LARGE HADRON COLLIDER

What's the big deal anyway?

Dr. Gail Van Ekeren

Gill St.Bernards School

Secondary School

Freshman Physics Course

LHC - the aim of the collider:

To smash protons moving at 99.999999% of the speed of light into each other and so recreate conditions a fraction of a second after the big bang. The LHC experiments try and work out what happened. See short introductory video:

http://lhc-machine-outreach.web.cern.ch/lhc%2Dmachine%2Doutreach/lhc-video-links.htm

OVERVIEW OF PRESENTATION

- 1. What do particle physicists do?
- 2. What are the structure and function of the parts of the LHC?
- 3. What are some LHC topics of interest to physicists?

WHAT DO PARTICLE PHYSICISTS DO?

- 1. Review of Standard Model
- 2. Unanswered questions
- 3. Frontiers of particle physics
  - a. Cosmic Frontier
  - b. Intensity Frontier
  - c. Energy Frontier

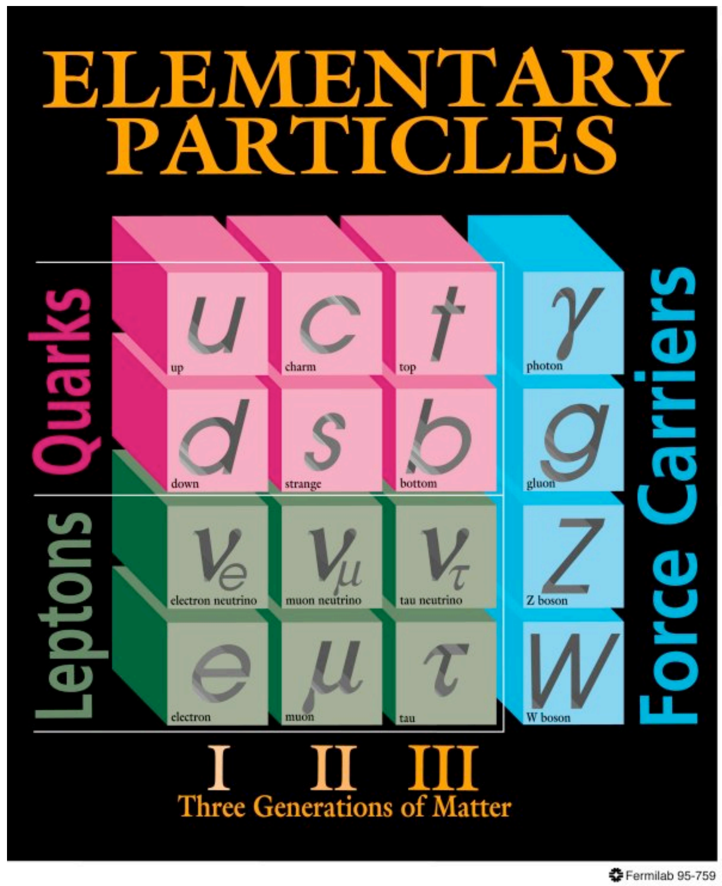
WHAT DO PARTICLE PHYSICISTS DO?

"Particle physics is the unbelievable in pursuit of the unimaginable. To pinpoint the smallest fragments of the universe you have to build the biggest machine in the world. To recreate the first millionths of a second of creation you have to focus energy on an awesome scale.”

The Guardian

- lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/

WHAT DO PARTICLE PHYSICISTS DO?
Review of Standard Model



www-d0.fnal.gov/Run2Physics/WWW/results/final/NP/N07B/standardmodel.jpg

WHAT DO PARTICLE PHYSICISTS DO?
Some unanswered questions

People have long asked,

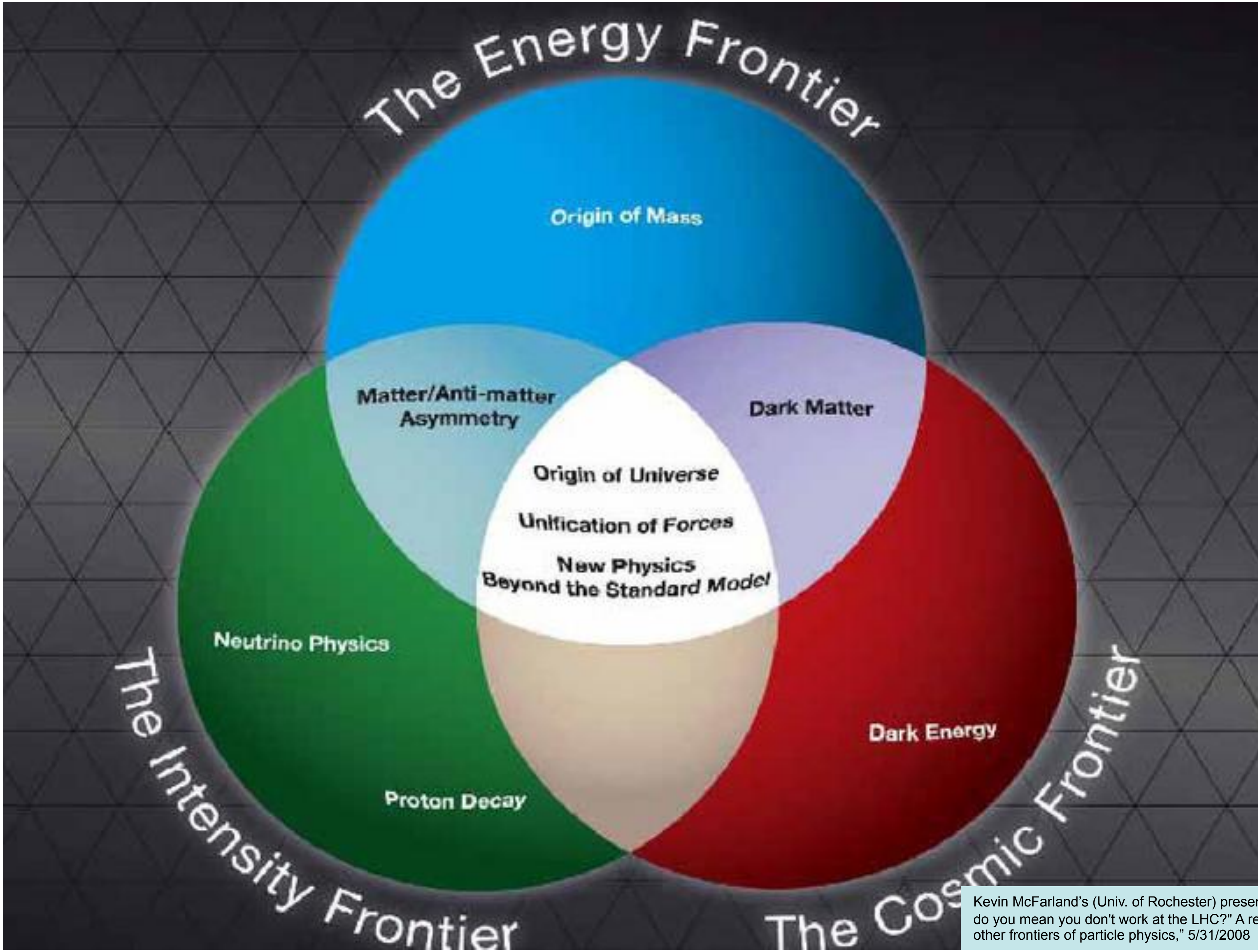
- "What is the world made of?”
- "What holds it together?”

Physicists hope to fill in their answers to these questions through the analysis of data from LHC experiments

WHAT DO PARTICLE PHYSICISTS DO?
Some unanswered questions

- Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
- What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?
- Why can't the Standard Model predict a particle's mass?
- Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
- Why are there exactly three generations of quarks and leptons?
- How does gravity fit into all of this?

www.particleadventure.org/frameless/beyond_start.html



Kevin McFarland's (Univ. of Rochester) presentation" What do you mean you don't work at the LHC?" A report from the other frontiers of particle physics," 5/31/2008

