Title: From the Higgs to the Heavens: Physics of the Large Hadron Collider

Date: Jul 26, 2012 10:30 AM

URL: http://pirsa.org/12070007

Abstract:
The world's most ambitious scientific experiment is buried 100 meters underground, straddling Switzerland and France. A billion times every minute, the Large Hadron Collider (LHC) slams together protons, while four giant detectors watch closely.

 So how does the Large Hadron Collider work? Why can slamming tiny particles into each other provide clues about the nature of all space and time? What mysteries are physicists trying to solve with data from the LHC, and what is the Higgs anyway? What might we learn next? How does the cutting edge of particle physics relate to the world around us, from the patterns of stars in the sky to the fact that they shine at all?

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does the Large Hadron Collider work? Why
can slamming tiny particles into each other provide clues about the nature of
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anyway? What might we learn next? How
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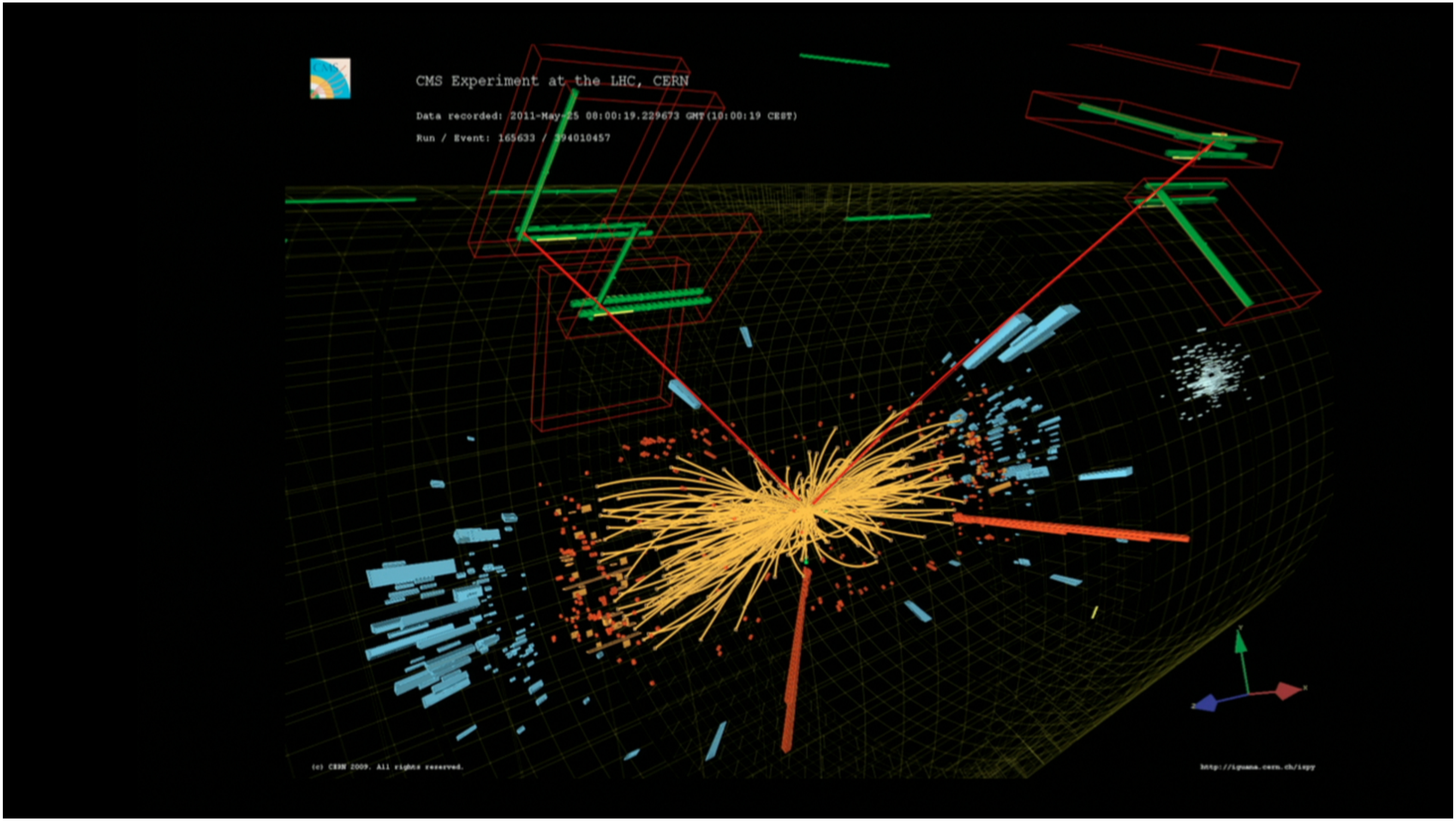
the patterns of stars in the sky to the fact that they shine at all?

From The Higgs to the Heavens

Physics of the Large Hadron Collider

Natalia Toro
Perimeter Institute


CMS Experiment at the LHC, CERN
Data recorded: 2011-May-25 08:00:19.229673 GMT(10:00:19 CEST)
Run / Event: 165633 / 394010457
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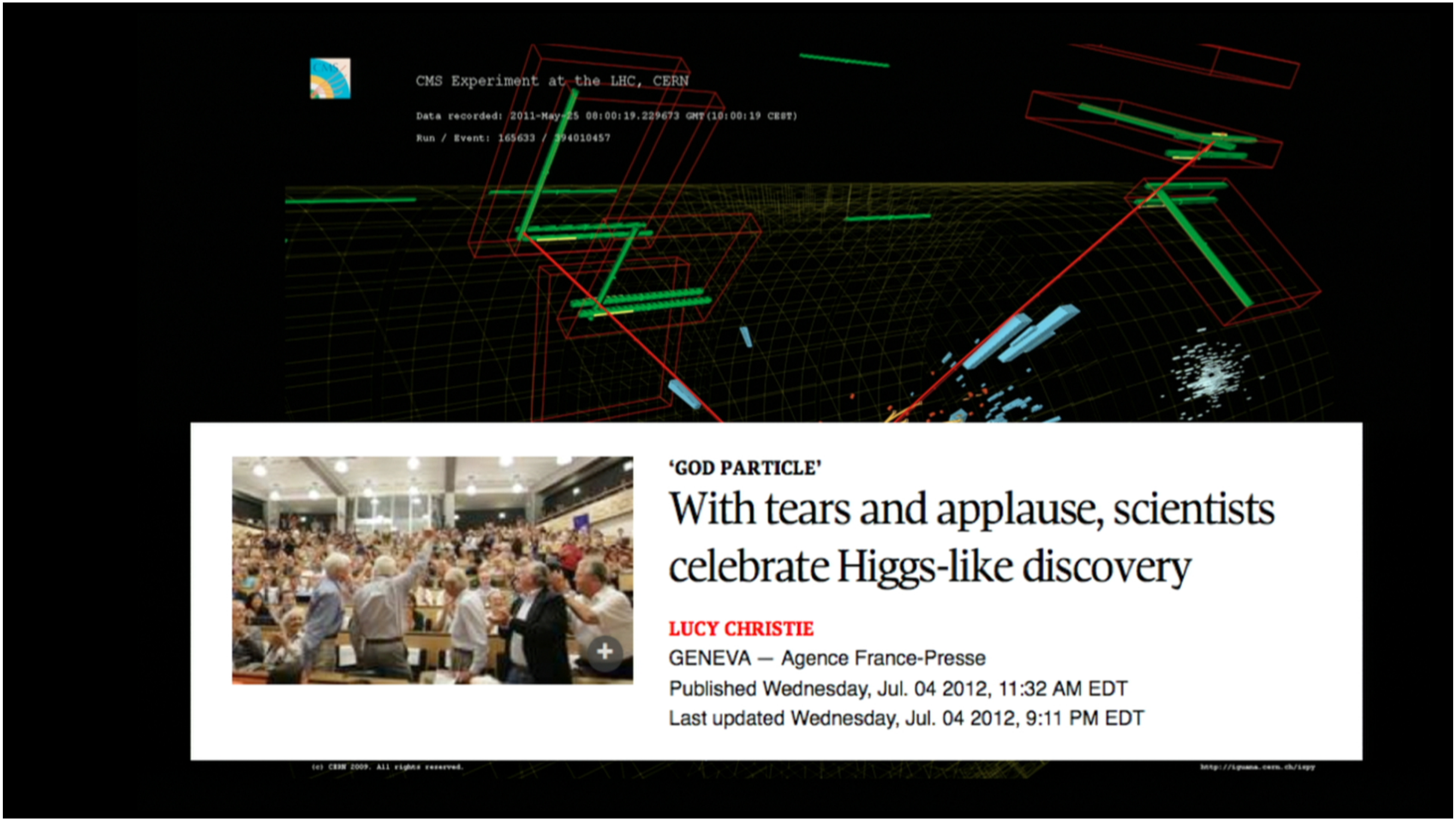
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'GOD PARTICLE'
With tears and applause, scientists celebrate Higgs-like discovery
LUCY CHRISTIE
GENEVA — Agence France-Presse
Published Wednesday, Jul. 04 2012, 11:32 AM EDT
Last updated Wednesday, Jul. 04 2012, 9:11 PM EDT
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CMS Experiment at the LHC, CERN
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• Why do we care so much about particles?
• How can we learn about them?
• Inside the Higgs discovery
and finally, a look beyond the Higgs
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A World of Particles

ALL observed phenomena can be <u>accommodated</u> by a quantum theory of interacting *particles*!

A World of Particles

ALL observed phenomena can be accommodated by a quantum theory of interacting *particles*!

Don't know **WHY** these particular particles
In some cases, don't know **HOW**, but we have specific theories that work.

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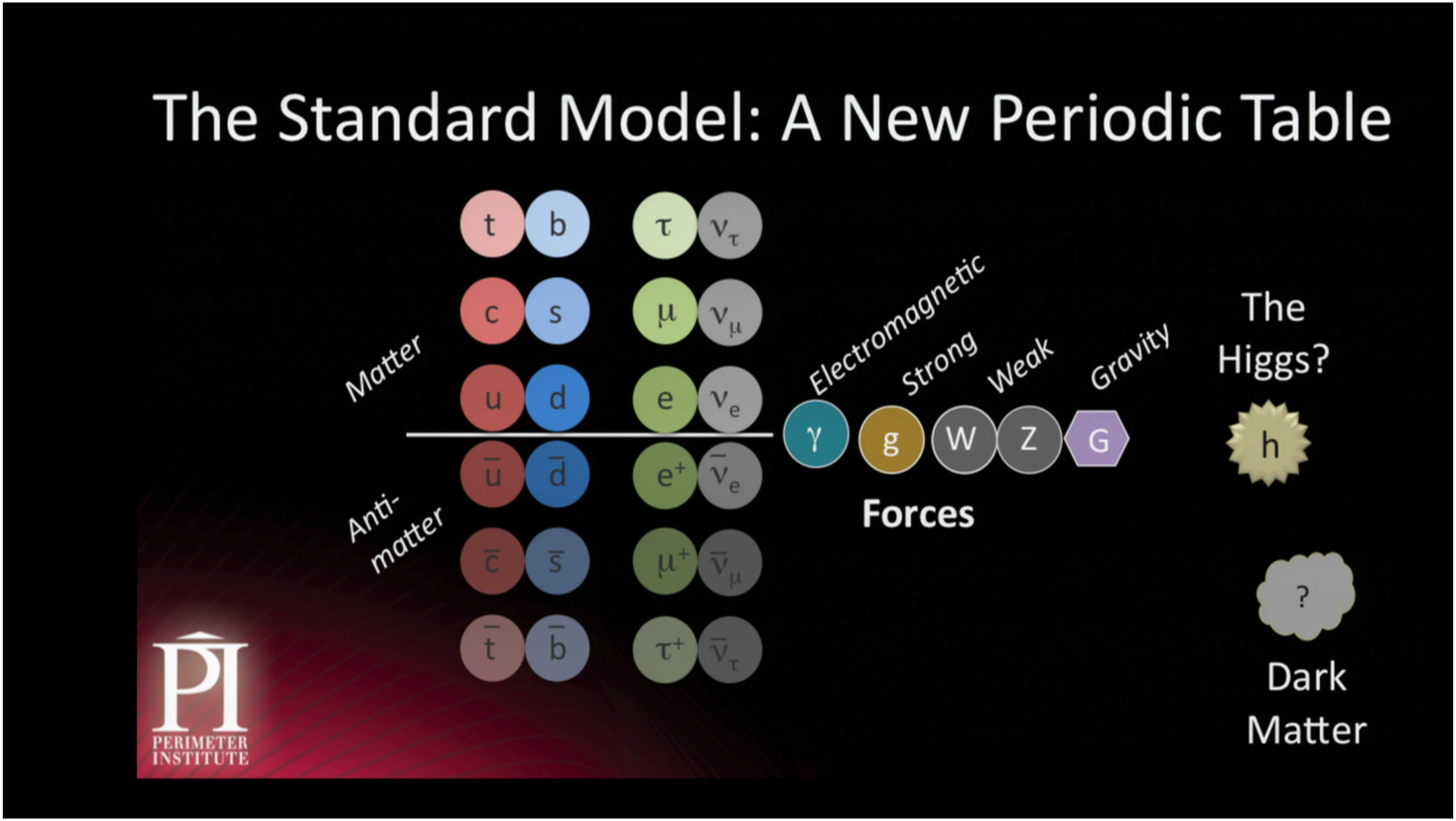
The Standard Model: A New Periodic Table
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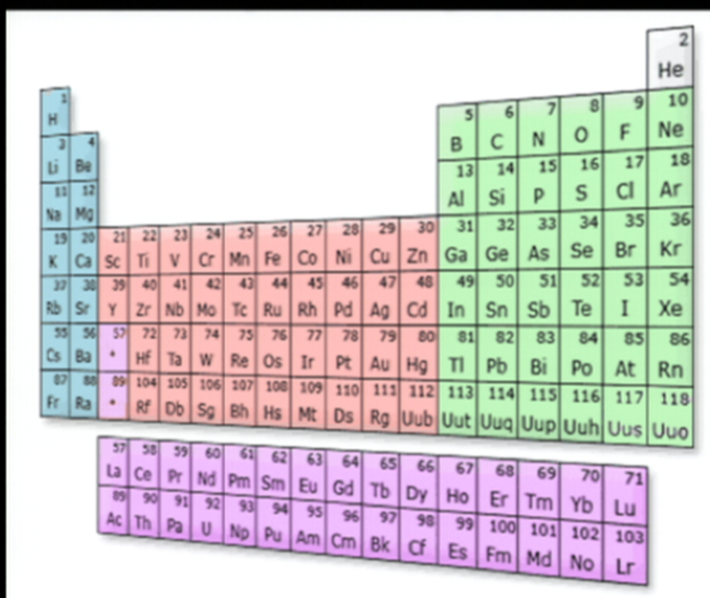
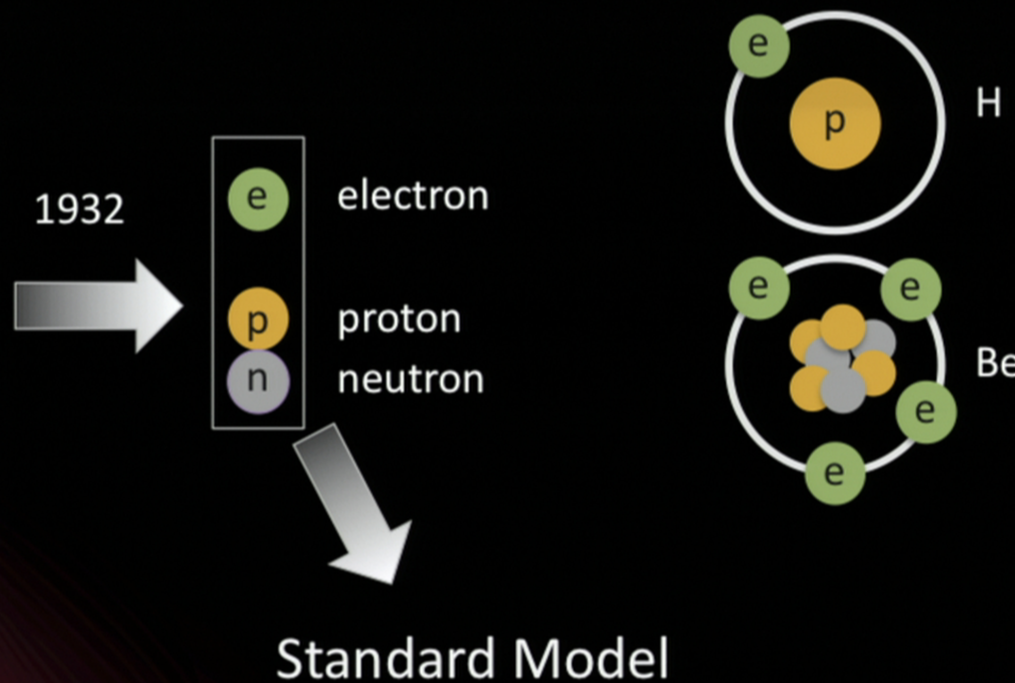
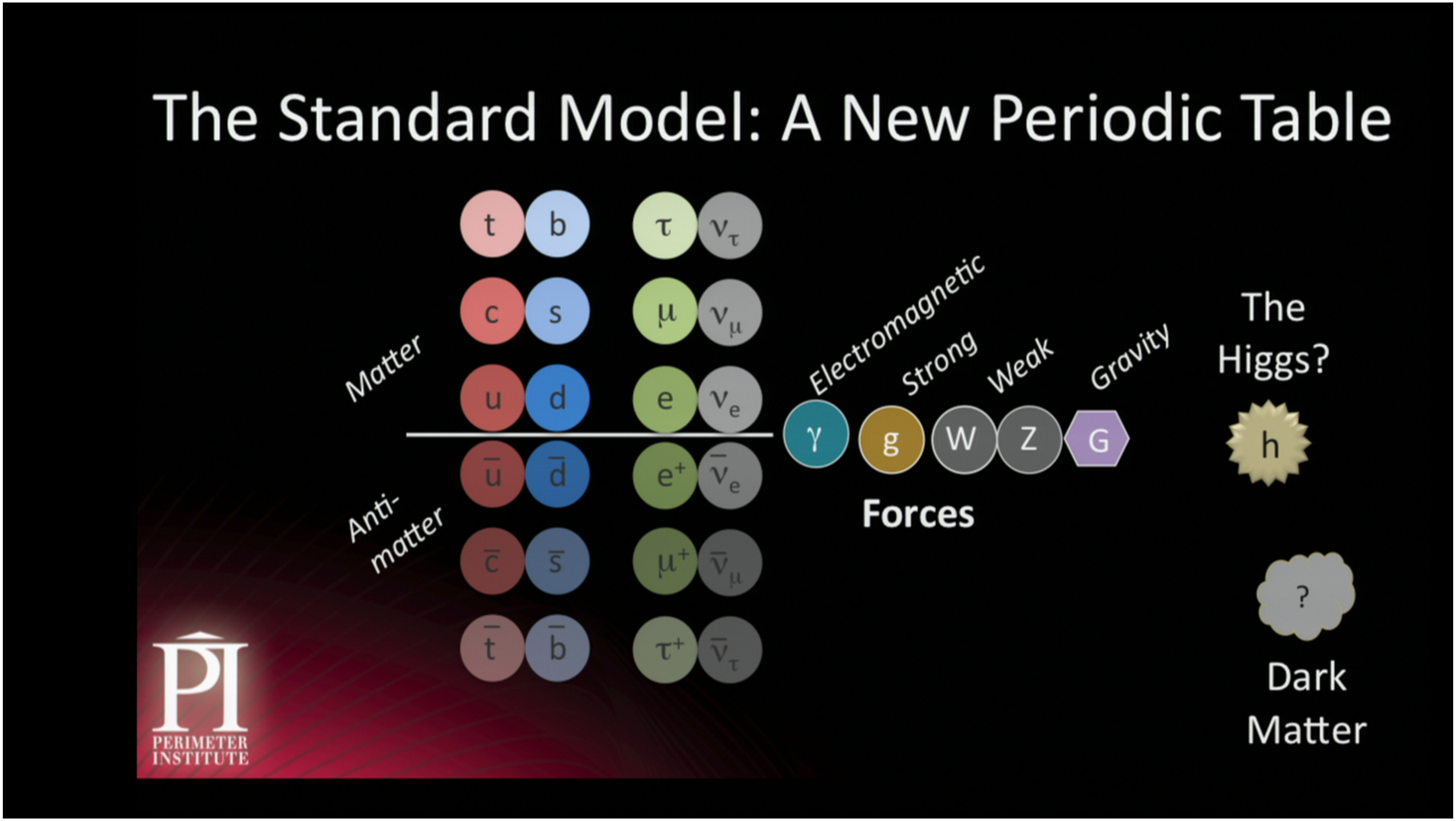
Particles as Building Blocks of Nature

A more fundamental structure underlying periodic table






The Standard Model: A New Periodic Table
Matter
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Dark Matter
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The Uncertainty Principle

$$\Delta p \, \Delta x \geq \hbar/2$$

Momentum uncertainty x Position Uncertainty

$$\Delta E \, \Delta t \geq \hbar/2$$

Energy uncertainty x Time Uncertainty

Werner Heisenberg

Quantum particles don't follow a single well-defined path, and we never know exactly where they are or where they're going.

