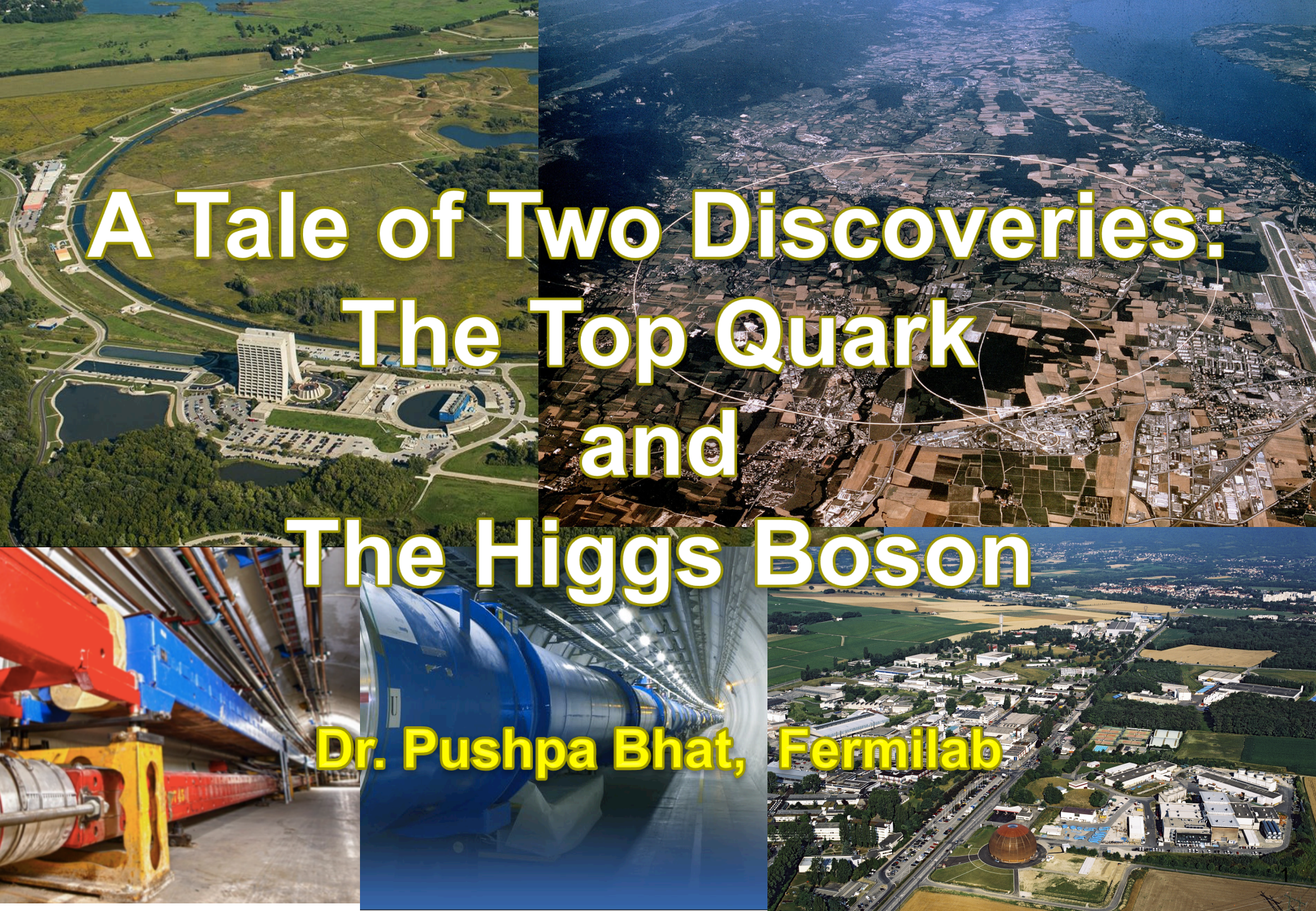


A Tale of Two Discoveries: The Top Quark and The Higgs Boson

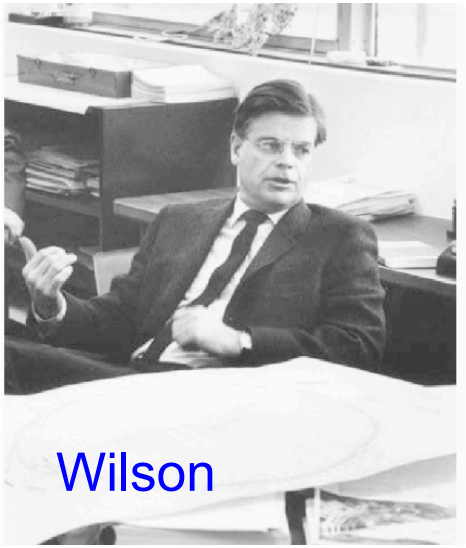
Dr. Pushpa Bhat, Fermilab

Welcome
to
Fermilab
The Premier US Lab
for Frontier Physics

A Very brief History

The Creation of Fermilab

- The National Accelerator Laboratory was created in 1967, on the Illinois prairie, to open a new frontier in the exploration of the deepest mysteries of matter and energy.
- Robert Rathbun Wilson (namesake of this building), born in Frontier, Wyoming, was the first director and architect of the Lab.
- The Lab was renamed Fermilab, to honor Enrico Fermi, a quintessential physicist, who had ushered in the Nuclear Age through his seminal experiment on nuclear fission, at the University of Chicago in 1942.


Wilson

Fermi

Fermilab Site c. 1967:
Former Village of Weston, Illinois

A National Laboratory on the Illinois Prairie

Pushpa Bhat, Fermilab

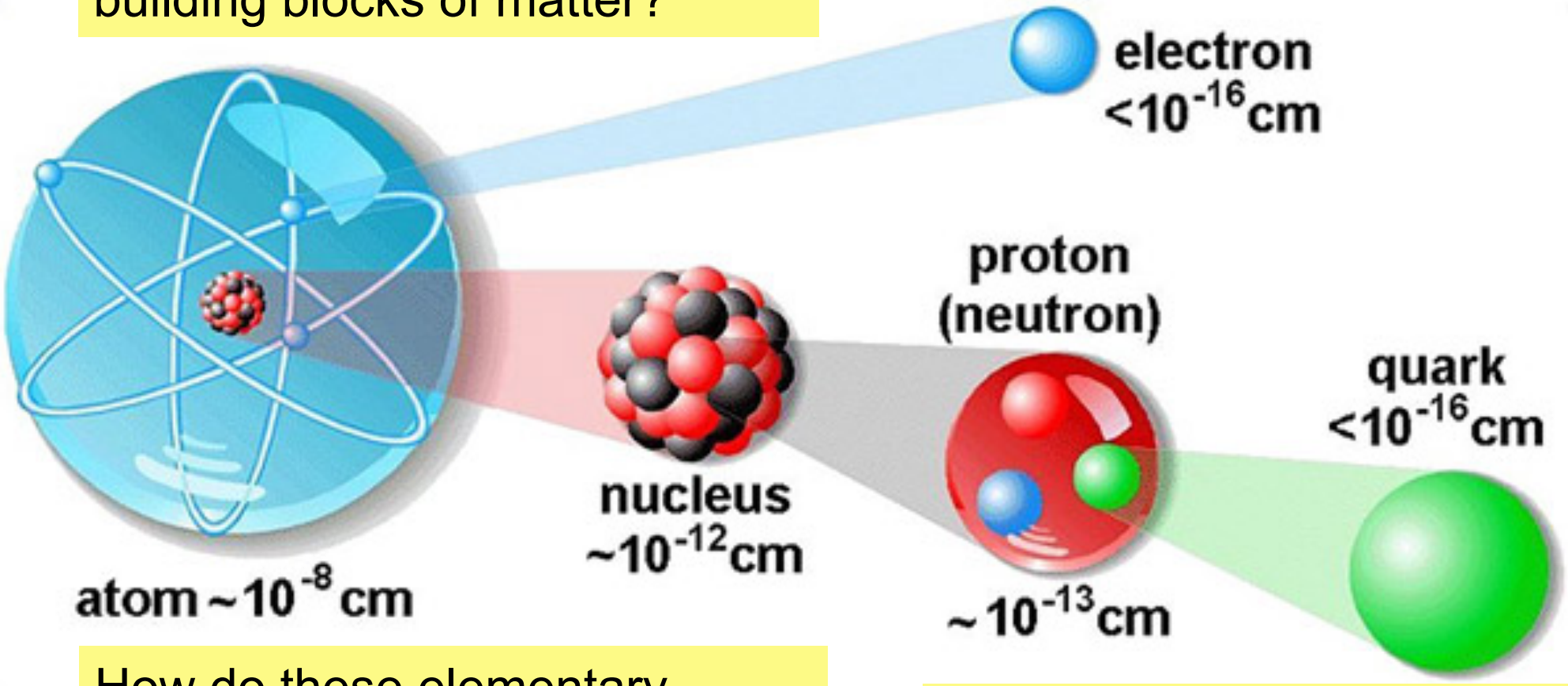
October 5, 2019

The Basic Questions

- What are the basic building blocks of matter?
  - "Elementary" or "Fundamental" Particles
- How do they interact with each other?
- How does nature behave at its most fundamental level?
- Can this explain the existence and evolution of the universe?

Probing Deep .. What is Elementary?