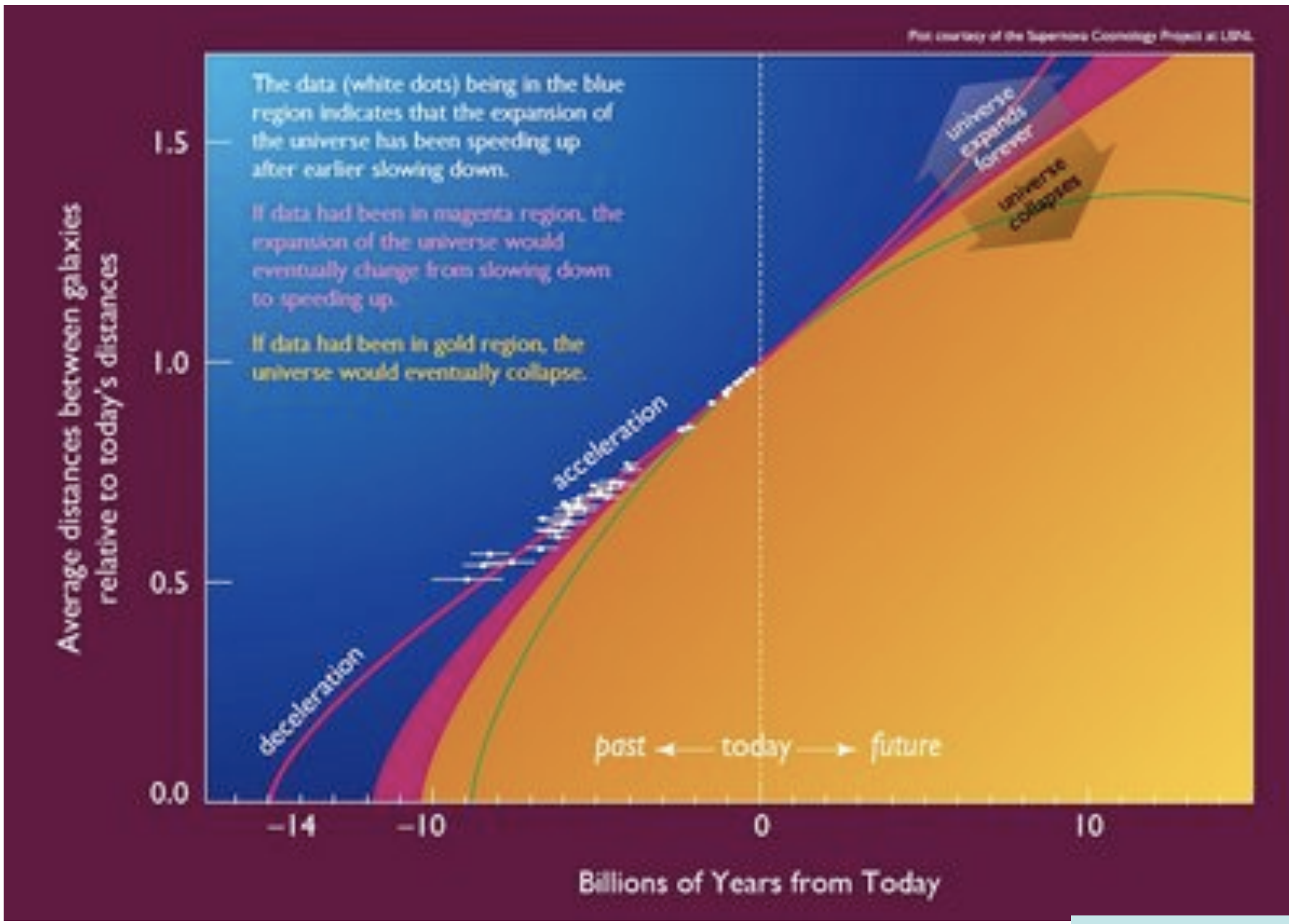
WHAT DO PARTICLE PHYSICISTS DO?

Frontiers

- **The Energy Frontier**,using high-energy colliders to discover new particles and directly probe the architecture of the fundamental forces.
- **The Intensity Frontier**, using intense particle beams to uncover properties of neutrinos and observe rare processes that will tell us about new physics beyond the Standard Model.
- **The Cosmic Frontier**, using underground experiments and telescopes, both ground and space based, to reveal the natures of dark matter and dark energy and using high-energy particles from space to probe new phenomena.

US Particle Physics: Scientific Opportunities A Strategic Plan for the Next Ten Years Report of the Particle Physics Project Prioritization Panel , 29 May 2008 p.7

WHAT DO PARTICLE PHYSICISTS DO?
Cosmic Frontiers

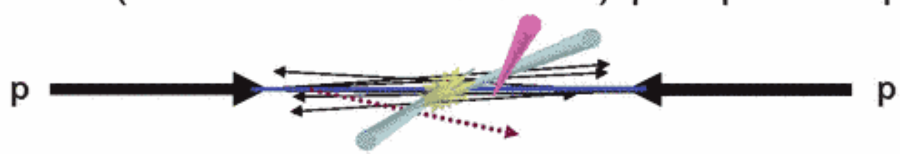


www.scholarpedia.org/article/
Dark_energy

WHAT DO PARTICLE PHYSICISTS DO?
Intensity Frontiers

What is the *Intensity* Frontier?

- The LHC is optimized for maximum energy in the collision of two protons
  - 14 TeV (or 0.0000002 Joules) per proton pair



  - occasionally a large fraction of that energy is available for production of new particles
  - therefore, LHC must store and collide many protons to be at the energy frontier

WHAT DO PARTICLE PHYSICISTS DO?
Intensity Frontiers

What is the *Intensity* Frontier?

- The LHC is optimized for maximum energy in the collision of two protons
- Other accelerators aim to create very high numbers of lower energy particles in colliding beams or single extracted beam
  - useful for creating large numbers of other particles to study their properties
  - we sometimes call these machines "factories"

WHAT DO PARTICLE PHYSICISTS DO?
Intensity Frontiers

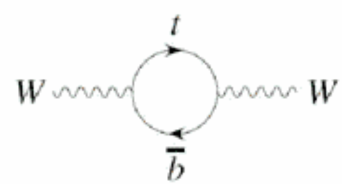
Where is the *Intensity* Frontier?

- There are many intensity frontiers
  - Bottom quarks: Stanford (recently ended) and KEK in Japan; next facility in Italy?
  - Charm quarks and tau leptons: Cornell (recently ended), Beijing
  - Weak bosons: successful CERN and Stanford programs concluded in the late 1990s
  - Neutrons and Photons: many facilities, mostly aimed at biological and material sciences
- Active development in particle physics: *proton sources for neutrinos*

WHAT DO PARTICLE PHYSICISTS DO?
Intensity Frontiers

What science is done at the ***Intensity*** Frontier?

- We study the "shadows" of high energy phenomena with quantum fluctuations



- We explore the most difficult corner of the known building blocks of matter… the neutrino

WHAT DO PARTICLE PHYSICISTS DO?
Intensity Frontiers

WHAT ARE QUANTUM FLUCTUATIONS?

- Quantum fluctuation = the temporary change in the amount of energy in a point in space,
- Due to Werner Heisenberg's uncertainty principle.
  $\Delta E \Delta t = h/2\pi$
- Conservation of energy can appear to be violated, but only for small times.
- Allows creation of particle-antiparticle pairs of virtual particles.

en.wikipedia.org/wiki/Quantum_fluctuation

WHAT DO PARTICLE PHYSICISTS DO?
Energy Frontiers

- Instead of creating many particles in “particle factories,” physicists collide two streams of particles at a time, each with extremely high energy

- The energy of the collisions in the LHC increase by one order of magnitude the energies in previous studies

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC

Overview

The Large Hadron Collider (LHC) is located in a circular tunnel 27 km (17 miles) in circumference. The tunnel is buried around 100 m (about the size of a football field) underground.

It straddles the Swiss and French borders on the outskirts of Geneva..

lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Overview

The LHC is designed to collide two counter rotating beams of protons. Proton-proton collisions are foreseen at an energy of 7 TeV per beam.

- The beams move around the LHC ring inside a continuous vacuum guided by magnets.
- The magnets are superconducting and are cooled by a huge cryogenics system. The cables conduct current without resistance in their superconducting state.
- The beams will be stored at high energy for hours. During this time collisions take place inside the four main LHC experiments.

lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/

Animation of collision:http://www-visualmedia.fnal.gov/VMS_Site/gallery/v_animations.html

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Overview

Lets see what happens to the protons!

"The beams are made up of bunches containing billions of protons. Traveling at a whisker below the speed of light they will be injected, accelerated, and kept circulating for hours, guided by thousands of powerful superconducting magnets.
For most of the ring, the beams travel in two separate vacuum pipes, but at four points they collide in
the hearts of the main experiments, known by their acronyms: ALICE, ATLAS, CMS, and LHCb. The experiments' detectors will watch carefully as the energy of colliding protons transforms fleetingly into a plethora of exotic particles." www.symmetrymagazine.org/cms/?pid=1000095

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
The “Racetrack”

- Circular with 27 km circumference
  Linear track-run out of “real estate”

- 40,000 leak tight pipe junctions

- Vacuum: 10^{-10}Torr or 3 million molecules/cm^3 (sea level-760 Torr)
  Protons must avoid collisions with other gas molecules

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
The Proton Beam

- Sources of protons-bottles of hydrogen gas
- 2808 bunches of protons in routine beam
- Stored energy of 350 MJ
- Beams are focused by magnets into a 40-μm -cross-section
- Pt 6 of LHC has beam dumping system
- Collimation system keeps beam from melting metal

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC

The Proton Beam

Why is luminosity important?

Luminosity determines the probability of collision

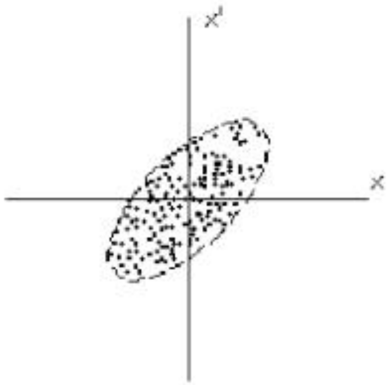
"Among the responsibilities of Princeton's team are the measurement and delivery of the luminosity to CMS."