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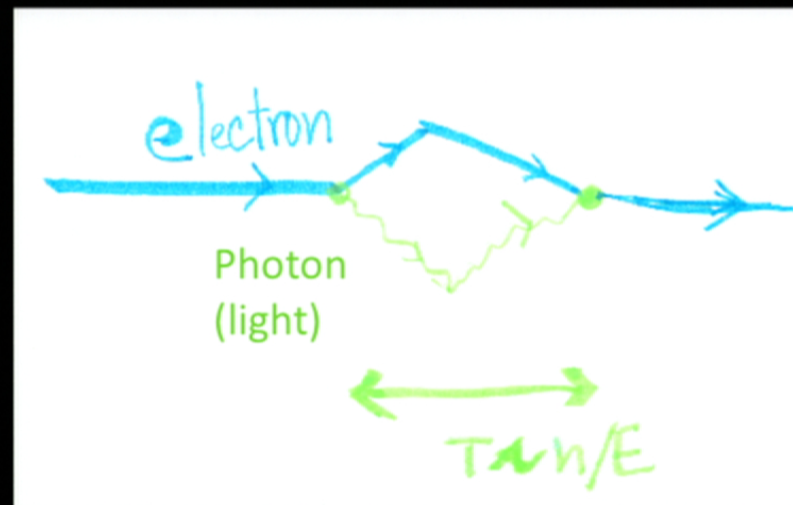
The Uncertainty Principle

$$\Delta p\, \Delta x \geq \hbar/2$$

$$\Delta E\, \Delta t \geq \hbar/2$$



Werner Heisenberg

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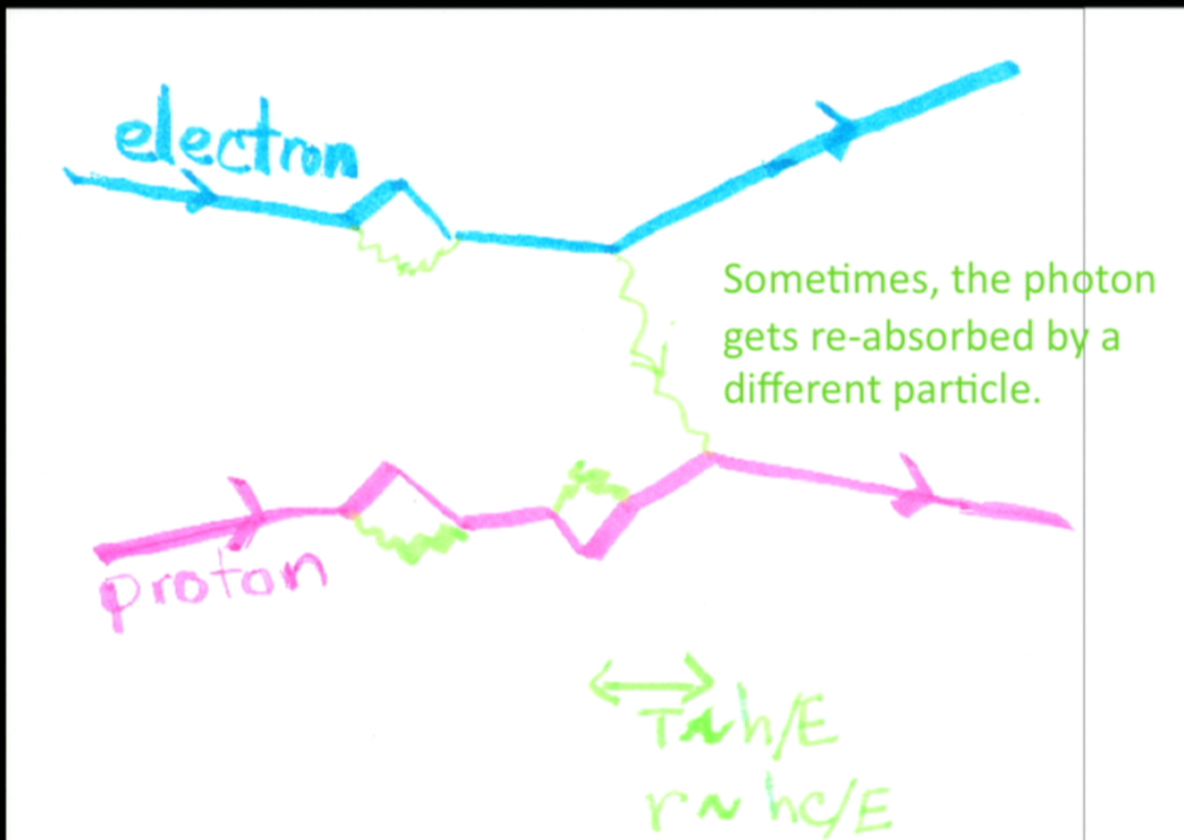
Can never be sure whether an electron is "just an electron" or accompanied by some photons

Quantum Particles and Forces

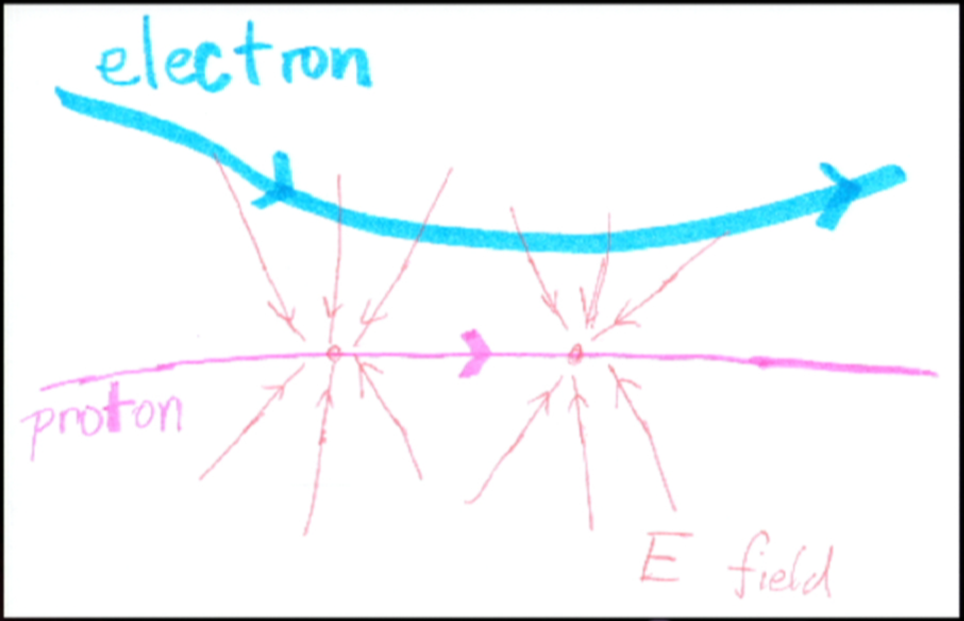


Richard Feynman

This continual absorption and emission of “virtual” photons is one way of understanding an electric force.

Classical Light and Forces

Proton produces **electric field** in empty space, which in turn bends electron (and vice versa)



NO Quantum Mechanics Here!

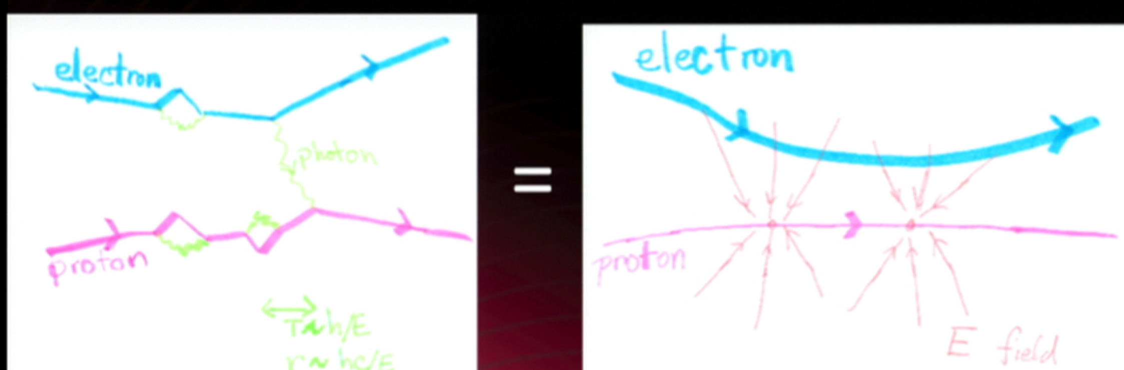
Maxwell + Quantum => Particles

Electromagnetic fields

Electromagnetic waves (light)

A “smallest wave”, or particle of light (photon)

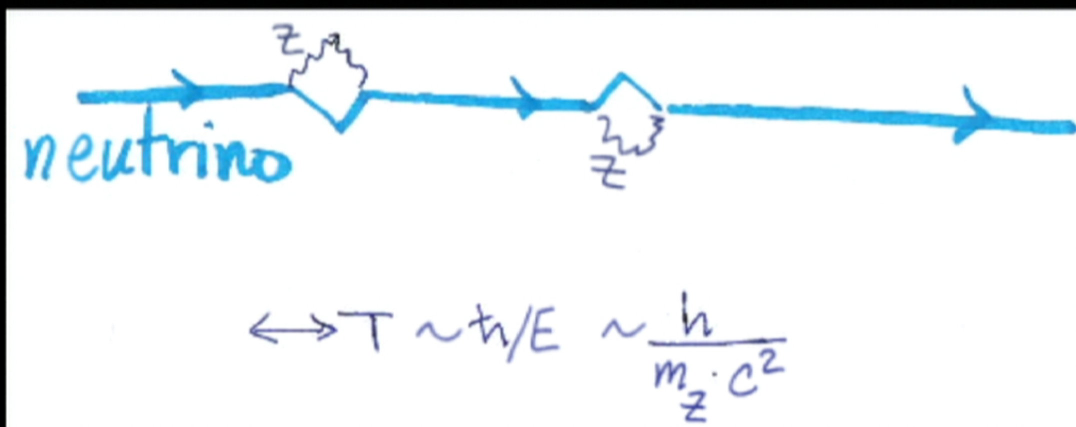
Particles + Quantum + Local Interaction=> Fields



The classical field is the effect of quantum exchanges of many photons

Why are Weak Interactions Weak?

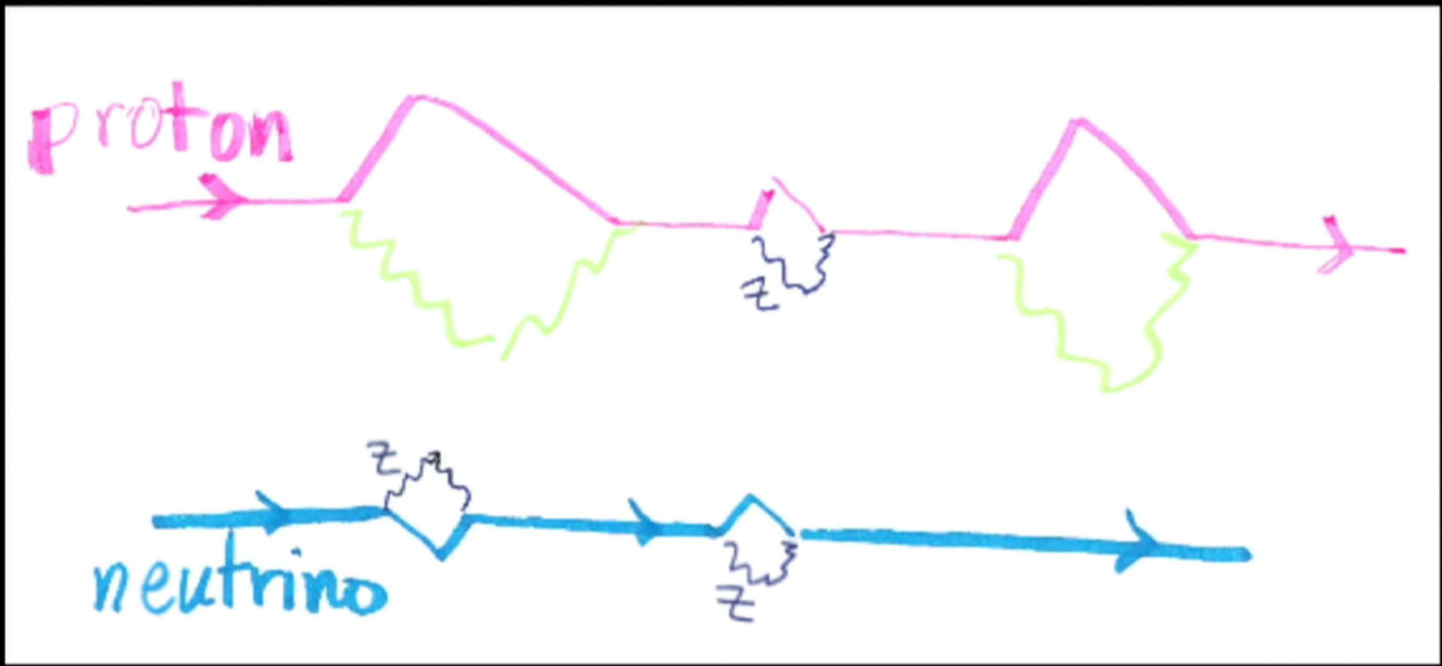
Electromagnetism = exchange of photons – they have no mass, no minimum energy
Weak force = exchange of W and Z particles – they are **heavy** (100x the mass of proton)



Large Z mass => "virtual" Z's exist for a very long time, and they don't travel very far.

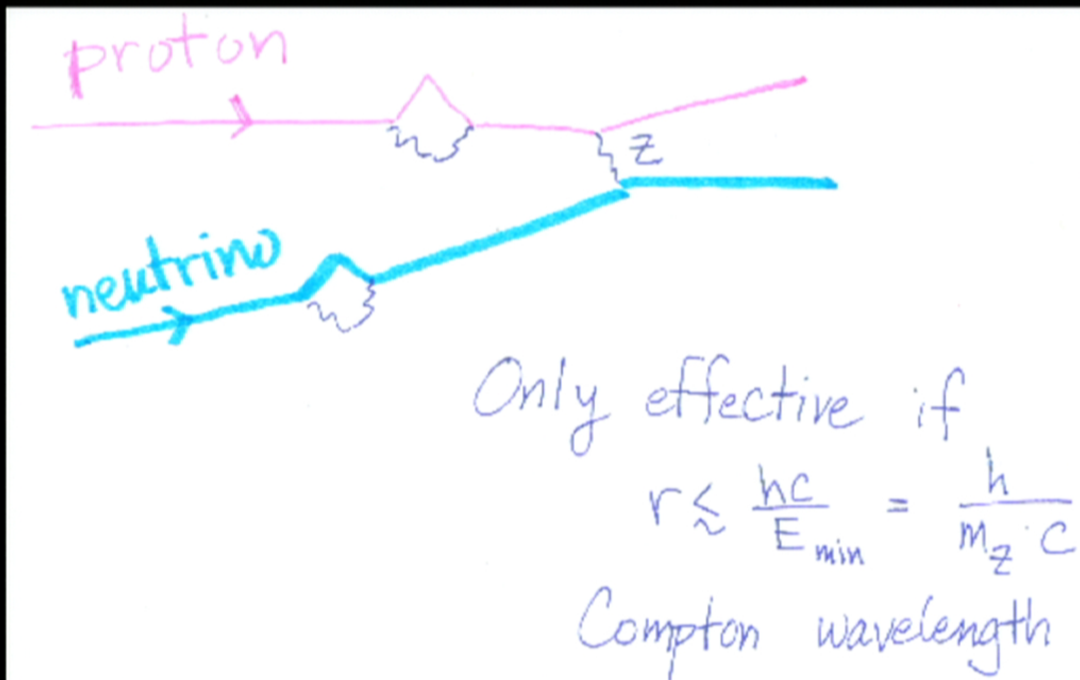
Why are Weak Interactions Weak?

At large distances, a proton and neutrino sail right past each other:



Why are Weak Interactions Weak?

At large distances, a proton and neutrino sail right past each other
At small distances, they will interact by exchanging Z particles:

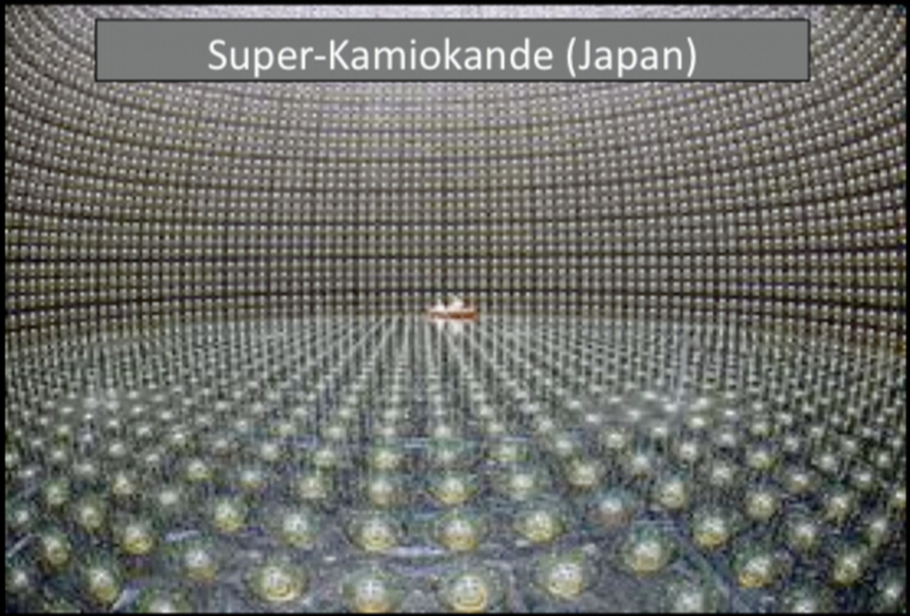


At these small distances, (about 1/100 the size of a proton, or 10^{-18} m) the weak force is actually about 5 times stronger than electromagnetic force!

Why are Weak Interactions Weak?

At large distances, a proton and neutrino sail right past each other,
At small distances, they will interact by exchanging Z particles:

This is why physicists who study neutrinos need such big detectors!



Why are Weak Interactions Weak?

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To study weak interactions (or other new forces) of ordinary matter, we need to look at very short distances <–> very high-momentum particles

$$\Delta p \, \Delta x \geq \hbar/2$$

This is why we need accelerators!

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What is a particle?

- Building block of quantum theory that can incorporate all observed phenomena, matter, and forces
  - The mass of a particle dictates how far away its forces are felt – familiar forces (electricity, magnetism, gravity) come from massless particles
  - Heavier particles mediate short-range forces that are best studied with high-energy accelerators.

How did we figure this out?