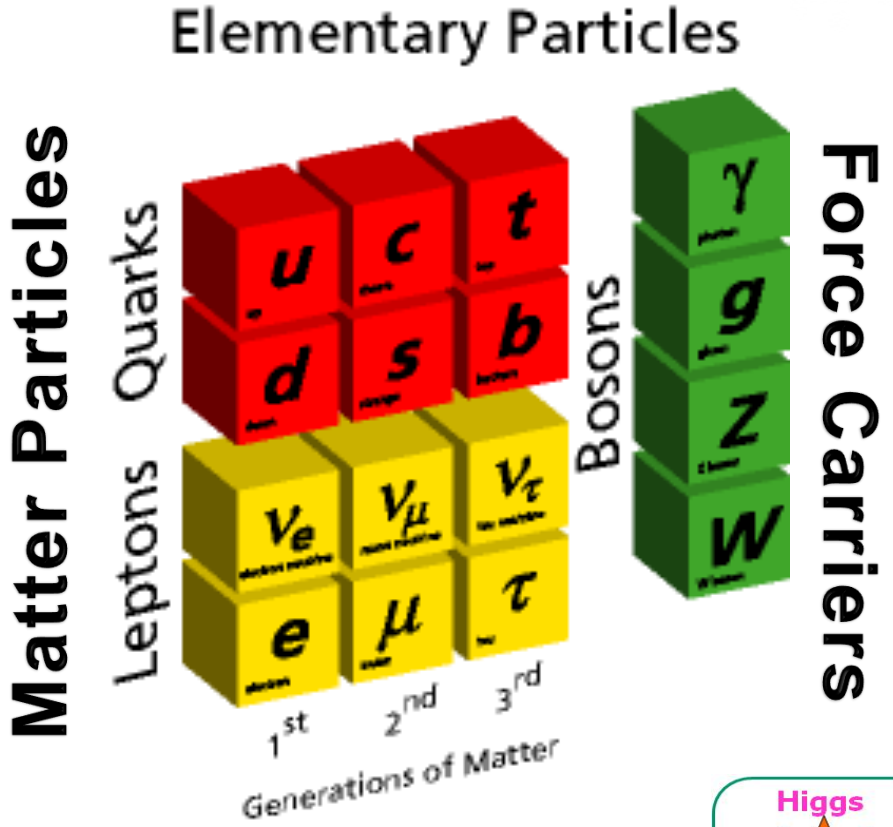
What are the most fundamental building blocks of matter?



How do these elementary particles interact?

Now probing distance scales ~ 10^{-21}m

The Standard Model of Particle Physics

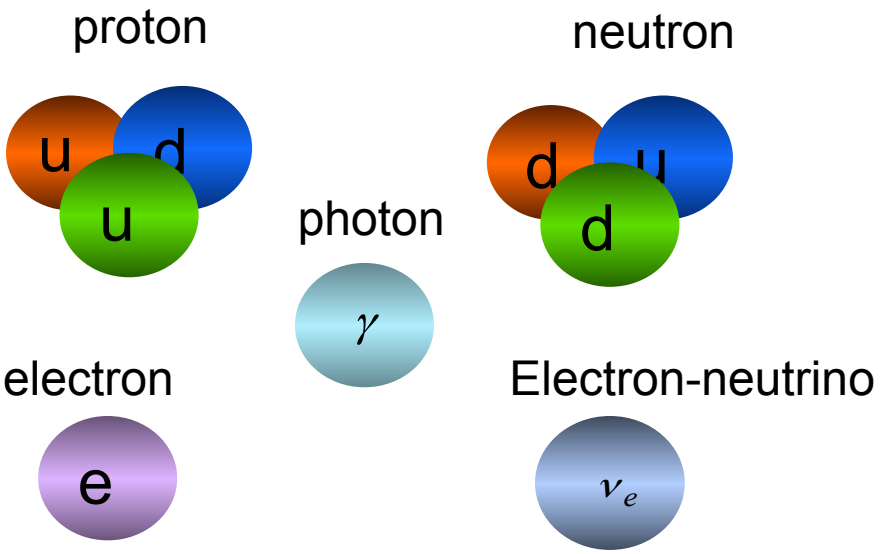


The Standard Model (SM) of Particle Physics is a **quantum field theory**

- 3 generations of **quarks** and **leptons** and
- 3 forces: **strong**, **electromagnetic** and **weak**
- and the **Higgs boson**

First elementary particle to Be discovered: electron in 1897

Our ordinary world



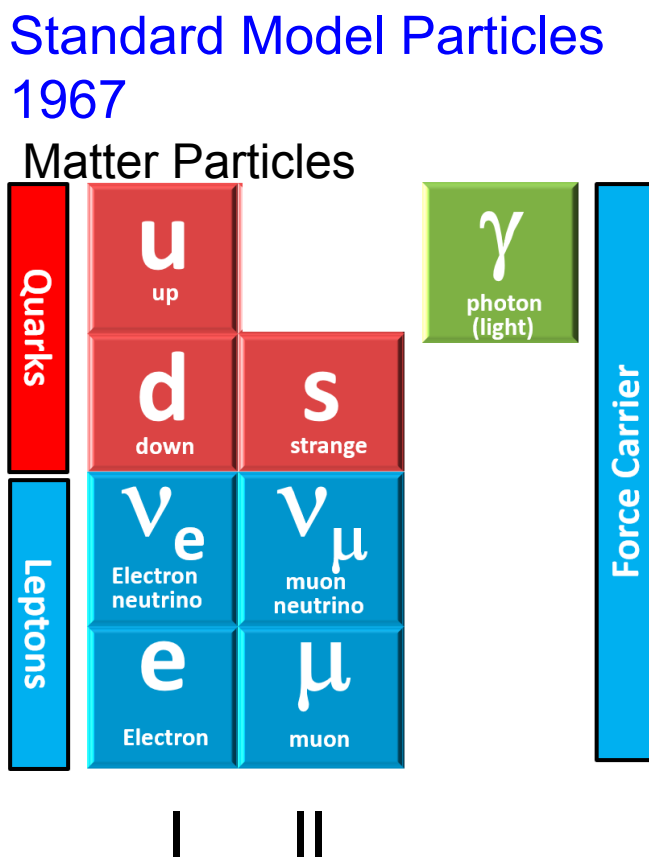
Everything we know is made up of these particles

For every type of particle there is an antiparticle (Dirac)

Nature seems to have heavier copies of the first generation particles

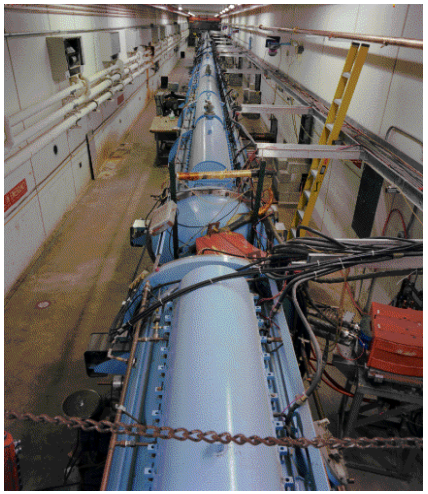
Prologue 1967

- The theoretical formulation of the Standard Model of Particle Physics begins in the 1960's
- In 1962, Leon Lederman and his colleagues show that there are two distinct neutrinos (Brookhaven, NY)
- 1964 Quark Model, Gellmann and Zweig
- 1967 Hints of "quarks" in deep inelastic e-p scattering experiments at SLAC, CA
- There were high energy accelerators on the US east and west coasts, CERN,..
- A strong desire to build a 100-1000 GeV accelerator in the Midwest.

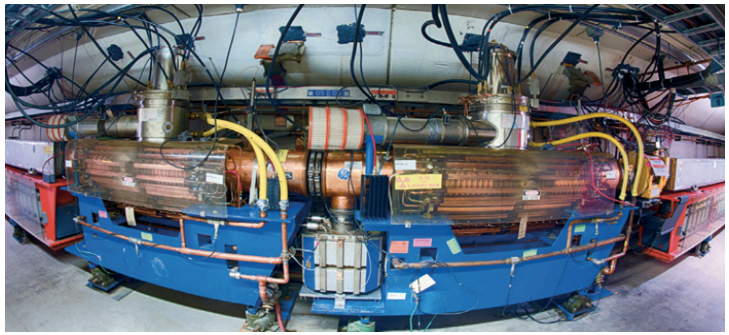


Accelerators built 1968-71

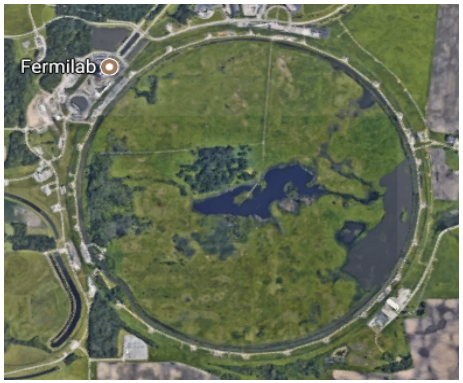
Cockroft-Walton
720 keV



Linear Accelerator
(Linac)
170 m long
200 MeV



Booster 8 GeV
Rapid-cycling synchrotron
0.5 km circumference



Main Ring Accelerator
6.4 km circumference
200 – 400 GeV

Accelerator Reaches Design Energy!!!
… And Beyond!