Princeton Physics News, vol.2 issue 2,Fall 2006

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
The Proton Beam

What is luminosity?

"Luminosity is the number of particles per unit area per unit time times the opacity of the target" en.wikipedia.org/wiki/Luminosity#In_scattering_theory_and_accelerator_physics



Cross section of a sample particle beam is pictured. Assume targets are completely opaque, with an opacity of 1.

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
The Proton Beam

What is luminosity?

$$L = f\,n\,\frac{N_1 N_2}{A} \qquad \text{where}$$

f is the revolution frequency (c/27 km)

n is the number of bunches in one beam in the storage ring. (2808 bunches)

Ni is the number of particles in each bunch (billions)

A is the cross section of the beam (40 μm)

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
The Proton Beam

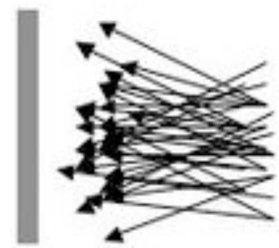
What is luminosity?

- maximum luminosity for LHC: $10^{34}/cm^2s$
- proton cross section: $\sim 20 \times 10^{-25} cm^2$
- 20 collisions in each bunch crossing
- 1 bunch crossing every 25 ns
- ~1 250 000 000 collisions each second

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
The Proton Beam

What is collimation?

Collimation is the use of lenses (magnets in this case) to cause the proton beams to travel parallel to each other. The bottom diagram illustrates collimated light.



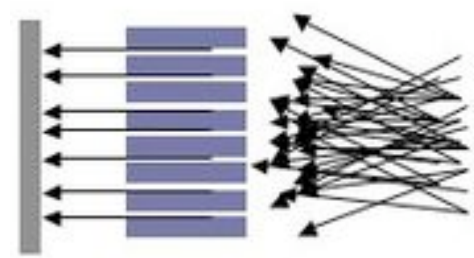


Diagram: http://en.wikipedia.org/wiki/Collimated_light

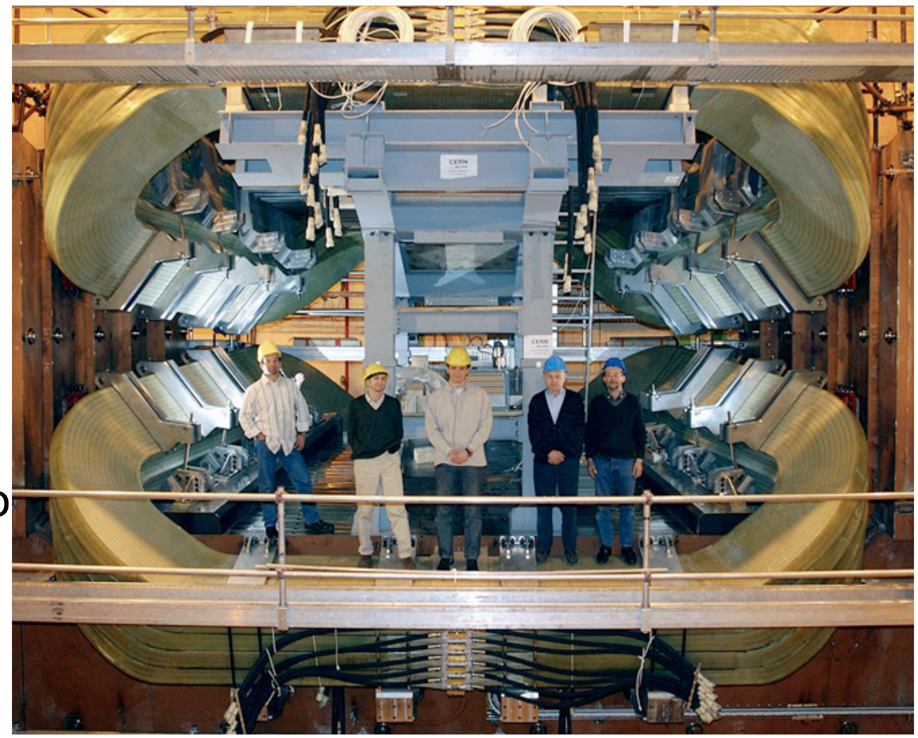
THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Magnets

The final megamagnet of the LHC was ceremonially lowered into place through a special shaft on April 26, 2007.

news.nationalgeographic.com/news/2007/04/images/070430-collider-magnet_big.jpg

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Magnets

"To help identify the explosion of particles produced when protons are smashed together, particle detectors typically include a powerful magnet. LHCb is no exception. The experiment's enormous magnet consists of two coils, both weighing 27 tonnes, mounted inside a 1,450 tonne steel frame. Each coil is constructed from 10 'pancakes', wound from almost 3,000 metres of aluminium cable." lhcb-public.web.cern.ch/.../Magnet-en.html



public/Objects/Detector/Magnet1.jpg

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC

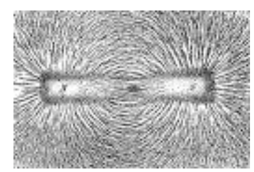
Magnets

Some Magnet Facts

- 58 different kind of magnets
- ~93 000 magnets
- Superconducting magnets sit in 1.9 K bath of superfluid helium at atmospheric pressure

www.print.org.nz

Not your everyday ordinary magnets!



chemistry.about.com

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Magnets

Some Magnet Facts

Dipole magnets:

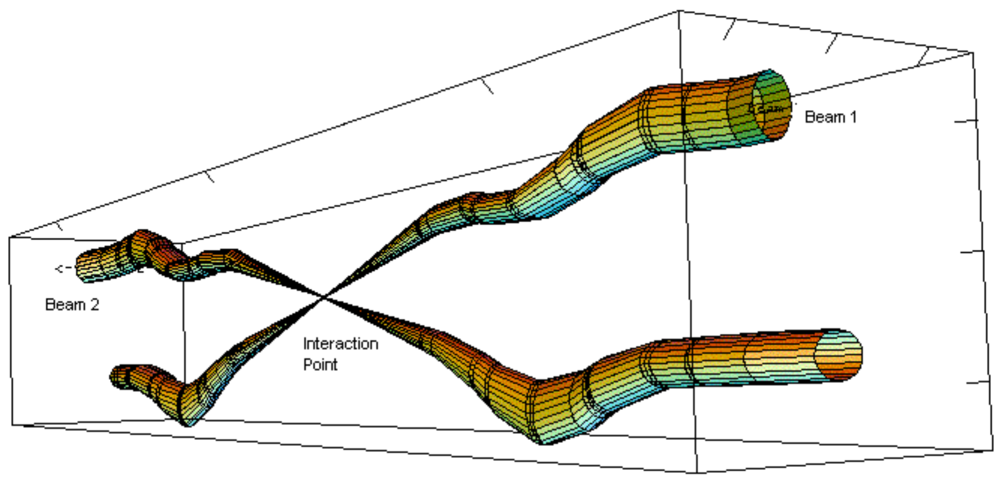
- cause protons to follow circular path
- produce magnetic field 100 000 times earth's magnetic field
- Main budget item
- 1232 dipole magnets
- 14.3 meters long; 35 tons each

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Magnets

Some Magnet Facts

- Other magnets
  - focus proton beam-see diagram
  - cause resulting particles to curve

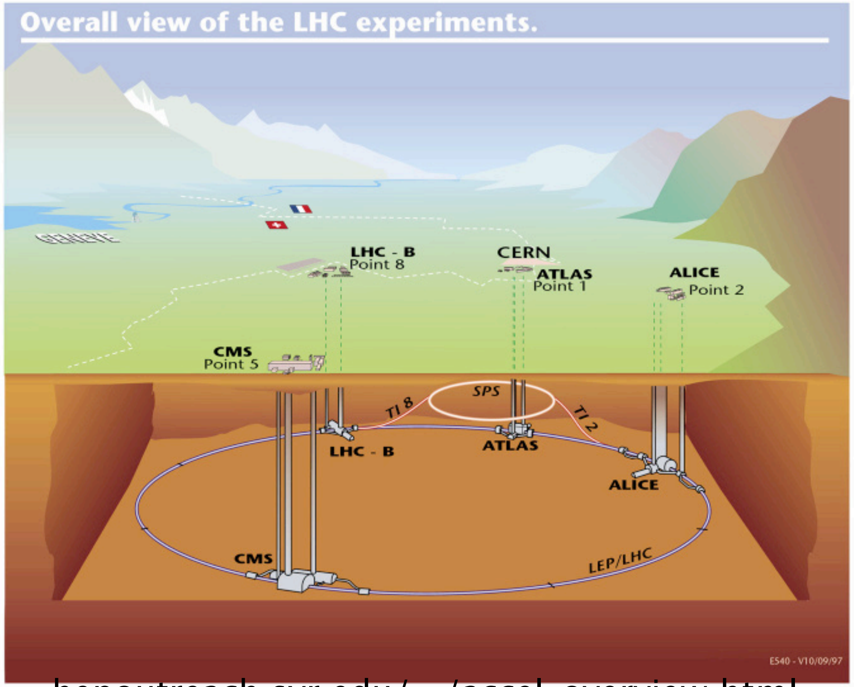
lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/collisions.htm