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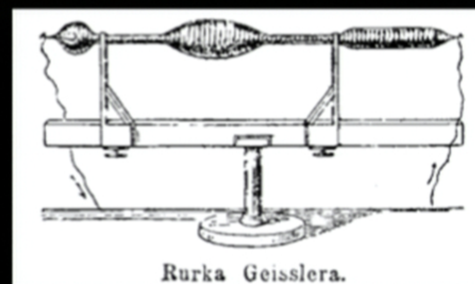
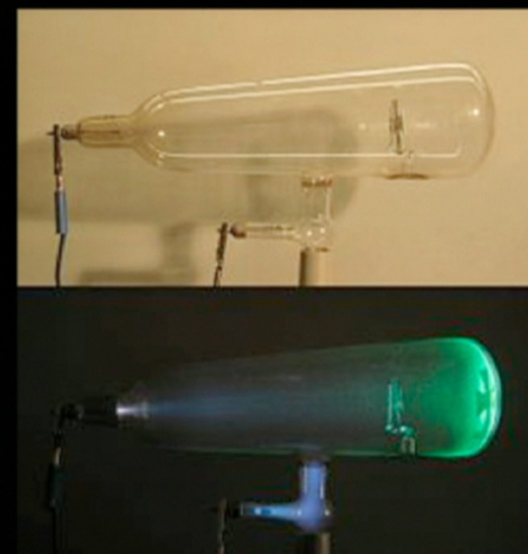
The First Particle Accelerators

Faraday, 1838

Geissler, 1857



Crookes 1869-75



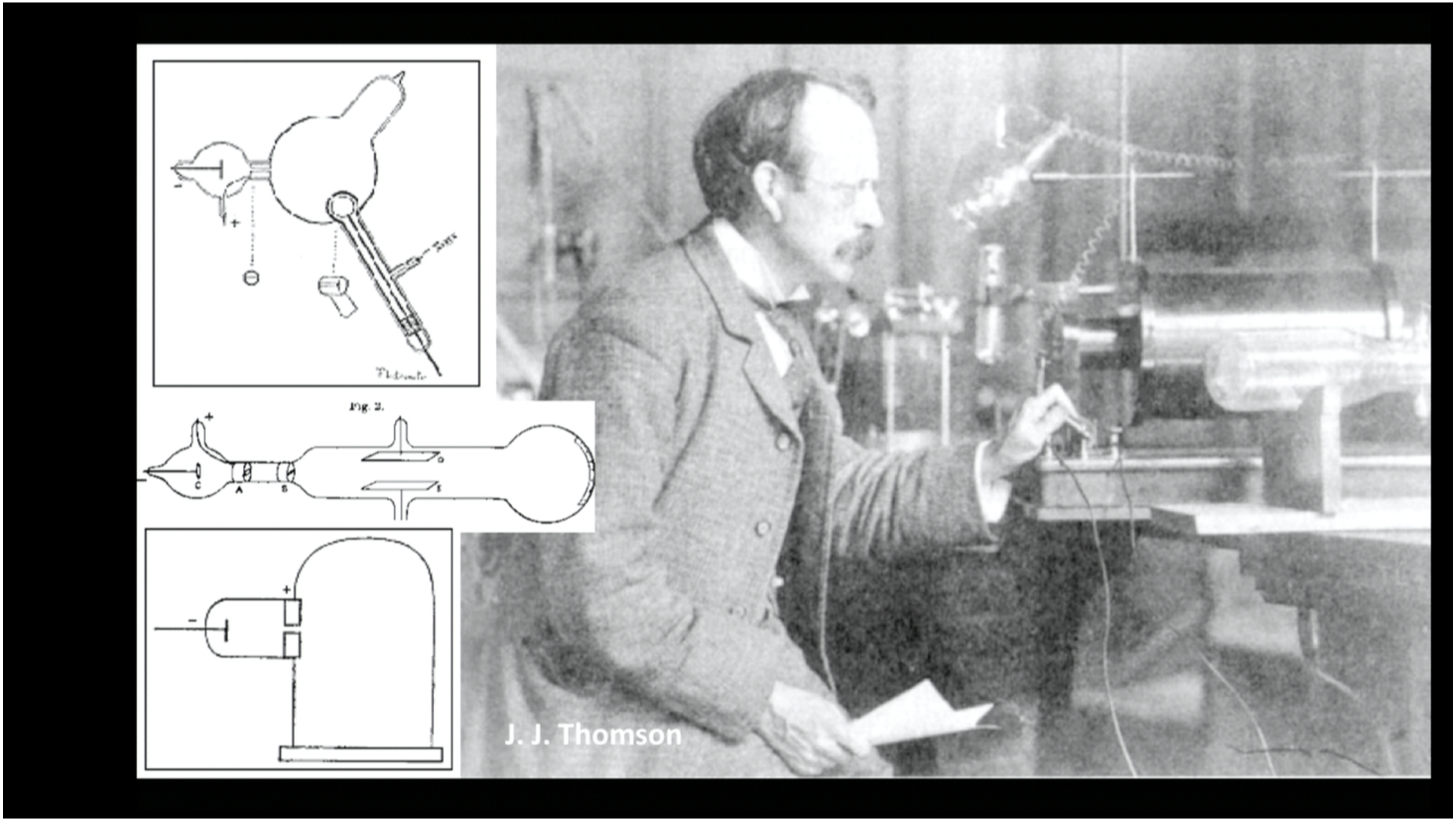
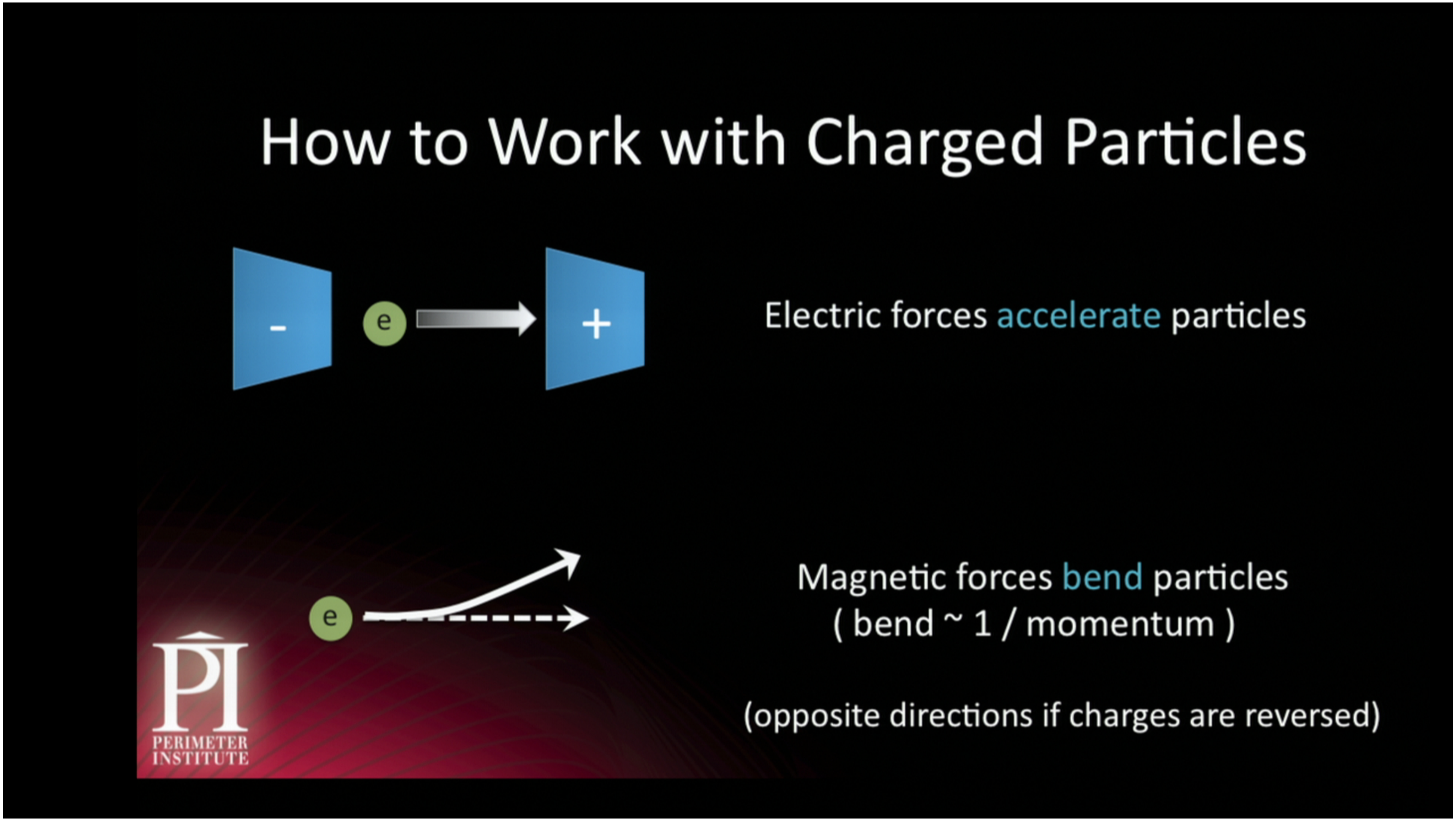


Fig. 2.
J. J. Thomson


How to Work with Charged Particles
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Electric forces accelerate particles
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Magnetic forces bend particles
(bend ~ 1 / momentum)
(opposite directions if charges are reversed)
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How to Work with Charged Particles

Electric forces accelerate particles

Magnetic forces bend particles
(bend ~ 1 / momentum)

(opposite directions if charges are reversed)

Anti-matter

Carl Anderson — 1932

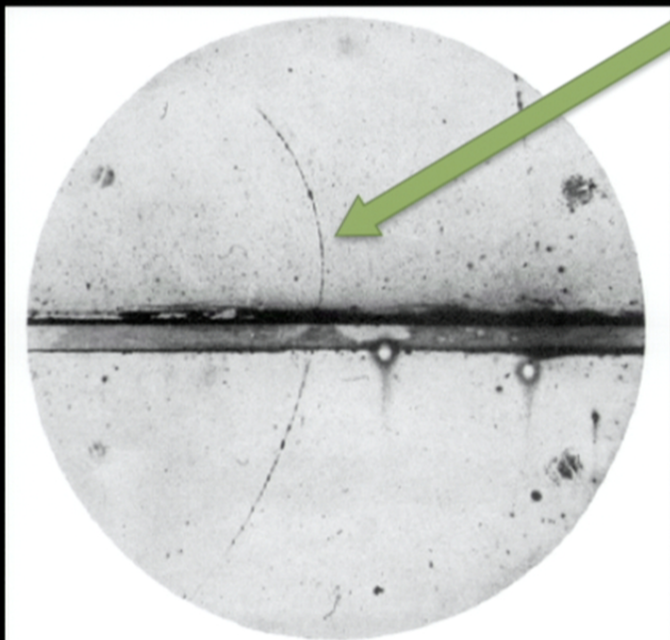
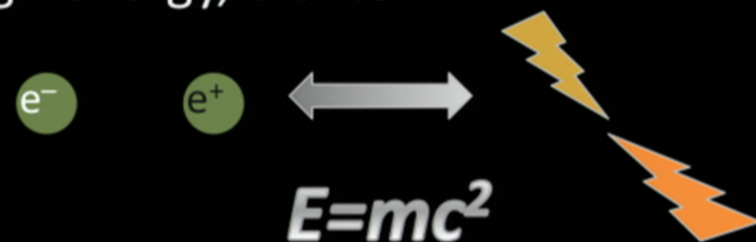


Fig. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

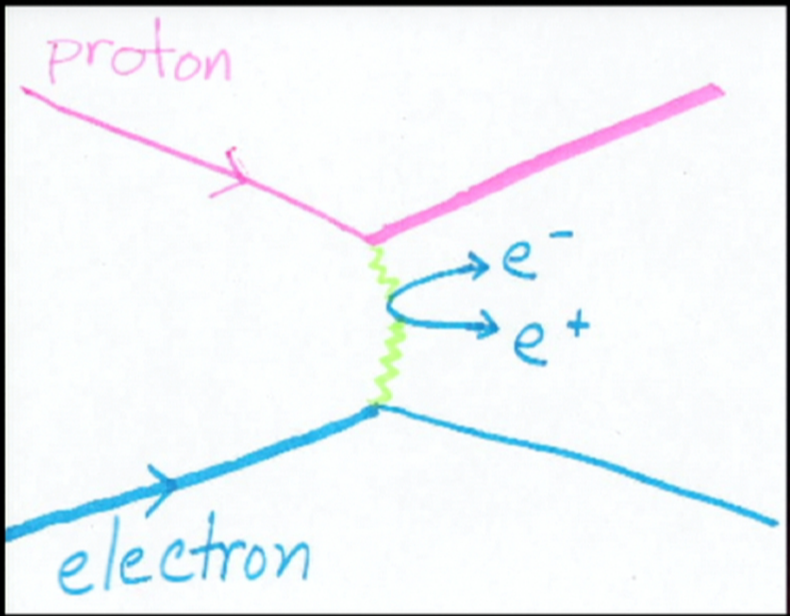
The positron (predicted by Dirac) behaved like an electron, except with the opposite charge.

In Dirac's theory, the electron (or any particle) could be destroyed – or, given enough energy, created:



An Example

In a very close collision between an electron and a proton, the electric potential energy $U \sim e^2/r$ at closest approach is bigger than its mass energy $m_e c^2$ – this potential energy can be converted into mass:



In fact every reaction that conserves **energy, momentum, and charge** (and a few other things) will happen some fraction of the time:

"Everything not forbidden is compulsory."

The Other Forces

- Neither strong nor weak are observable in everyday world (for very different reasons!)
- We've learned about them through creation & destruction of particles.


The Strong Force
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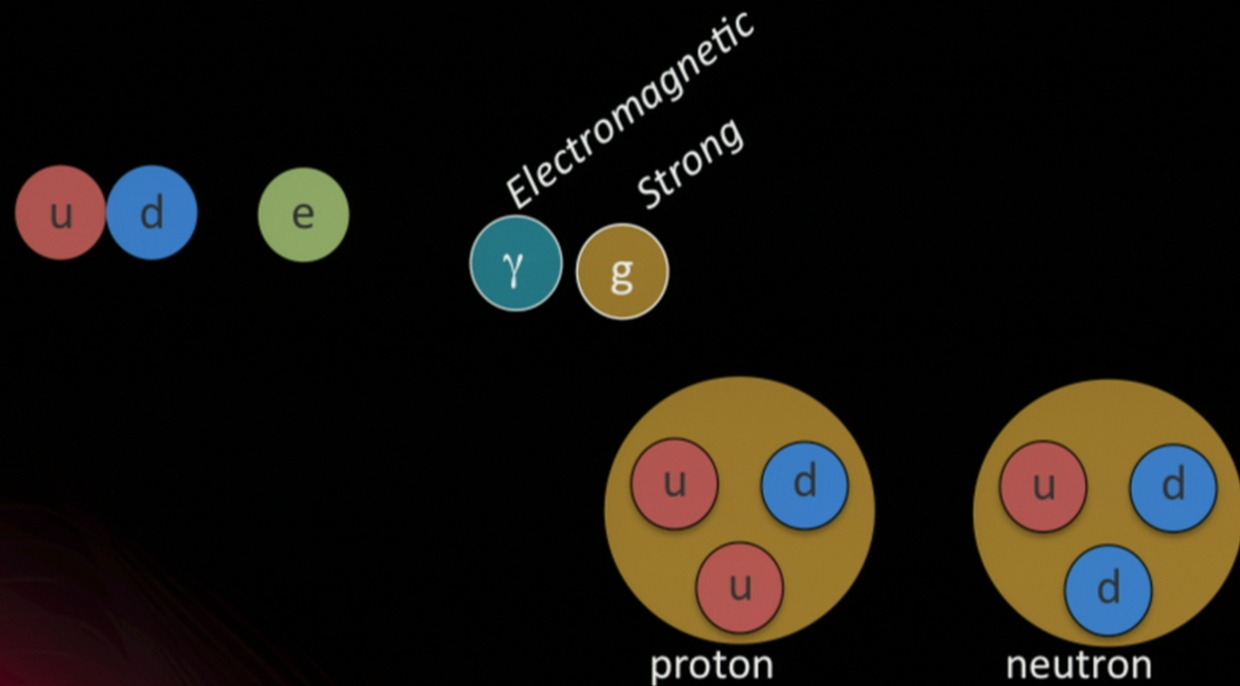
The Strong Force



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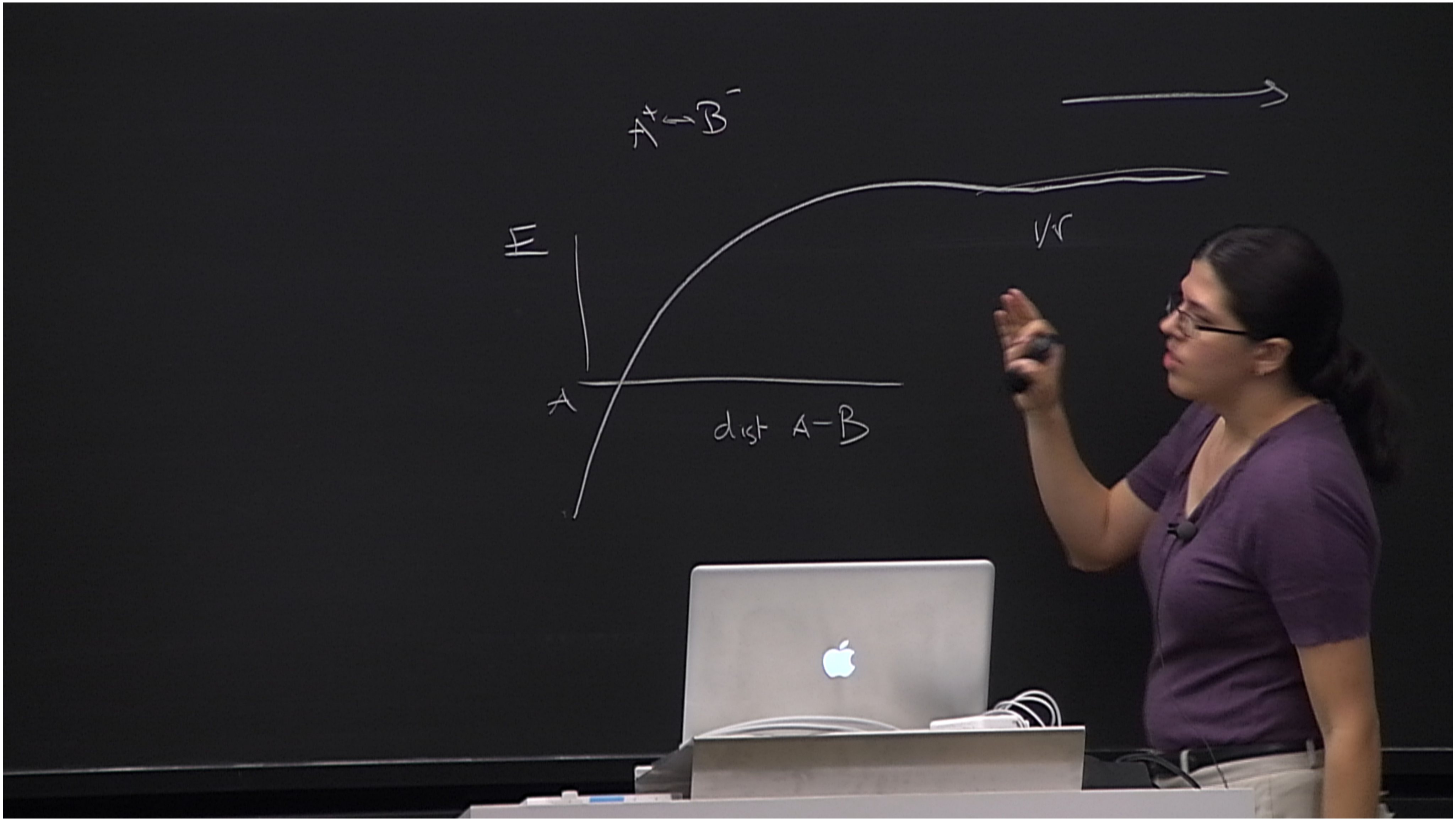
$A^+ \leftrightarrow B^-$
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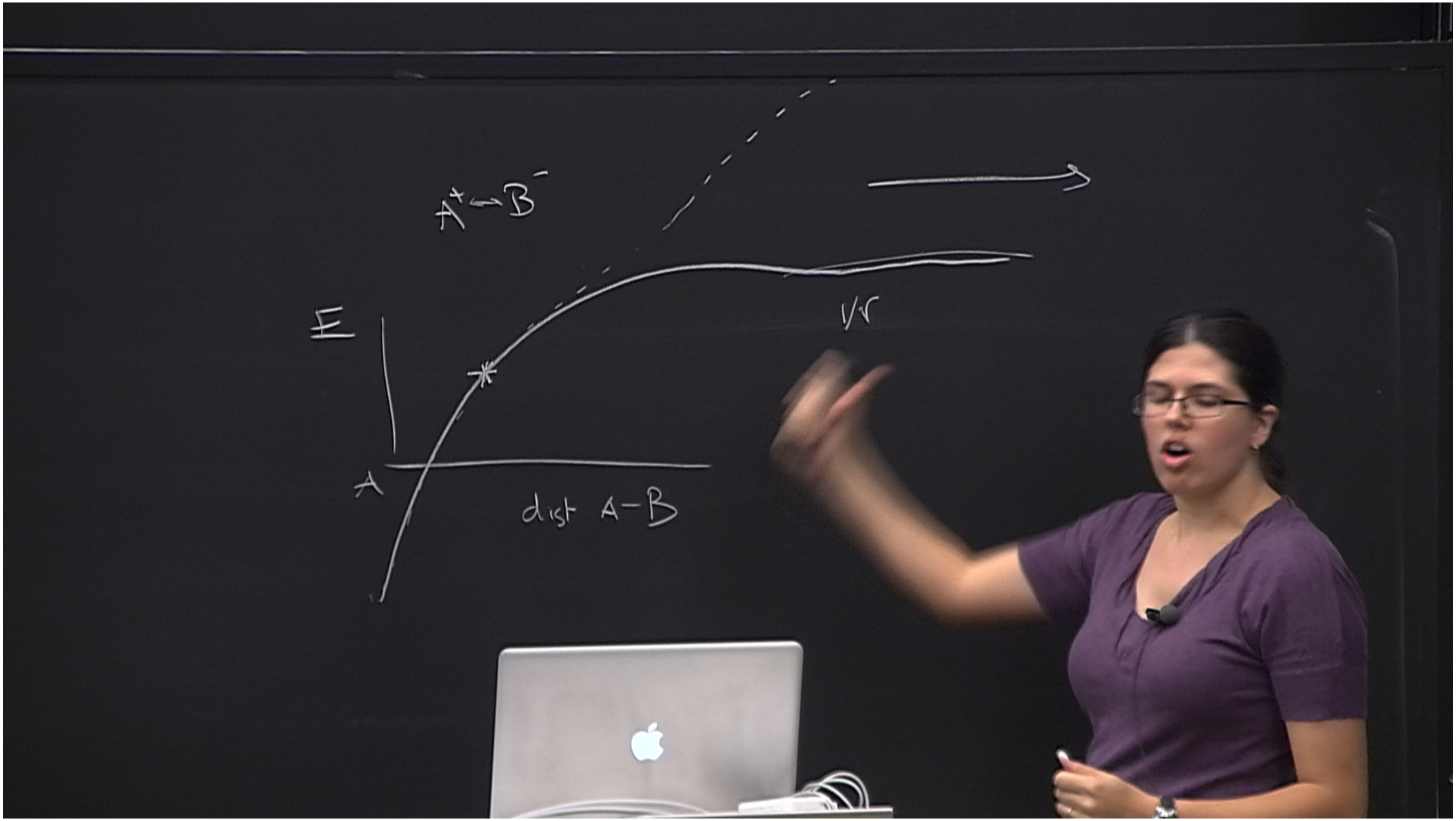
dist A–B