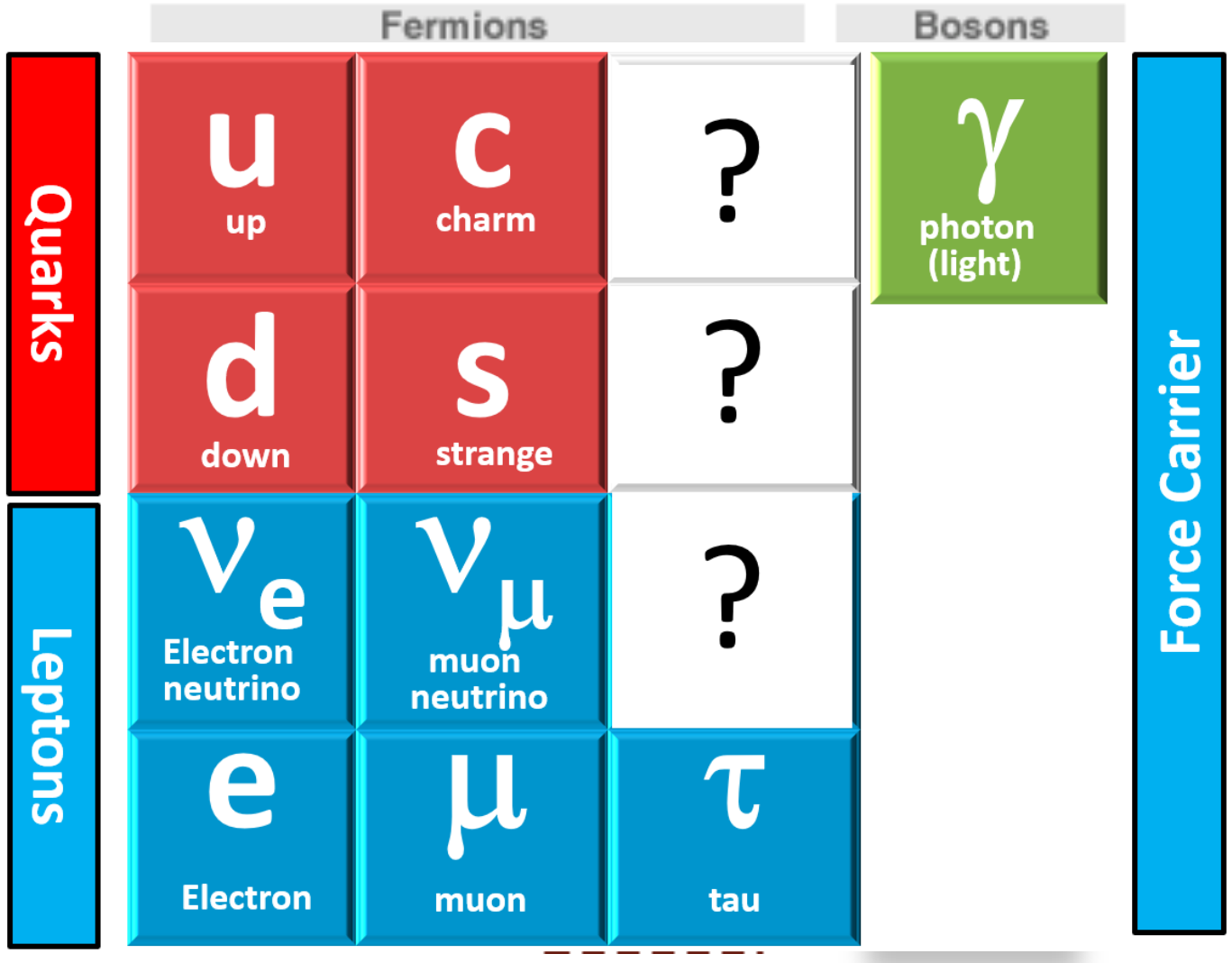
Accelerator at 200 GeV March 1, 1972

< 5 years from start of the brand new Lab

< 2.5 years after groundbreaking for Main Ring

By 1976, the Accelerator had reached the world record proton beam energy of 500 GeV

The Standard Model, Circa 1975



The First Big Discovery: The Beauty/Bottom (b) Quark

- In 1977, Leon Lederman (2nd director of the Lab) and his group discover the b-quark
  - There *is* a third generation of quarks!
  - A top quark and tau-neutrino are required to complete the quark and lepton doublets.

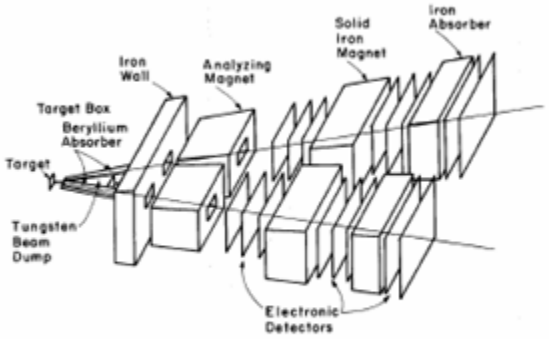


Figure 118. Schematic sketch of Fermilab dimuon experiment which led to the discovery of the Upsilon particle.

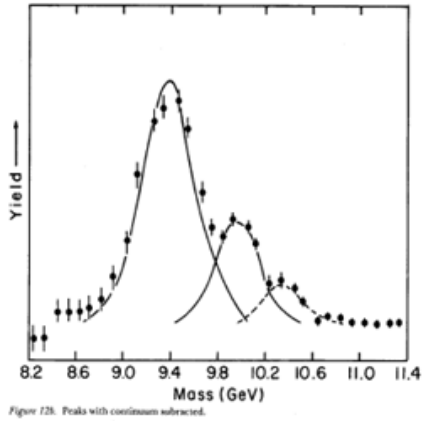
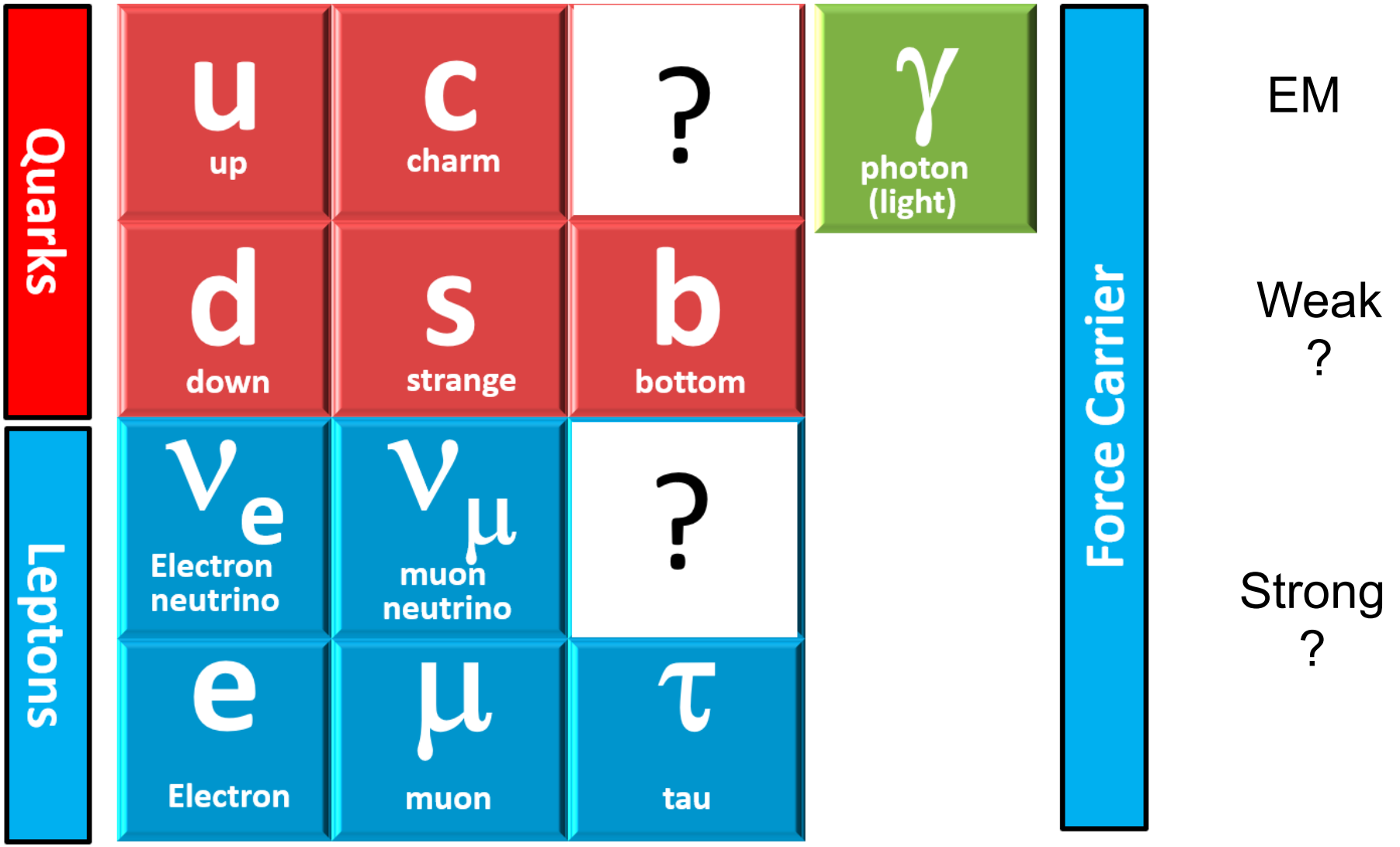


Figure 120. Peaks with continuum subtracted.

Lederman won the Nobel prize in 1988 for a previous discovery of muon neutrino, along with two others

Standard Model (end of 1977)



Race for the Top Quark

Pursuit of the Top Quark

- The discovery of the b-quark meant that its "isospin" partner top quark had to exist!

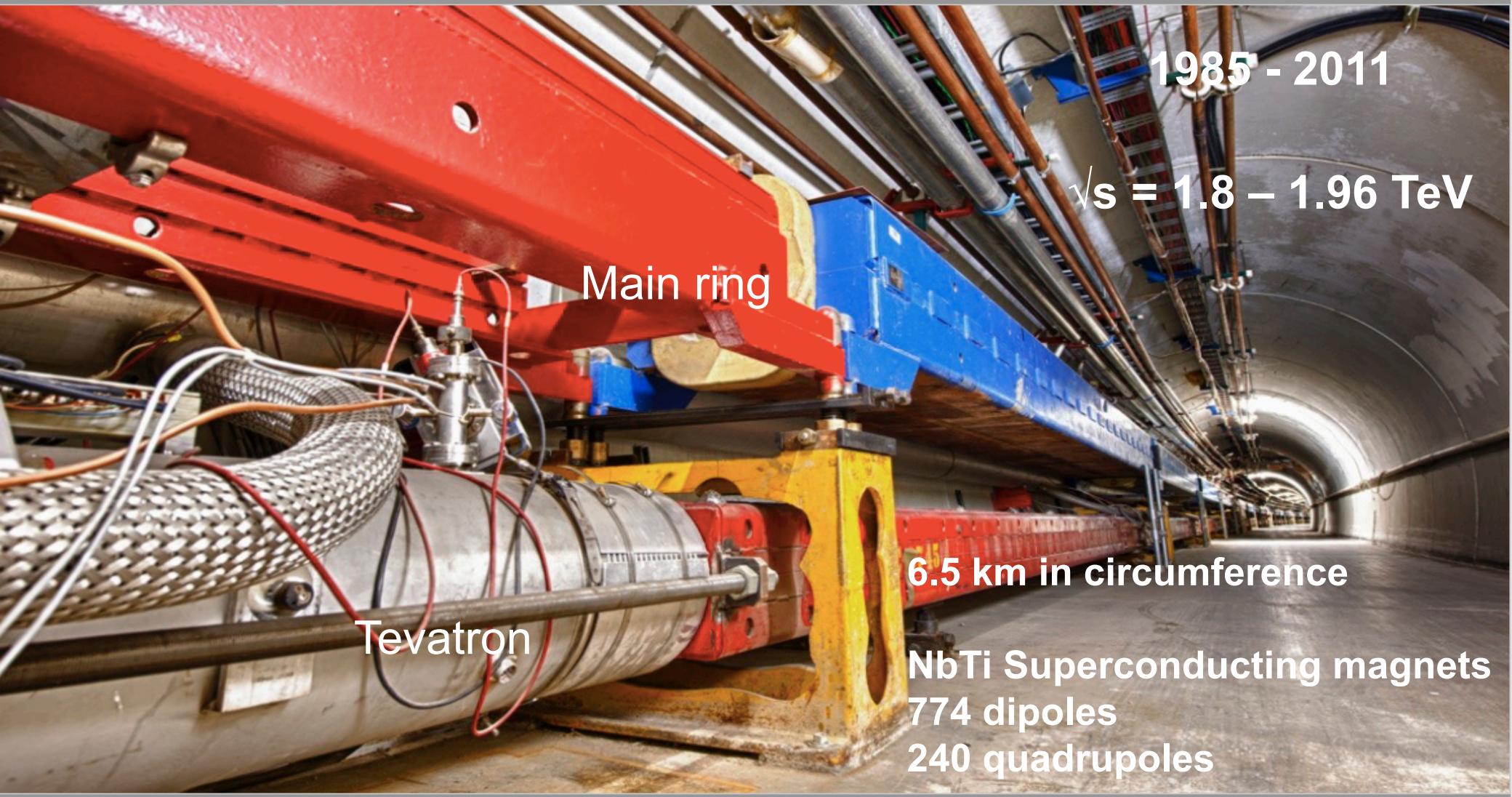
- Searches for the top quark began in earnest shortly after the discovery of the b-quark at various accelerator facilities around the world.

