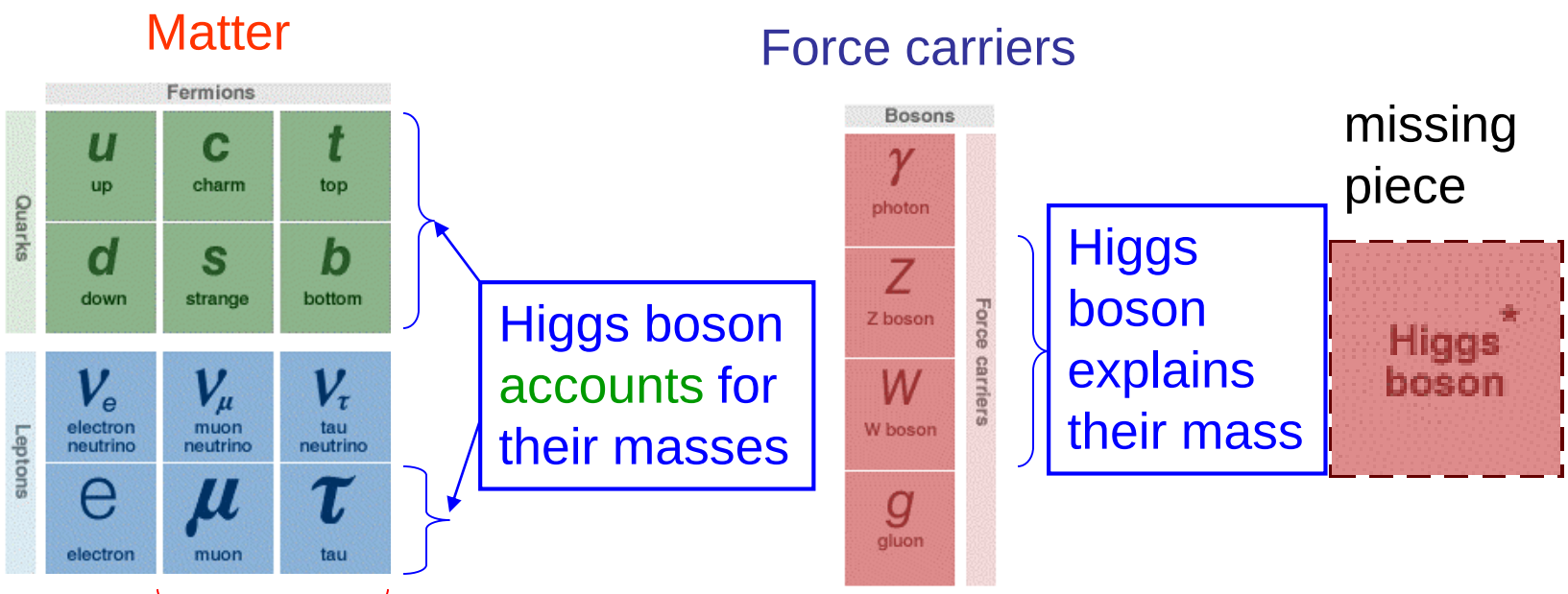
Without mass for elementary particles,
the world would look very different

Photons have
no mass,
zip around
at speed of light

If electrons also had no mass,
they would zip around at speed of light too

→ All atoms, all matter would instantly fly apart!

Higgs completes “Standard Model” – description of matter & subatomic forces



a bizarre set of numbers (in units of proton mass)

heavier cousins, only made at accelerators, decay fast

stable, everyday matter

$m_u = 0.003$ $m_c = 1.3$ $m_t = 184$

$m_d = 0.006$ $m_s = 0.12$ $m_b = 5.0$

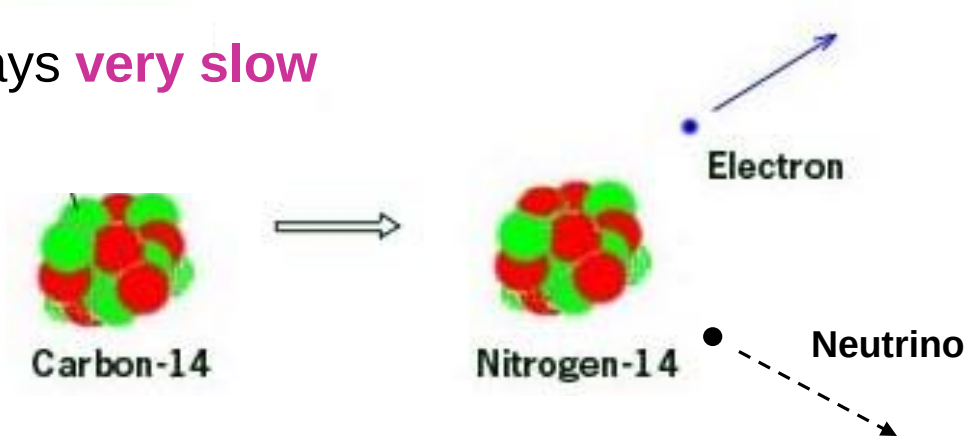
$m_e = 0.0005446$ $m_\mu = 0.1126$ $m_\tau = 1.894$

The Weak Force

- Responsible for some kinds of radioactivity
- Only force neutrinos can feel
- Carried by weak bosons

W^+ W^- Z

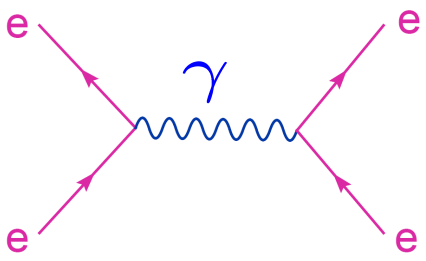
Weak decays **very slow**



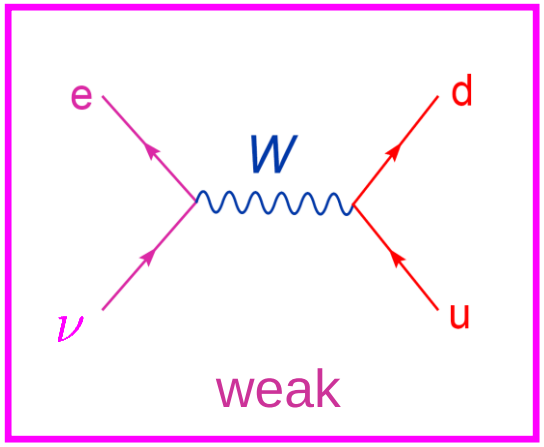
Carbon-14 decay takes 6,000 years!

Why so slow? Most subatomic processes over in blink of an eye.

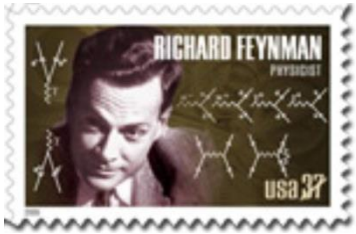
Electromagnetism *vs.* Weak Force



electromagnetism



weak



Many similarities, but one **big** difference:

- photon a **massless particle**

→ **always** travels at speed of light
force long range

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- *W* and *Z* **very massive** (100 times proton mass)

→ **force very short range** (1/100 of proton radius)

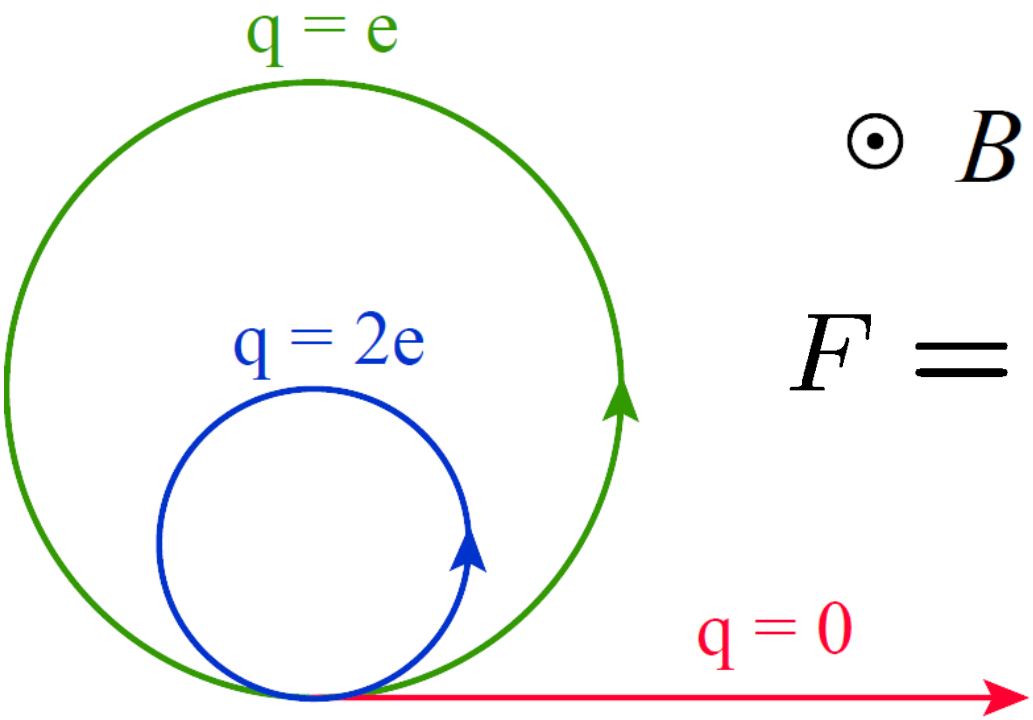
→ **Weak processes very slow!**

“Origin of curvature from magnetic field”

Photon, a particle, comes with

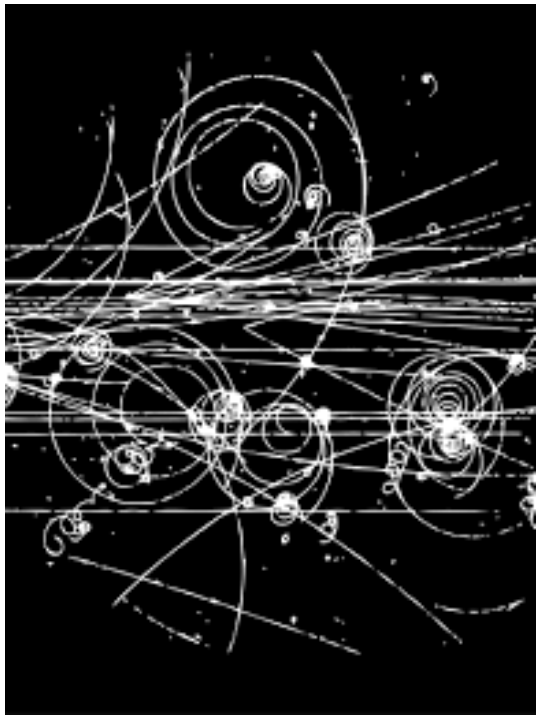
electric & magnetic fields

- Those fields alter trajectories of particles that talk to the photon (have electric charge)
- We can change E and B fields easily