$A^+ \leftrightarrow B^-$
E
A
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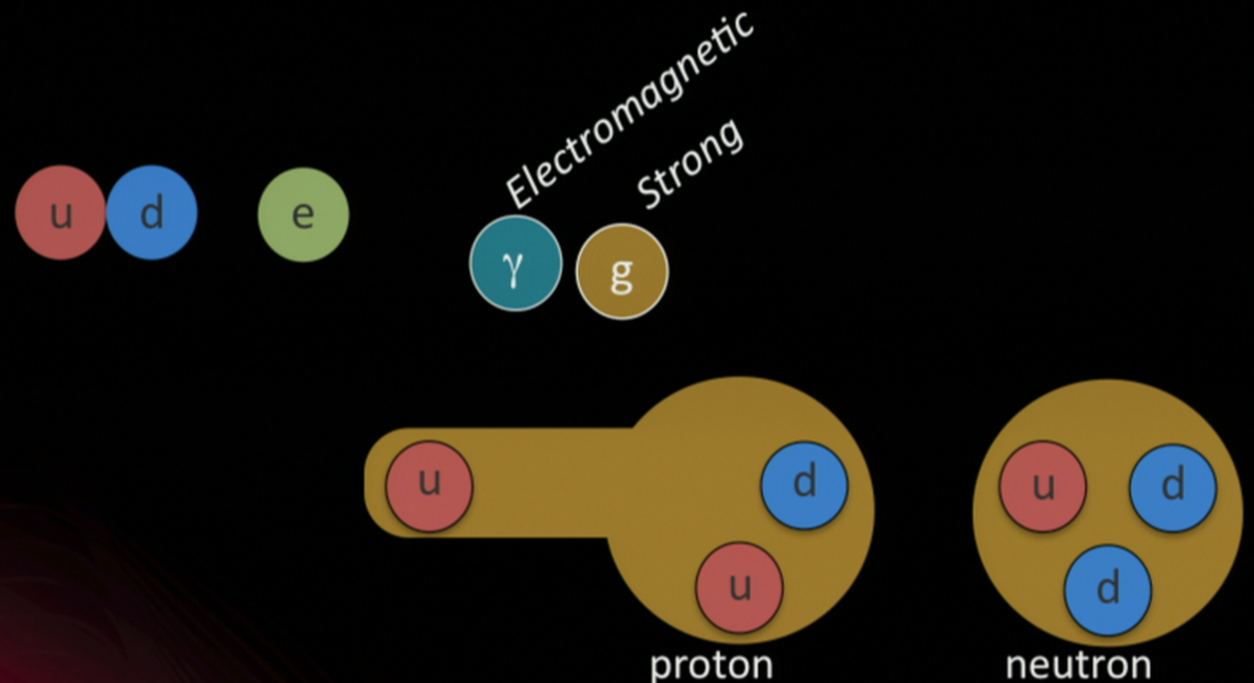
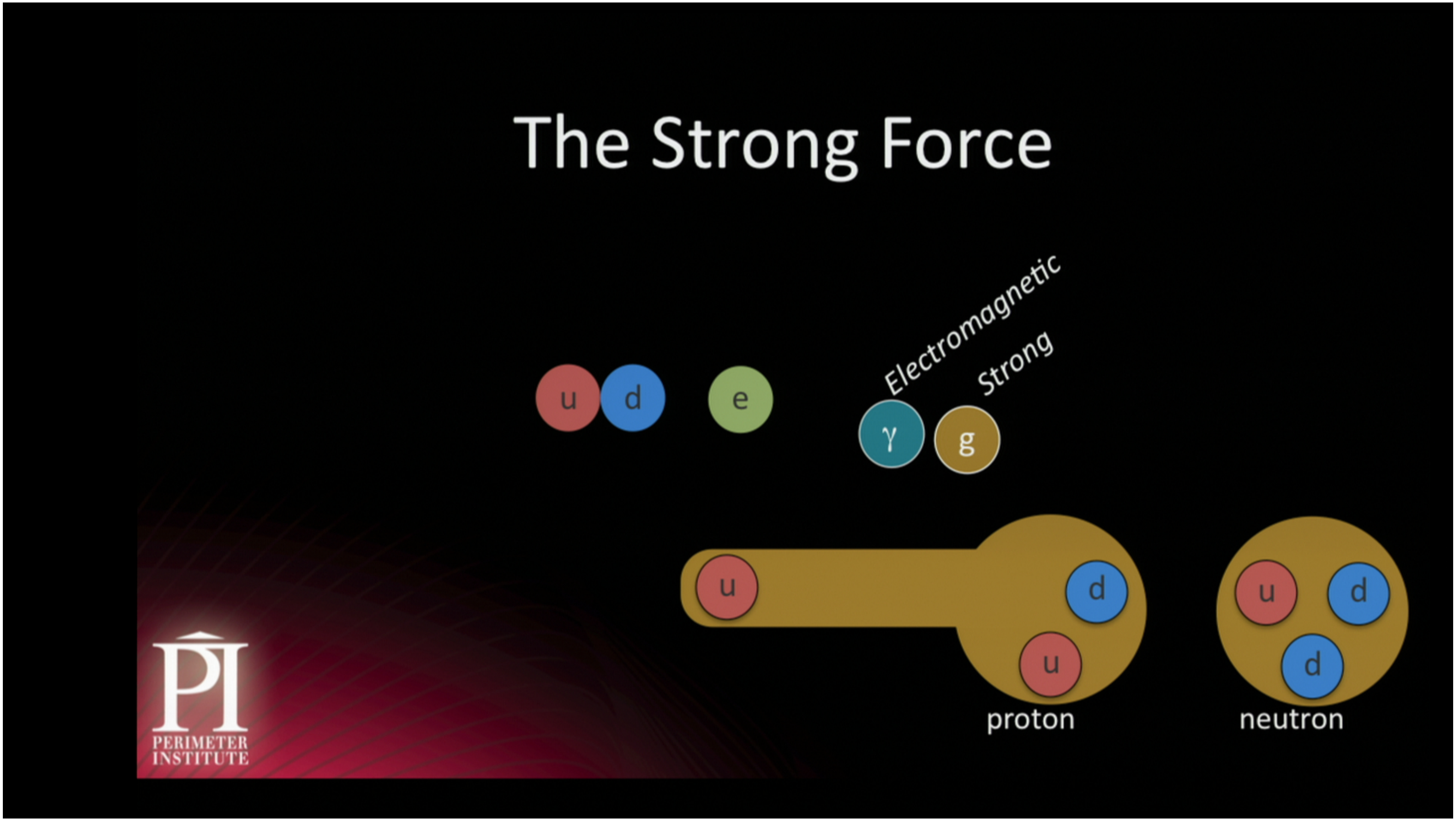
1/r

The Strong Force




The Strong Force
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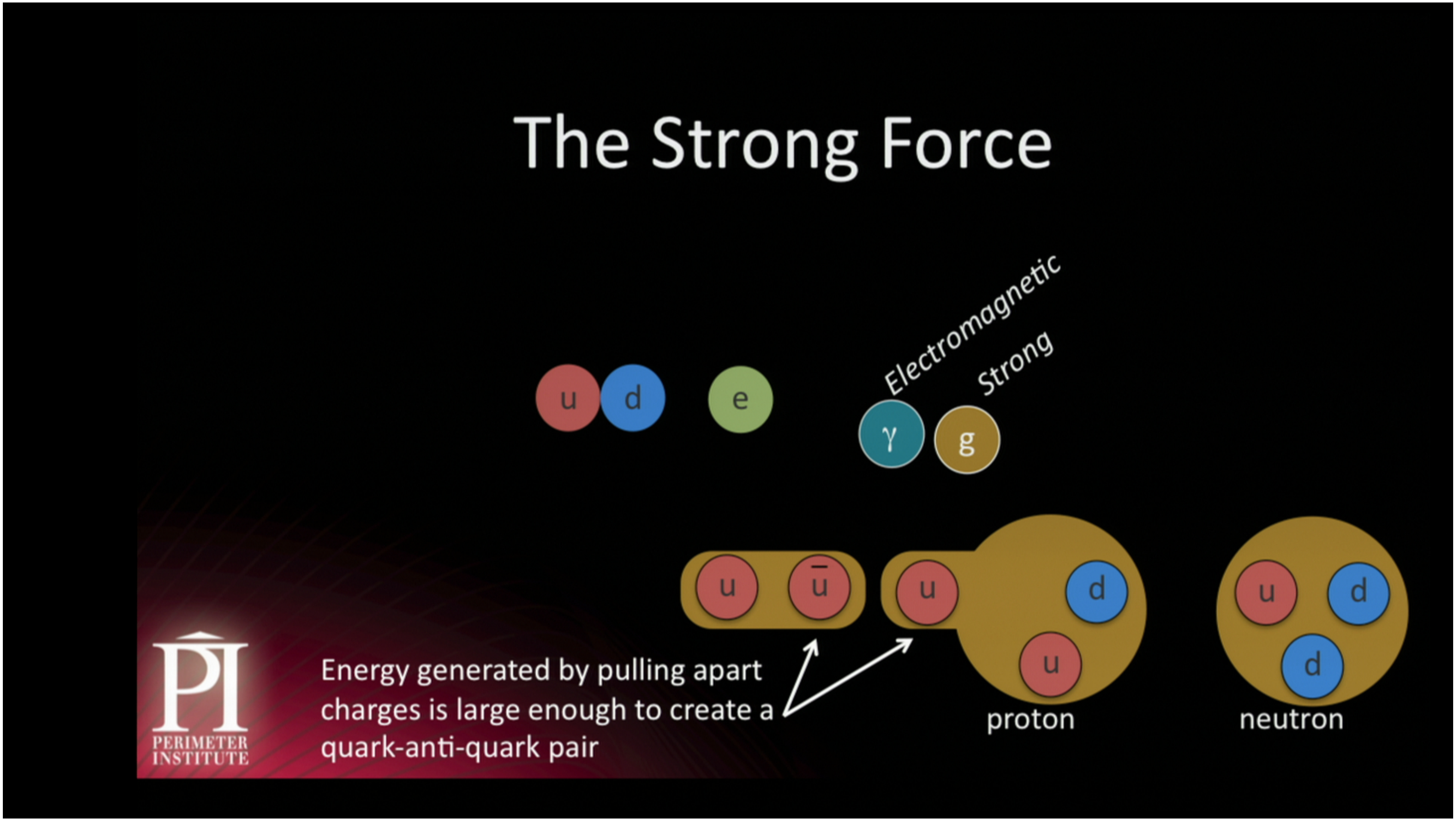
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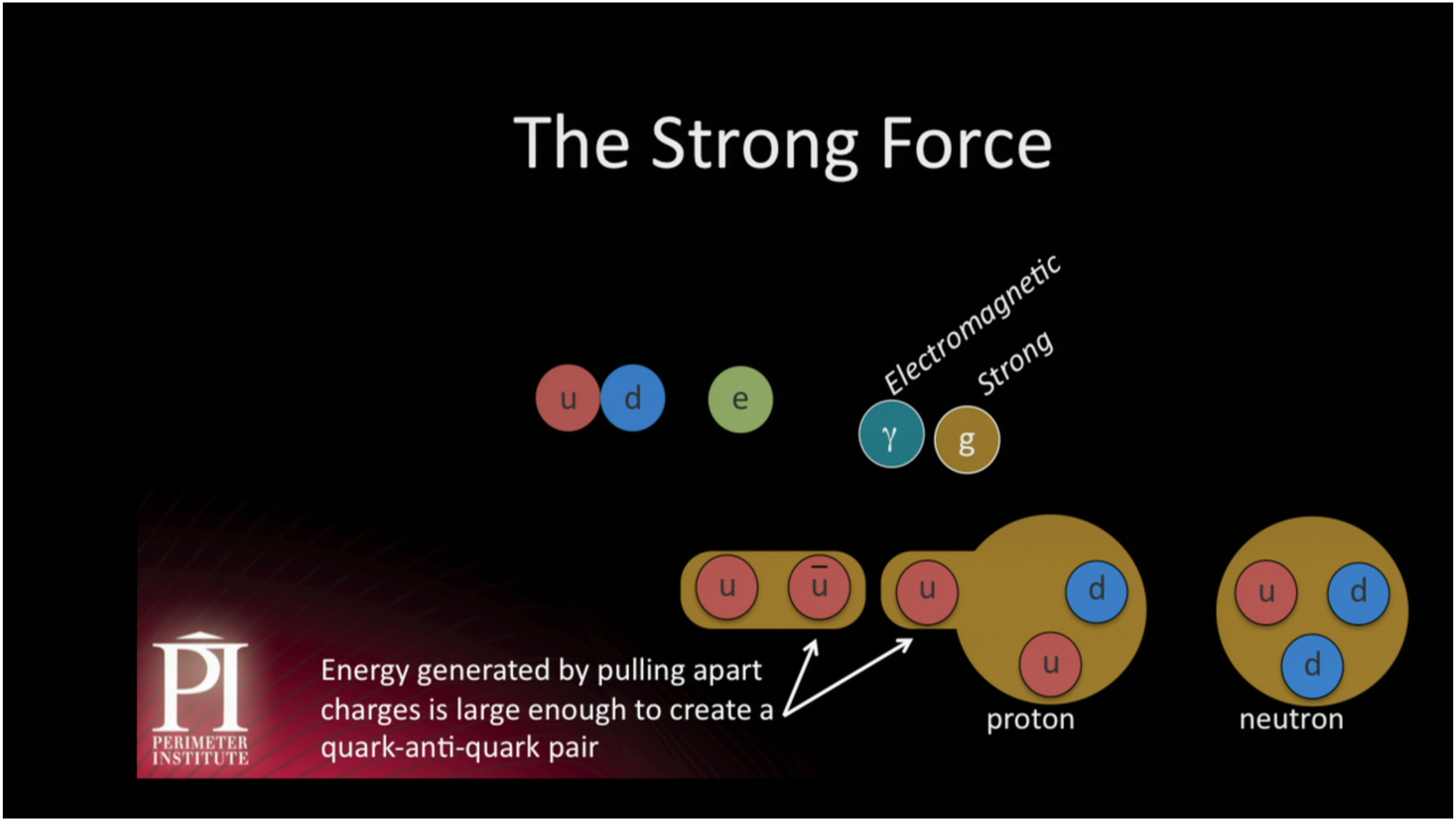
Energy generated by pulling apart charges is large enough to create a quark-anti-quark pair


The Strong Force
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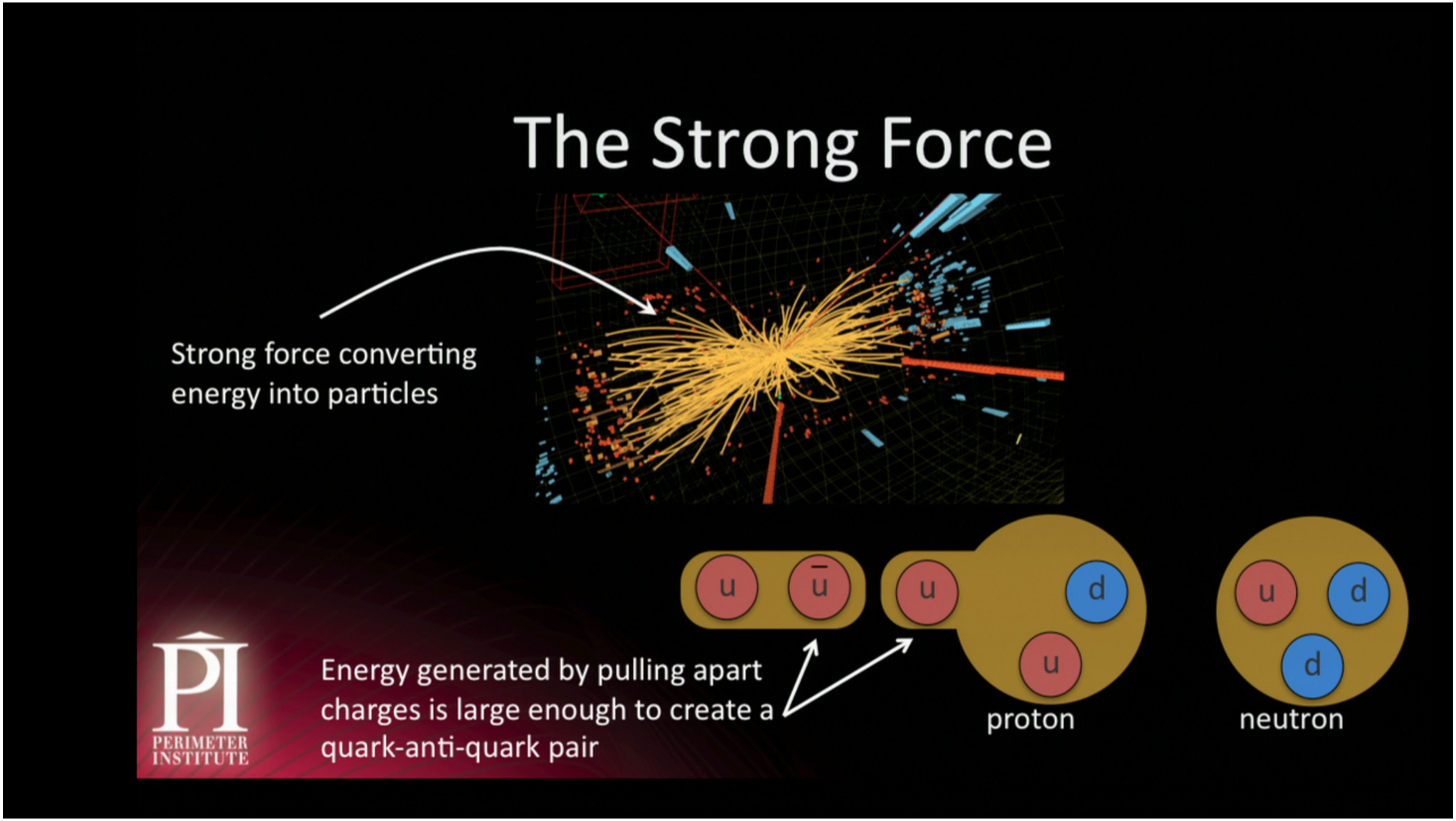
The Strong Force
Strong force converting energy into particles
Energy generated by pulling apart charges is large enough to create a quark-anti-quark pair
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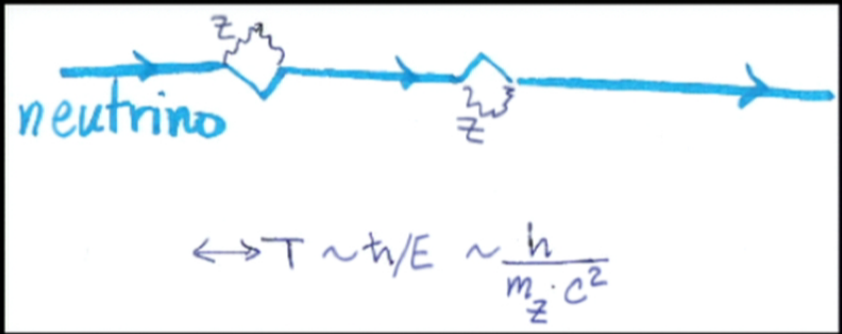
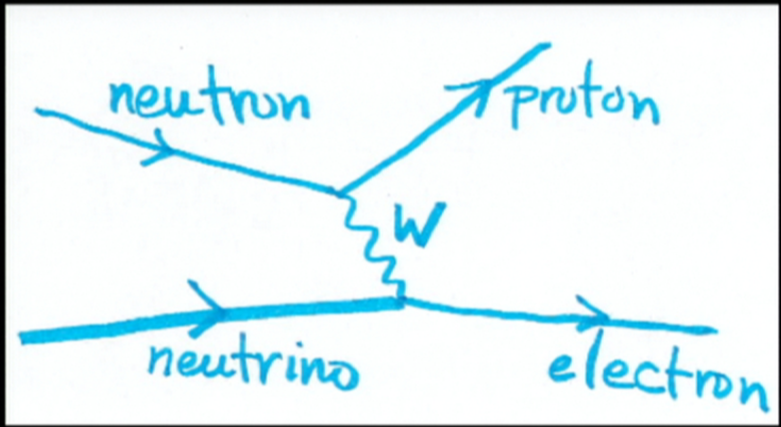
Weak Force