Relative beam sizes around IP1 (Atlas) in collision

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC

Detectors



hepoutreach.syr.edu/.../accel_overview.html

6 areas around circumference that will collect and analyze data

- ATLAS
- CMS
- ALICE
- LHCb
- TOTEM (minor study)
- LHCf (minor study)

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Detectors

A Toroidal LHC ApparatuS (ATLAS)

- 46 meters long, 25 meters high, 25 meters wide
- Core: Inner tracker detects and analyzes momentum of particles
- Outside: Calorimeters analyze energy by absorbing particles; only muons go through calorimeter
- Outside calorimeter: Muon Spectrometer; charged particle sensors can detect changes in magnetic field; momentum of muons can be determined
- http://atlas.ch/multimedia/html-nc/feature_episode1.html

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC

Detectors

Compact Muon Solenoid (CMS)

- Large detector like ATLAS
- Inside a large solenoid with magnetic field 100 000 times that of earth

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC

Detectors

A Large Ion Collider Experiment (ALICE)

- Collides iron ions to study conditions right after big bang
- Expect to see ions break apart into quarks and gluons
- Time Projection Chamber (TPC) exams and reconstructs particle trajectories
- Also has muon spectrometer

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Detectors

Large Hadron Collider beauty (LHCb)

- Searches for beauty quarks as evidence of antimatter
- Series of small detectors stretch 20 meters in length around collision point
- Detectors move easily in tiny precise ways to catch unstable, short-lived beauty quarks

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Detectors

TOTal Elastic and diffractive cross section Measurement (TOTEM)

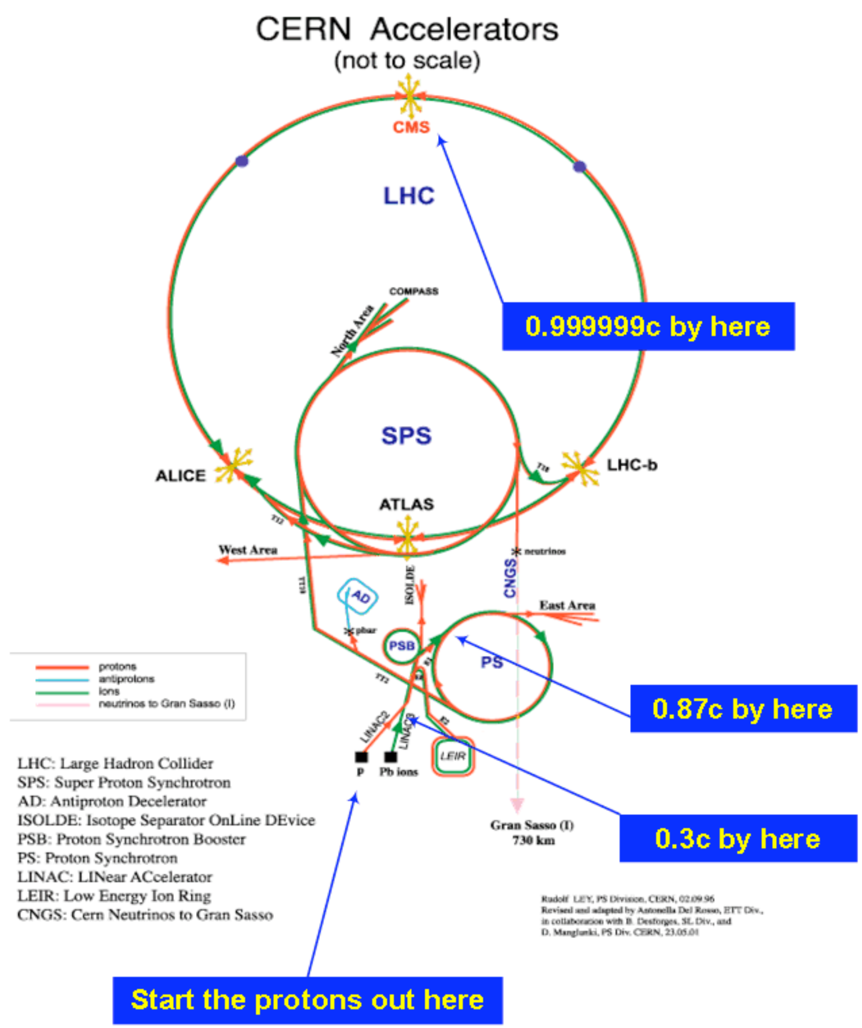
Studies luminosity and proton size

Large Hadron Collider forward (LHCf)

Simulates cosmic rays in controlled environment so scientists can develop ways to study naturally-occurring cosmic rays

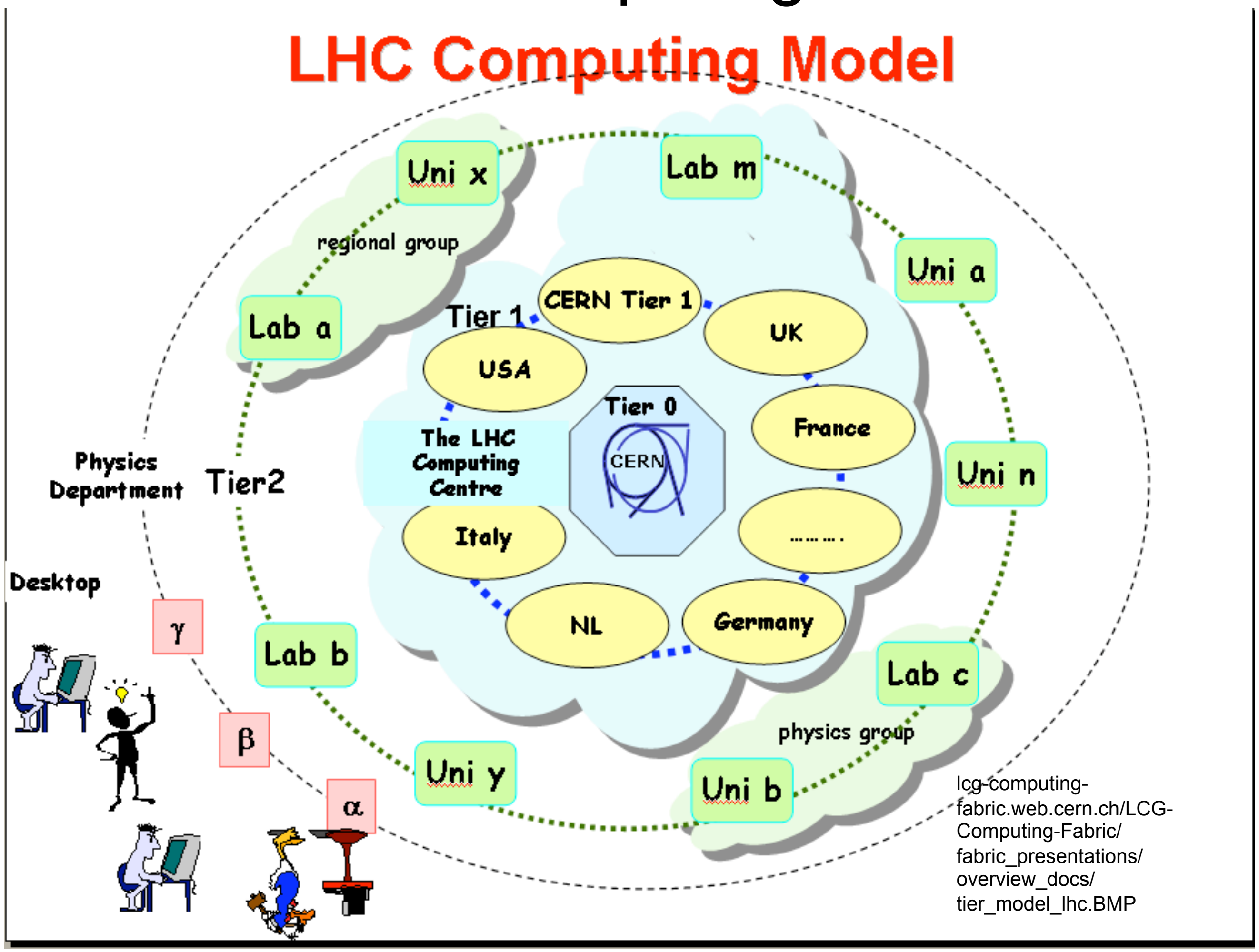
THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC

Accelerators



THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC

Computing



lcg-computing-fabric.web.cern.ch/LCG-Computing-Fabric/fabric_presentations/overview_docs/tier_model_lhc.BMP

THE STRUCTURE AND FUNCTION OF THE PARTS OF THE LHC
Computing

- LHC will produce ~ 15 petabytes (15 million Gigabytes) of data annually.
- Data will be accessed and analyzed by thousands of scientists around the world.