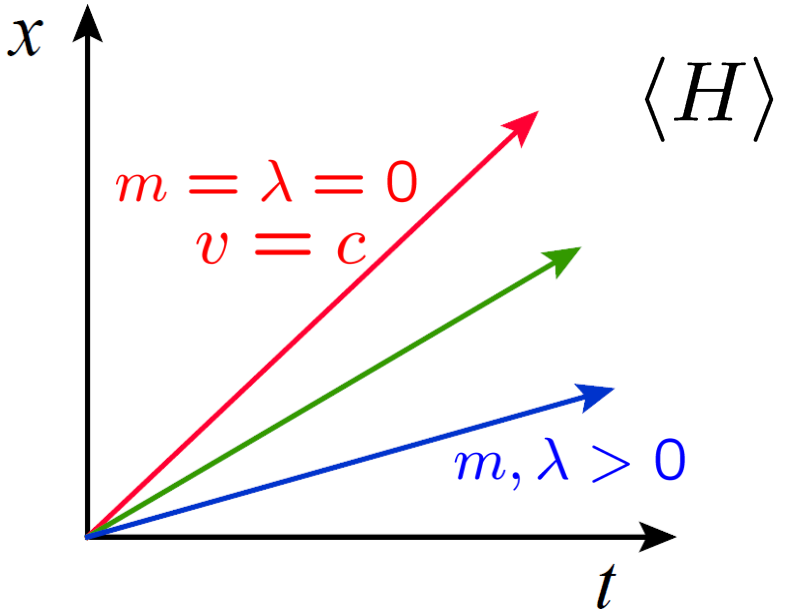
$\odot\ B$

$$F = qvB$$



Origin of mass from Higgs field

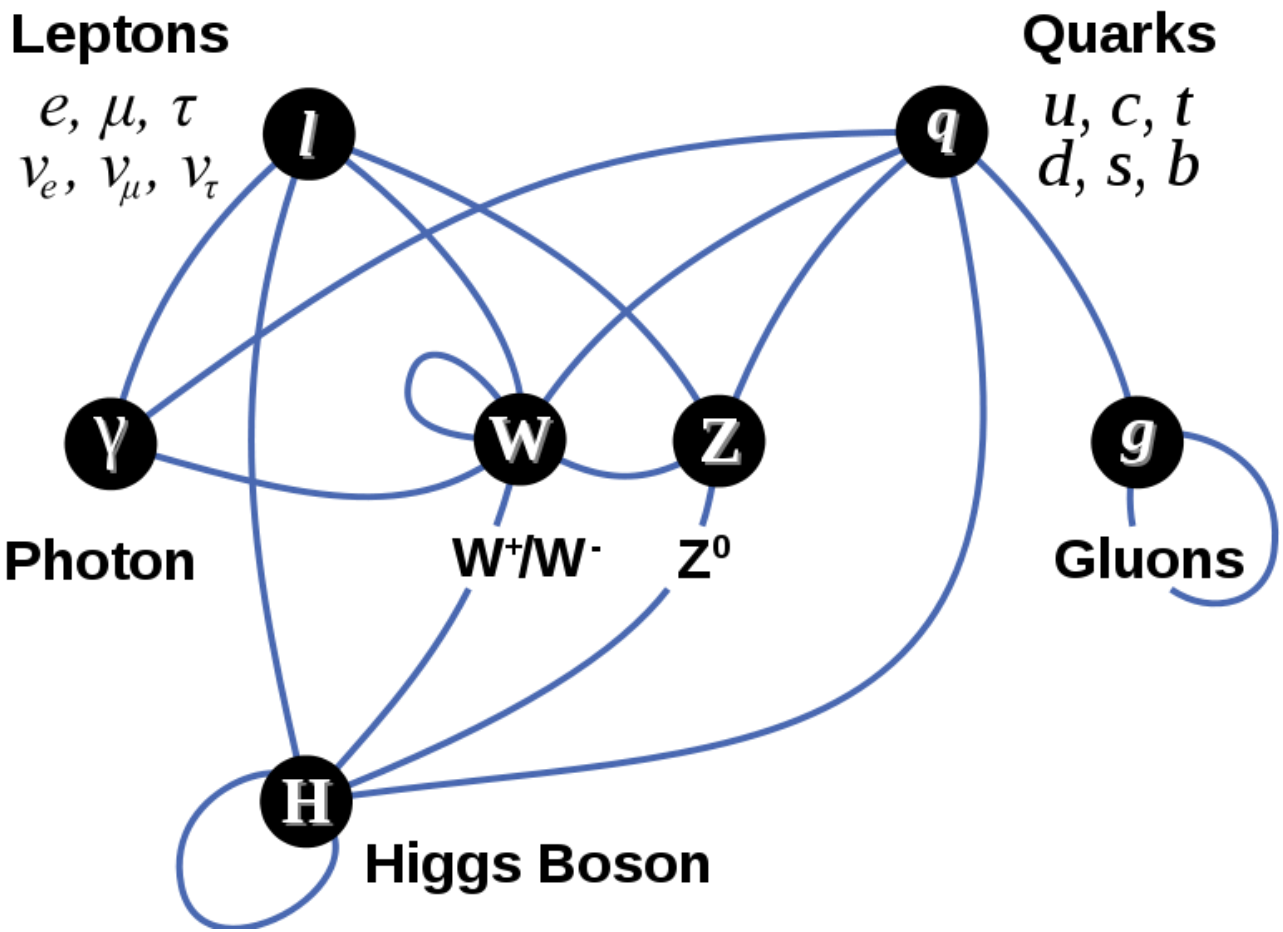
- Higgs boson, a particle, comes with Higgs field $\langle H \rangle$
- Higgs field alters trajectories of particles that talk to it (→ have mass)
- **Can't** change the Higgs field; costs too much energy.
- Higgs field has always been turned on, since first nanosecond after Big Bang
- Constant everywhere in space



$$m = \lambda \langle H \rangle$$

HIGGS IS A

Higgs talks to almost everyone



…but not equally

Why so elusive?

- Higgs boson talks mostly to heavy particles

- Heavy particles decay quickly: can't make particle beams out of them, to collide at accelerators!

proton: $m_u = 0.003$, $m_d = 0.006$

electron: $m_e = 0.0005446$

$m_c = 1.3$ $m_s = 0.12$ $m_\mu = 0.1126$

$m_t = 184$ $m_b = 5.0$ $m_\tau = 1.894$

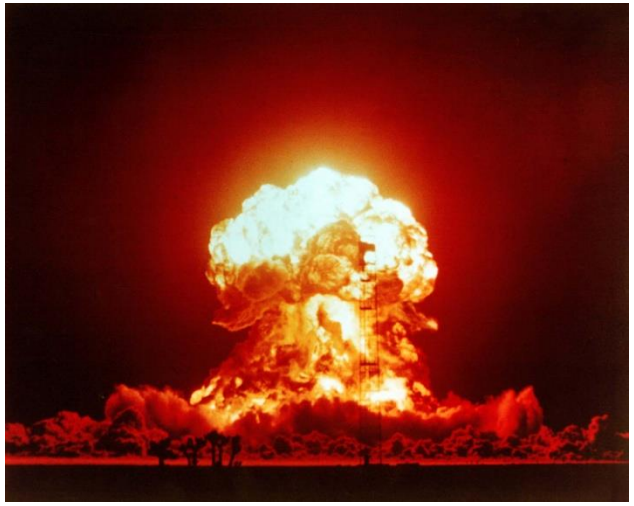
talk to Higgs, but decay fast

→Very small probability of making Higgs boson in collisions of electrons, protons

Energy ←→ mass

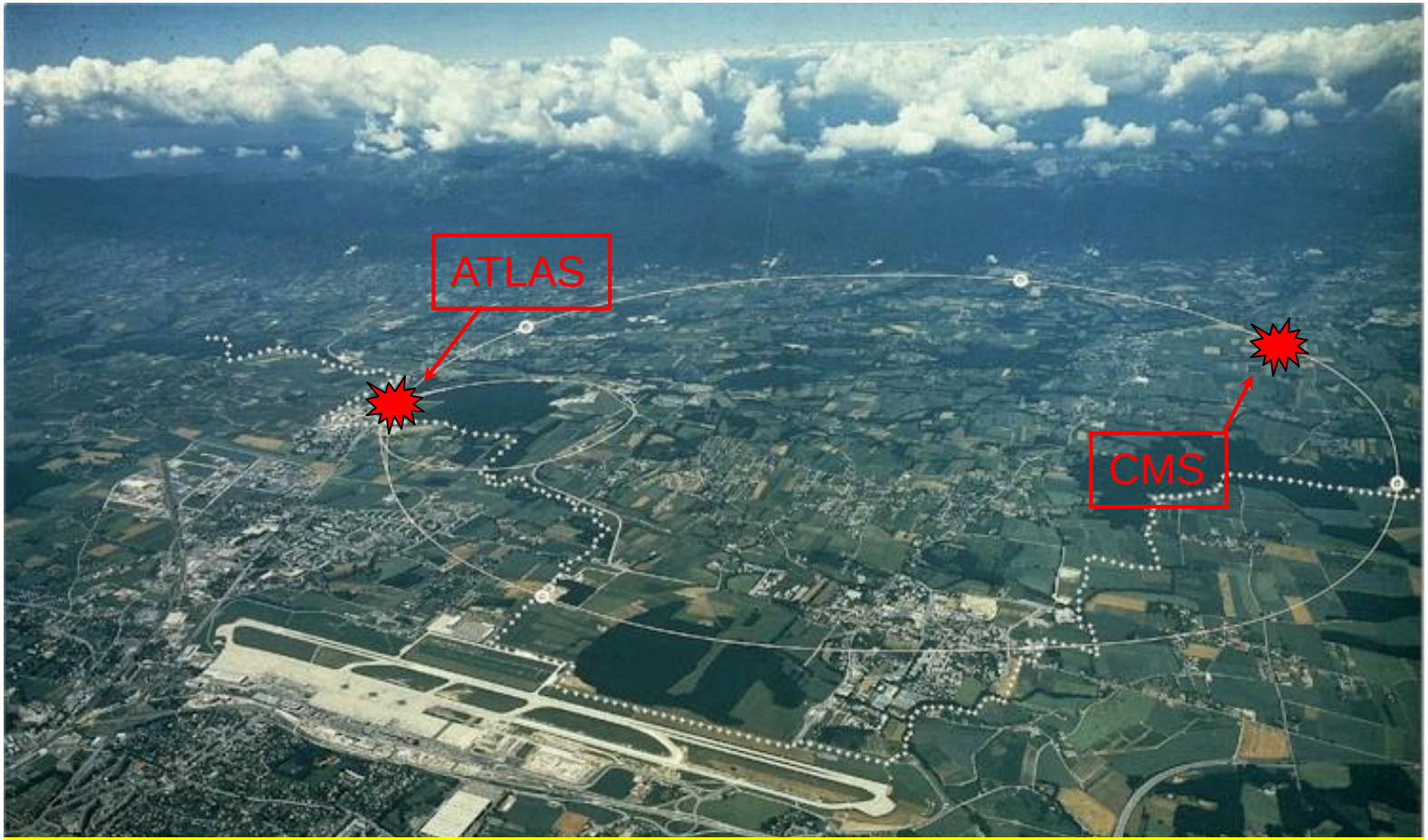
Einstein: $E = mc^2$

All matter contains energy, stored in its mass



Need lots of energy to make a very heavy particle

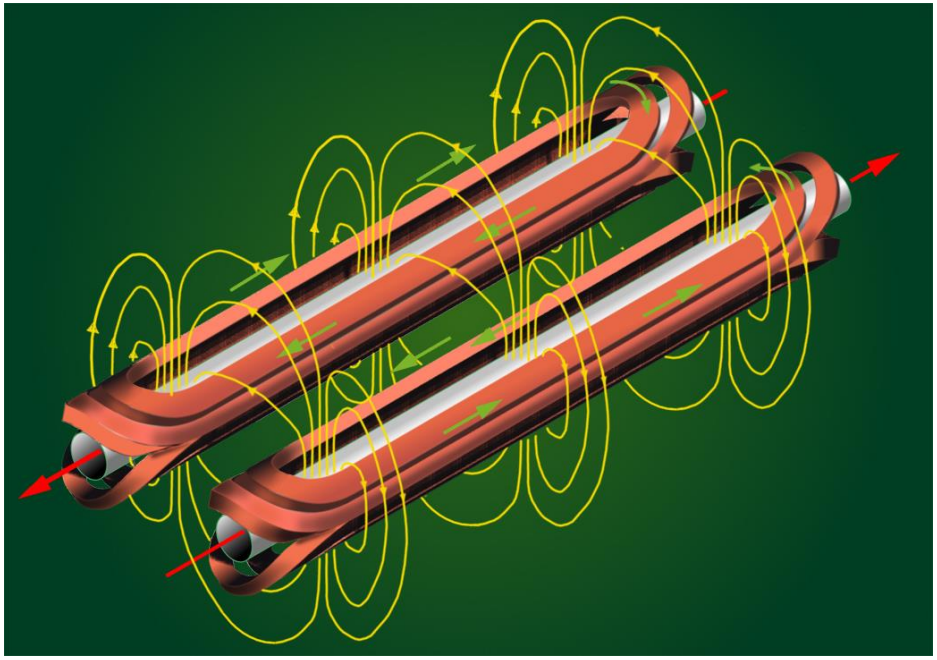
The Large Hadron Collider



World's most powerful particle collider, 27 km around CERN, Geneva, Switzerland
Collides protons at 13,000 GeV. 2008 → 2030??