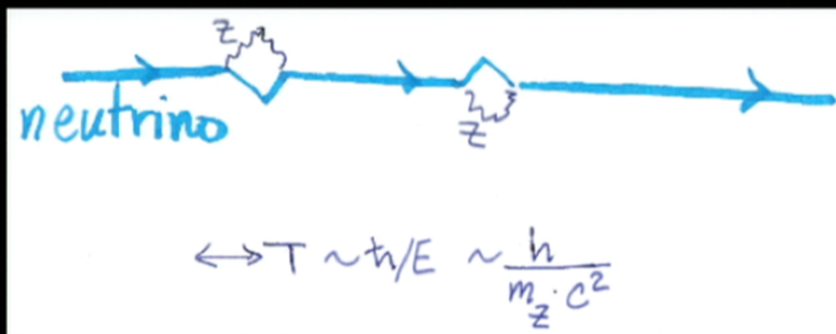


We've already met the Z particle, which mediates forces much like electromagnetism, but only over very short distances.

Its cousin, the W, is itself electrically charged, and the force that it mediates changes one type of particle into another.



Weak Force



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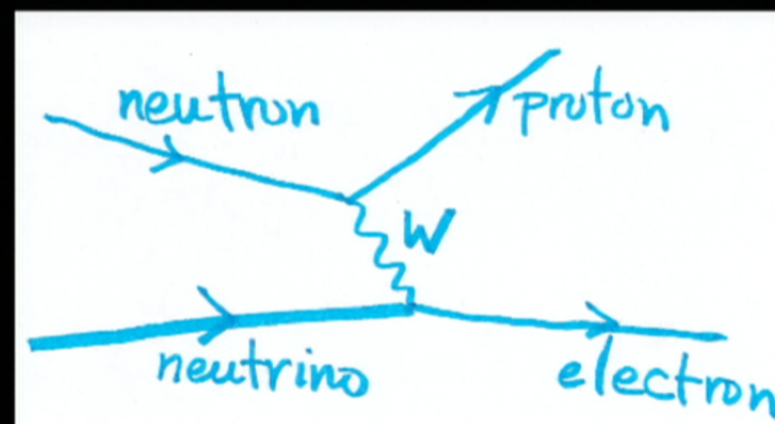
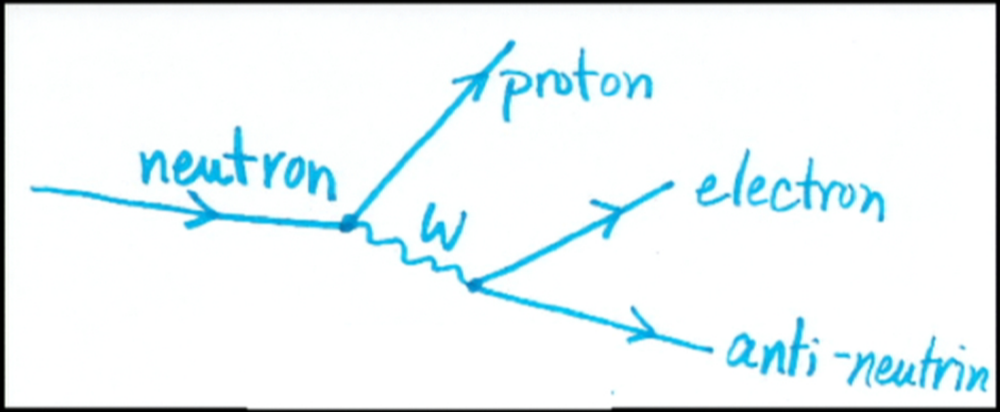


Weak Force & Beta Decays

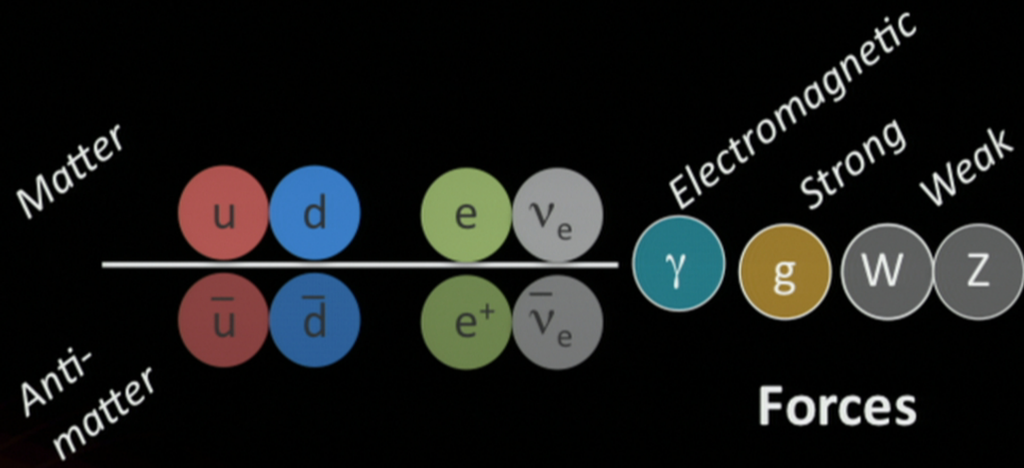
The neutron is heavy enough that it can decay, through the same interaction (just rearranging the particle legs)



This is a rare process, because all the action must happen in a region of size $h/(m_W c^2)$...

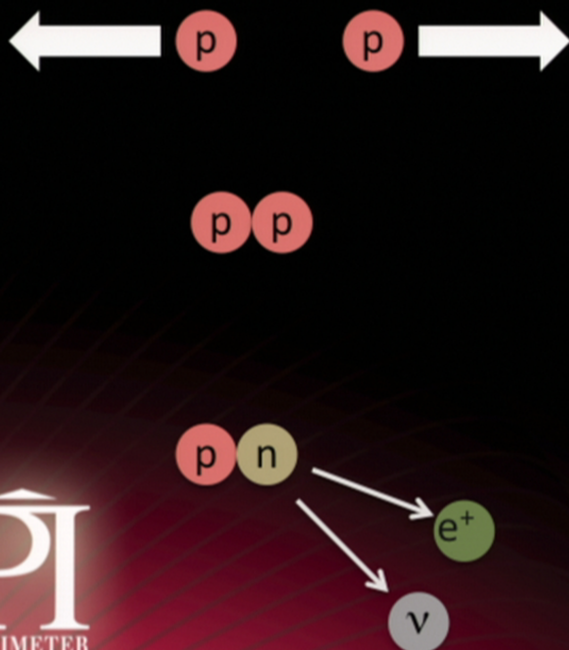
...but the size of the other particle wavefunctions is much bigger than this!

The Matter and Forces of Nature



Powering the Sun

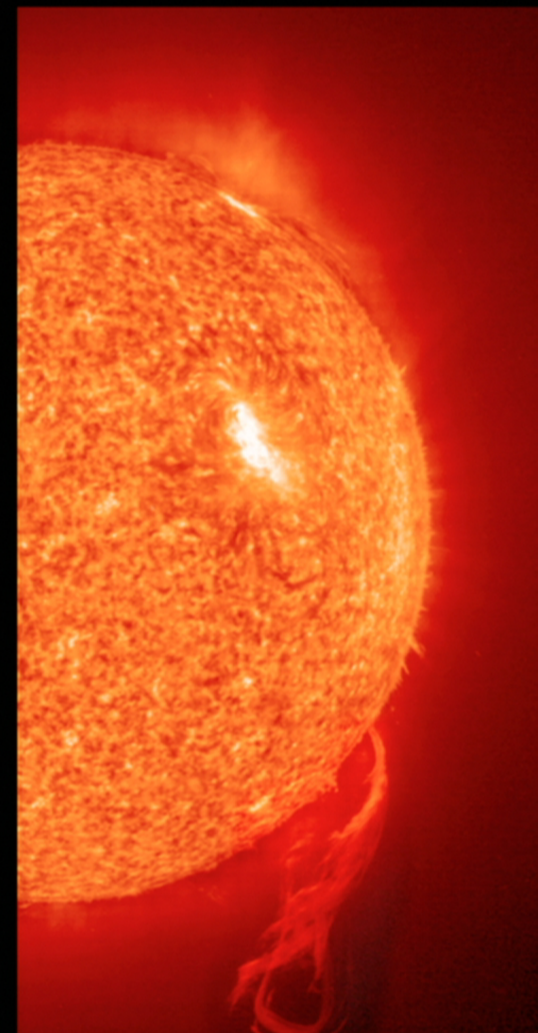
The Forces at Work



Equal electric charges repel

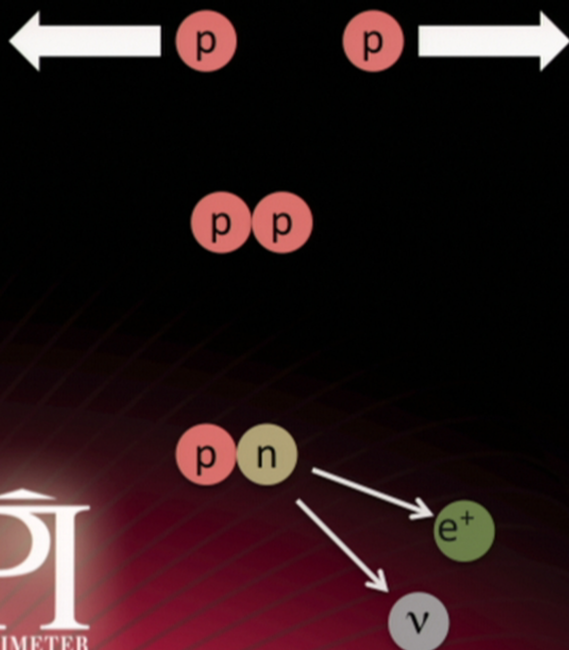
Short-range strong force pulls them together – but not enough

Finally weak force transmutes to stable deuterium



Powering the Sun

The Forces at Work



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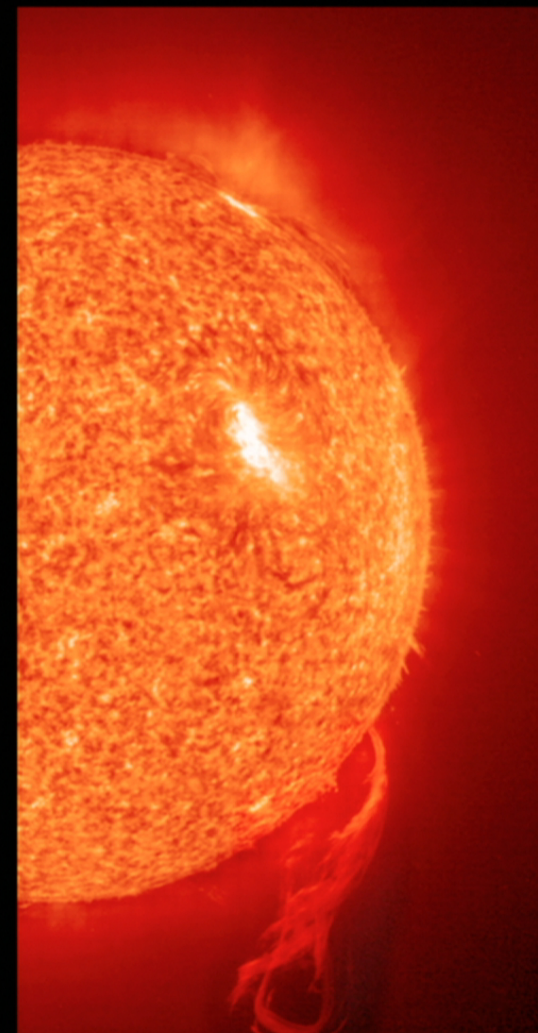

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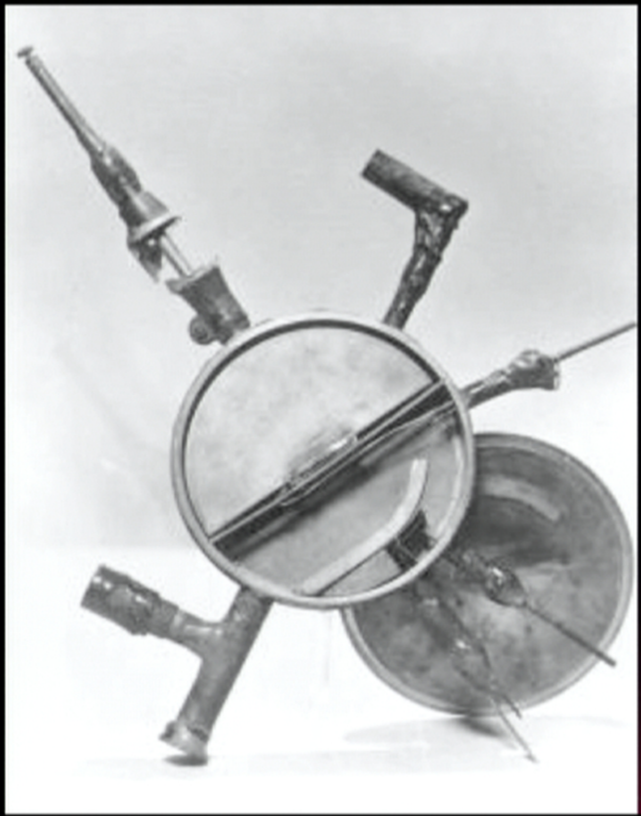
What is a particle?

- Building block of quantum theory that can incorporate all observed phenomena, matter, and forces

- Particles can be created & destroyed
  - These processes have to conserve charge
  - But **every** charged particle has an anti-particle, and so the particle+anti-particle can **always** be created, if a process has enough energy ($E=mc^2$)
  - So one good way to hunt for new forces and new patterns in nature is by looking for new particles!

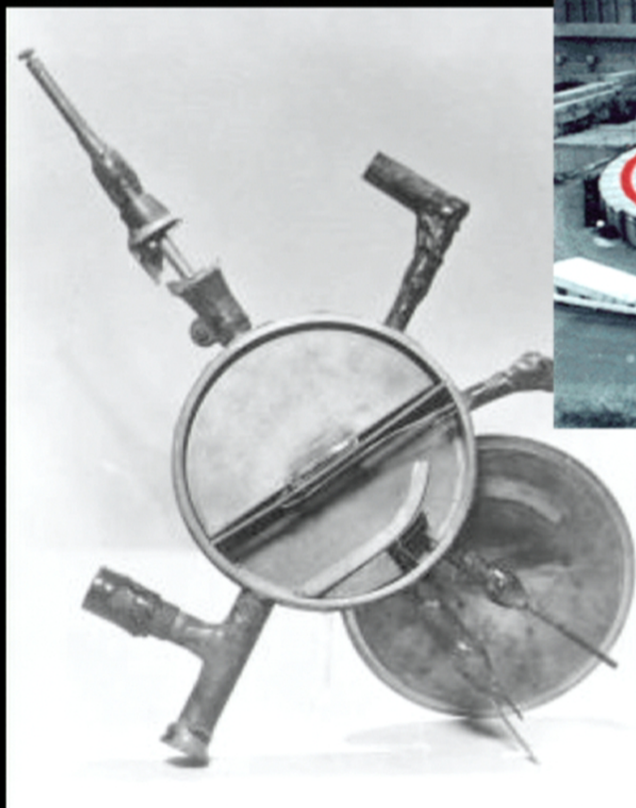
Searching for New Matter

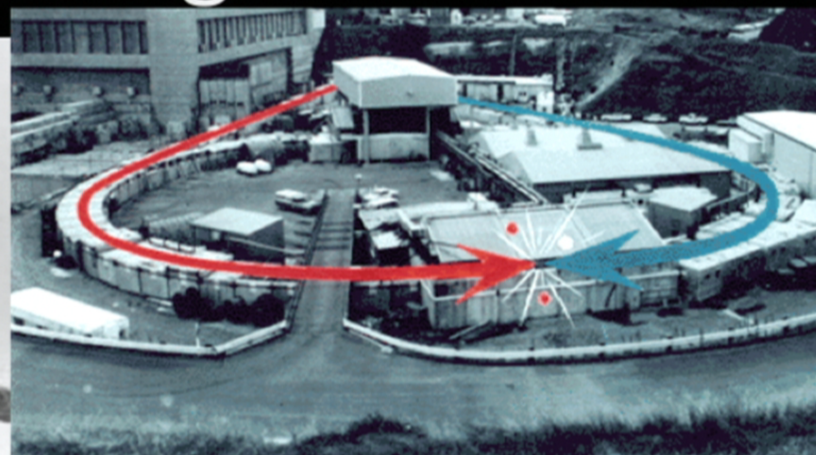


First cyclotron, Berkeley 1931
(Szillard and Lawrence)