"The mission of the LHC Computing Grid (LCG) is to build and maintain a data storage and analysis infrastructure for the entire high energy physics community that will use LHC"

Lcg.web.cern.ch/LCG

TOPICS OF INTEREST
Higgs Particle

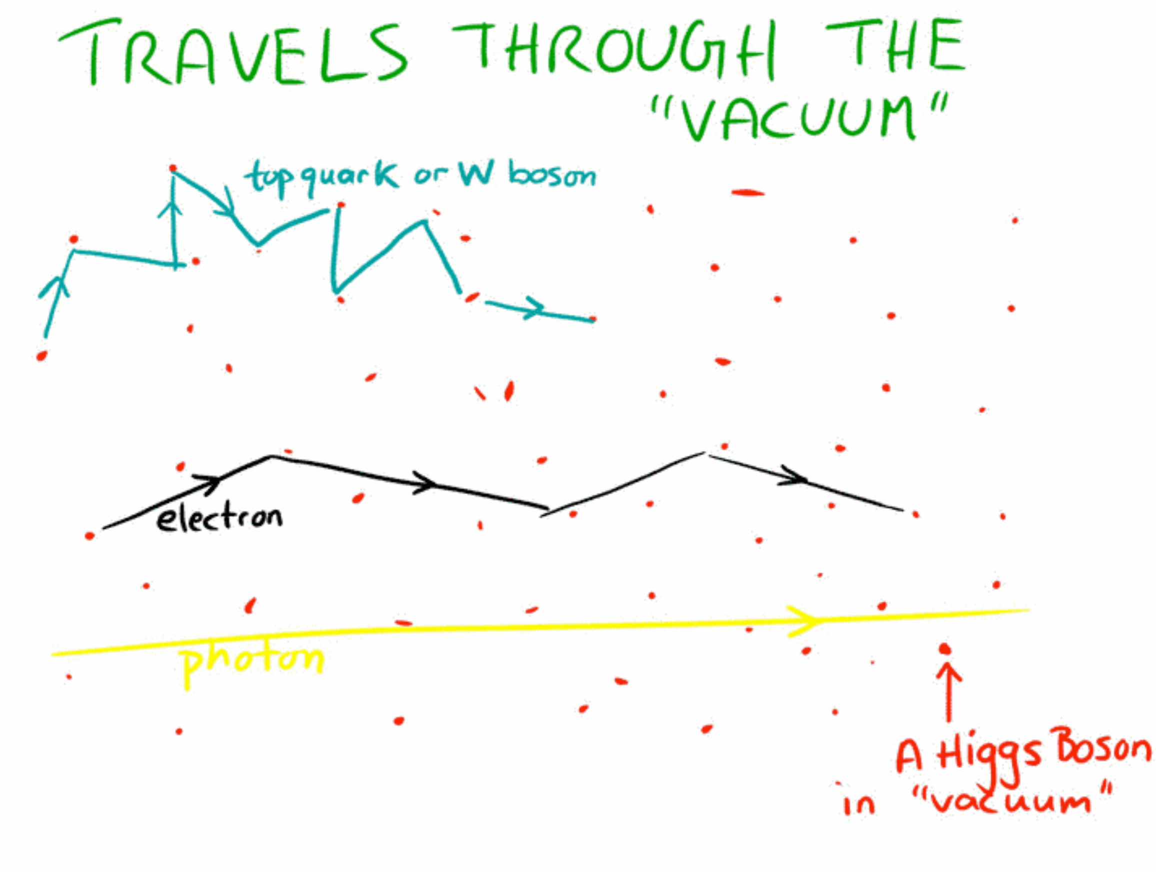
HIGGS SEEN AT LHC!

Peter Higgs, the man for whom the Higgs boson particle was named tours the LHC

www.fnal.gov/pub/presspass/press_releases/cdms-result-2008.html
Alan Walker/AFP/Getty Images

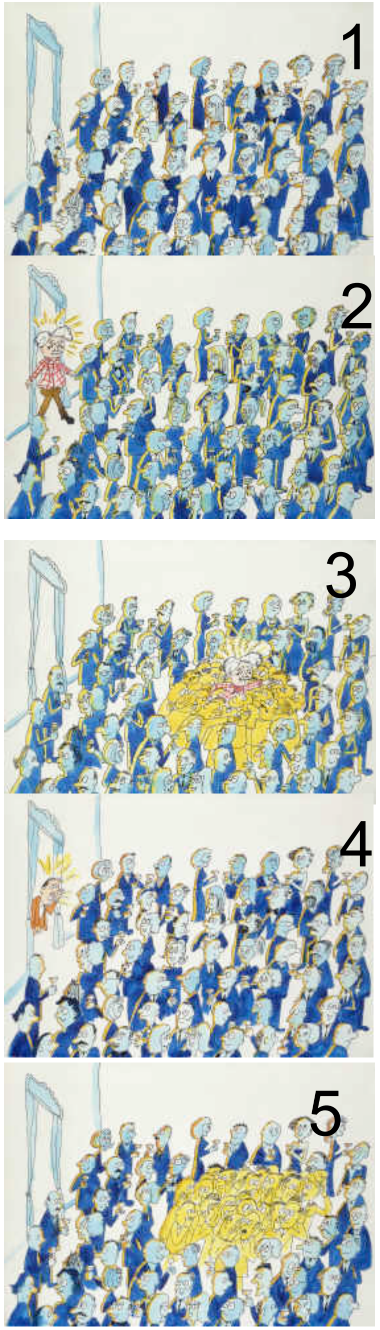
TOPICS OF INTEREST
Higgs Particle

What role does the Higgs Particle Play?



Higgs particle interacts with particles, thus slowing them down. This results in energy converted into mass.

Raman Sundrum (Johns Hopkins Univ,KITP Teachers Conference, 5/31/2008



THE HIGGS MECHANISM

1.To understand the Higgs mechanism, imagine that a room full of physicists quietly chattering is like space filled only with the Higgs field....

2. a well known scientist walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step ...

3. this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field ...

4. if a rumour crosses the room ...

5. it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.

www.pparc.ac.uk/ps/bbs/bbs_mass_hm.asp

TOPICS OF INTEREST
Higgs Particle

What do we already know about the Higgs Particle (experimentally)?

- Precision measurements of electroweak observables exclude a Standard Model Higgs boson mass of 170 GeV/c2 at the 95% confidence level[9] as of August 2008 (incorporating an updated measurement of the top quark and W boson masses)
  www.physorg.com/news137076565.html, via Wikipedia
- The non-observation of clear signals leads to an experimental lower bound for the Standard Model Higgs boson mass of 114 GeV/c2 at 95% confidence level.
- A small number of events were recorded by experiments at LEP collider at CERN that could be interpreted as resulting from Higgs bosons, but the evidence is inconclusive.
- Searches for Higgs Bosons (pdf), from W.-M. Yao et al. (2006). "Review of Particle Physics". J Phys. G 33:

TOPICS OF INTEREST
Higgs Particle

How will Higgs Particle be made at LHC?

Feynman

diagrams

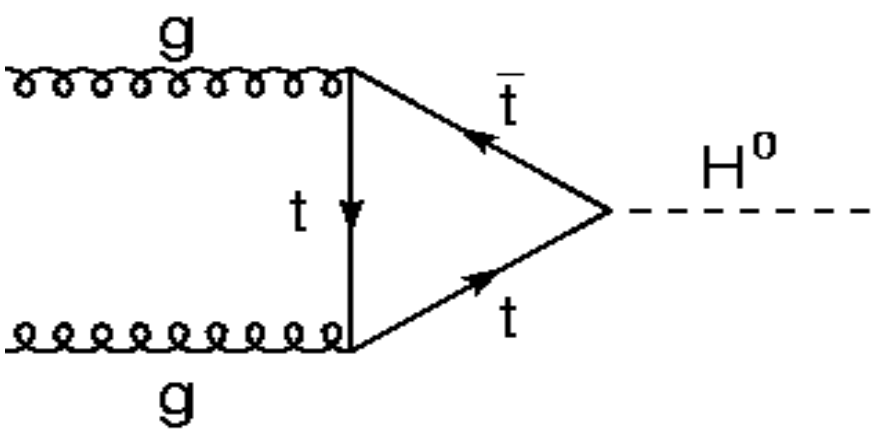
- Gluon fusion

b. Vector boson fusion

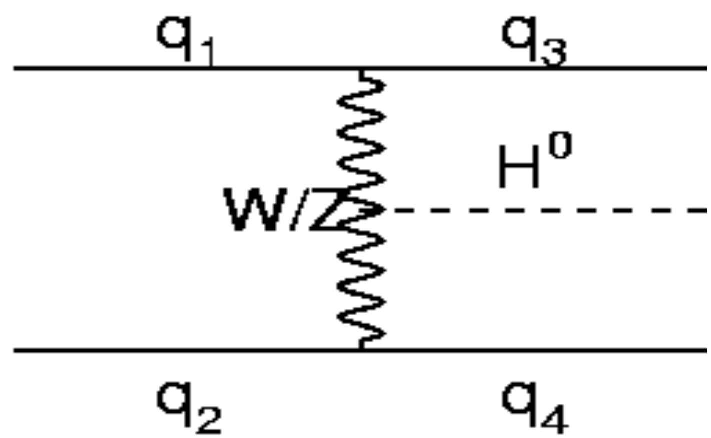
d. Assoc prod with W

d. Assoc prod with top

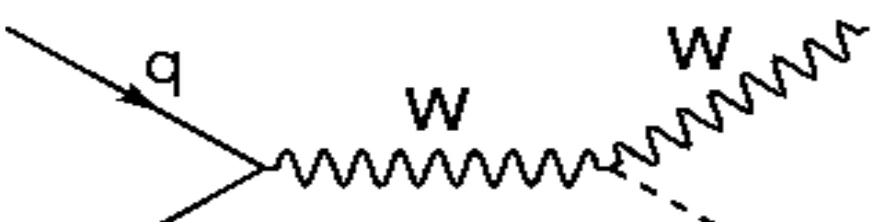
(a)