Main LHC tunnel

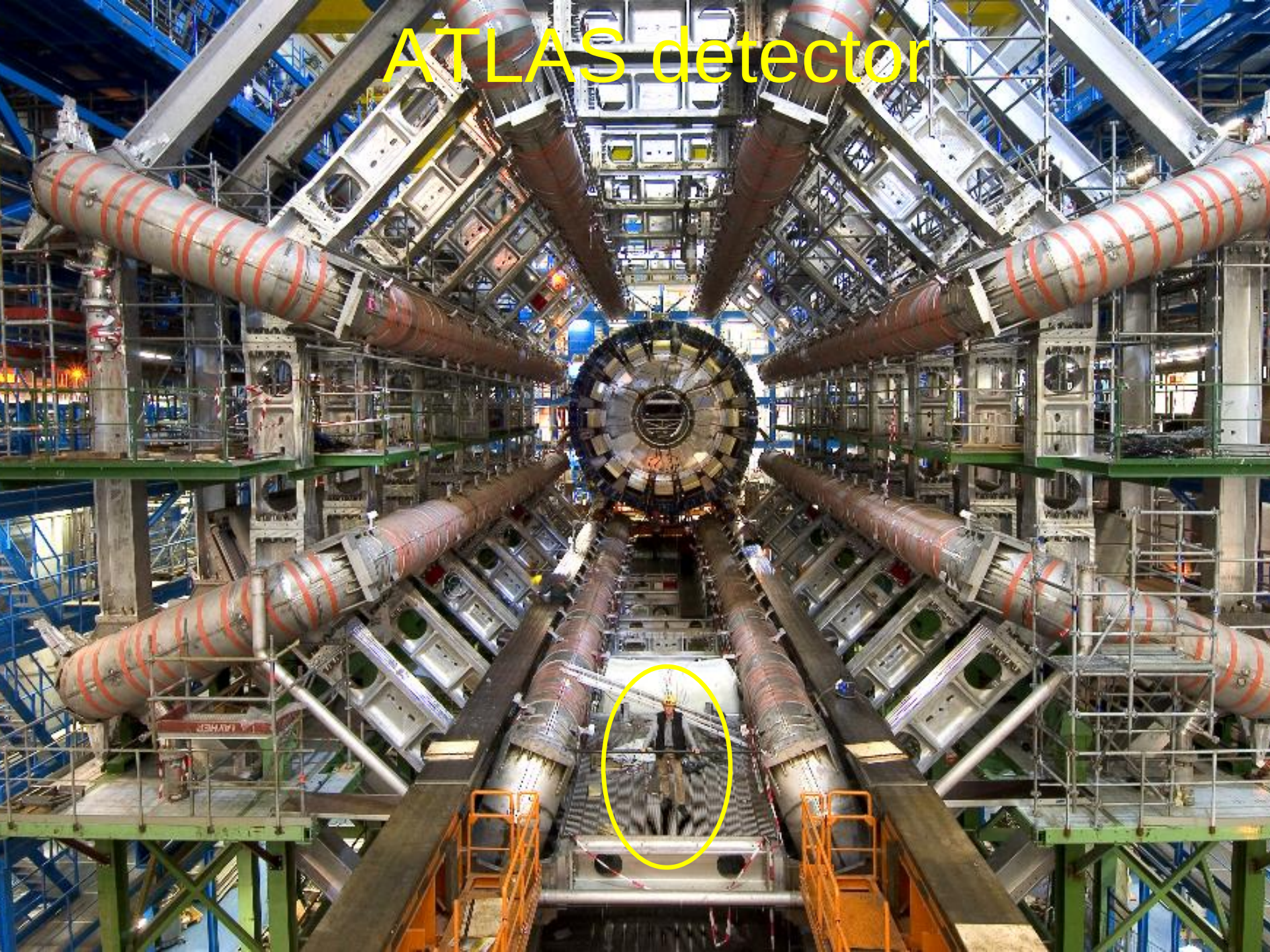
LHC dipole magnets



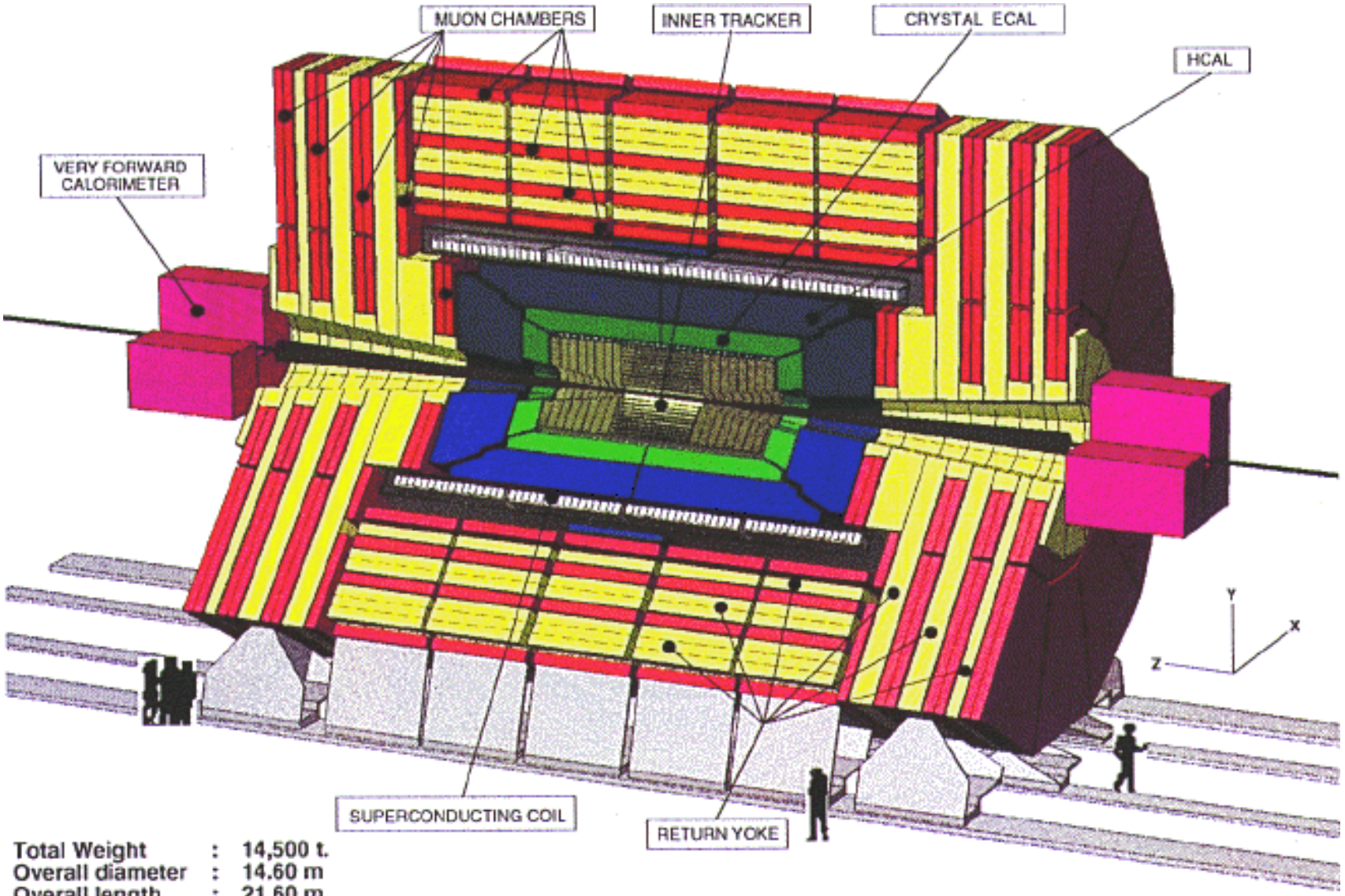
To bend protons moving at 99.999999% of speed of light around a circle, need a 27 km ring almost completely filled with a magnetic field of 8 tesla

More than the field in an MRI, more than 100,000 times Earth's field

Superconducting Niobium-Titanium chilled to 1.9 degrees from absolute zero

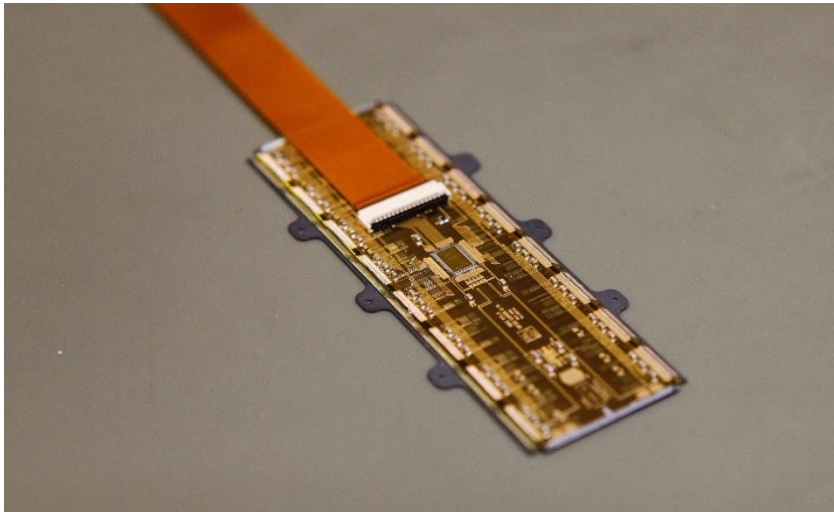

ATLAS detector

CMS detector

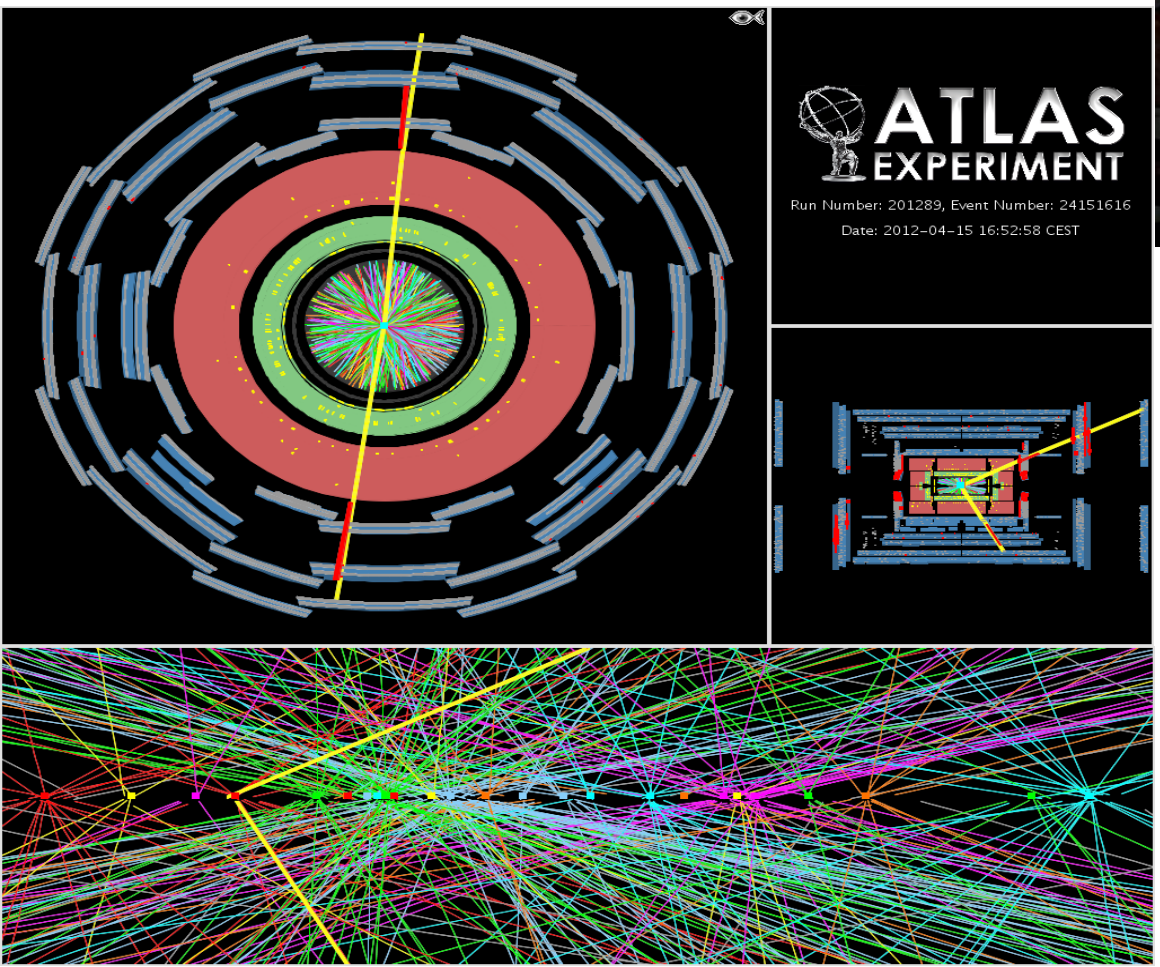


Detector construction:
unique blend of ship-building
and nano-fabrication

3,000 collaborators each
in ATLAS and in CMS

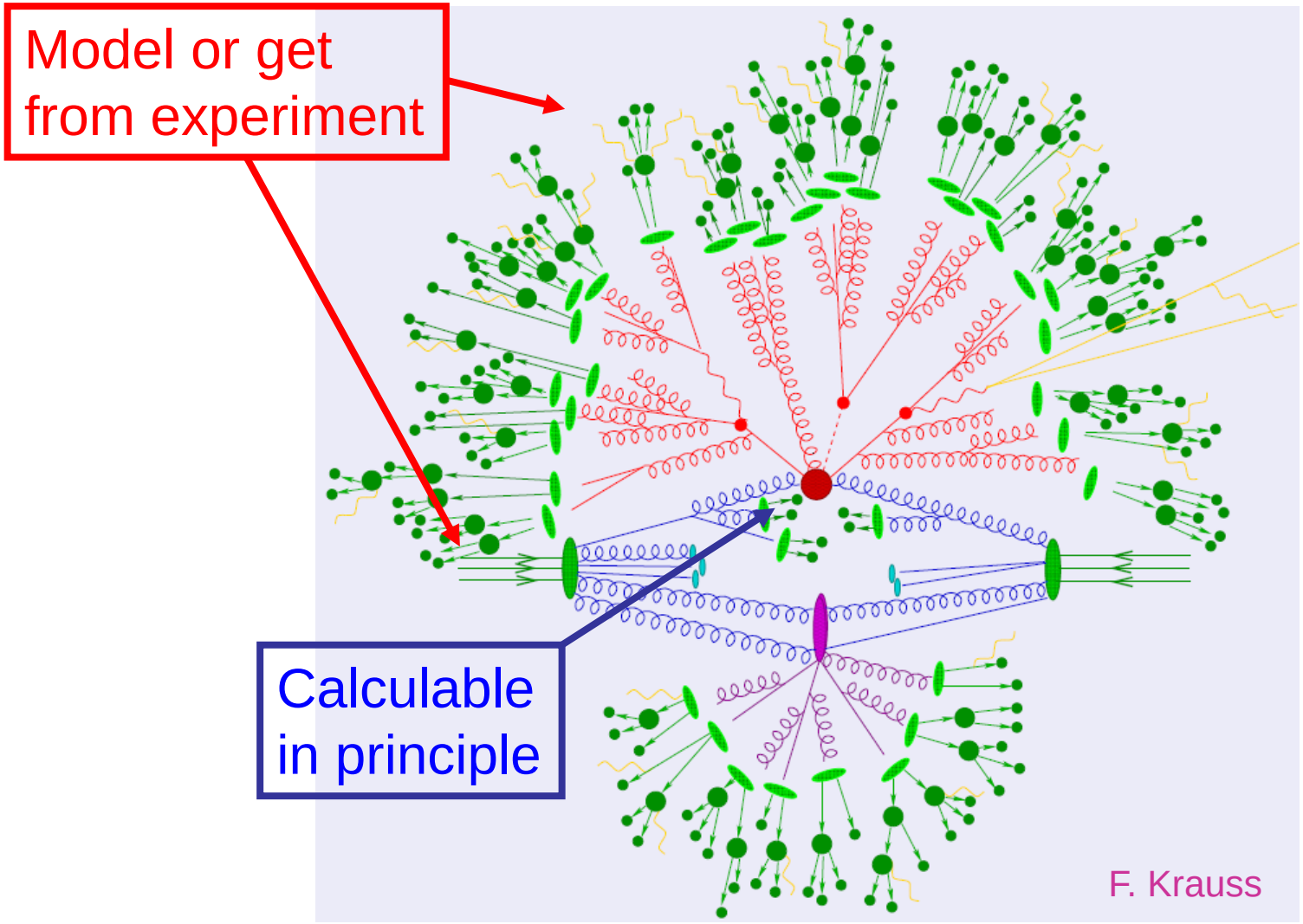


LHC: the ultimate data firehose

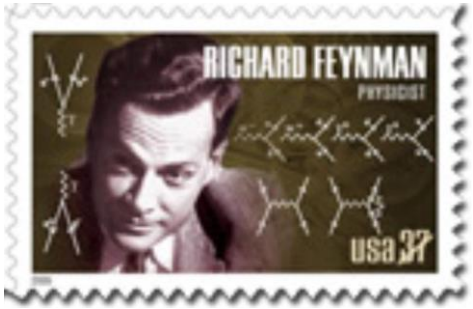


- About 20-60 simultaneous proton-proton collisions
- Repeated 20 million times a second!
- Can only afford to save a few hundred events per second for later study.
- “Trigger” electronics decides very quickly which events to keep.