- Based on the masses of charm and bottom quarks a top-antitop bound-state was expected ~30 GeV.

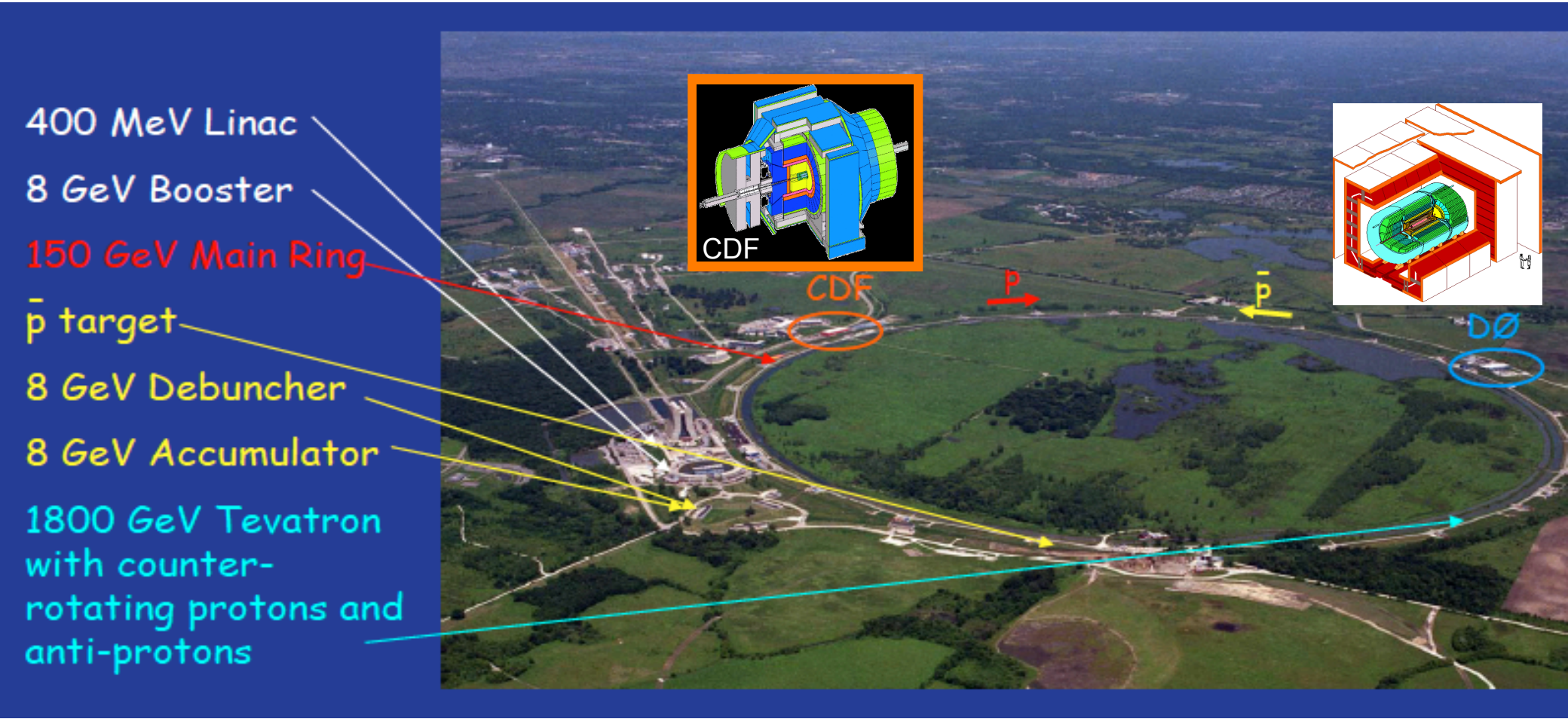
The Tevatron Collider

- In 1978, decision made to build a superconducting accelerator in the same tunnel as the Main Ring Accelerator at Fermilab, to ramp the energy to 1 Trillion Electron Volts (TeV).
  - This "Energy Doubler" (Tevatron) completed in 1983.
  - Total cost of the Tevatron Project: $120 M
- Feb. 16, 1984: First beams at 800 GeV
- Antiproton Source: Initiated in 1981 and completed in 1985.

The Tevatron

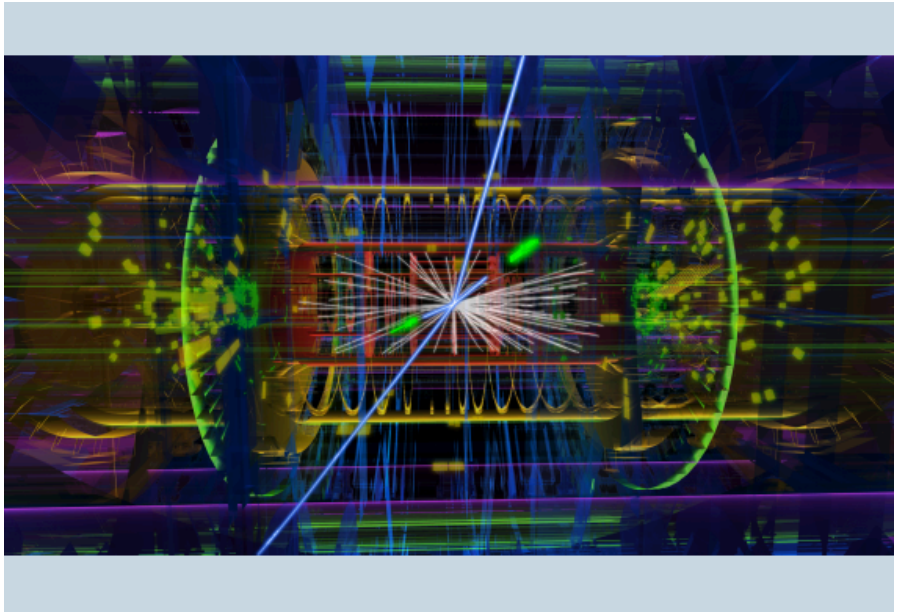


The Collider Complex



Creation, Detection & Discovery

- Particle collisions at very high energies can create lots of all sorts of particles (via $E=mc^2$) and some extraordinary ones, such as the top quark or the Higgs boson!
- Particle detectors track, identify and measure We detect, identify, "measure" particles produced in collision "events"



- Detectors are large, multi-layered, multi-system detectors surrounding the collision region
- Many storeys high, ~ thousands of tons each, millions of electronic readout channels, have multi-tiered data-acquisition systems
- Produce photographic-like pictures of each collision event

Pursuit of the Top Quark at Lepton Colliders

- Searches at e+e- colliders
  - PETRA(1979-84) at DESY Lab in Germany
    - Discovers the "gluon" in 1979.
    - No sign of the top quark!
  - TRISTAN (1986-90) in Japan
    - Built specifically to search for top quarks!
    - No top signal.
  - SLC (Stanford) and LEP at CERN (1989-90);
    - Precision measurements at these machines (particularly LEP) provide indirect constraints on the top quark mass!
    - No top signal! Limit of $m_t > 45.8$ GeV/c^2

Pursuit of the Top at Hadron Colliders

- Proton-antiproton colliders were developed in 1980s at CERN and Fermilab
- Super Proton AntiProton Synchrotron (SppS) at CERN
  - UA1 and UA2 experiments
  - 1984: UA1 reports evidence for top quark with m_t~40 GeV. With more data and analysis, signal vanishes! False alarm!
  - 1989: No top signal yet!
  - A limit of 77 GeV set!
- CERN was out of the running!