Combined electric force and magnets to reach unprecedented particle energies

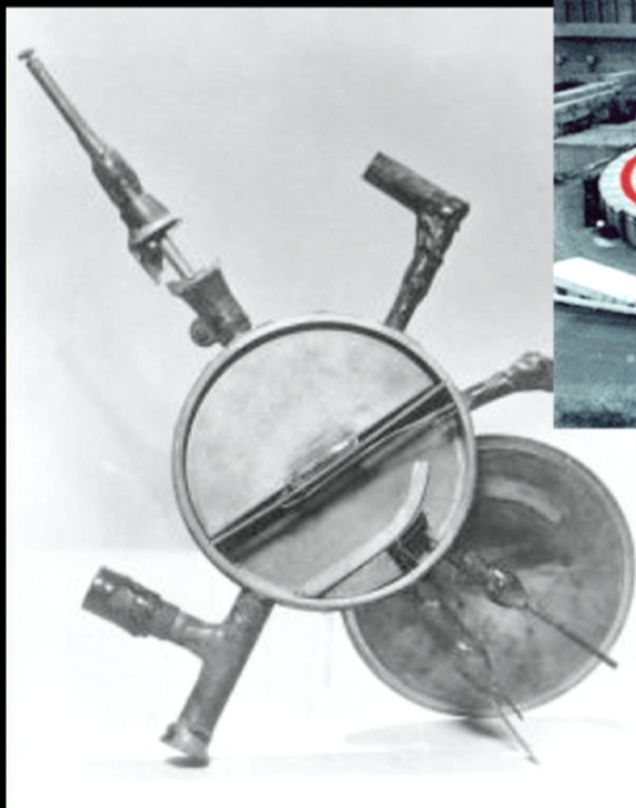
Searching for New Matter

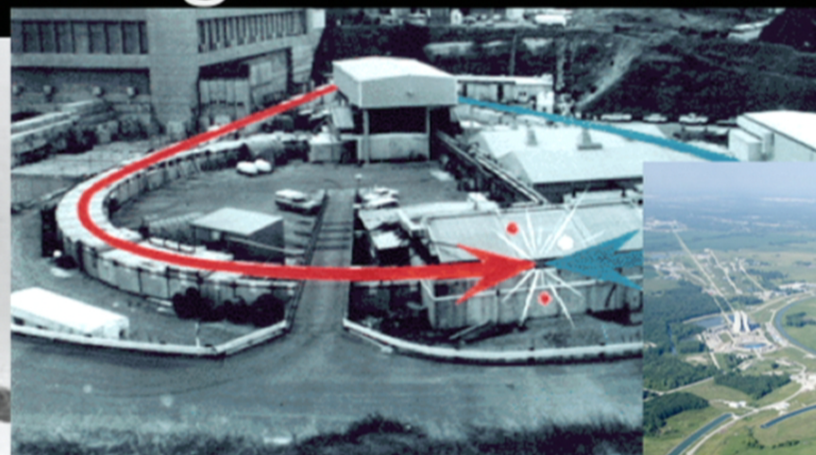




SPEAR (SLAC, near San Francisco) 1972:
Early colliding beam experiment,
Discovery of τ and co-discovery of
charm quark

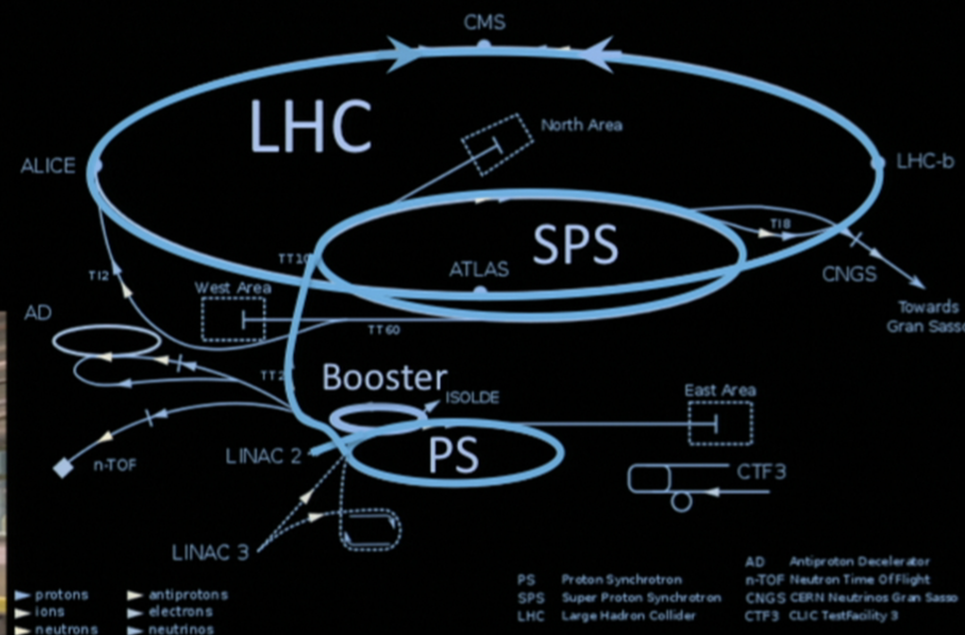
Searching for New Matter





Tevatron (Fermilab, near Chicago) 1983

Discovery of the top quark and world's 2nd-highest energy collider



CMS
LHC
North Area
ALICE
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TI8
ATLAS
TI2
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Towards Gran Sasso
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TT2
Booster
ISOLDE
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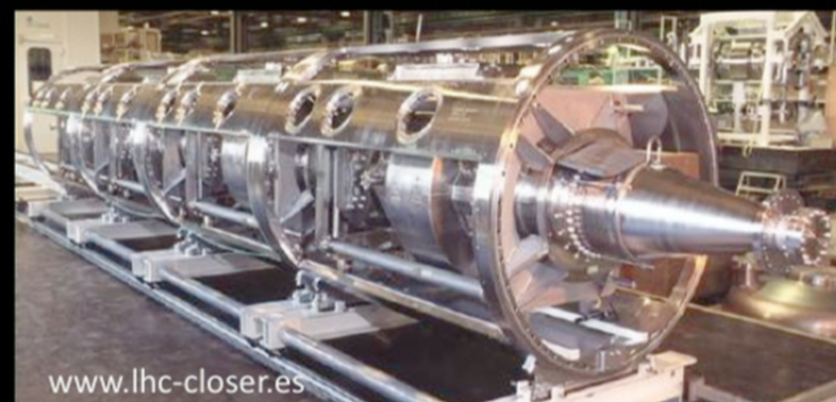
neutrinos
PS Proton Synchrotron
SPS Super Proton Synchrotron
LHC Large Hadron Collider
AD Antiproton Decelerator
n-TOF Neutron Time Of Flight
CNGS CERN Neutrinos Gran Sasso
CTF3 CLIC TestFacility 3

Accelerating the Protons

Same principle as the cathode ray tube, on a much larger scale



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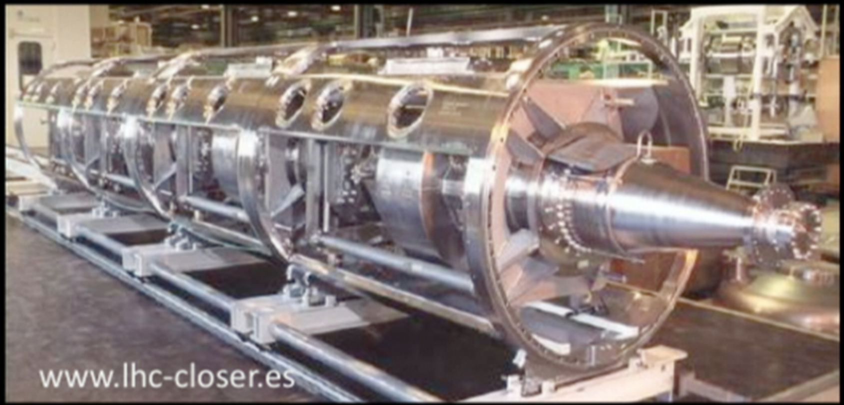

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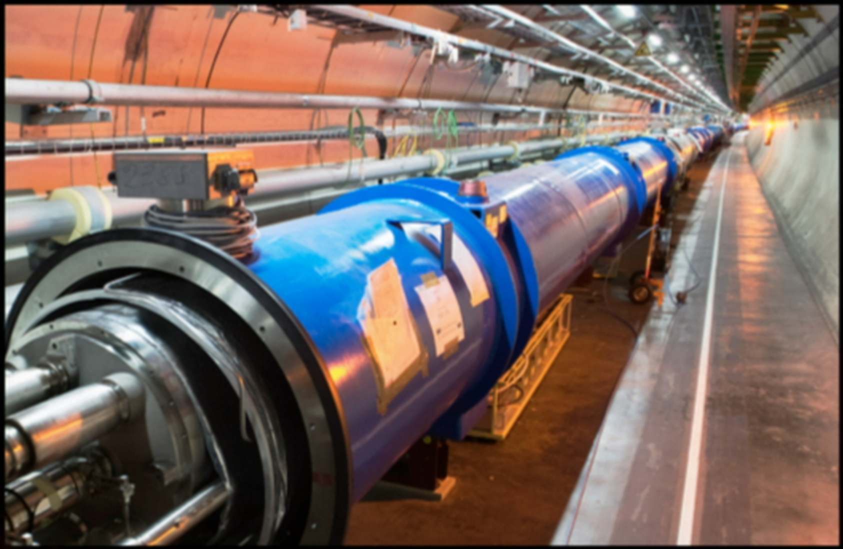
Why is the LHC so large?

Highest energy proton beams (by 4–7x)

At this energy, each magnet can only bend the protons by 7 cm

The LHC is as small as it can possibly be, with protons closing the circle.



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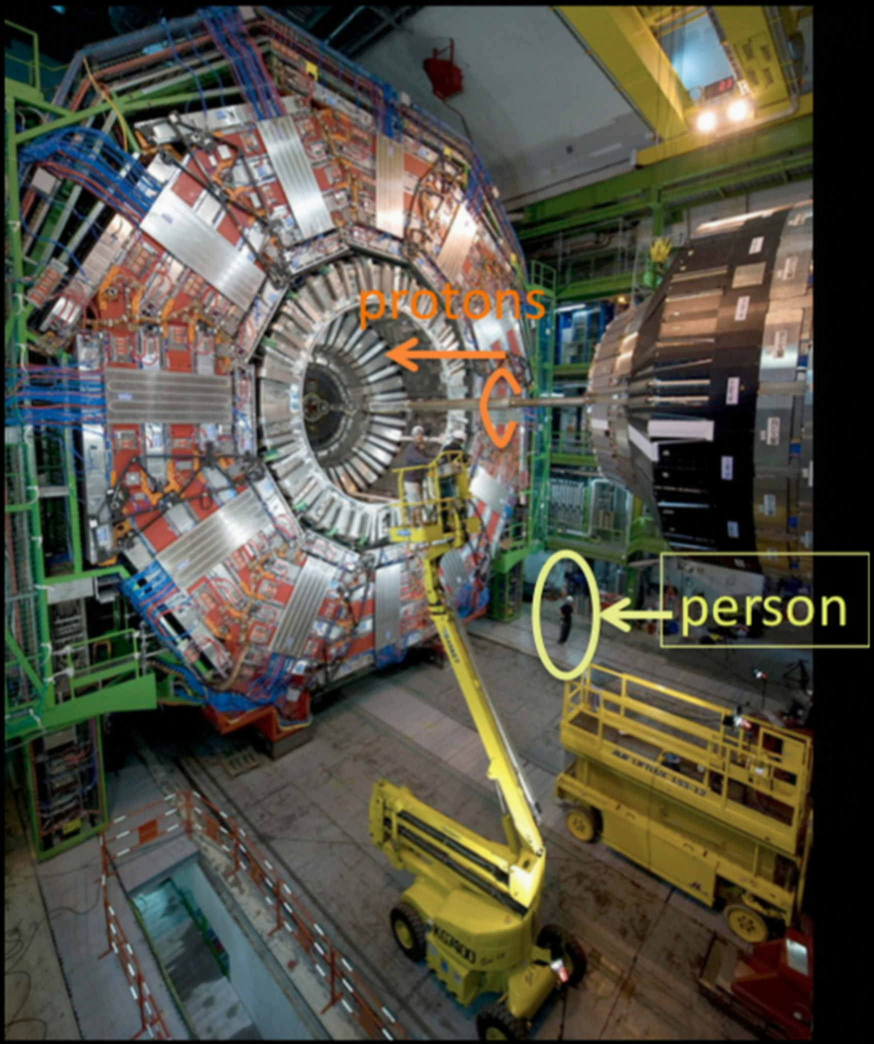
Collision points

At four points around the ring, the clockwise & counter-clockwise beams of protons pass through each other.

Most of the protons don't interact much, and go around again. But at every crossing, ***some*** protons do collide – sometimes spectacularly.

Each layer responds differently to particles:



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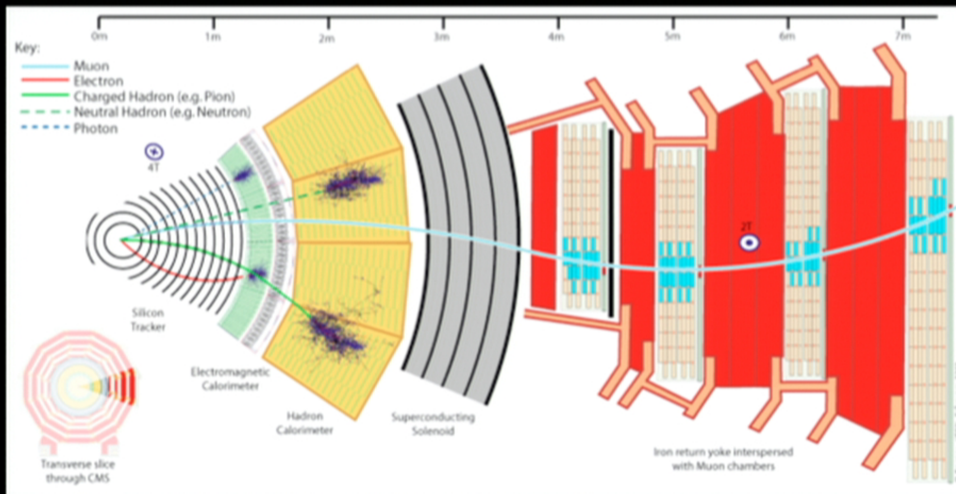
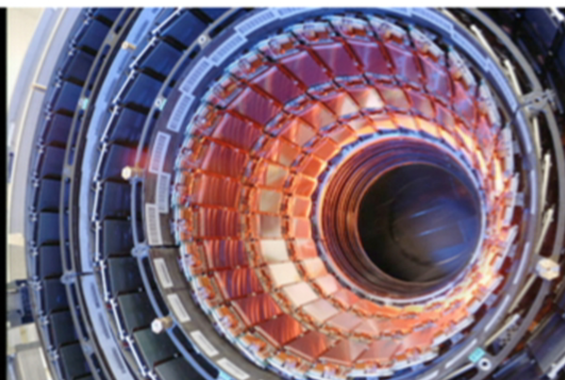
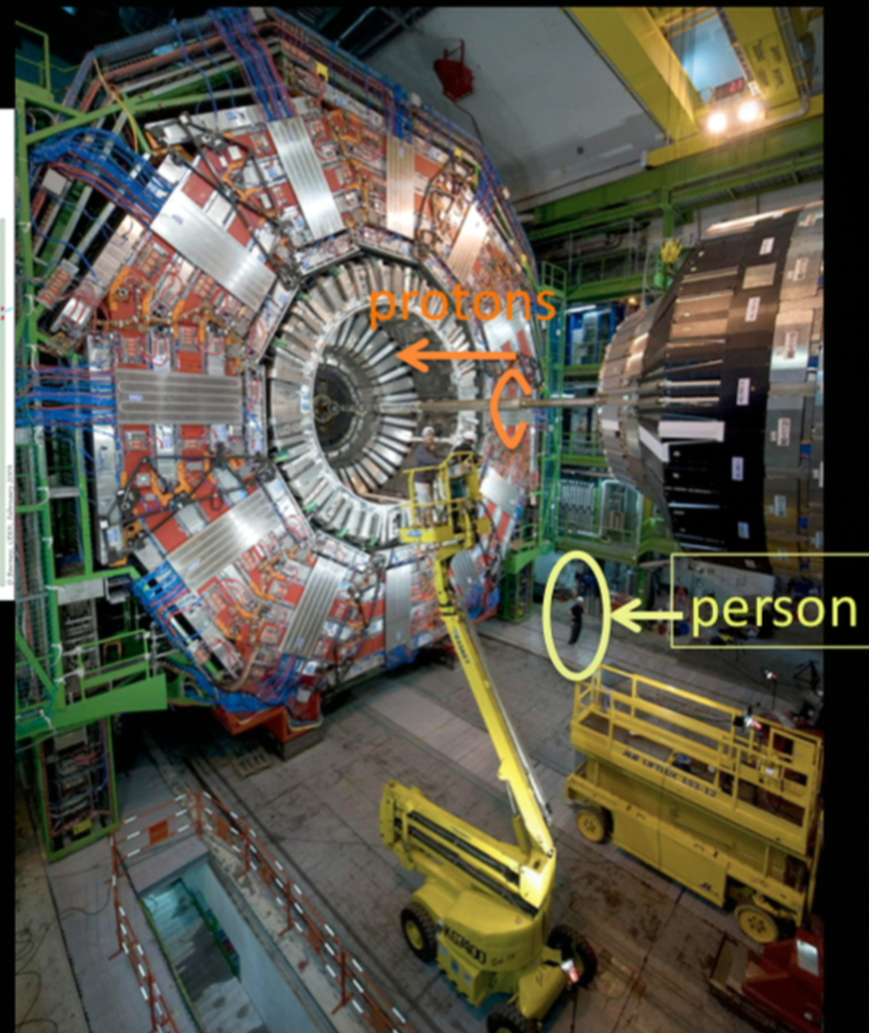
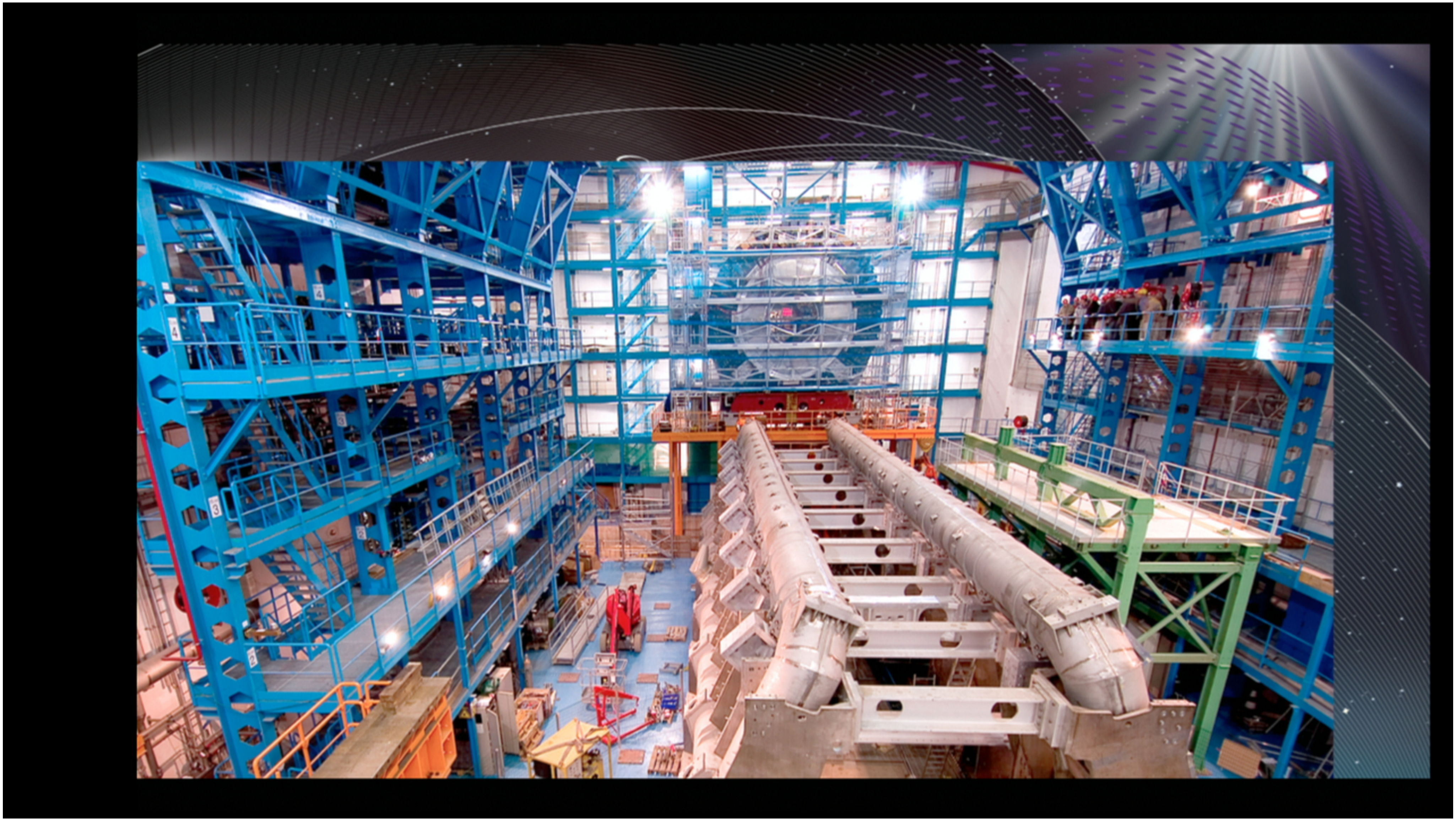
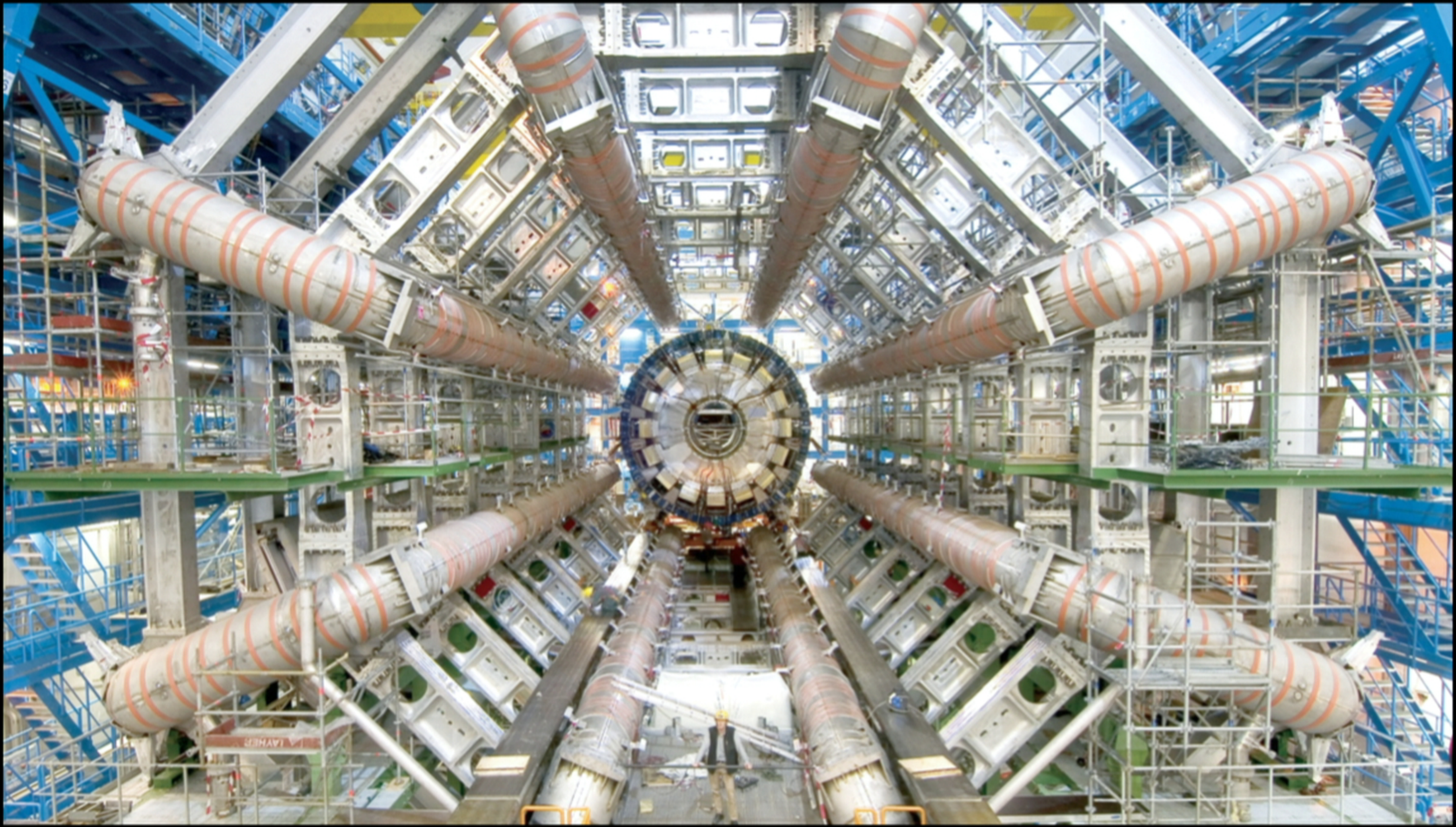