Typical LHC Collision

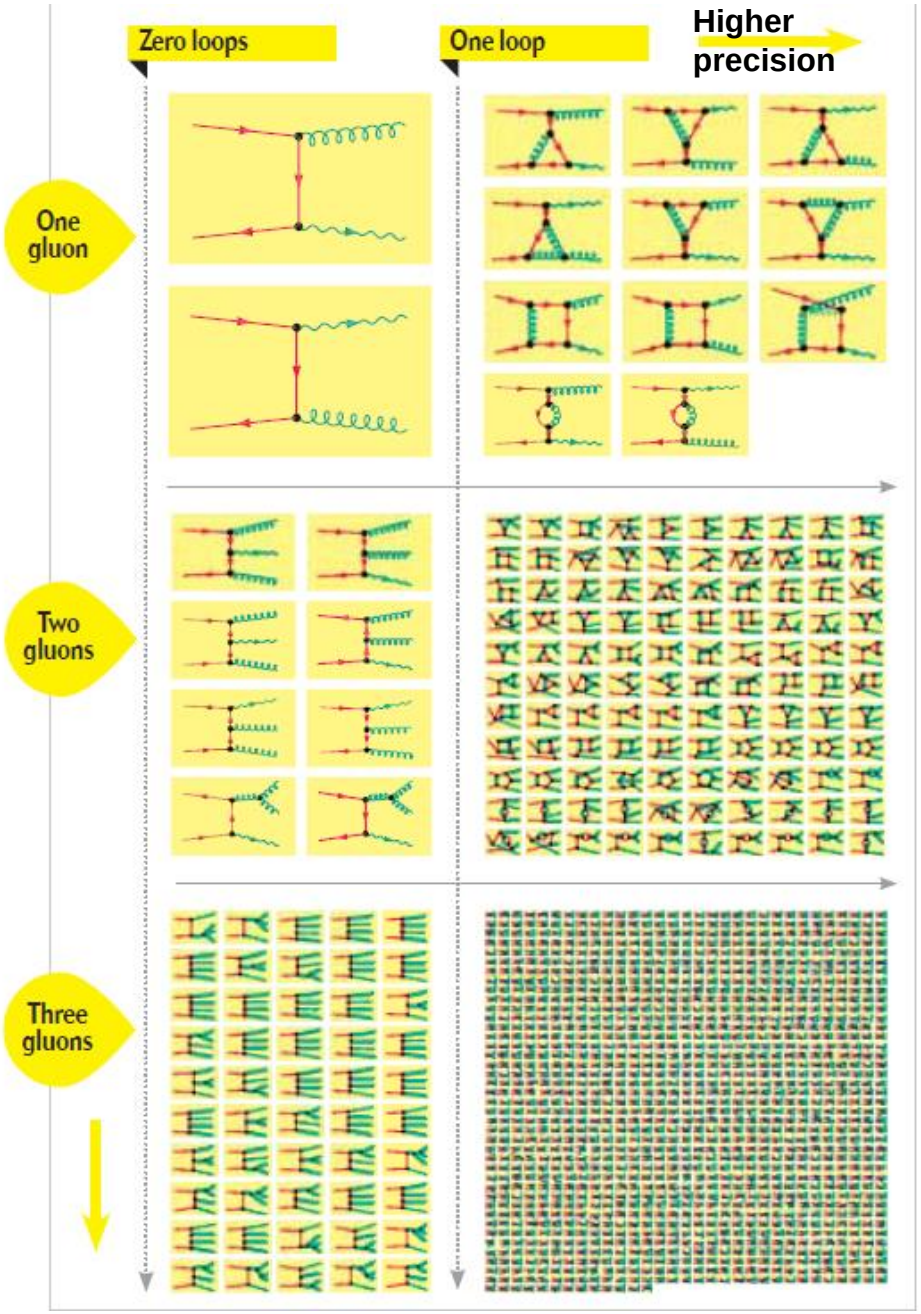


“in principle” can be a big challenge

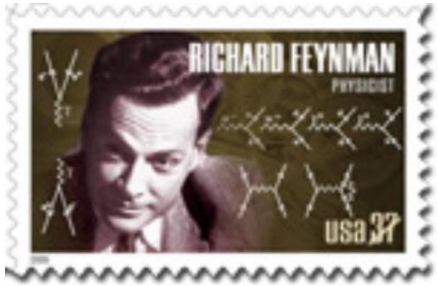


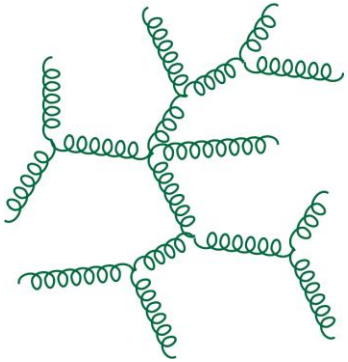
Feynman diagrams for

$$q\bar{q} \rightarrow W + 1, 2, 3 \text{ gluons}$$

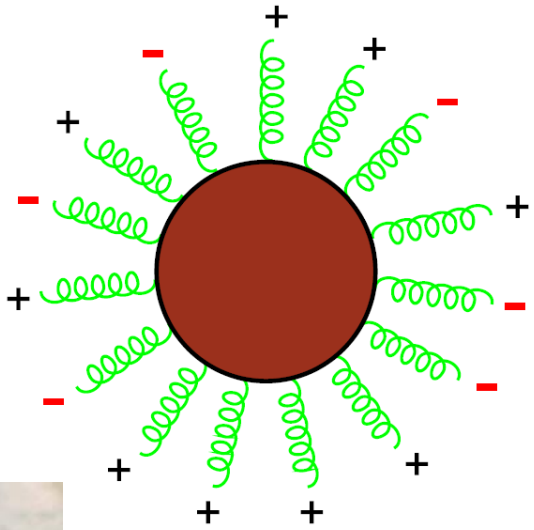


Granularity vs. Fluidity





+ …



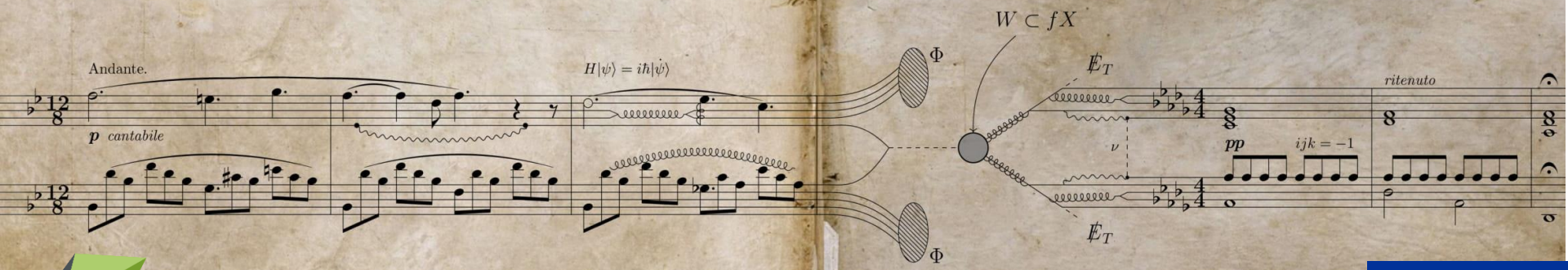
Amplitudes 2019

Trinity College Dublin

1-5 July 2019

Organizers:

Ruth Britto
Vittorio Del Duca
Tristan McLoughlin
Donal O'Connell
Jaroslav Trnka
Dmytro Volin



SAGEX
Scattering Amplitudes: from Geometry to Experiment

IOP Institute of Physics In Ireland

LHC as of July 4 2012

- Over 800 trillion proton-proton collisions

- Fewer than 800 Higgs boson candidate events

- In last 7 years, 30 times as many collisions

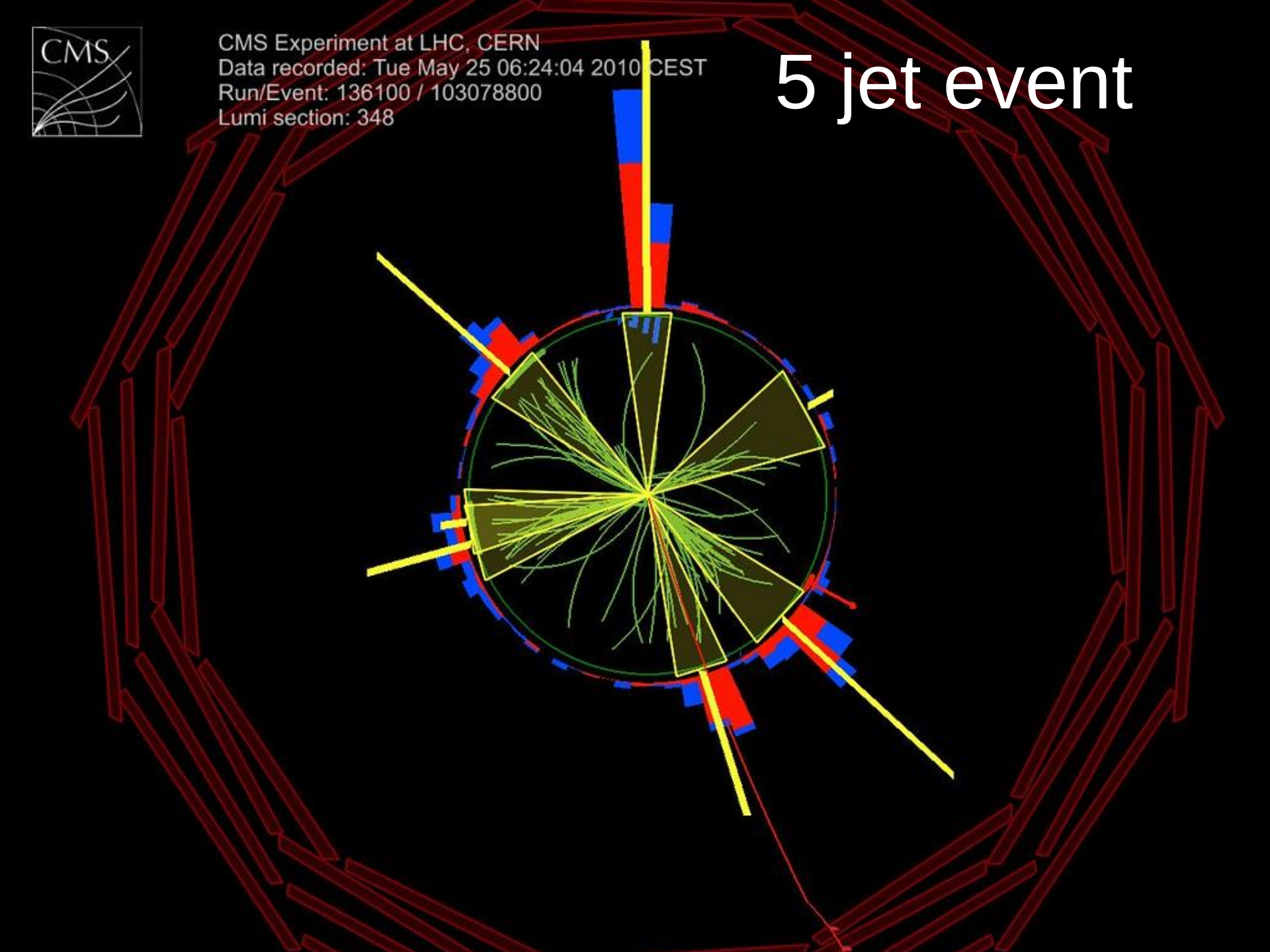
Possible Higgs “Disguises” (ways to decay)

• When Higgs boson is produced, it instantly decays, usually to heaviest pair of particles it can