UA1 and UA2 make major discovery of the W and Z bosons in 1983

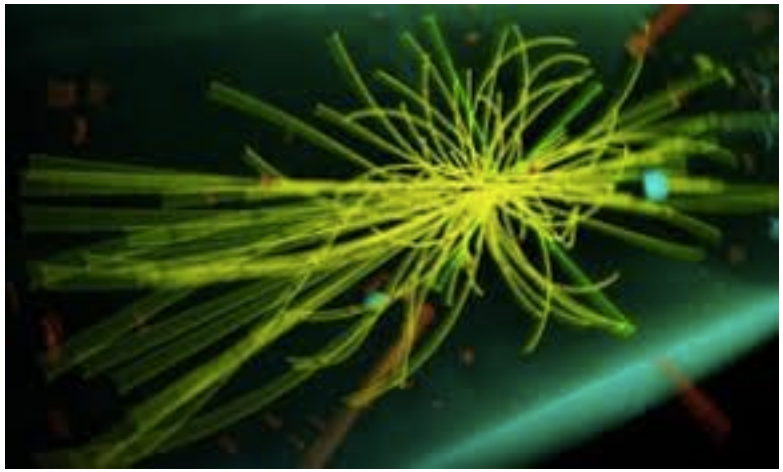
The Tevatron was the only collider (until 2009 when LHC came along) that was powerful enough to produce the top quarks

The CDF detector

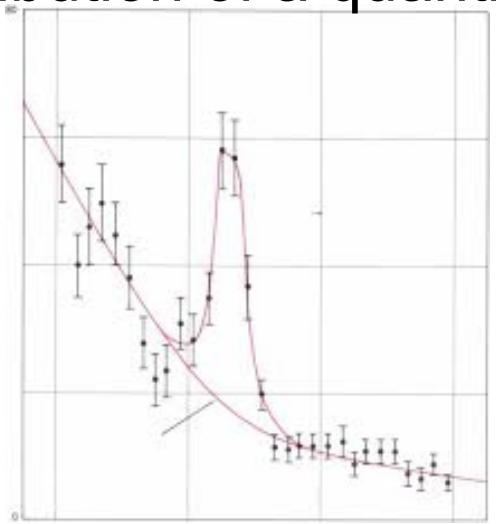
The DØ Detector Commissioned in 1992

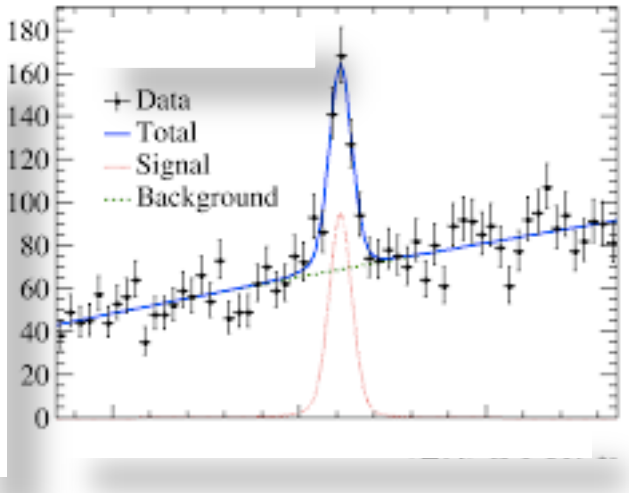
How do we find new particles?

Search for particles/events with expected (or unexpected) characteristics of new particles



Look for a bump/peak in a distribution of a quantity





Race for the Top

- Two major collider experiments at the Teavtron: CDF and DØ
- CDF: First collisions @1.6 TeV Oct. 13, 1985; 1.8 TeV Nov. 30, 1986.
- 1992: DØ detector joins CDF for the historic collider Run.
- 1992: CDF sets a limit of m_t>91 GeV, searching for top with mass above W mass.
- 1994: DØ sets a limit of m_t>131 GeV
- Race heats up!!

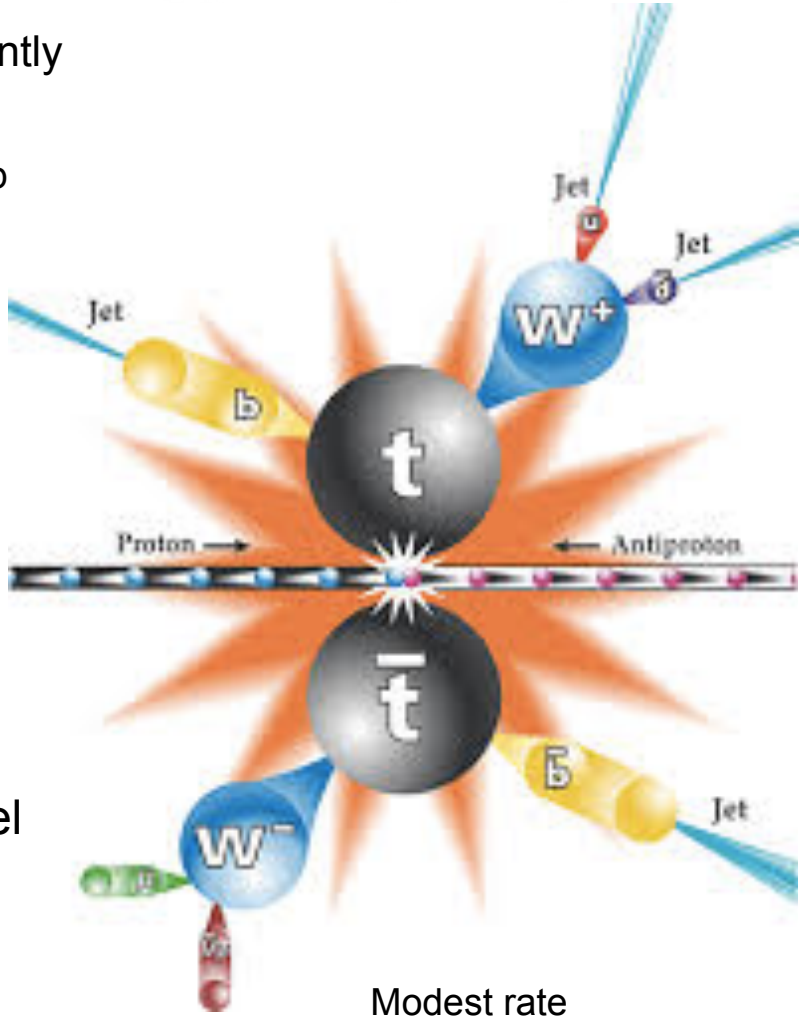
Top Production and Decays

Top quarks dominantly produced in pairs

$t \rightarrow W^+ + b$; $t^- \rightarrow W^- + b$

$W \rightarrow l\nu$, lepton

$W \rightarrow q\bar{q}'$, "jets"

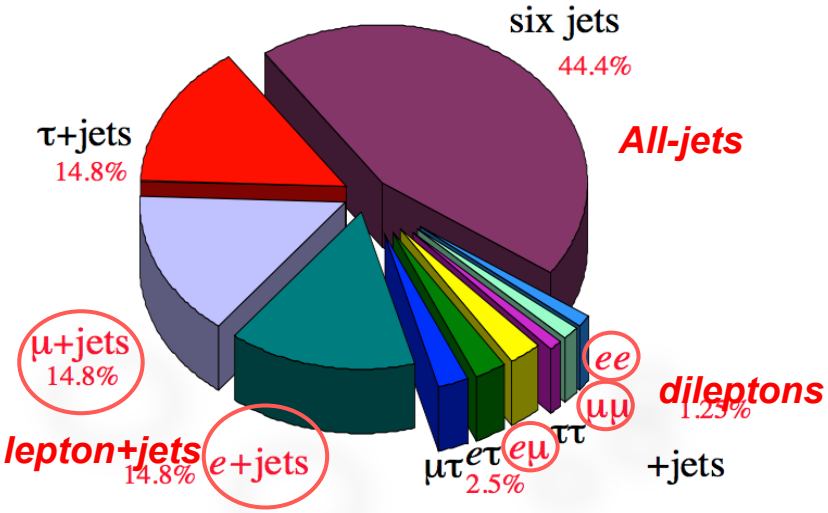


Several other processes not containing top quarks can mimic the signature

- Set criteria to select candidate events
- See if there is an excess
- Look for a mass peak

Lepton+jets
Happened to be the golden channel for discovery

Modest rate
Moderate background

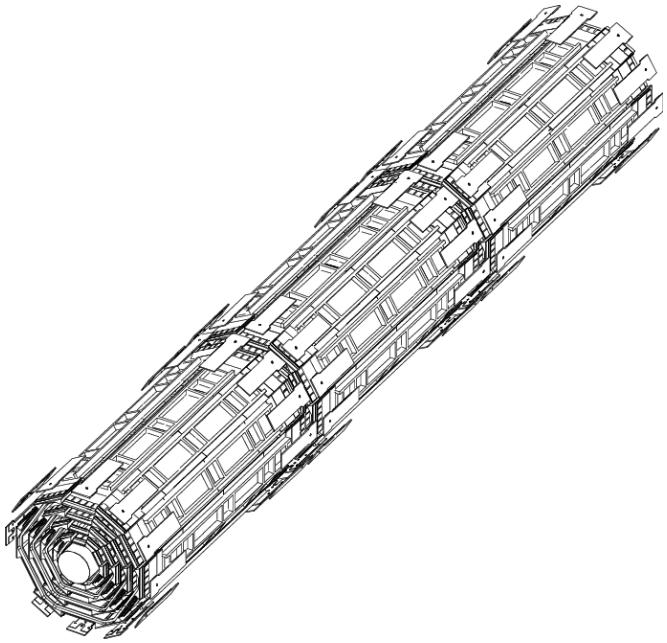


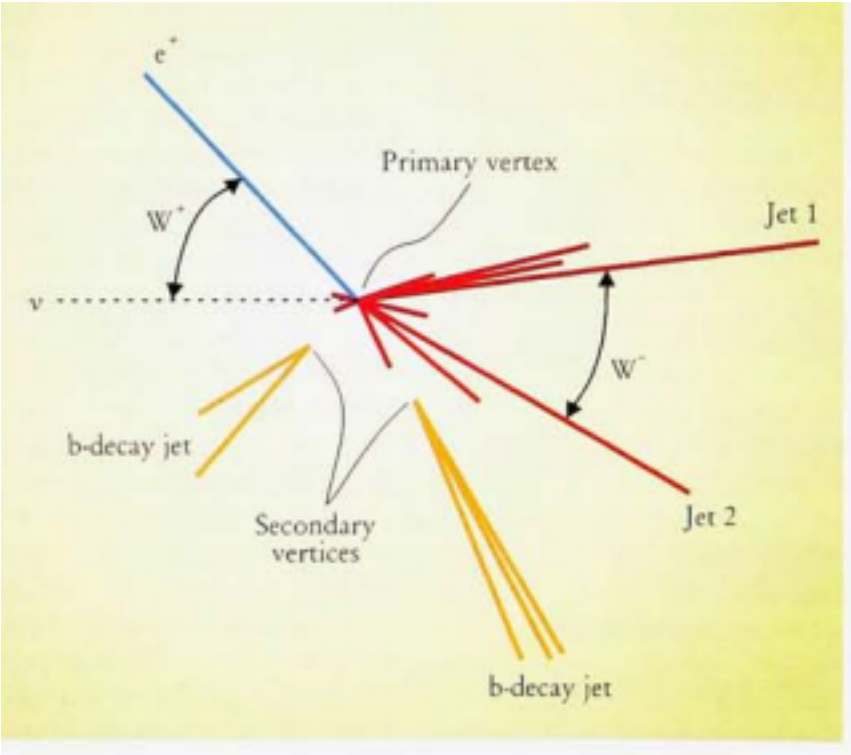
Separating Signal from Background

- Important characteristics of top-quark (pair) events
  - 2 b-jets (coming from b-quarks)
    - A secondary displaced vertex where the b-hadron decays can be used to tag the b-jets
    - CDF had a Secondary Vertex Detector (SVD) to tag b-jets
    - DØ had to use other means such as soft leptons in b-jets
  - High energy leptons (e/μ/τ) and/or jets
  - Missing transverse energy when neutrinos are present
- Use kinematic and topological quantities to separate signal from background