(b)



(c)



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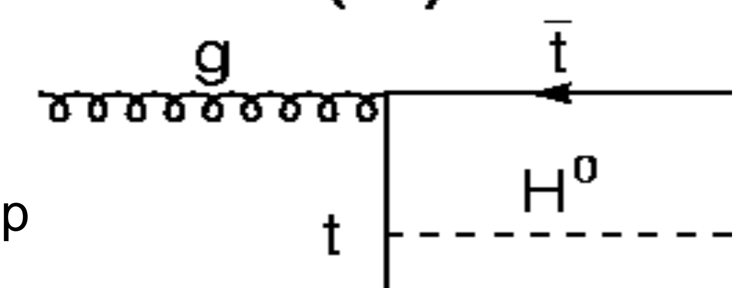


TOPICS OF INTEREST
Higgs Particle

How will Higgs Particle be detected at LHC?

Products depend on Higgs' mass.

www.hep.lu.se/atlas//thesis/egede/thesis-node14.html

MASS	DECAY PRODUCTS
>2 top quarks	Z bosons
Below 2 top quarks	Bottom quarks
Medium range	??
Light	2 photons

TOPICS OF INTEREST

Dark Matter

Humans in the Universe

Science has been mostly about our bodies.

What are we made of?

How do we interact with things?

www.minority-speak.com

Dr. Frankenstein in *Frankenstein (1931)*

Thread in history of science: human-centered science is less and less the full story of our universe.

TOPICS OF INTEREST

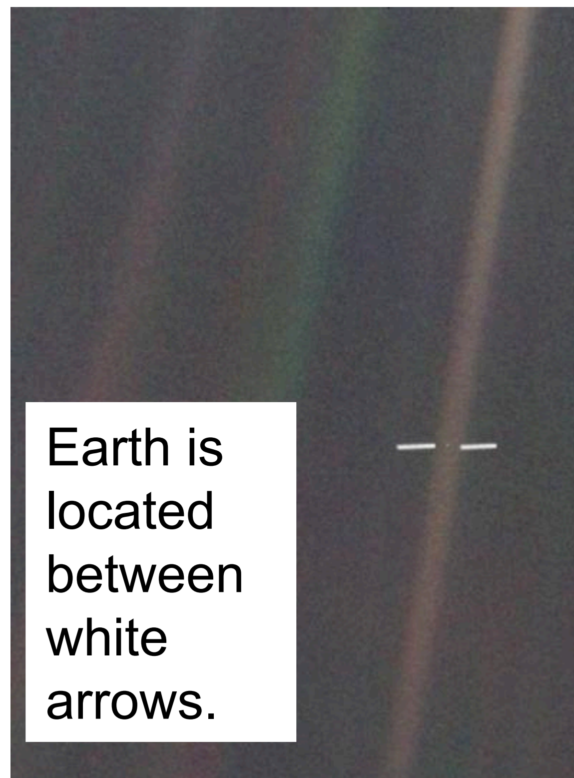
www.phys.lsu.edu

Dark Matter

A PALE BLUE DOT

On October 13, 1994, the famous astronomer Carl Sagan was delivering a public lecture at his own university of Cornell. During that lecture, he presented this photo:

www.bigskyastroclub.org/pale_blue_dot.html



www.phys.lsu.edu

TOPICS OF INTEREST

Dark Matter

A PALE BLUE DOT

The previous photo was taken by Voyager 1 in 1990 as it sailed away from Earth, more than 4 billion miles in the distance… Quite by accident the earth was captured in one of the sun's rays.

www.bigskyastroclub.org/
pale_blue_dot.html

This picture is an enlargement. Earth can be seen as a tiny blue dot.

His speech is included at the end of the presentation.

TOPICS OF INTEREST

Dark Matter

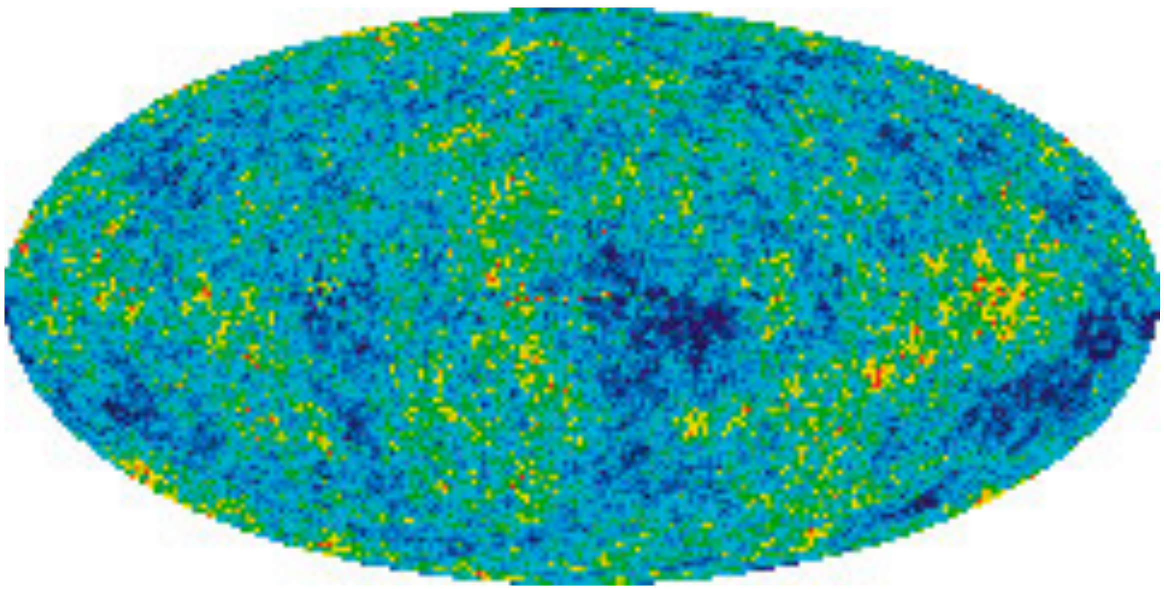
WMAP

- The Wilkinson Microwave Anisotropy Probe (WMAP) mission reveals conditions as they existed in the early universe by measuring the properties of the cosmic microwave background radiation over the full sky.
- This microwave radiation was released approximately 380,000 years after the birth of the universe. WMAP creates a picture of the microwave radiation using differences in temperature measured from opposite directions
- map.gsfc.nasa.gov/mission/index.html

TOPICS OF INTEREST

Dark Matter

WMAP



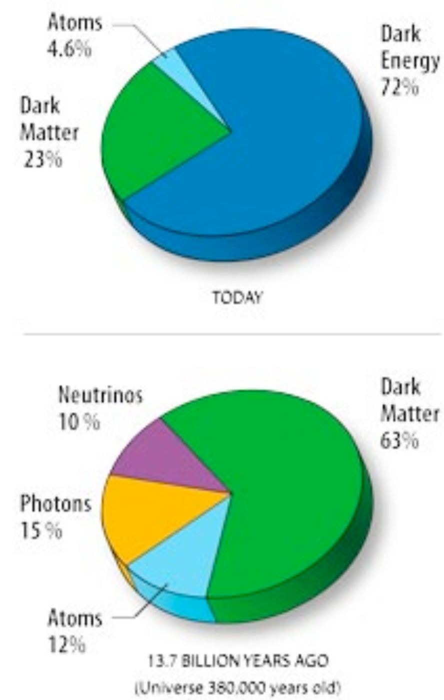
TOPICS OF INTEREST

Dark Matter

WMAP-composition of the universe

WMAP measures the composition of the universe. The top chart shows a pie chart of the relative constituents today. A similar chart (bottom) shows the composition at 380,000 years old (13.7 billion years ago) when the light WMAP observes emanated.