• Usually decays to quarks and gluons

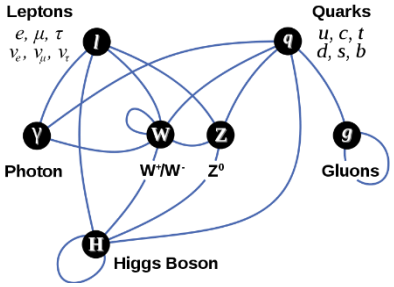
• Or to *W* or *Z* particles, which usually decay to quarks too

quark and gluon “disguises” very effective at proton colliders, Because they make **jets** and **jets are copious** at the LHC
→ **very large backgrounds**


CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348

5 jet event

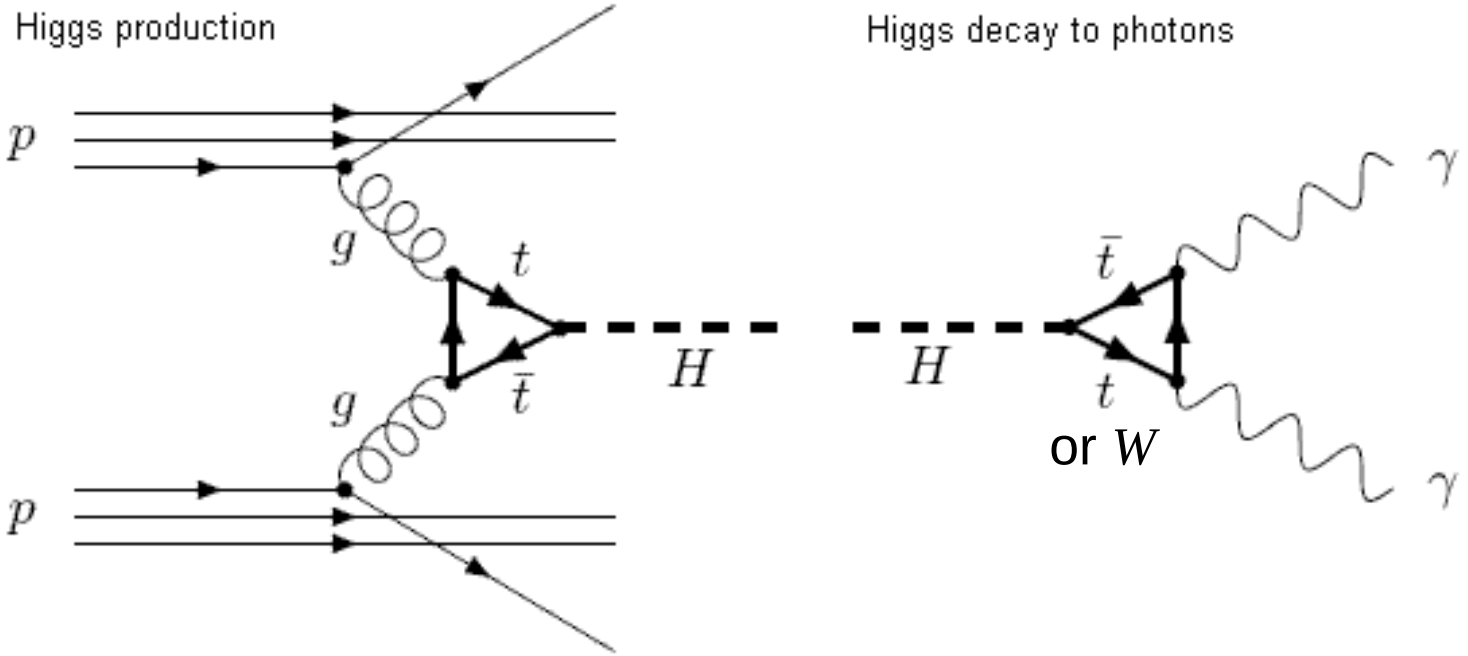
Decay to pure light



One of best cases:

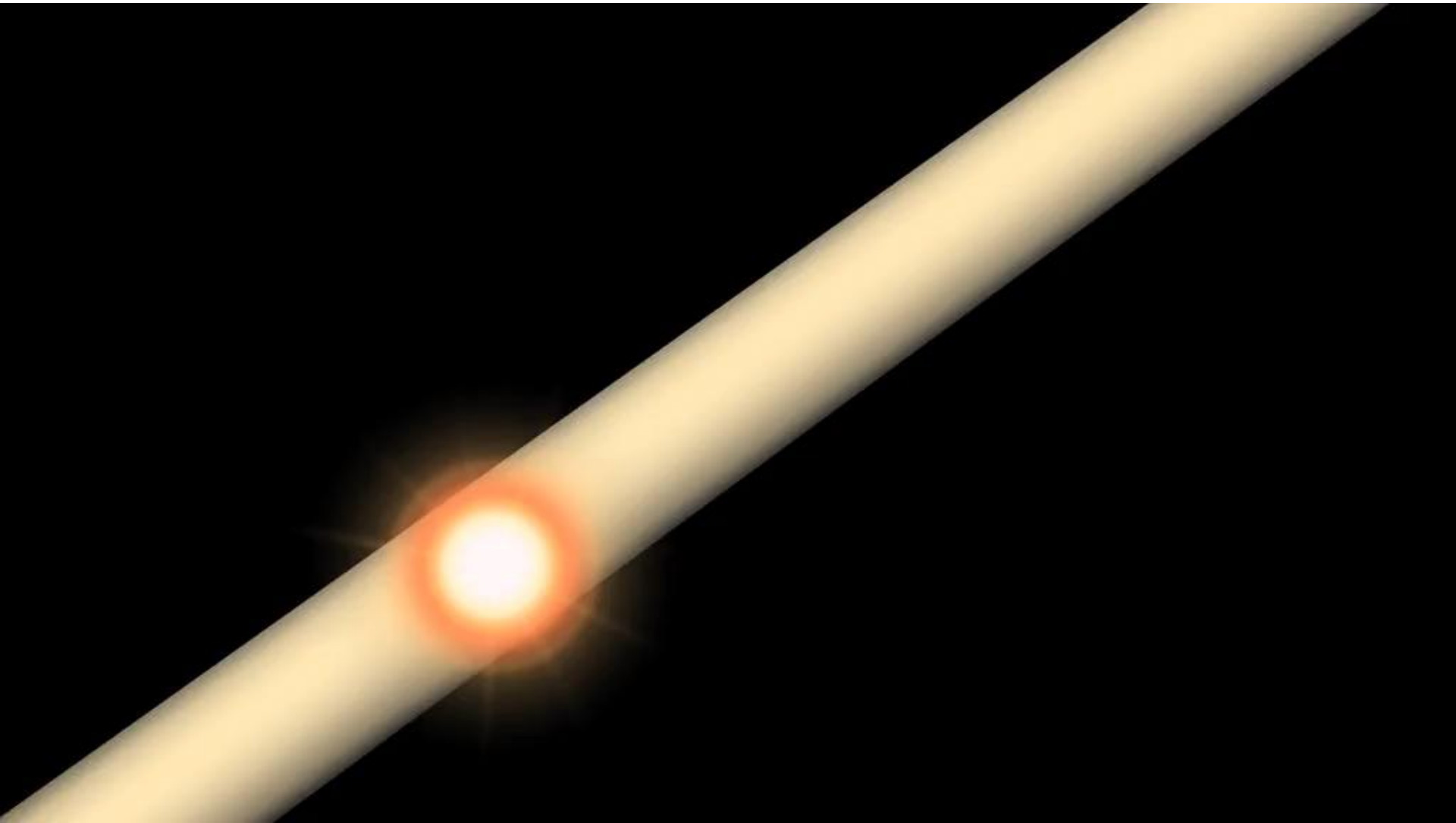
Two very high energy photons (gamma rays) (0.2% of time)

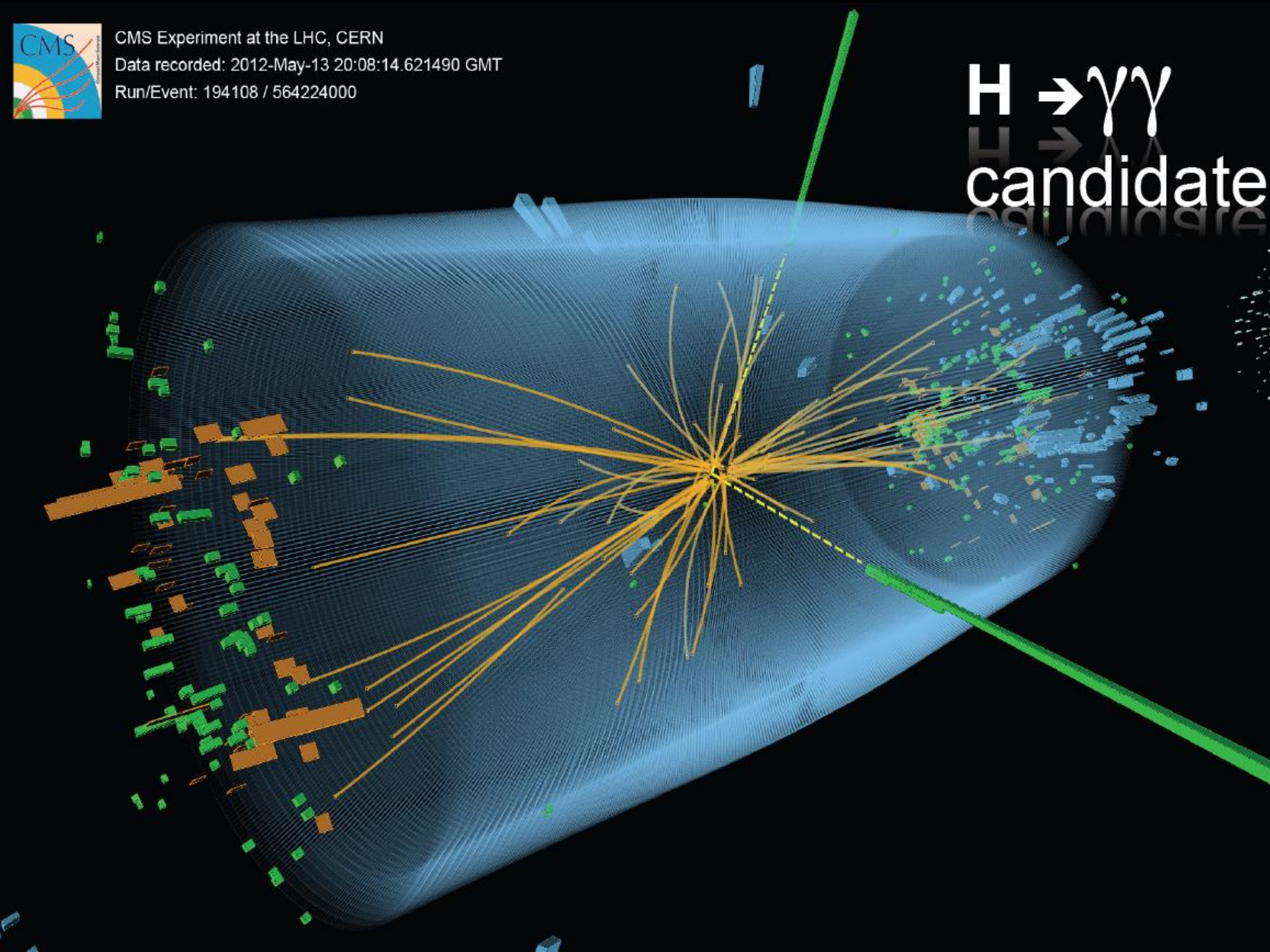
Photons and gluons have no mass, talk to Higgs through quantum loops via two heavy, charged particles: top quark and W boson.