Use of Advanced Technology

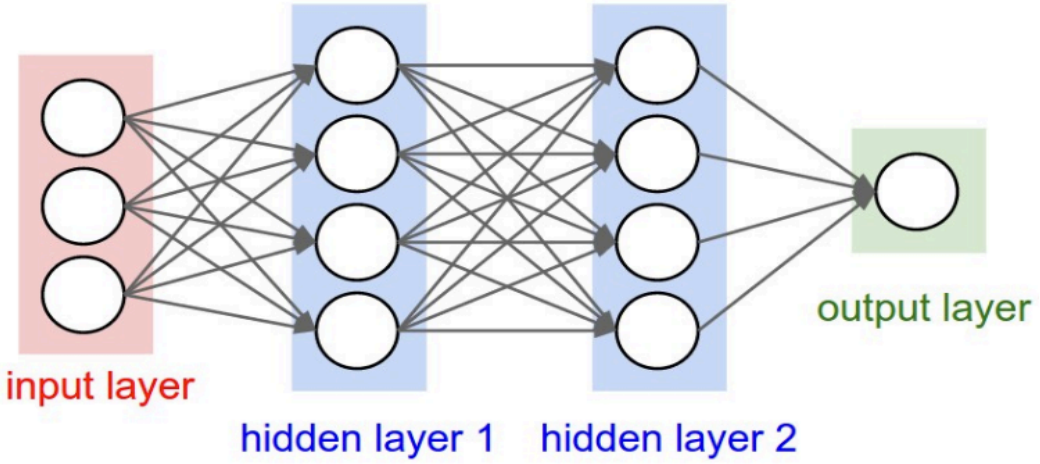
- The CDF Silicon Vertex Detector
  - High resolution instrument for tracking and identifying b-quark jets





Revolutions in Data Analysis: Machine Learning

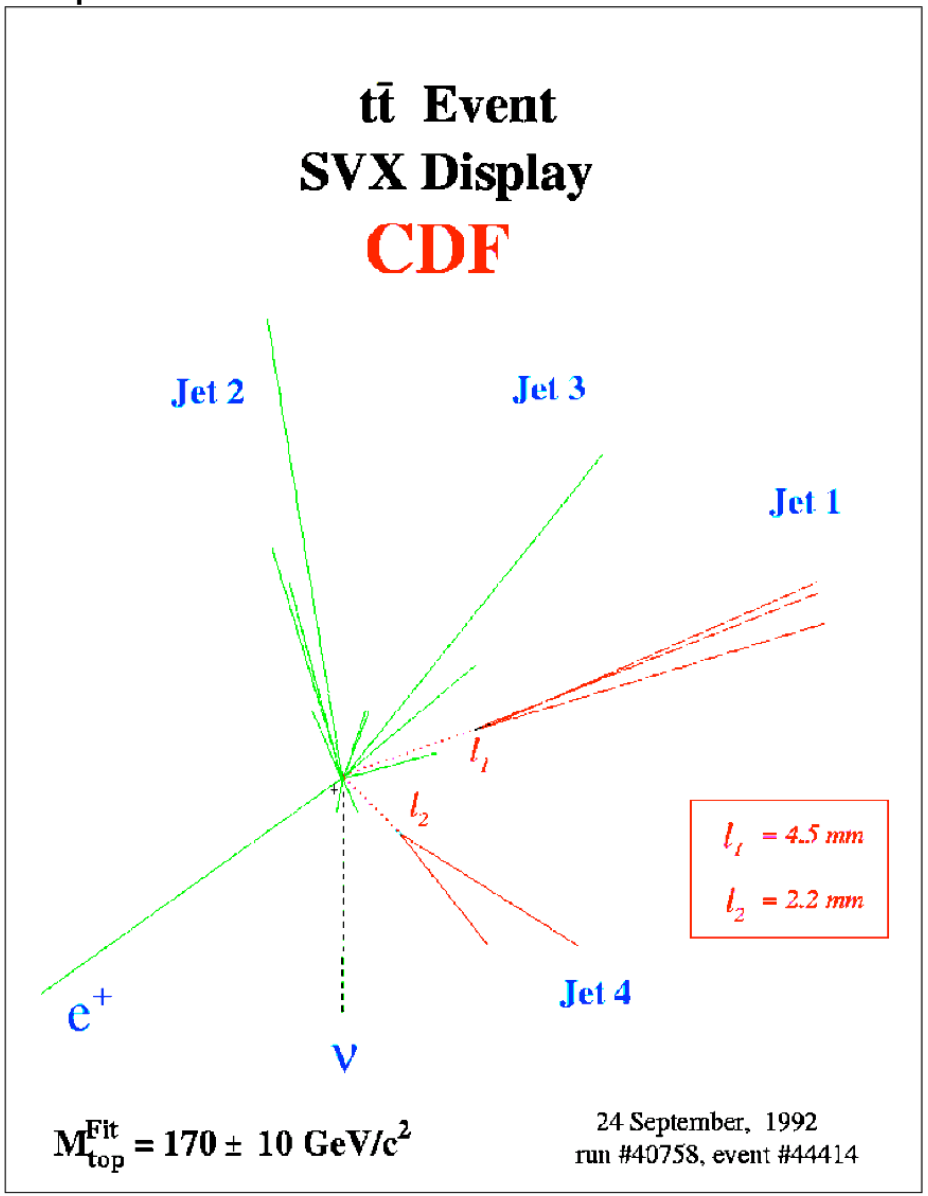
- There was a renaissance in neural networks (NN) in the late 1980s when effective algorithms for training artificial NN was rediscovered.



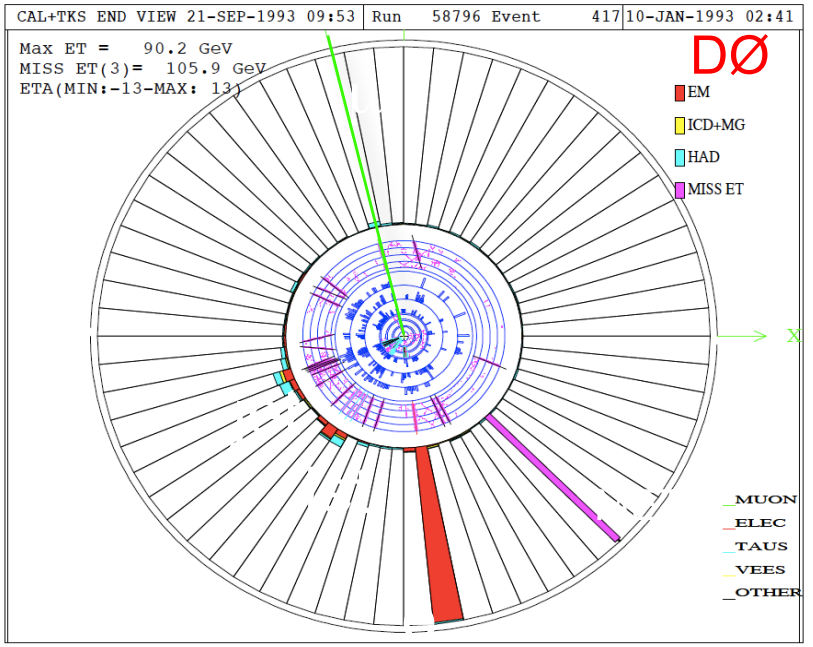
- Adopted use of Neural Networks to discriminate top quark events from background events @DØ, starting in 1990.

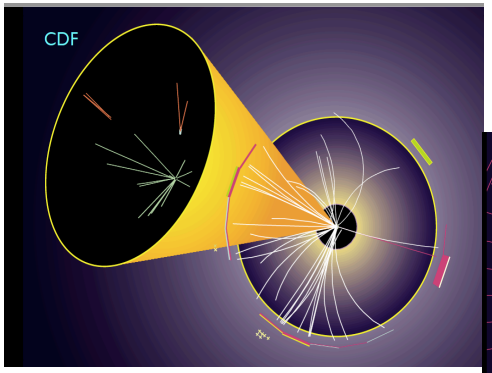
Early Top Quark Pair Candidate Events

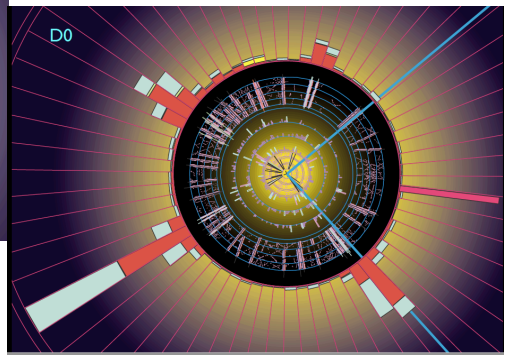
Sep. 1992



Jan. 1993







Evidence builds up!

- April 1994
  - CDF announced evidence for top quarks being produced at the Tevatron!
  - The probability of background faking the signal was 0.26%
    - 12 Candidate events
  - DØ had 9 candidate events and with 3.8±0.9 events found the probability fro background fluctuation to be 2.7%

DØ

SPECIAL EDITION

FermiNews

The Newsletter of the Fermi National Accelerator Laboratory

FERMILAB SCIENTISTS PRESENT NEW EVIDENCE IN THE SEARCH FOR THE TOP QUARK

This morning, April 26, Fermilab experimenters announced new results in the search for the top quark. In two colloquia in Ramsey Auditorium, spokespersons for CDF and DZero discussed their experiments.