map.gsfc.nasa.gov/news/index.html

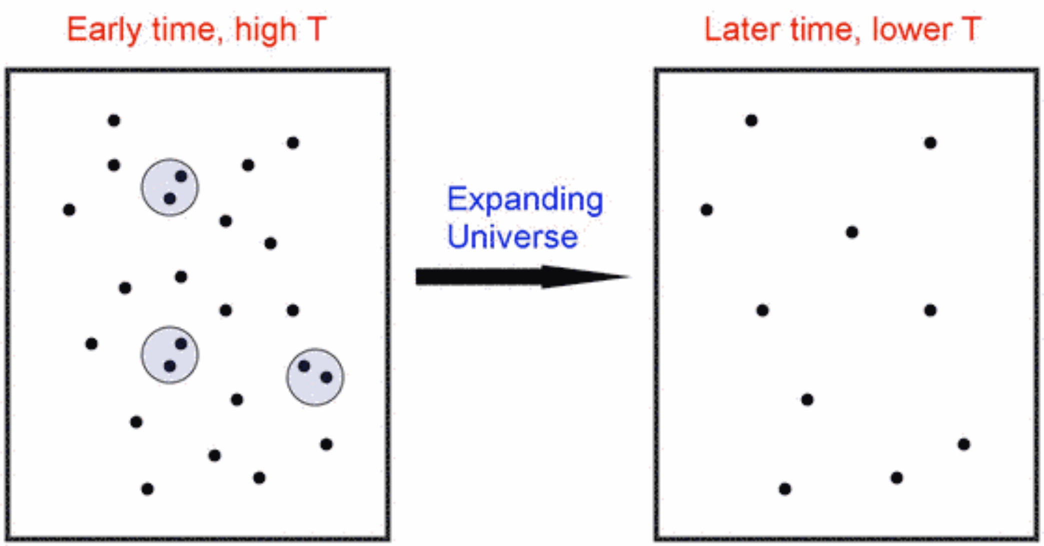


Credit: NASA/WMAP Science Team

TOPICS OF INTEREST

Dark Matter

Freeze-Out of Dark Matter



DM pairs come close enough to interact.

Never close enough to interact: “freeze-out”.

19

TOPICS OF INTEREST

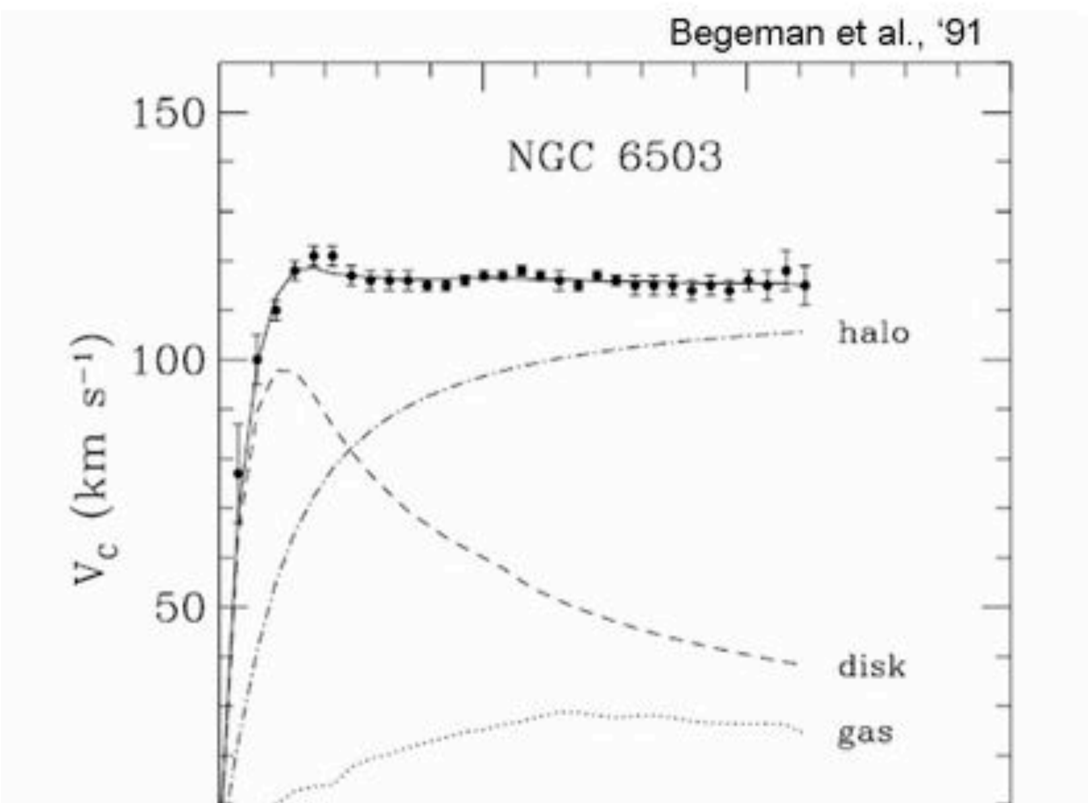
Dark Matter

Vera Rubin

- Vera Rubin is an astronomer who has done pioneering work on galaxy rotation rates. Her discovery of what is known as "flat rotation curves" is the most direct and robust evidence of dark matter.
- Studied outer regions of galaxies because most astronomers were studying inner regions and she wanted to balance career and family, so chose seemingly less competitive area.
- Throughout education she worked with great physicists including Richard Feynman and George Gamow:
  - Vassar College AB 1948
  - Cornell University MA 1951
  - Georgetown University PhD 1954
  - Princeton University-would not accept her into astronomy program. Began accepting women in 1975

TOPICS OF INTEREST
Dark Matter

Galaxy Rotation Curves



Lowell Observatory

$$v(r) = \sqrt{\frac{GM(r)}{r}} \rightarrow \frac{1}{\sqrt{r}}$$

TOPICS OF INTEREST

Dark Matter

Existing Evidence

Cluster smashup is dark matter proof

- Recent Hubble image is of another "bullet cluster."
- 5.6-billion light years away; further away and older than earlier discovered bullet cluster
- Composite image from optical and x-ray telescopes

Image from Hubble Space Telescope courtesy of NASA, ESA, CXC, M. Bradac (University of California, Santa Barbara), and S. Allen (Stanford University)

From National Geographic News, Aug. 27, 2008

TOPICS OF INTEREST

Dark Matter

Existing Evidence

Cluster smashup is dark matter proof

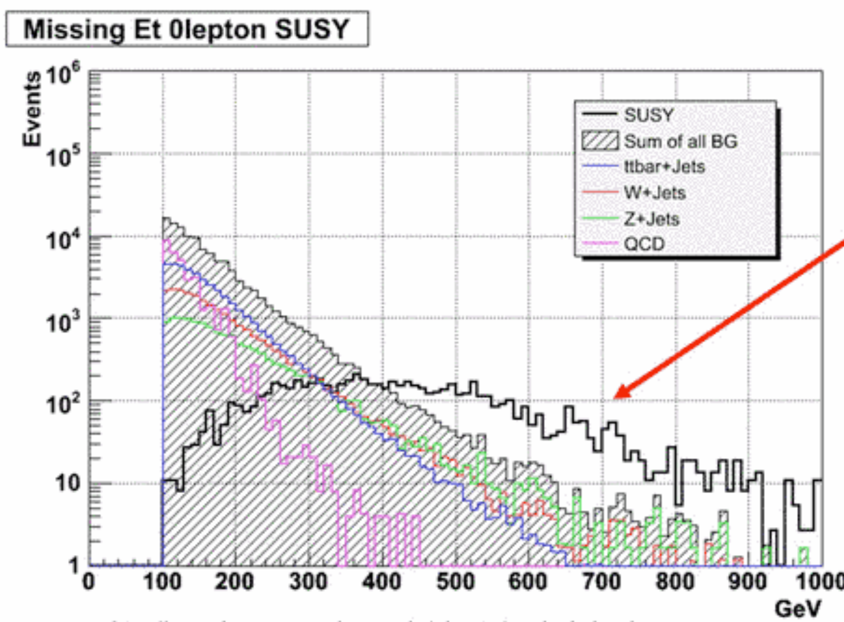
- Ordinary matter (pink) slows down during collision
- Most of cluster's mass (blue) keeps up speed, passing through the visible matter, creating clumps that are moving away from collision
- Astronomers think clumps are dark matter.

Image from Hubble Space Telescope courtesy of NASA, ESA, CXC, M. Bradac (University of California, Santa Barbara), and S. Allen (Stanford University)
From National Geographic News,
Aug. 27, 2008

TOPICS OF INTEREST

Dark Matter

Inferring Dark Matter



http://www.icepp.s.u-tokyo.ac.jp/~kenta/analysis.html

This tail in large missing energy at the collider infers existence of dark matter.

Many other channels confirm it, and confirm LSP from supersymmetry is the dark matter.