Deduce mass of Higgs particle from energies and angles of two photons

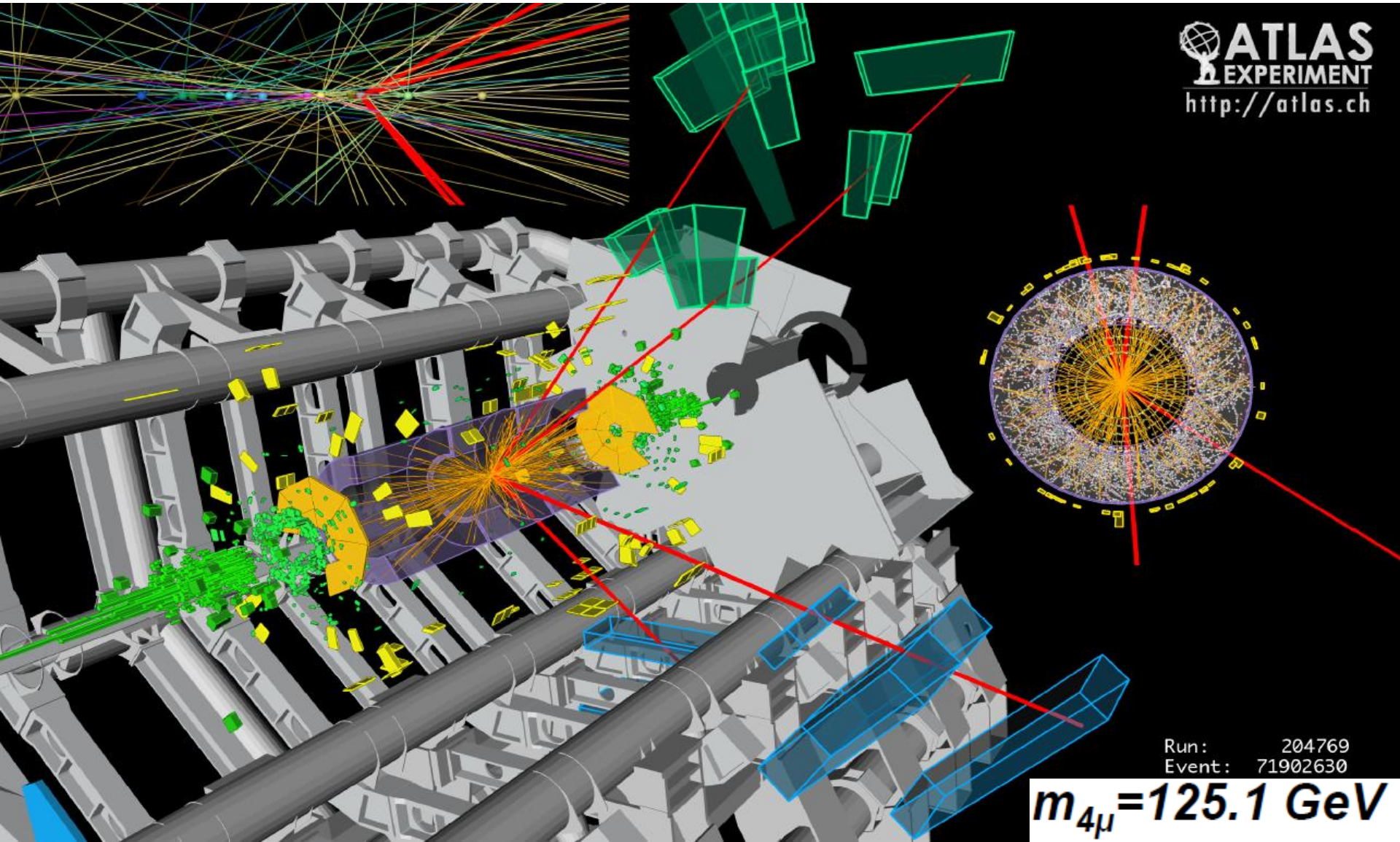
LHC: The Movie




CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
candidate

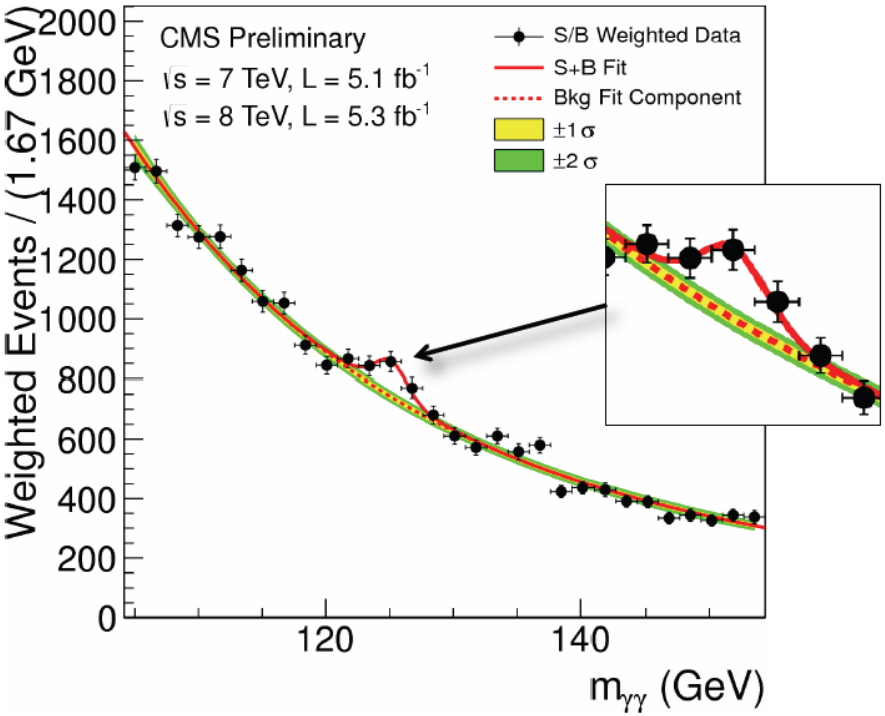
“Golden mode”:

H → Z Z → $\mu^+\mu^-\ \mu^+\mu^-$



After 50 year hunt, Higgs boson discovered at LHC exactly 7 years ago!

July 4, 2012




July 4, 2012
Rolf Heuer, CERN DG
Joe Incandela, CMS spokesperson
Gerry Guralnik
Carl Hagen
Francois Englert
Peter Higgs
Fabiola Gianotti, ATLAS Spokesperson, later CERN Director General
Steve Myers LHC
Nobel Prize 2014
+ 10,000 more

Historical Irony

In 1967, Steven Weinberg and Abdus Salam used ideas of Higgs and others to explain electron mass and weak boson mass. Also earlier ideas by Sheldon Glashow.

Nobel 1979

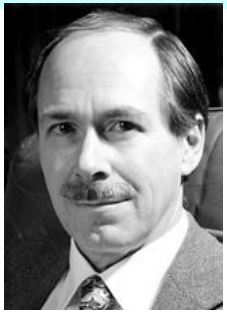

Weinberg

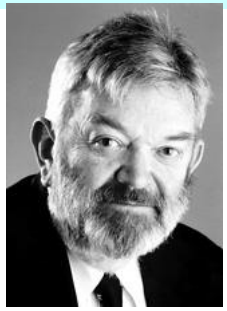

Salam

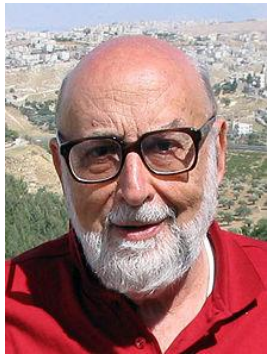

Glashow

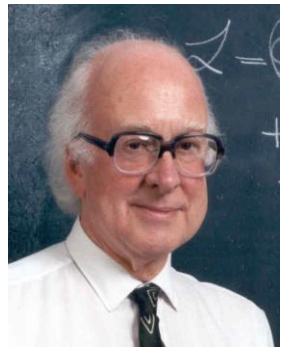
1967 work ignored until 1972 paper by Gerard ’t Hooft and Martinus Veltman, relying even more explicitly on Higgs’ idea

Nobel 1999


‘t Hooft

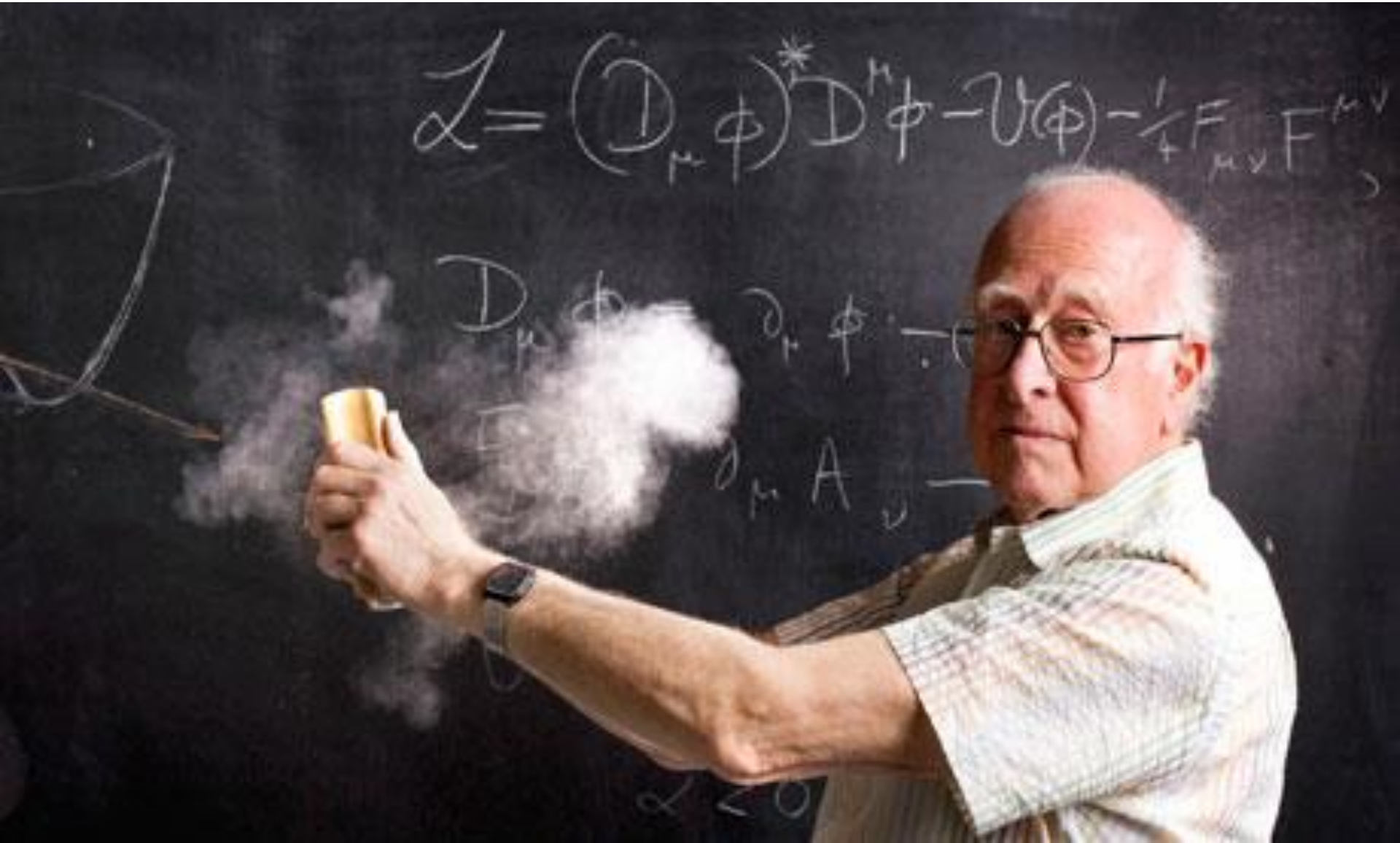

Veltman





Englert, Higgs
Nobel 2014

Are we done?

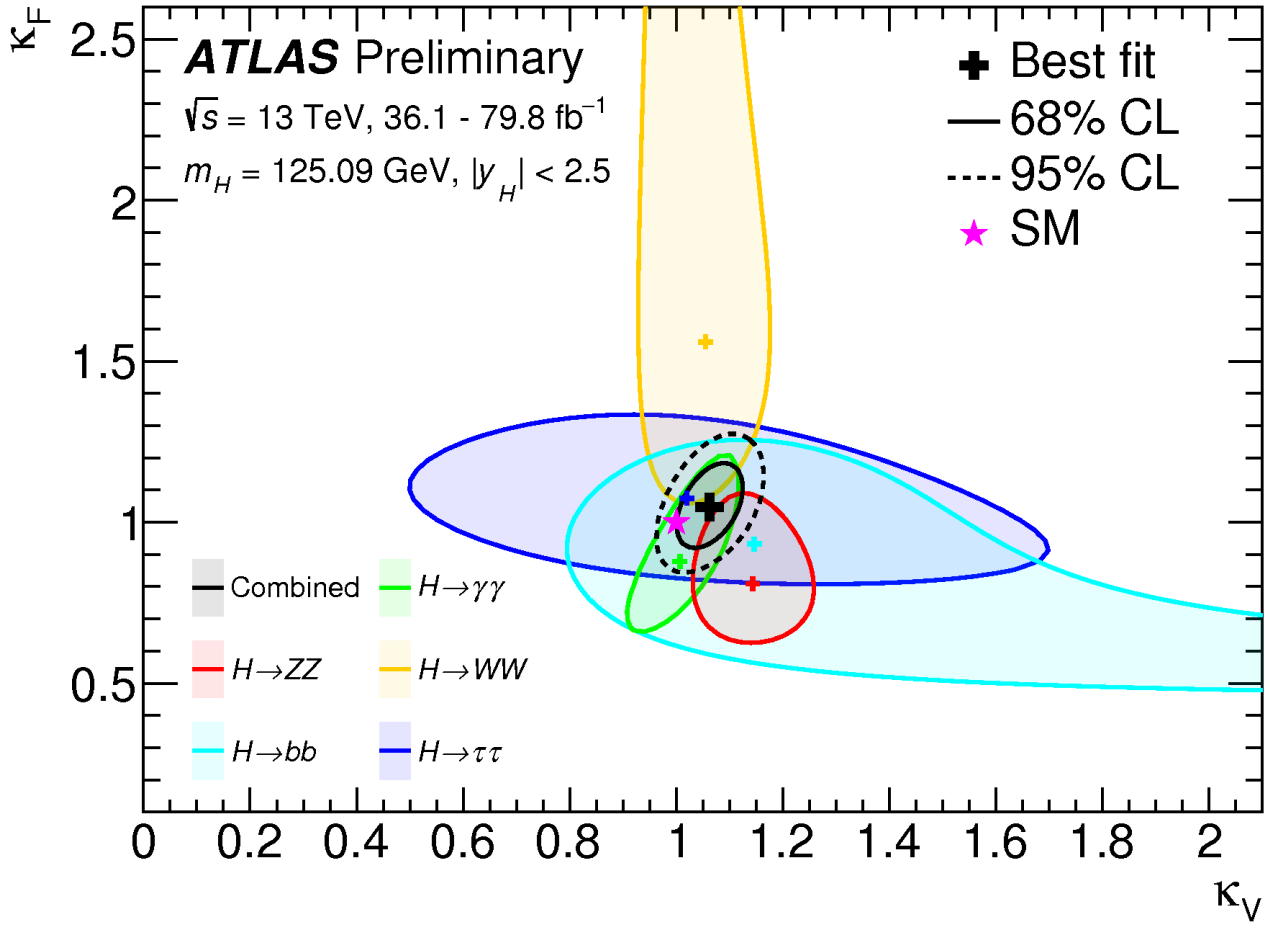


Profiling the Higgs boson

How do we know it's Higgs, instead of something else?