The Collider Detector at Fermilab collaboration presented the first direct experimental evidence for the top quark, a subatomic particle that is the last undiscovered quark of the six predicted by current scientific theory. Scientists worldwide have sought experimental evidence for the top quark since the discovery of the bottom quark at Fermilab in 1977.

A research paper, submitted Friday, April 22, to *The Physical Review* by the 440-member CDF collaboration, presents evidence for the production of top quarks in world-record high-energy collisions between protons and antiprotons, their antimatter counterparts, at Fermilab's Tevatron particle accelerator. The CDF collaboration presented its results at today's scientific colloquium held at Fermilab.

CDF researchers stopped short of claiming discovery of the top quark, however. "We have not yet observed enough examples of top quark production to establish the particle's existence beyond question," said CDF cospokesperson Melvyn Shochet. "Nevertheless, this new evidence points strongly to the existence of the sixth and final quark that we have been seeking for so long." He added that the collaboration expects data from the collider run now underway at Fermilab to yield enough additional top quark events in the next few months to confirm the particle's existence and to improve the precision of measurements of its mass. The Tevatron is the world's highest energy accelerator, the only one capable of producing the top quark.

"I share the excitement of the scientists at Fermilab and around the world who have contributed to this success," said U.S. Secretary of Energy Hazel R. O'Leary. "These results give new impe-

Continued on back

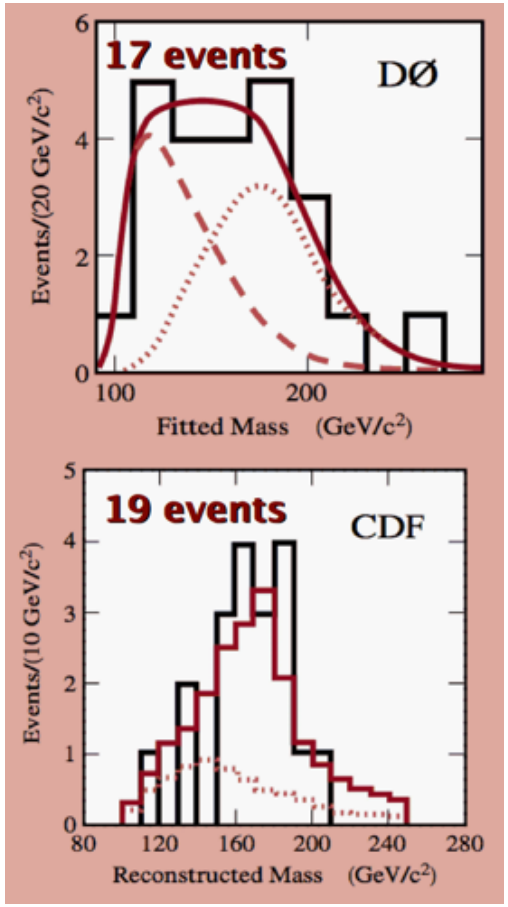
"The search for the top quark has been a research effort of heroic proportions. It is gratifying that after more than a decade of intensive searching, we are beginning to observe direct evidence of the top quark.

"As the power of the Tevatron and the collider detectors is improved over the next four years, including the completion of Fermilab's Main Injector, the experimenters will find still more evidence for its existence.

"The top quark, a subatomic particle that appears to be heavy as an entire gold atom, may well unlock some of nature's best-kept se-

Top Quark Discovery, March 1995

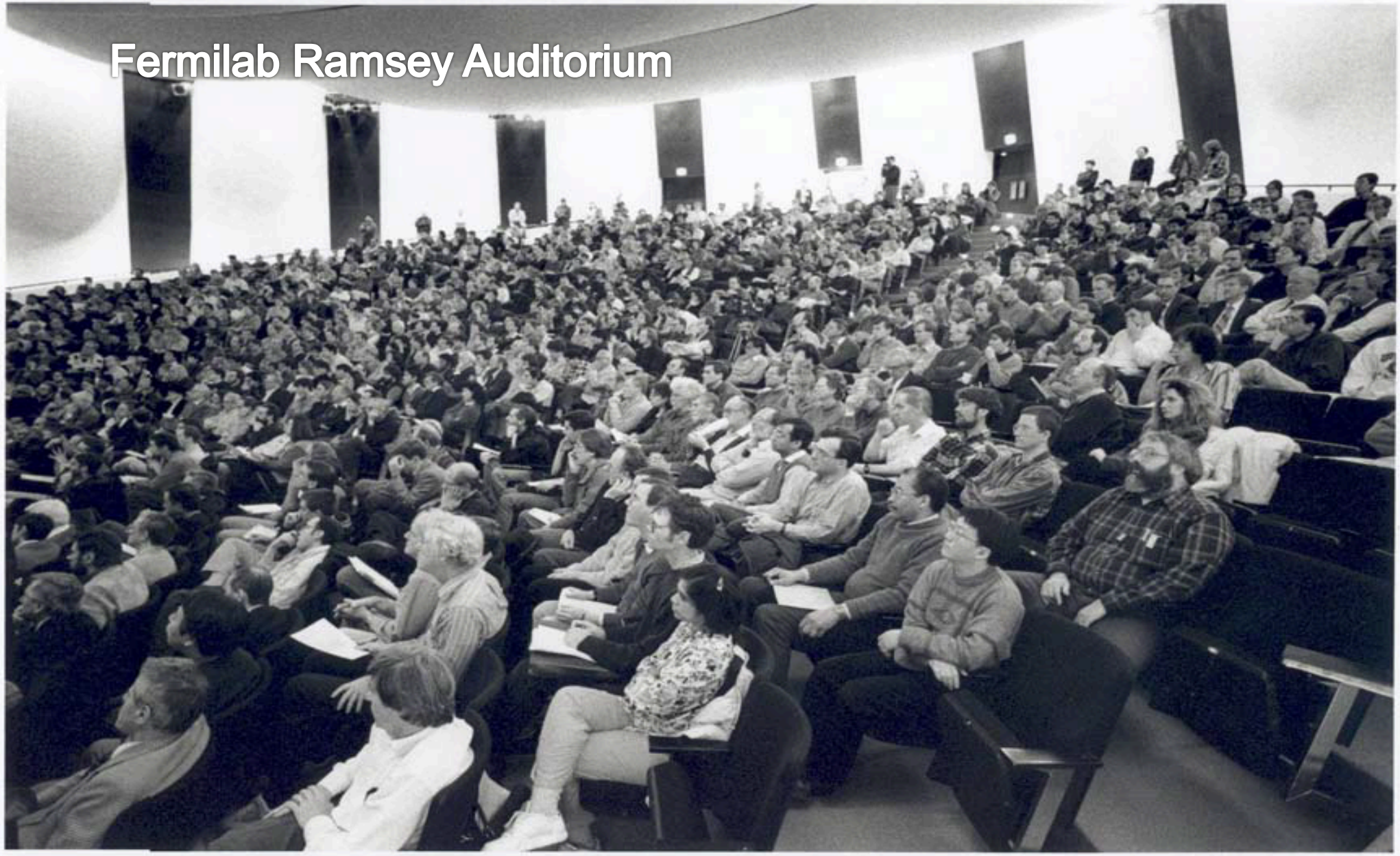
$199^{+19}_{-21}(\text{stat}) \pm 22(\text{syst})$



$176 \pm 8(\text{stat}) \pm 10(\text{syst})$

- Finally, by March 1995, both experiments had seen enough candidate events
  - CDF's probability for background fluctuation was 1×10^{-6} (4.8 σ) and for DØ it was 2×10^{-6} (4.6 σ)
- The top quark was finally discovered 18 years after the b-quark discovery!
- It was found to be very heavy at ~175 GeV
- Top quark is extremely short-lived
  - Lifetime ~ 10^{-25} s!

Top Quark Discovery March 2, 1995



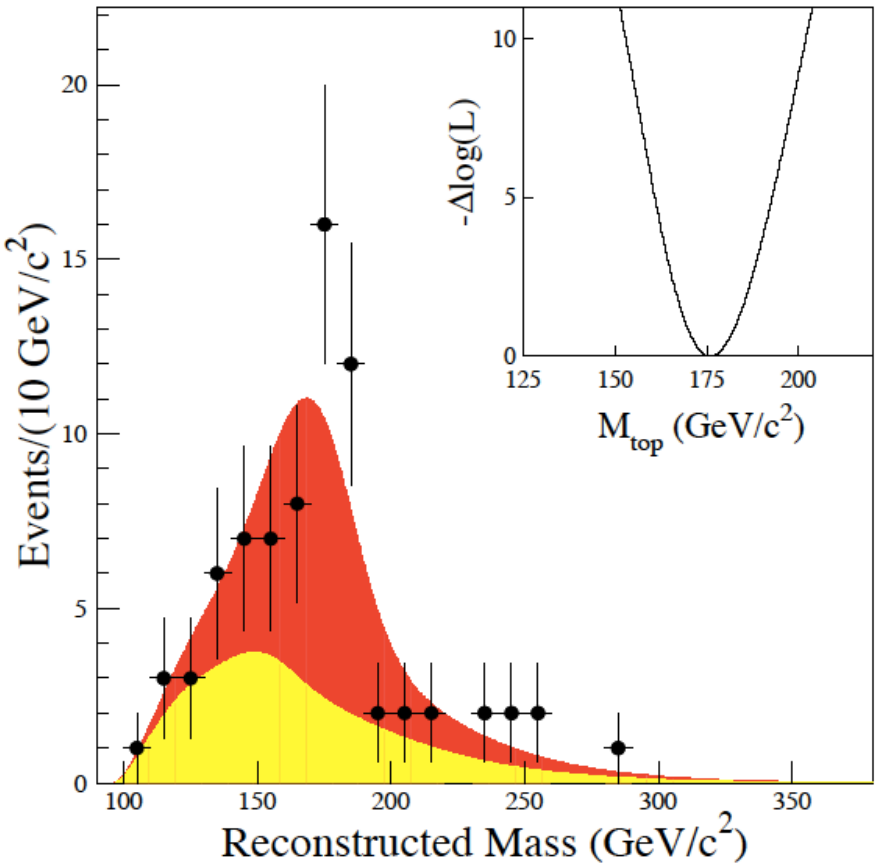
Top Quark Discovery March 2, 1995

Bellettini (CDF) , Grannis (DØ), FNAL Director Peoples, Montgomery (DØ), Carrithers (CDF)