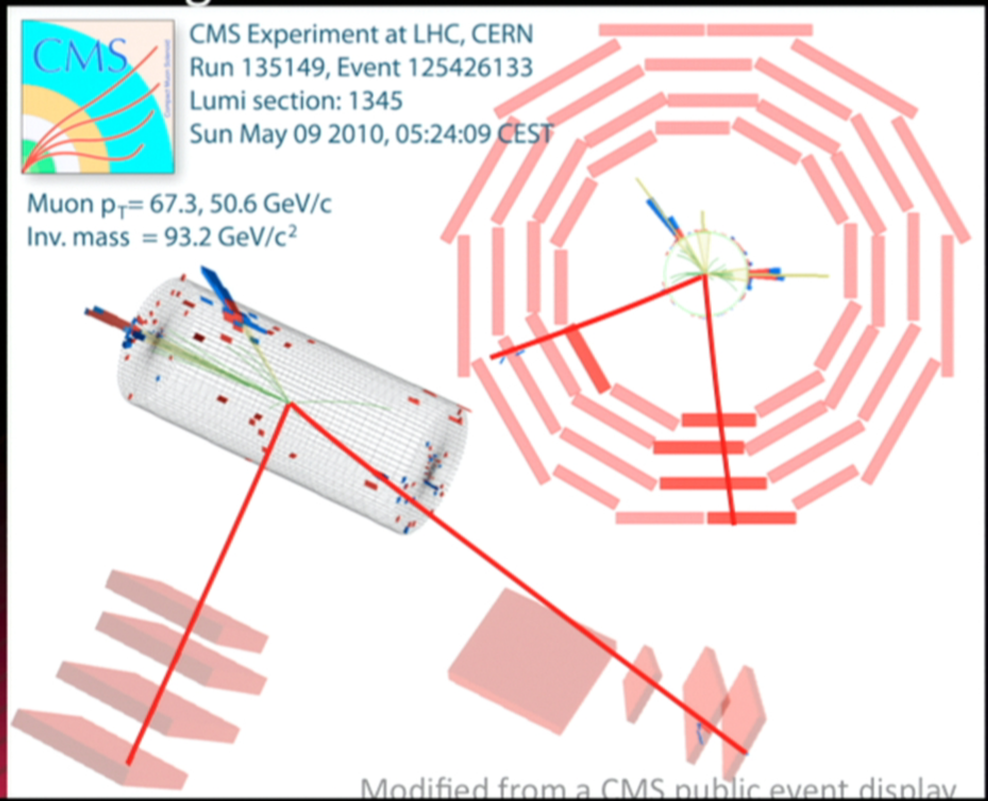
Inner layer (Silicon tracker)







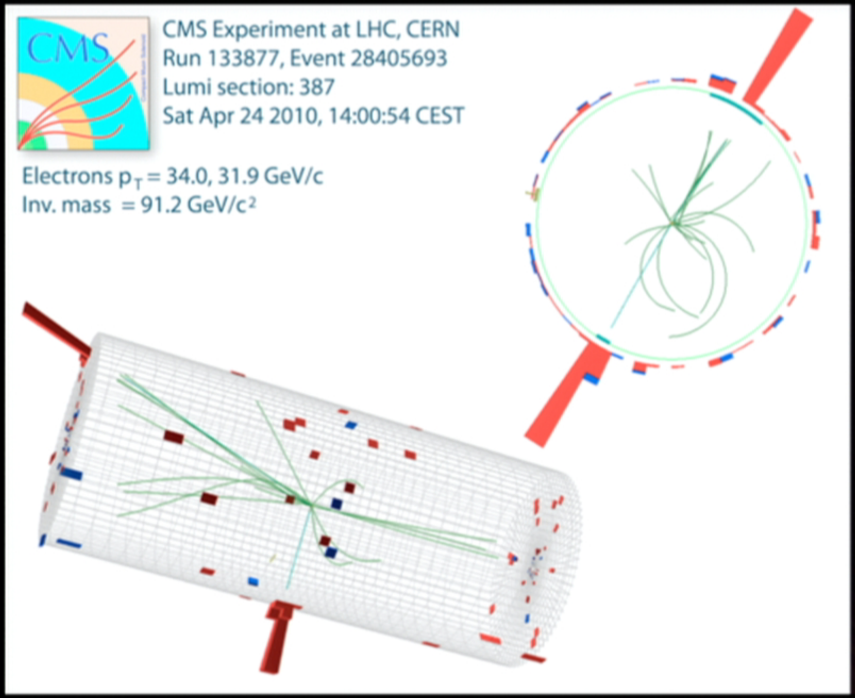
Many of the particles we want to study decay almost instantly – The detectors take "pictures" of the decay products, which can be pieced back together.



The red lines are signals of a muon and anti-muon – ***probably*** produced by a decaying Z particle

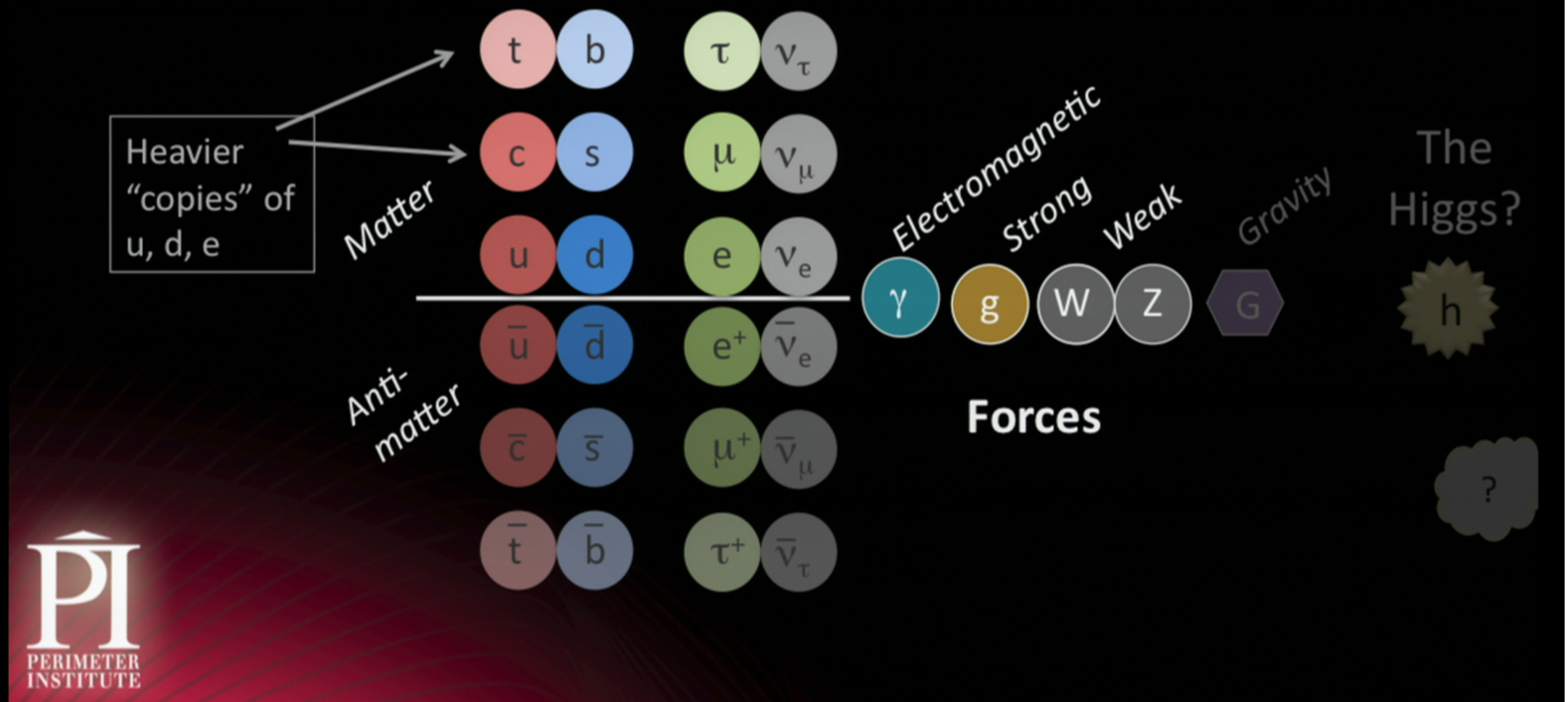
Just remember: everything that is allowed will happen some of the time, but we can't predict when!

We can't predict when a Z is produced, or how it decays



We can only calculate the probability of each type of decay, and compare it to the fraction of collision events where it actually happens.

Particles "seen" as of July 3, 2012



The Weak-Force Conundrums

A thought experiment:

Can calculate the **probability** that these W's scatter under electric and weak forces.

For very high-energy Ws, the probability we calculate exceeds 100%

(this problem only arises because the W has mass)

Nonsense – the theory **must** be incomplete!

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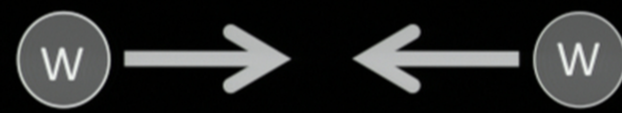

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The Weak-Force Conundrums

What can solve them?

There must be a new force that changes how W's interact
– it must be carried by one or more new particles:
the Higgs particle(s)

Its couplings to the W and Z must be precisely related to their masses, to fix the scattering calculation.

In fact, the necessary couplings to **all** the "fundamental" particles are **proportional to their masses**

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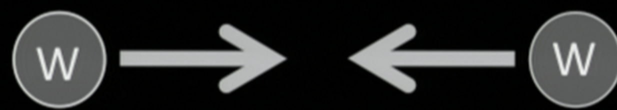

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Solving the Weak-Force Conundrums

Every force in nature has both particles and fields:

Electromagnetic Particles (light)

Electromagnetic Fields

Electric fields can accelerate,
Magnetic fields can bend,
but Higgs fields can **give** inertia, or mass

All of the fundamental particle masses seem to comes from (one or more) Higgs field filling all of space.

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This makes the Higgs field **very** important!

- Without a Higgs field, the electron would have no mass, and there would be no stable atoms
- The W and Z bosons would be (almost) massless – radioactive decay would be much faster
- The proton would be heavier than the neutron, and would decay into it (instead of the other way around)

So it's well worth our time to understand how it works… by looking for the Higgs particle!

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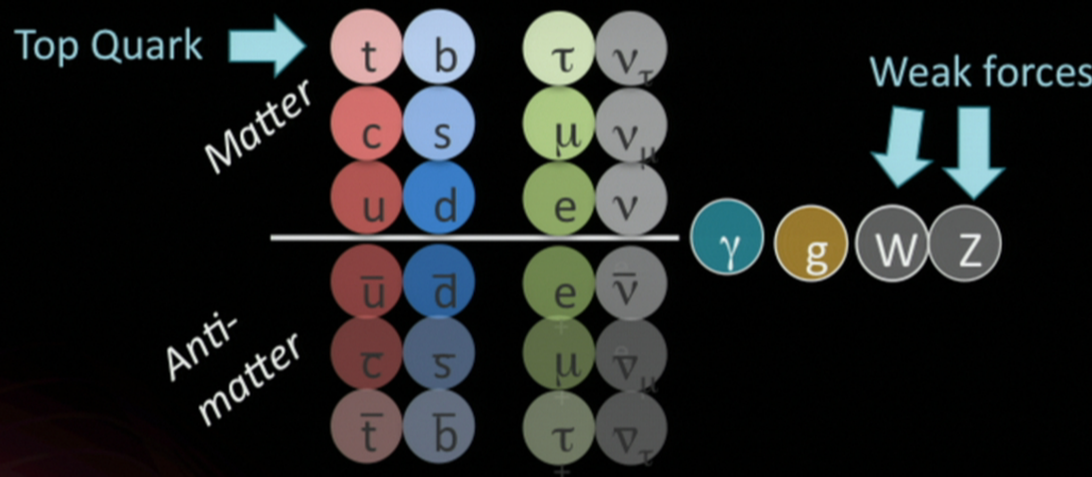
Tools for Higgs-Hunting

Heavy particles have **strongest** Higgs-charges – but decay fast.



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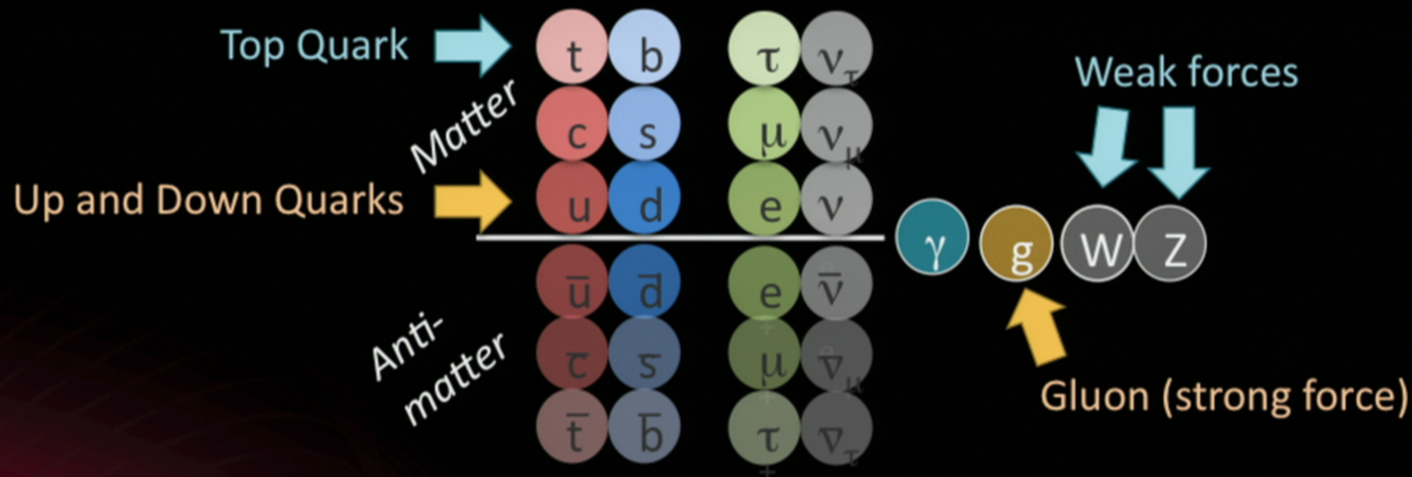
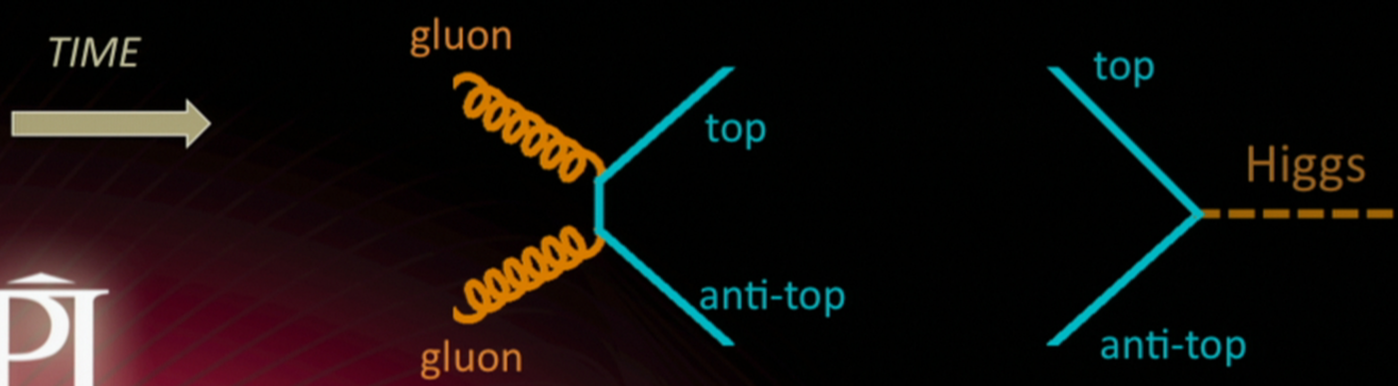


Ordinary matter made of **light particles** with **weakest** Higgs-charges (u,d charge about 0.00003)

Higgses through Quantum Mechanics

Although the gluons inside the proton have no Higgs-charge, they talk to top quarks which have a **HUGE** Higgs charge!