- Measure particle's properties
  - mass
  - spin
  - how often it is produced
  - probability of each "disguise
- Compare with expectations for Higgs versus alternatives
- Already done **pretty well** at LHC

Testing different Higgs “disguises”



So far, looks like Standard Model Higgs boson to within 10%

Why might Higgs picture still be incomplete?

"The Higgs is like a plumber with duct tape, holding the Standard Model together."

- Michael Turner

Higgs boson fixes a crucial problem, and accounts for the origin of mass, but it leaves a lot unexplained

For example, it does not explain this bizarre set of numbers

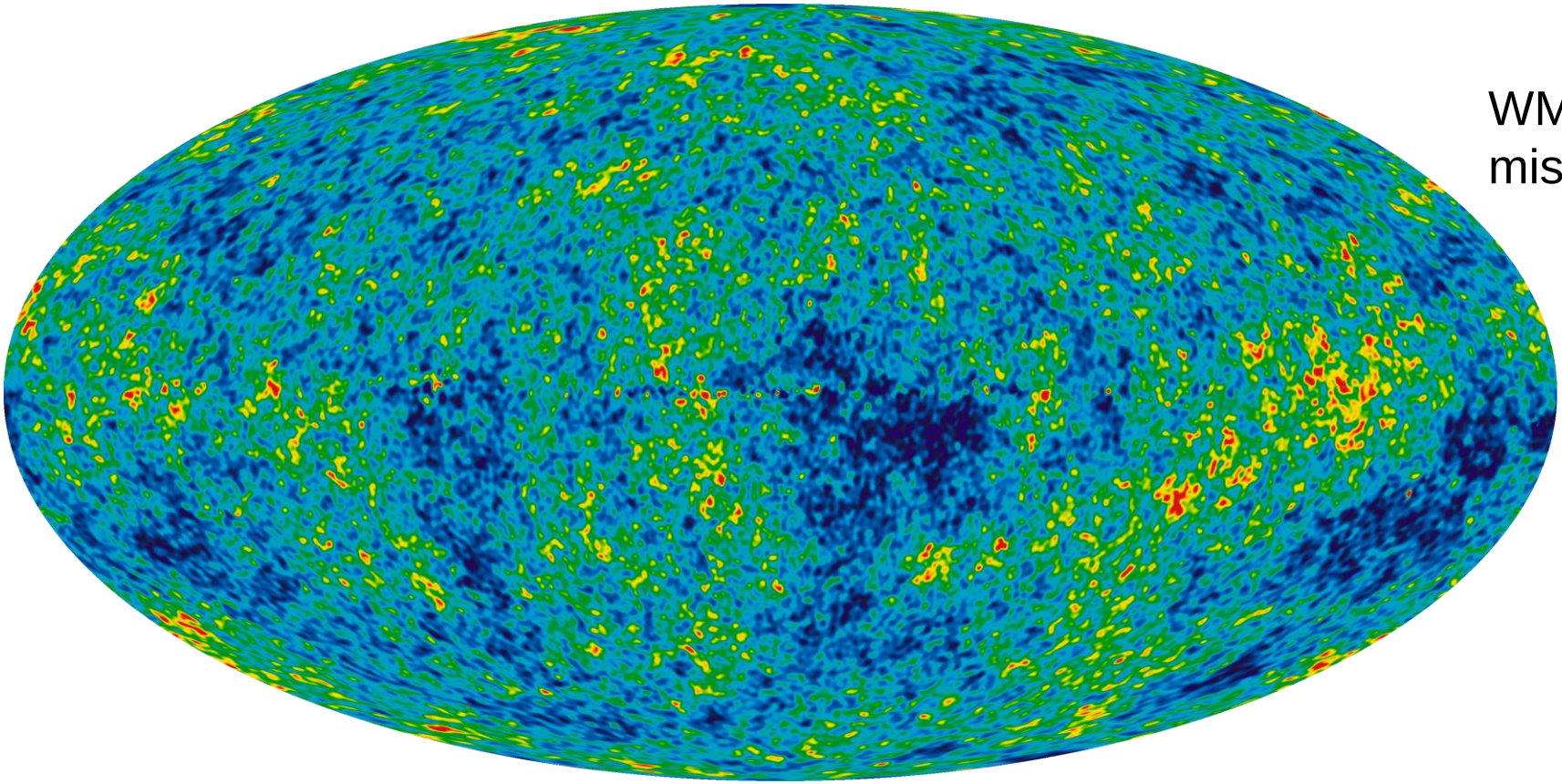
$m_u = 0.003$	$m_c = 1.3$	$m_t = 184$
$m_d = 0.006$	$m_s = 0.12$	$m_b = 5.0$
$m_e = 0.0005446$	$m_\mu = 0.1126$	$m_\tau = 1.894$

What if Higgs picture is incomplete?

- Then something else is nearby – “new physics”
- But what?
- Maybe a new symmetry or law of Nature
- Maybe more than 3 dimensions of space
- Maybe Higgs boson is a composite particle
- …
- Lots & lots of ideas, but no-one really knows.

- LHC also explores this question directly
- Hundreds of different searches for new particles
- **So far, nothing else has turned up!**

The universe seen in microwaves



WMAP
mission

Hot and cold spots: evidence for another scalar field present at the beginning of creation: the inflaton

(how) is it related to the Higgs boson?

Conclusions

- Hunt for Higgs boson was long and arduous, but LHC experiments discovered a new particle that closely resembles it
- Is solution to “origin of mass” really as simple as imagined almost 50 years ago?
- More data should eventually tell!
- Quest for higher precision at LHC involves theorists too, computing scattering amplitudes to more quantum loops
- And understanding better what makes the universe tick

Thanks!

For the opportunity to tell you a little about this quest tonight

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 764850 (SAGEX).

Thanks also to the IOP In Ireland and the US Department of Energy

SAGEX
Scattering Amplitudes: from Geometry to Experiment

IOP | Institute of Physics In Ireland

Office of Science
U.S. Department of Energy

Extra Slides

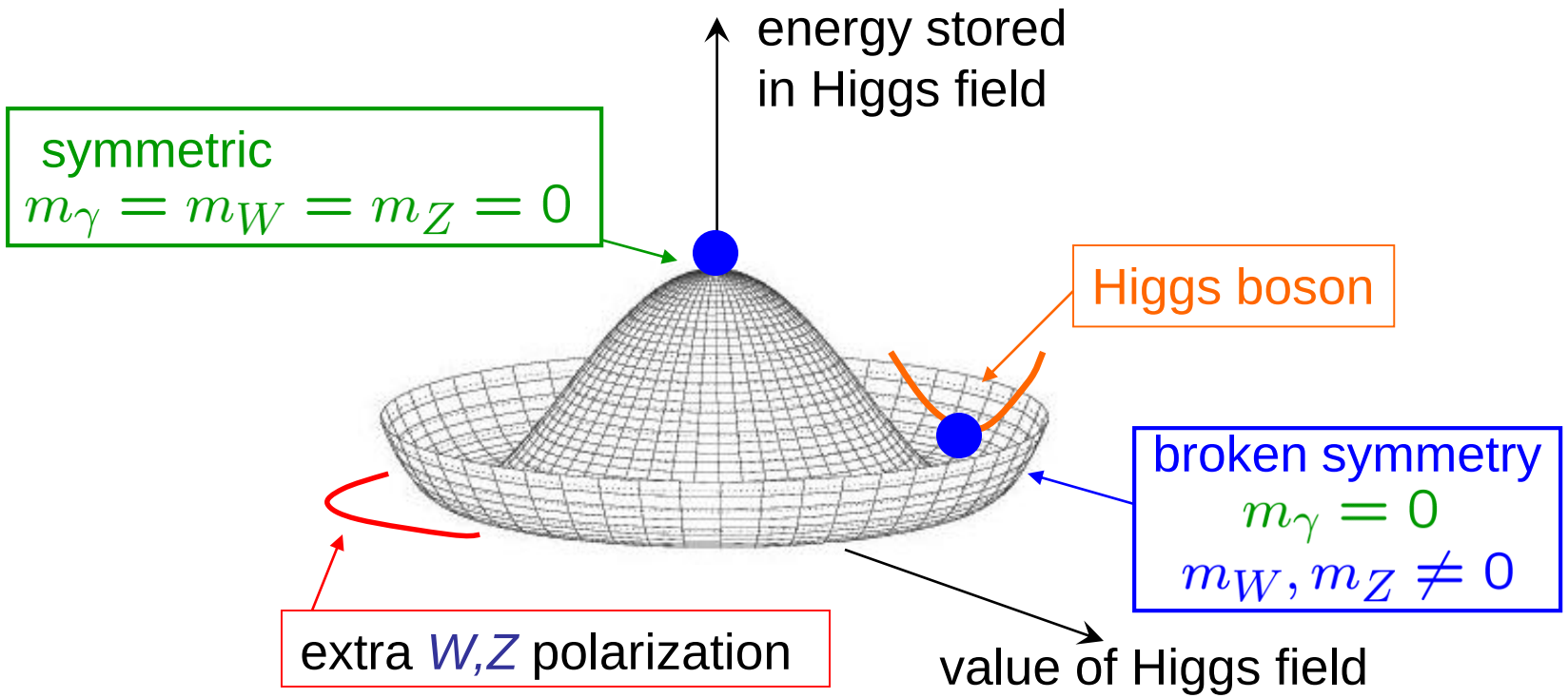
Fear of Public Speaking

POWERED BY 23ANDME RESEARCH

Lance, based on your genetics and other factors, you are **less likely** to have a fear of public speaking.

Higgs mechanism & broken symmetry

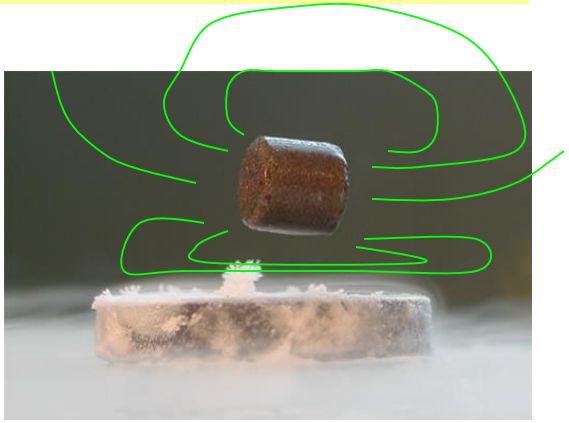
- "Mexican hat" describes energy contained in Higgs field as a function of its value.
- Minimized for nonzero values.
- Why energy should have this form is still a mystery.



Higgs mechanism & superconductivity

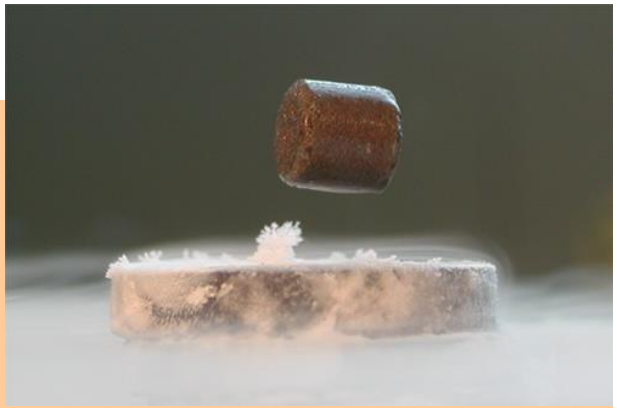
If certain materials are cooled way down, they suddenly lose all electrical resistance → superconductivity

Magnetic fields cannot penetrate far into a superconductor. Superconductors levitate magnets by pushing out the magnetic fields



Means that photon is short-range, or massive, inside a superconductor.
But this is just how the *W* and *Z* behave **everywhere** in space!

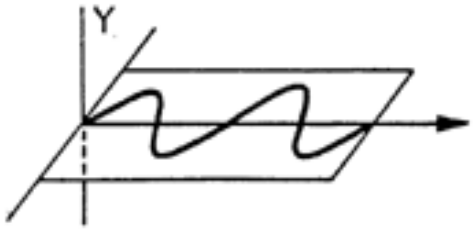
Higgs mechanism – the ultimate superconductor

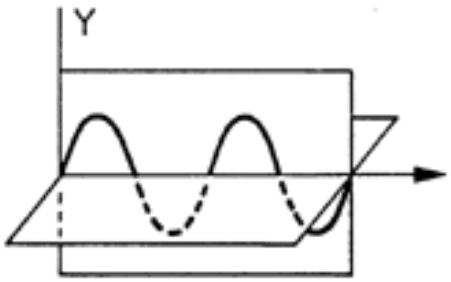


- Fills entire universe
- Universe has been superconducting since a billionth of a second after the Big Bang
- Excludes weak magnetic fields a trillion times more effectively than the strongest electromagnetic superconductor (1/100th of proton radius is really short!)