TOPICS OF INTEREST

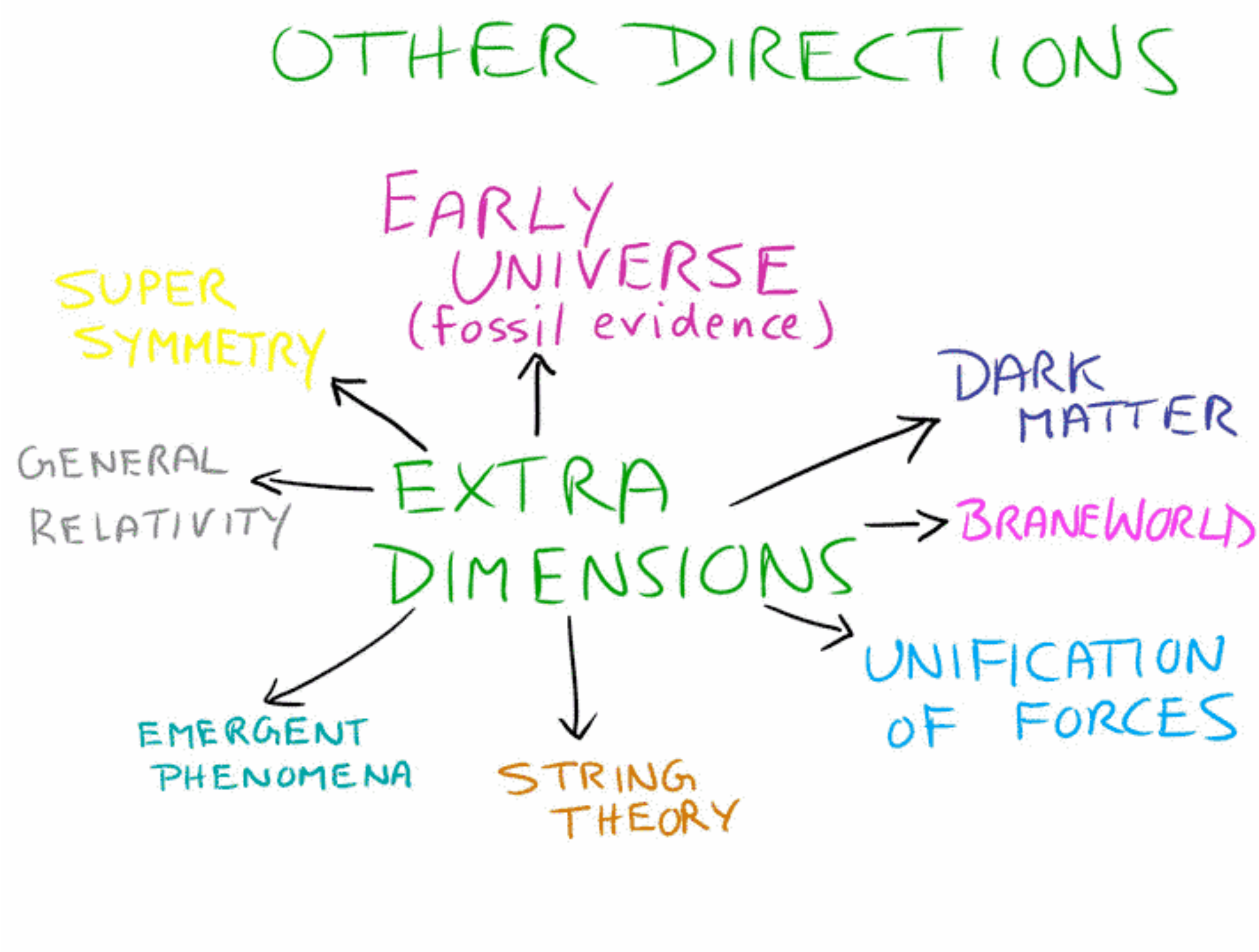
Dark Matter

Other Confirming Experiments

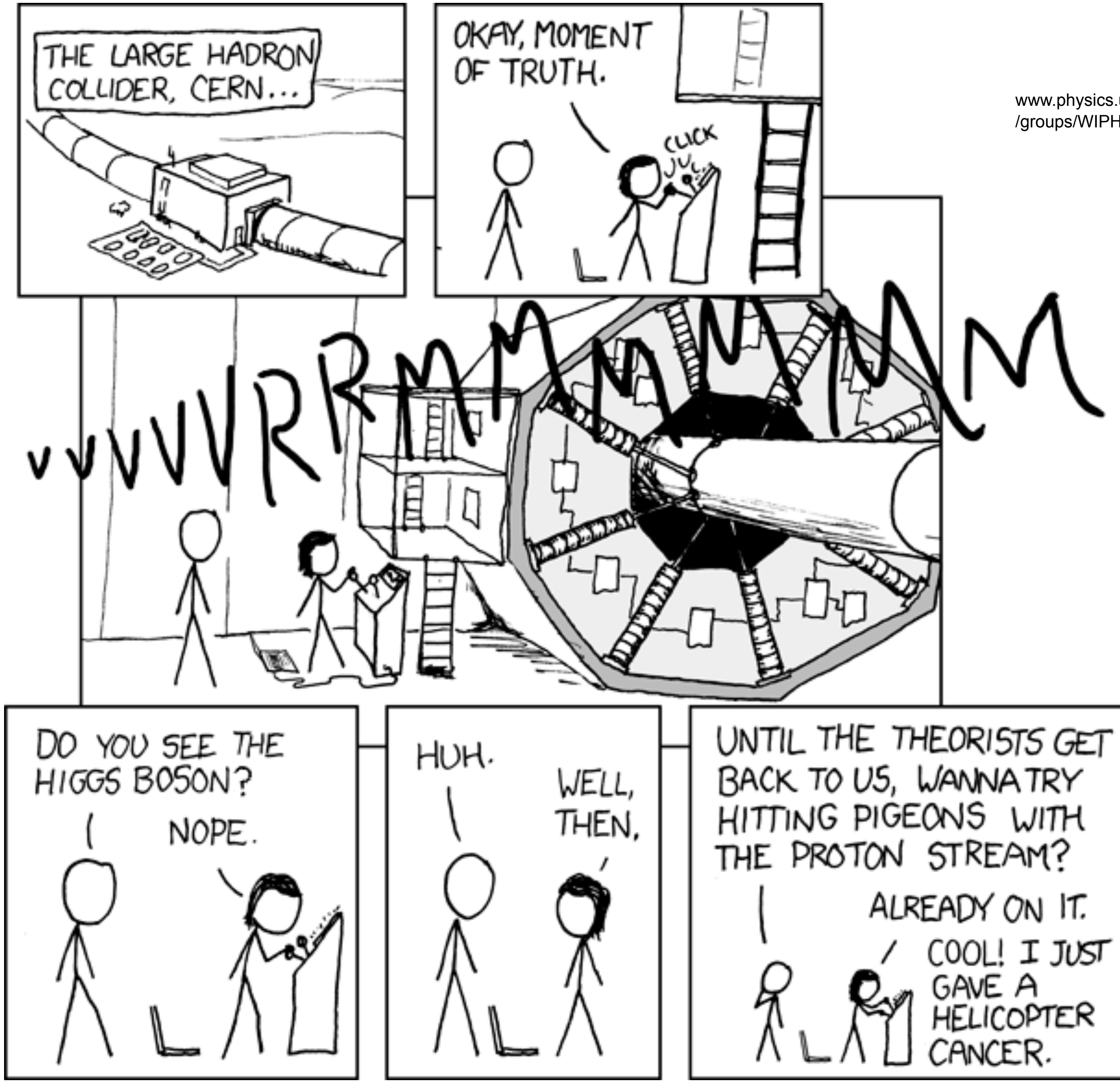
- We could infer dark matter's existence through the use of the Planck Surveyor, a satellite which, among other things, plans to look for gravitational lensing.
- The Gamma-ray Large Area Space Telescope (GLAST) will: "Search for signs of new laws of physics and what composes the mysterious Dark Matter."
- We could also directly detect dark matter using Xenon. The Large Underground Xenon Detector is an experiment where Xenon is placed in a cave deep underground, awaiting dark matter interactions.

- www.patrickgage.com/text/article/556/carnegie-mellon-2008-buhl-lecture-dark-matter

Exciting opportunities in particle physics



www.physics.uiuc.edu
/groups/WIPHYS/



“Pale blue dot” speech by Carl Sagan

"We succeeded in taking that picture [from deep space], and, if you look at it, you see a dot. That's here. That's home. That's us. On it, everyone you ever heard of, every human being who ever lived, lived out their lives. The aggregate of all our joys and sufferings, thousands of confident religions, ideologies and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilizations, every king and peasant, every young couple in love, every hopeful child, every mother and father, every inventor and explorer, every teacher of morals, every corrupt politician, every superstar, every supreme leader, every saint and sinner in the history of our species, lived there on a mote of dust, suspended in a sunbeam.

www.bigskyastroclub.org/pale_blue_dot.html

“Pale blue dot” speech by Carl Sagan

The earth is a very small stage in a vast cosmic arena. Think of the rivers of blood spilled by all those generals and emperors so that in glory and in triumph they could become the momentary masters of a fraction of a dot. Think of the endless cruelties visited by the inhabitants of one corner of the dot on scarcely distinguishable inhabitants of some other corner of the dot. How frequent their misunderstandings, how eager they are to kill one another, how fervent their hatreds. Our posturings, our imagined self-importance, the delusion that we have some privileged position in the universe, are challenged by this point of pale light. www.bigskyastroclub.org/pale_blue_dot.html

“Pale blue dot” speech by Carl Sagan

Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity -- in all this vastness -- there is no hint that help will come from elsewhere to save us from ourselves. It is up to us. It's been said that astronomy is a humbling, and I might add, a character-building experience. To my mind, there is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly and compassionately with one another and to preserve and cherish that pale blue dot, the only home we've ever known."

www.bigskyastroclub.org/pale_blue_dot.html