LHC

hypothetical top collider

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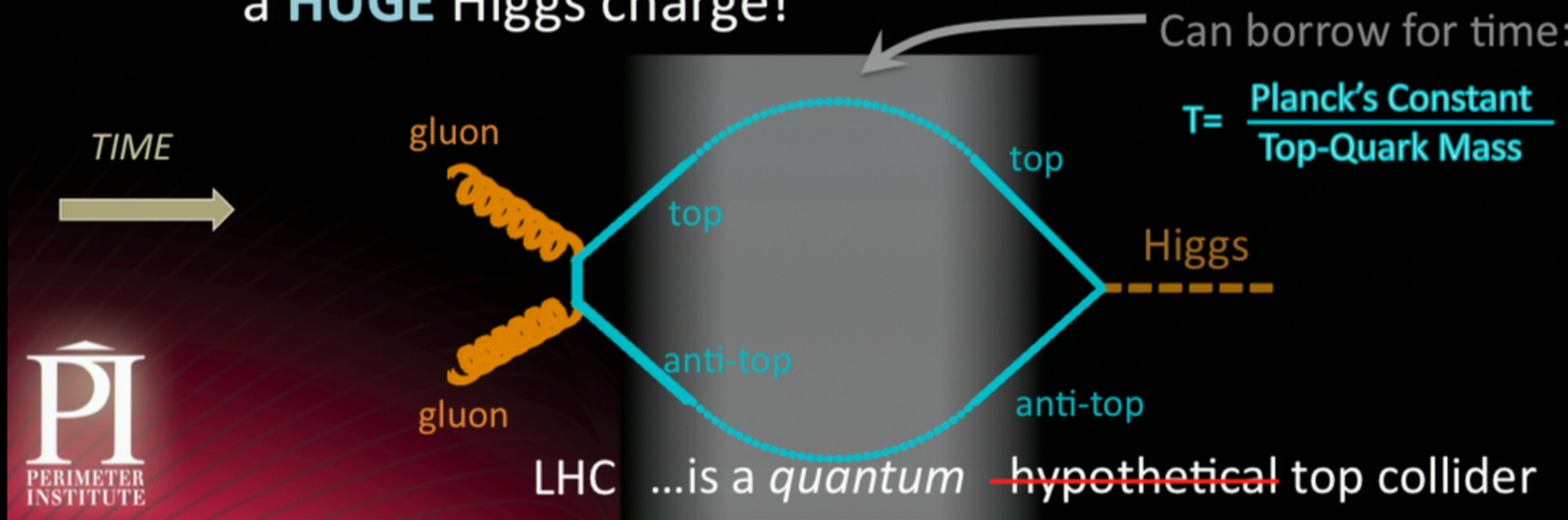

LHC ...is a *quantum* ~~hypothetical~~ top collider

Production rates

W boson (any decay)	**150 every second**
Top quark pair	Every two seconds
Light higgs boson	Five per minute
Light higgs (decay to photons)	Once every 3 hours

The preferred decay modes of the Higgs depend on its mass – so one has to look for it in many different places…

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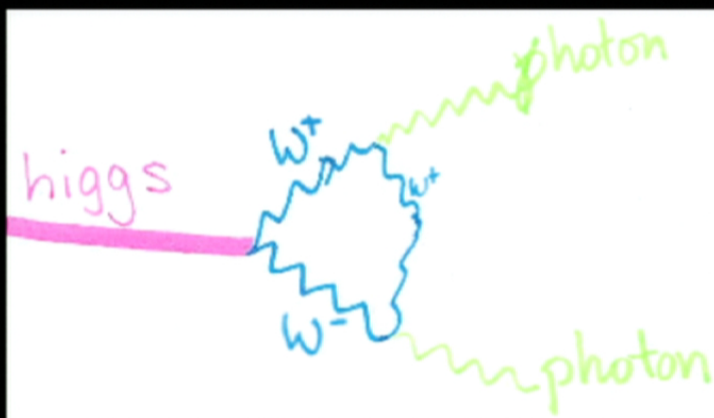
What does a Higgs look like?

The two most visible kinds of decay are into two photons, or four leptons (electrons or muons)

Both are predicted from the expected interaction of Higgs with weak bosons (W and Z)

+ the known interactions of particles



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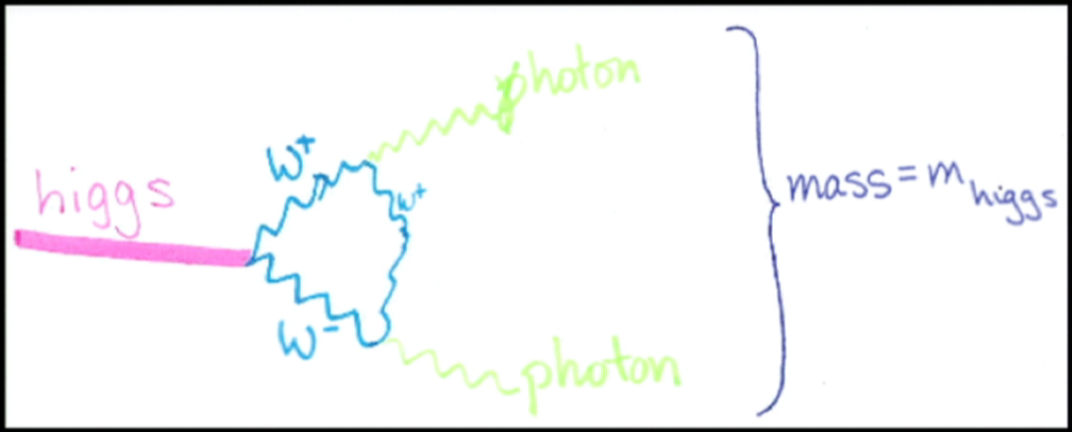

$$E_h^2 = (p_h c)^2 + (m_h c^2)^2$$
$$\rightarrow m_h = \sqrt{{E_h}^2/c^4 - {p_h}^2/c^2}$$

Conservation of energy & momentum:

$$E_h = E_1 + E_2$$
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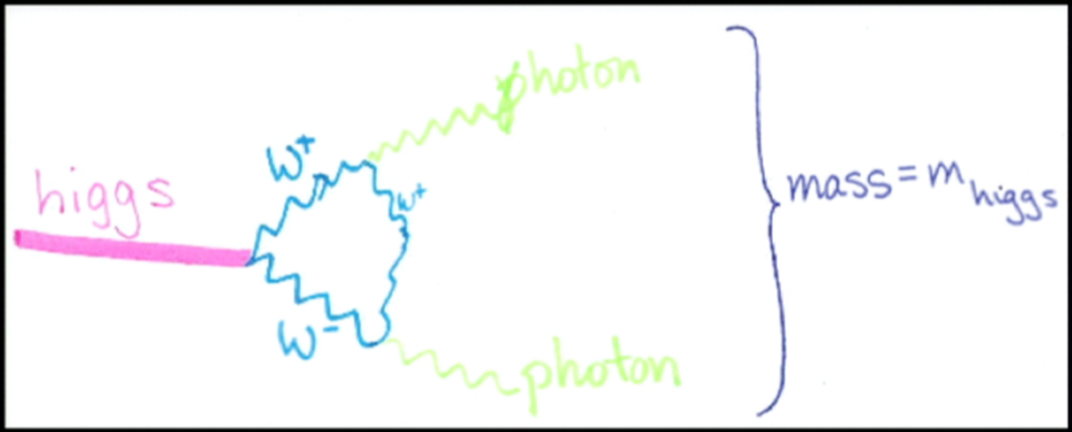

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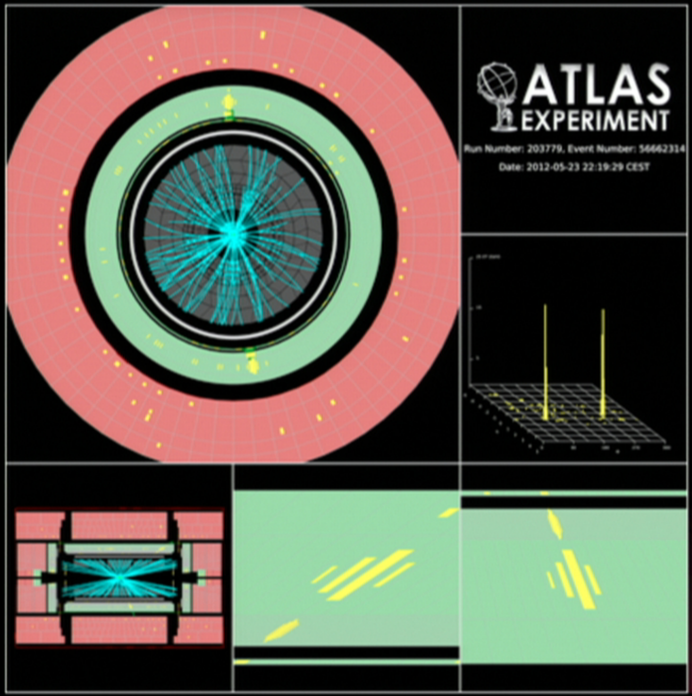
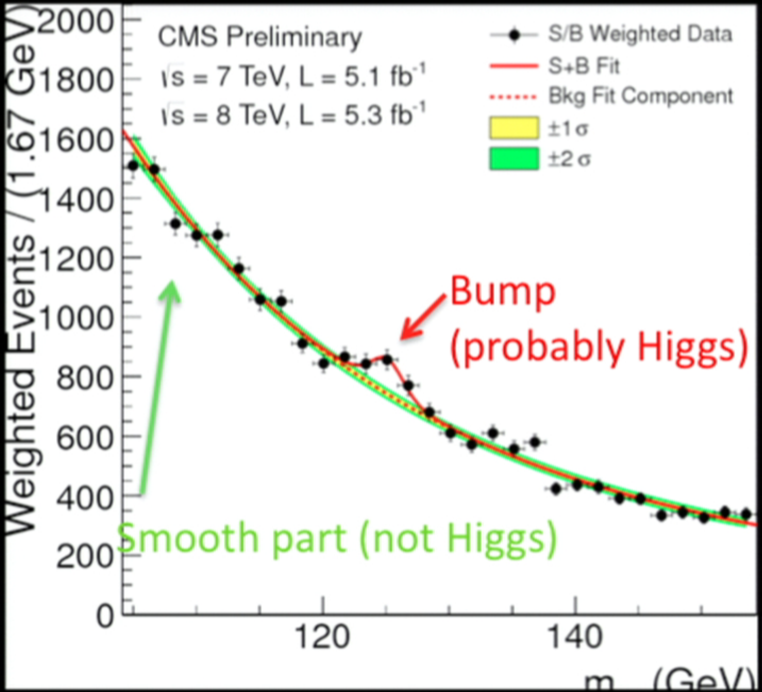
Looking for a Higgs

A Two-Photon Event

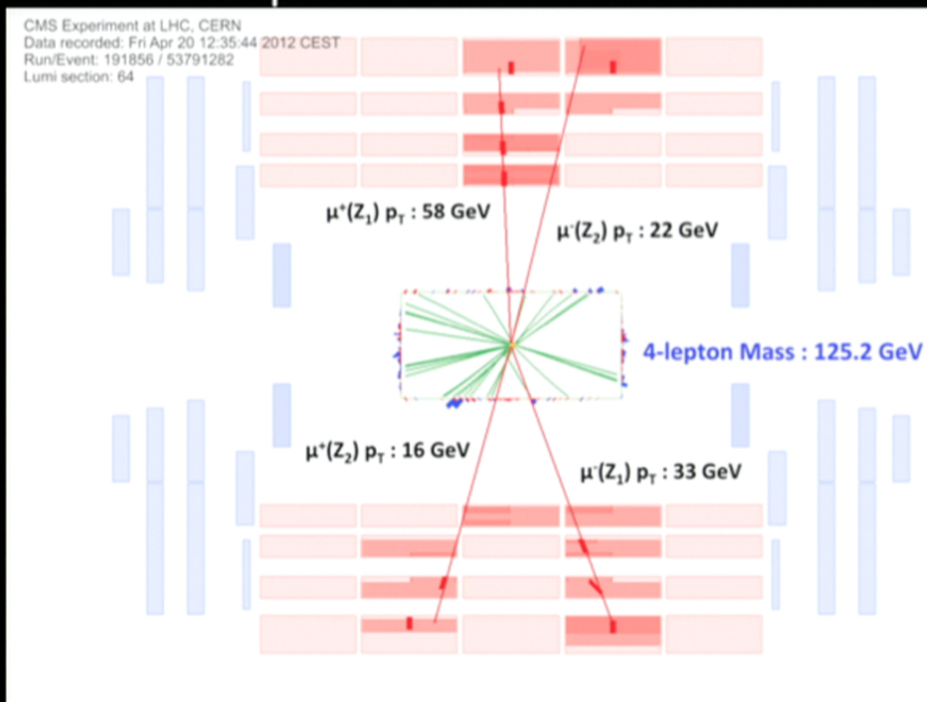


A year's wroth of two-photon masses



Is it really a Higgs?

A Four-Lepton Event



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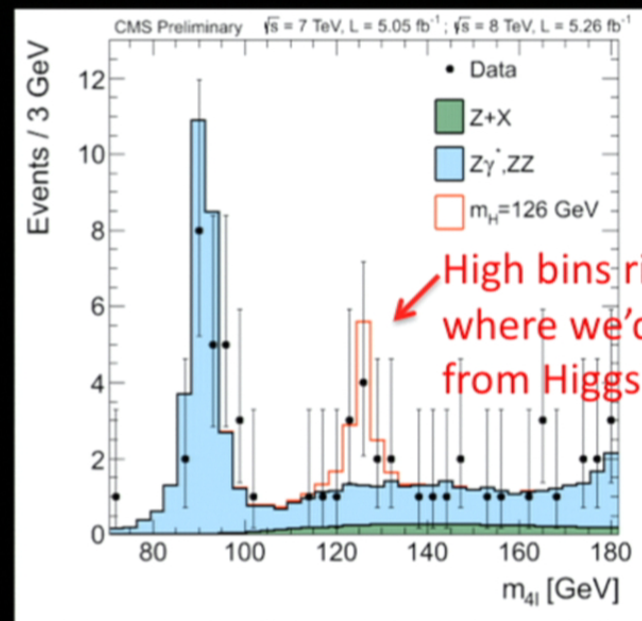
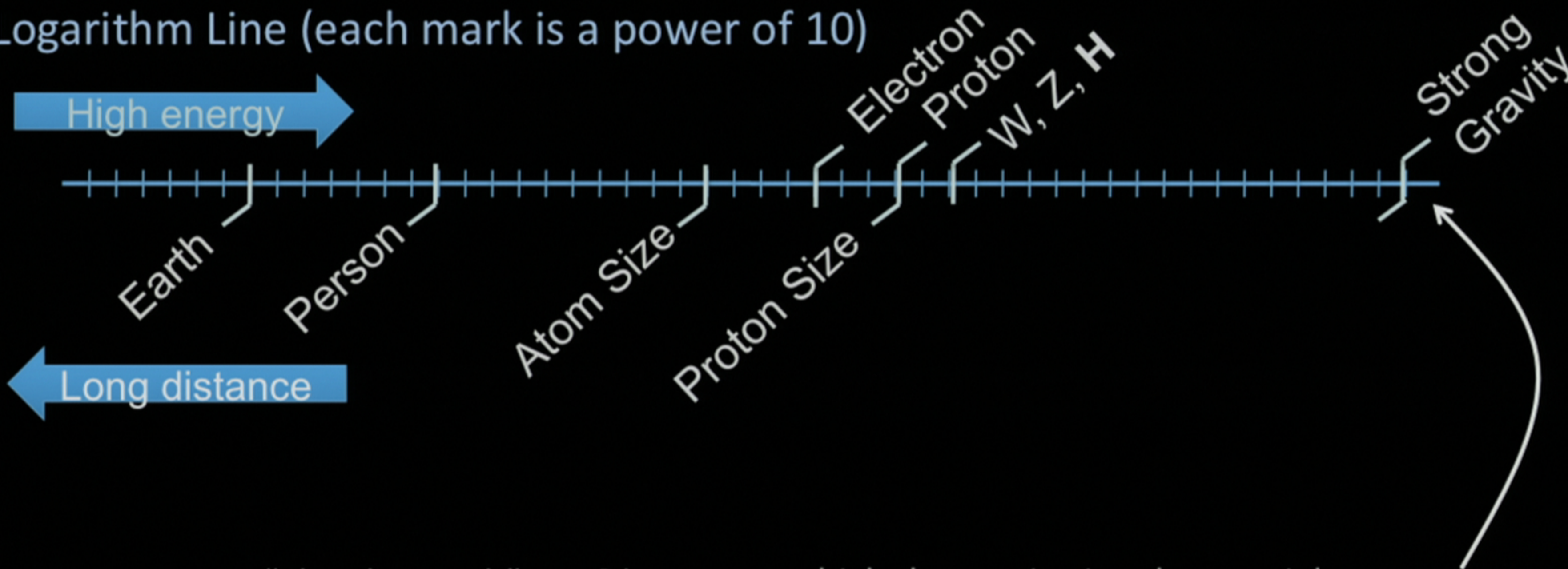


Success…and a puzzle!

- Predicted a Higgs particle based on consistency of quantum theory with W and Z
- A particle matching the predictions (so far) is showing up in data!
- Explains why W & Z have mass while photon & gluons do not – electric, weak, and strong forces all on same footing
  - So…what's the big puzzle??

The Puzzle of Scales

Logarithm Line (each mark is a power of 10)



"Planck Length": Distance at which the gravitational potential energy between two electrons is comparable to their electromagnetic energy ("Planck Energy"). The Standard Model **could** makes sense up to this energy!

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Quantum mechanics corrects the W mass:

$$M = M_{classical} + M_{quantum} \quad \text{and} \quad M_{quantum} = \# \times M_{largest}$$

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↑ 100,000,000,000,000,000x W mass?

$M_{quantum}$ = - 128,236,158,903,735,437
$M_{classical}$ = 128,236,158,903,735,438

Seems crazy! The closer $M_{largest}$ is to W mass, the less we need a crazy accident to explain our universe.

This is why most physicists expect new phenomena to "save the day" at an energy near the ones we've already studied.

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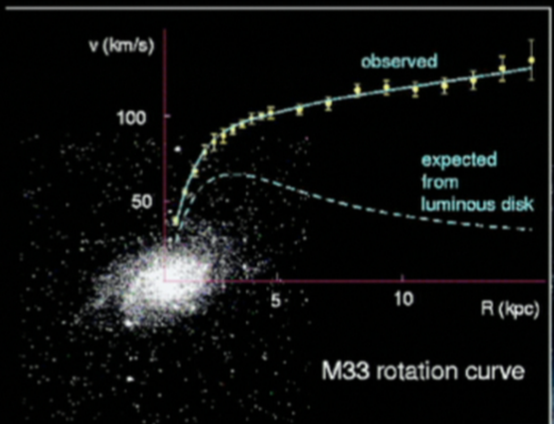
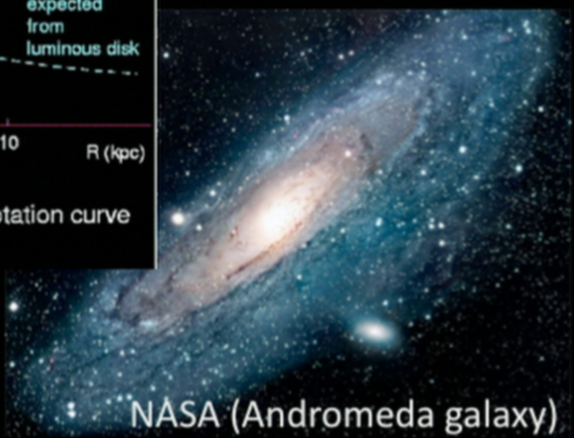
Is one of these particles the dark matter?





Galaxies appear heavier when "weighed" by the rotation of stars than we'd expect from the matter we see.

The other (dark) matter must be built out of a new particle that we haven't seen yet. Dark matter particles ***may*** be produced at the LHC.

The LHC in the Future

Whatever new particles we find at the LHC, there will be three important questions to answer:

1. What is it produced with? How does it decay?
2. What rules/principles can explain this behavior?
3. Can the new particle(s) shed light on dark matter, or the problems of weak interactions and scales?

The rules at work at the LHC are the same ones that govern physics in the stars and here in this room.

What do we expect?

Studying the things we **don't** understand has consistently broadened our understanding…often in more ways than we had expected

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We have **cause** to expect new discoveries – hopefully answers to some of our questions, and surprises more fascinating than any of us can imagine.

Stay Tuned!