2

2 = number of ways light (photons) can be oriented, or polarized





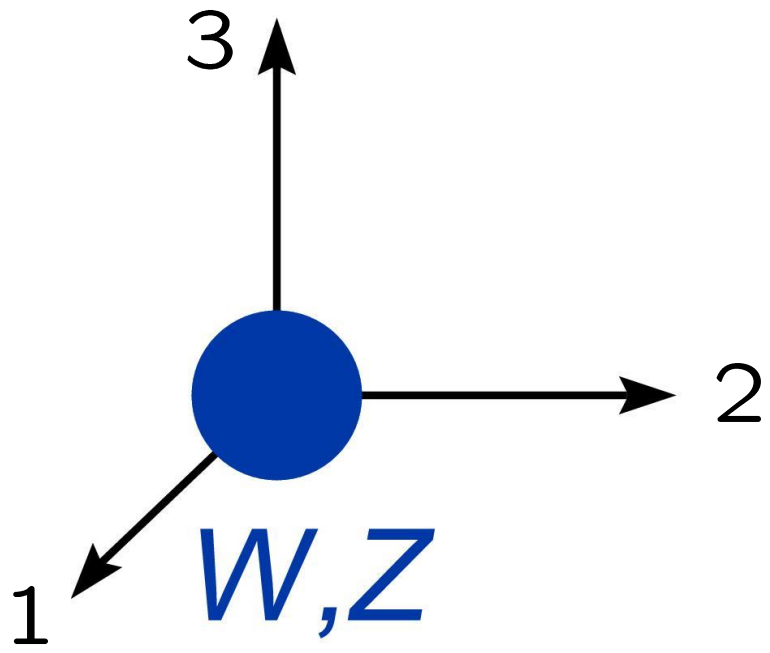
Linearly polarized light

photons always in motion

3

3 = number of ways *W* & *Z* can be oriented, or polarized

W & *Z* **massive**, **sometimes at rest**

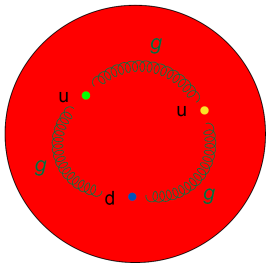


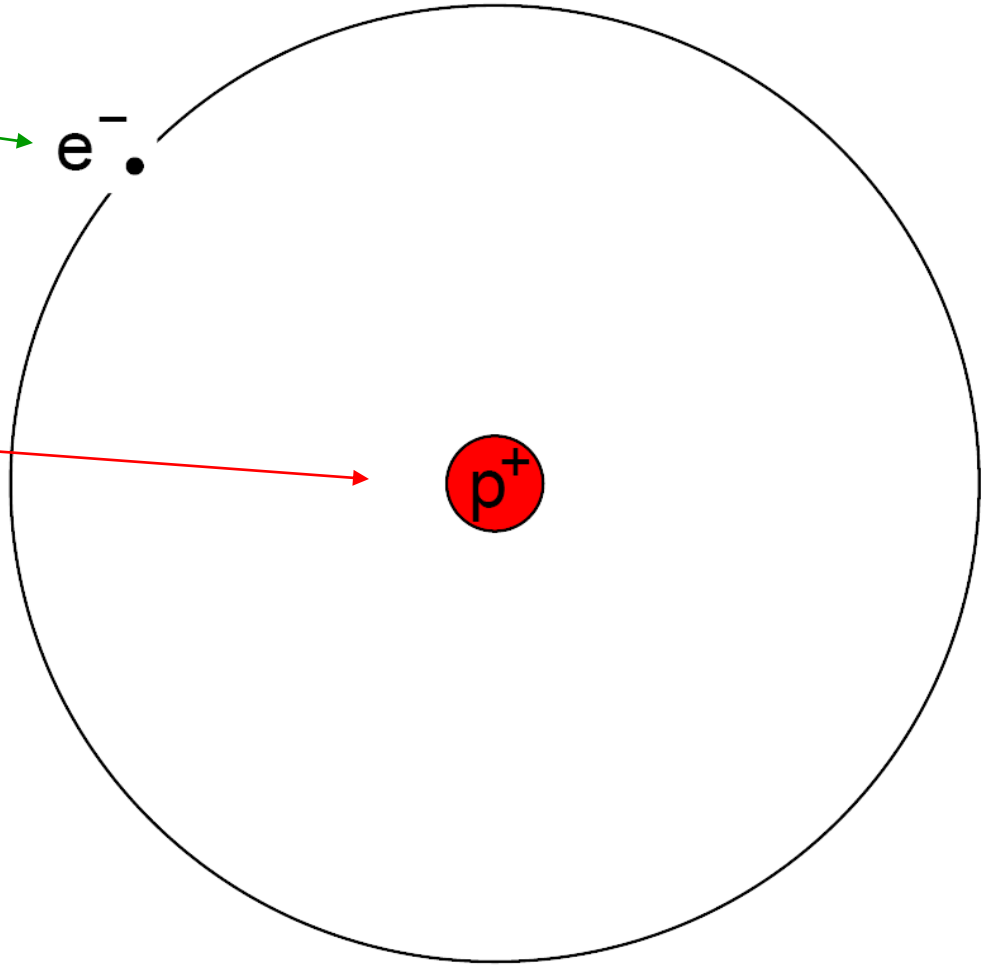
Where does extra polarization (3-2) come from?

Origin of what mass?

Higgs accounts for all of electron mass

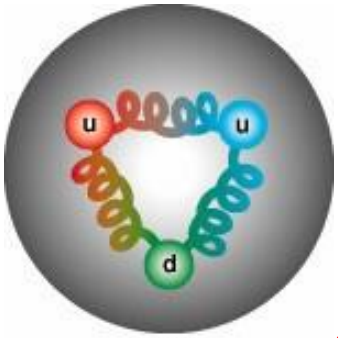
but only small part of proton mass
– most comes from kinetic energy of quarks & gluons zipping around



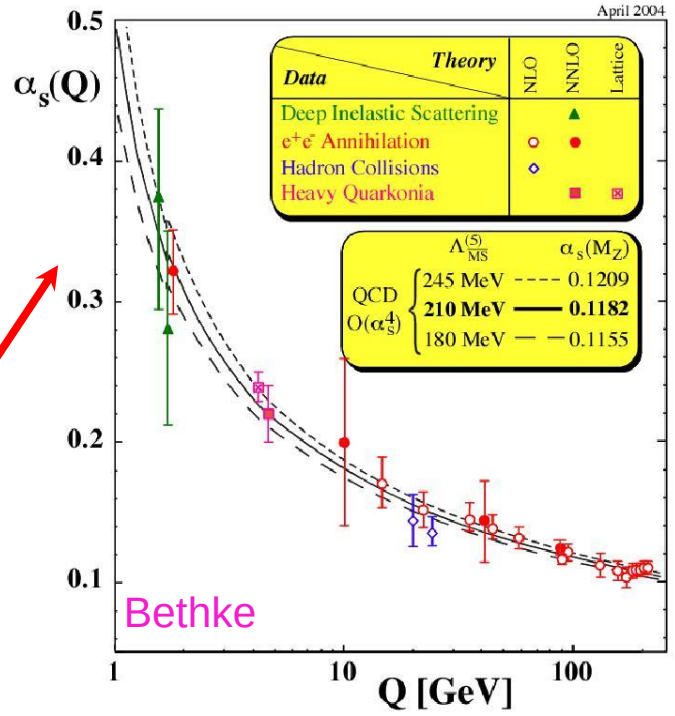


The Key of Asymptotic Freedom

Gluons anti-screen charge: Interaction strength α_s for QCD is a small number at short distances, so we can expand in this small parameter → perturbation theory → Feynman diagrams



confining



calculable

David Gross
Frank Wilczek
David Politzer, 1973
Nobel 2004

For use in case of 5σ Higgs discovery

1. Check label for "Champagne". (Do not use "Cava") Remove protective cover.

2. Gently twist cork to release fluid. (Aim away from face)

3. Apply fluid to Champagne flutes. Repeat until all flutes are filled.

the Official SLAC Theory Group Record of Wagers

"In physics, certainty is 8 to 5 odds"
– P. W. Anderson

By 1990 it will be well accepted that an elementary Higgs scalar particle does not exist.

YES	NO
Bob Holdom 3/84	Leonard Susskind 3/84 also super partners will exist by 1995
Michael Peskin 3/84 (I will bet 1 bottle of wine with anyone in column 2 who wishes to reciprocate) (closed April 1984)	Stuart Raby 3/84
Gabor Domokos 3/84	Howard Haber 3/84

Date: 6-DEC-1991 09:45:31.24
From: "Cosmas Zachos (708) 252 6207" <ZACHOS@ANLHEP>
To: mpeskin@slacvm.BITNET
Subject: validation of bet
X-ANJE-To: GATEWAY::"mpeskin@slacvm"

Dear Michael,
in confirmation of our bet of Wednesday,

I, Cosmas Zachos, or an exact replica, bet that
a minimal elementary Higgs will NOT be found with a mass below 180 GeV,
----discounting 2-gauge-boson-threshold effects.
The prize being a bottle of wine.

PS. the wine may well be BOUTARI, [but note, not "Cava Boutari", a serviceable cabernet-sauvignon by the same winery], the OUTSTANDING [and inexpensive] wine of Greece, extracted from an ancient grape variety.

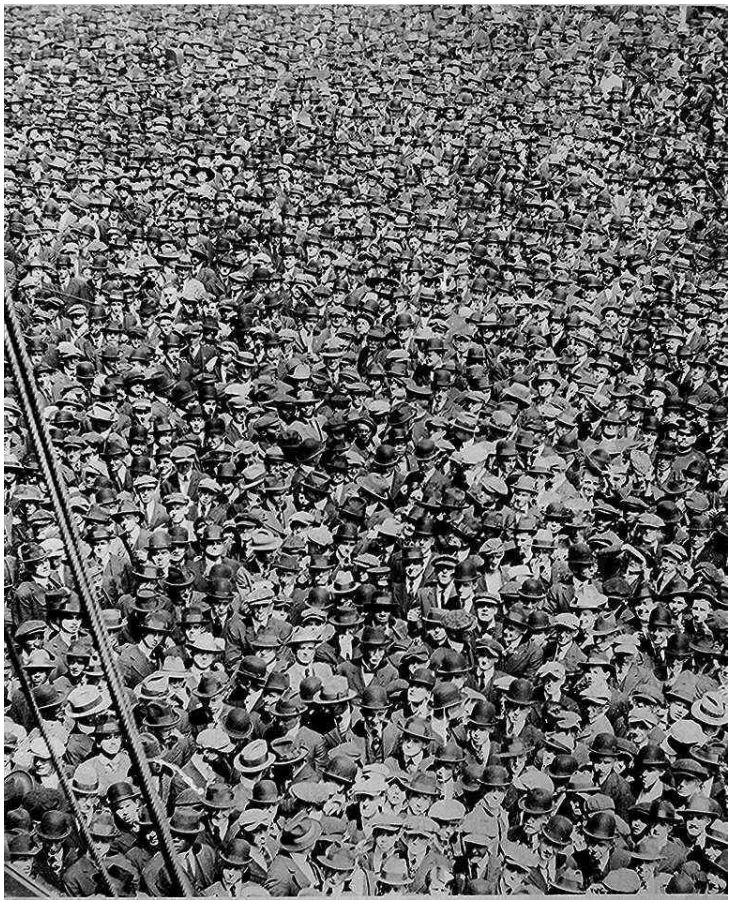
Cosmas

ok. Michael Peskin Dec 9, 1991

Searching for Higgs

How to pick Higgs out of a crowd?

vs.

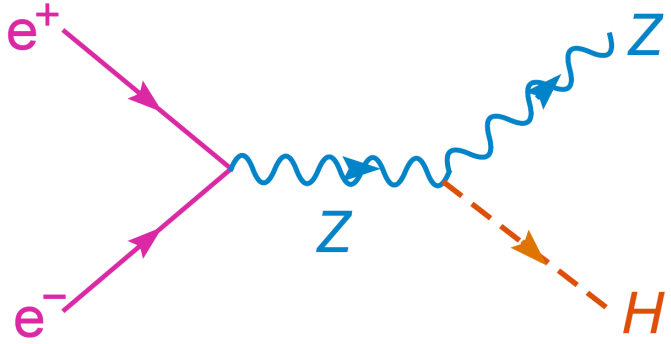


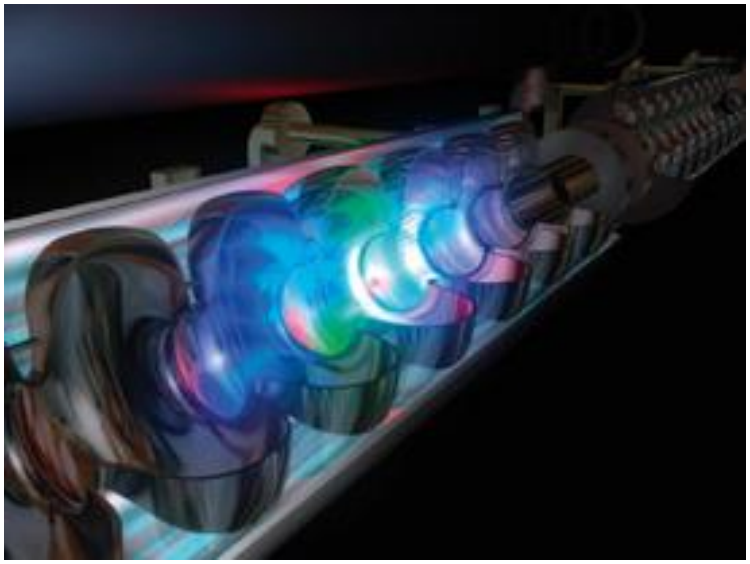
electron-positron colliders
– small backgrounds

proton colliders
– large backgrounds

International Linear Collider?

- 20-30 km long electron-positron collider, powerful enough to make Higgs + Z boson
- Measure many Higgs boson properties very precisely: 10% at LHC → few % at ILC
- First collisions in 2030?? Build in Japan??
- Or a circular machine with 80-100km circumference??





Last word in unmasking of Higgs boson?