Top quark mass

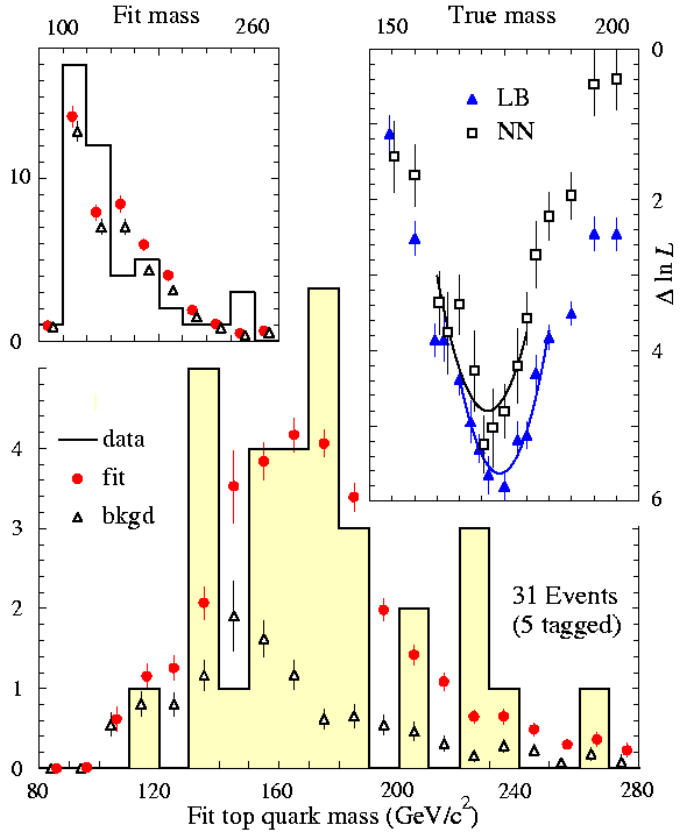
1998

CDF

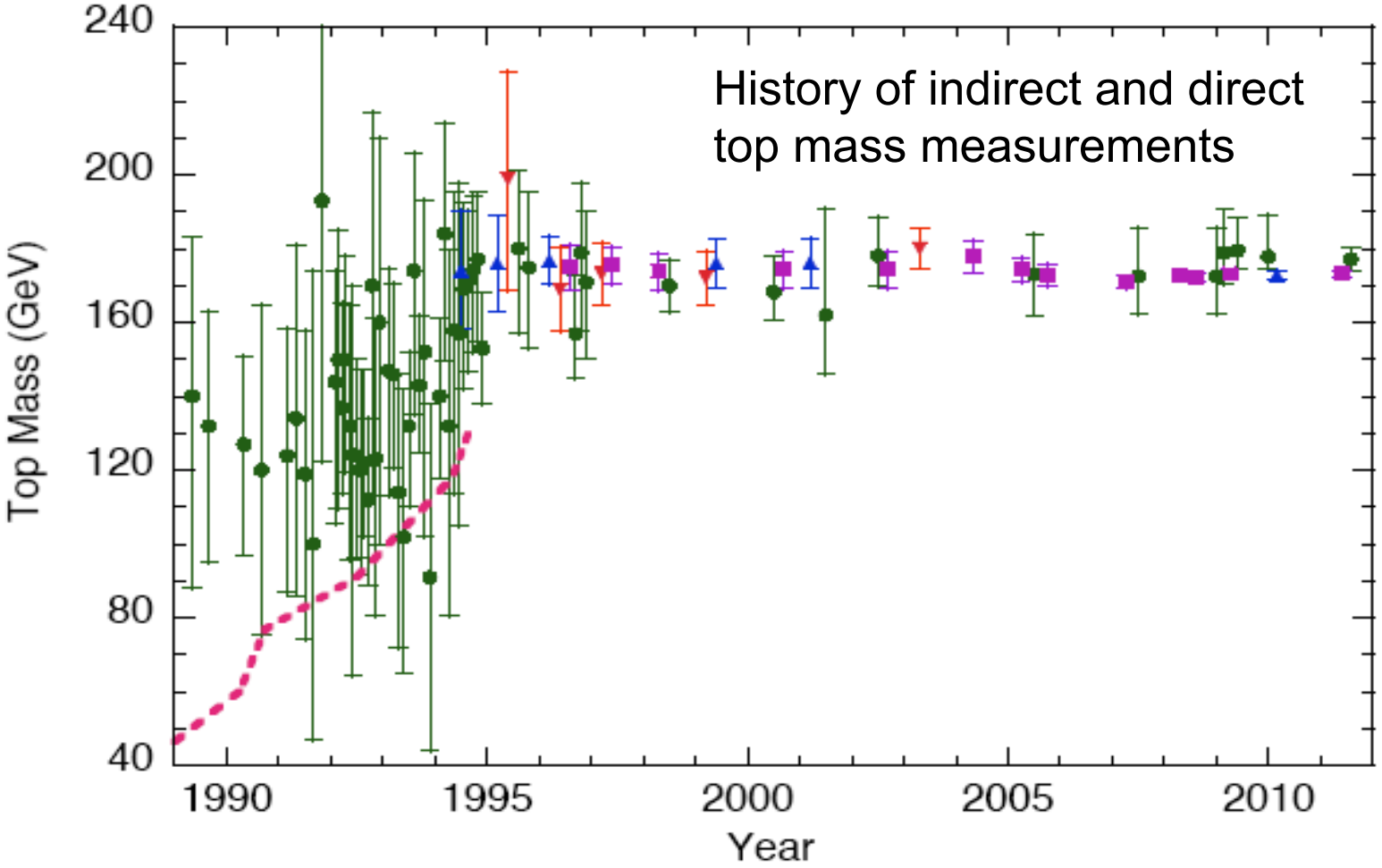


$m_t = 175.9 \pm 4.8(\text{stat.}) \pm 4.4\ (\text{syst.})\ \text{GeV}/c^2$

DØ



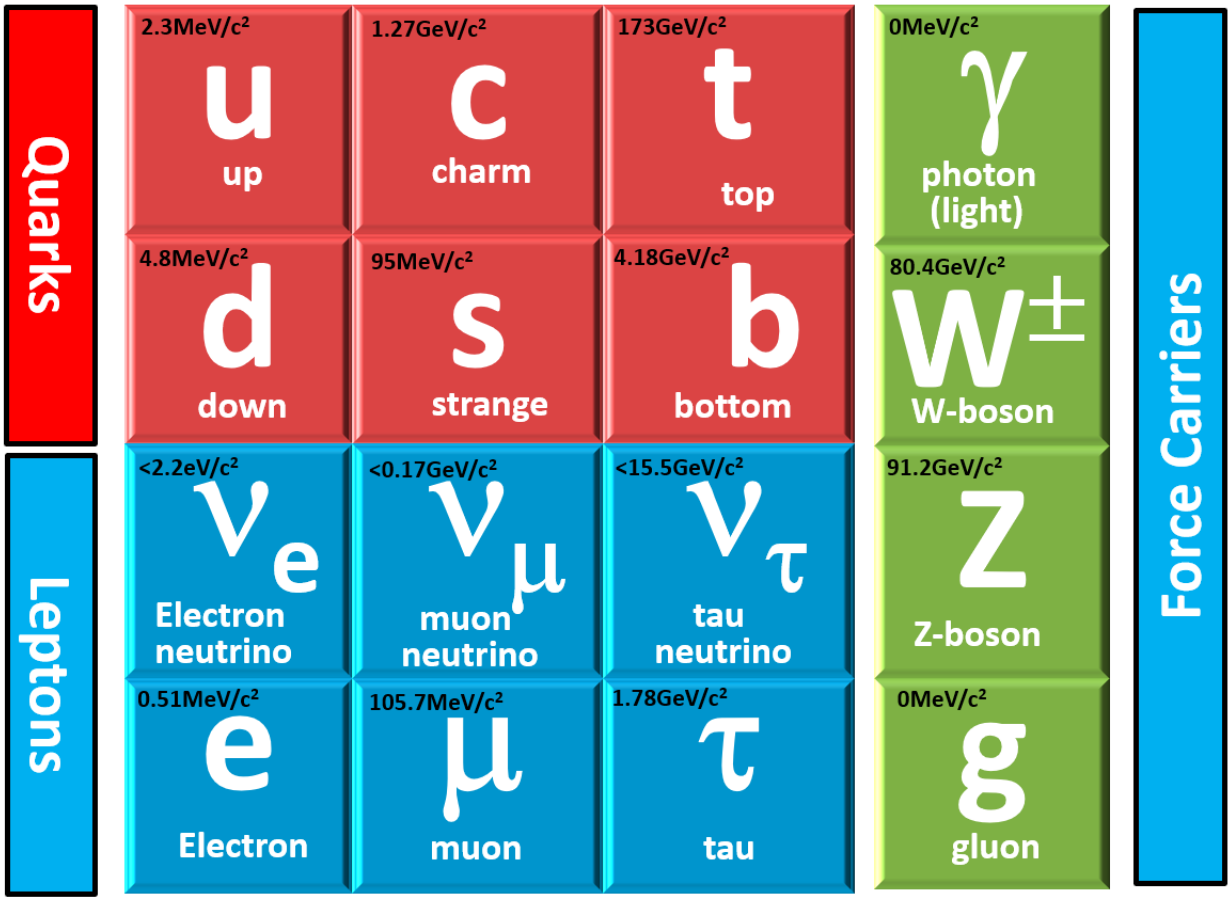
$m_t = 173.3 \pm 5.6(\text{stat.}) \pm 6.2\ (\text{syst.})\ \text{GeV}/c^2$



Green points: mass estimates from EW measurements
Dashed red line: 95% CL lower bounds on m_t from direct searches at CERN and Tevatron
Blue triangles: CDF measurements;
Red triangles: DØ measurements
Purple squares: mean m_t

Tevatron, LHC combination (20
m_t = 173.34 ± 0.76 GeV

The Standard Model circa 2000



$1\text{GeV}/c^2 = 1000\text{MeV}/c^2 = 1.783\times10^{-27}\text{kg}$

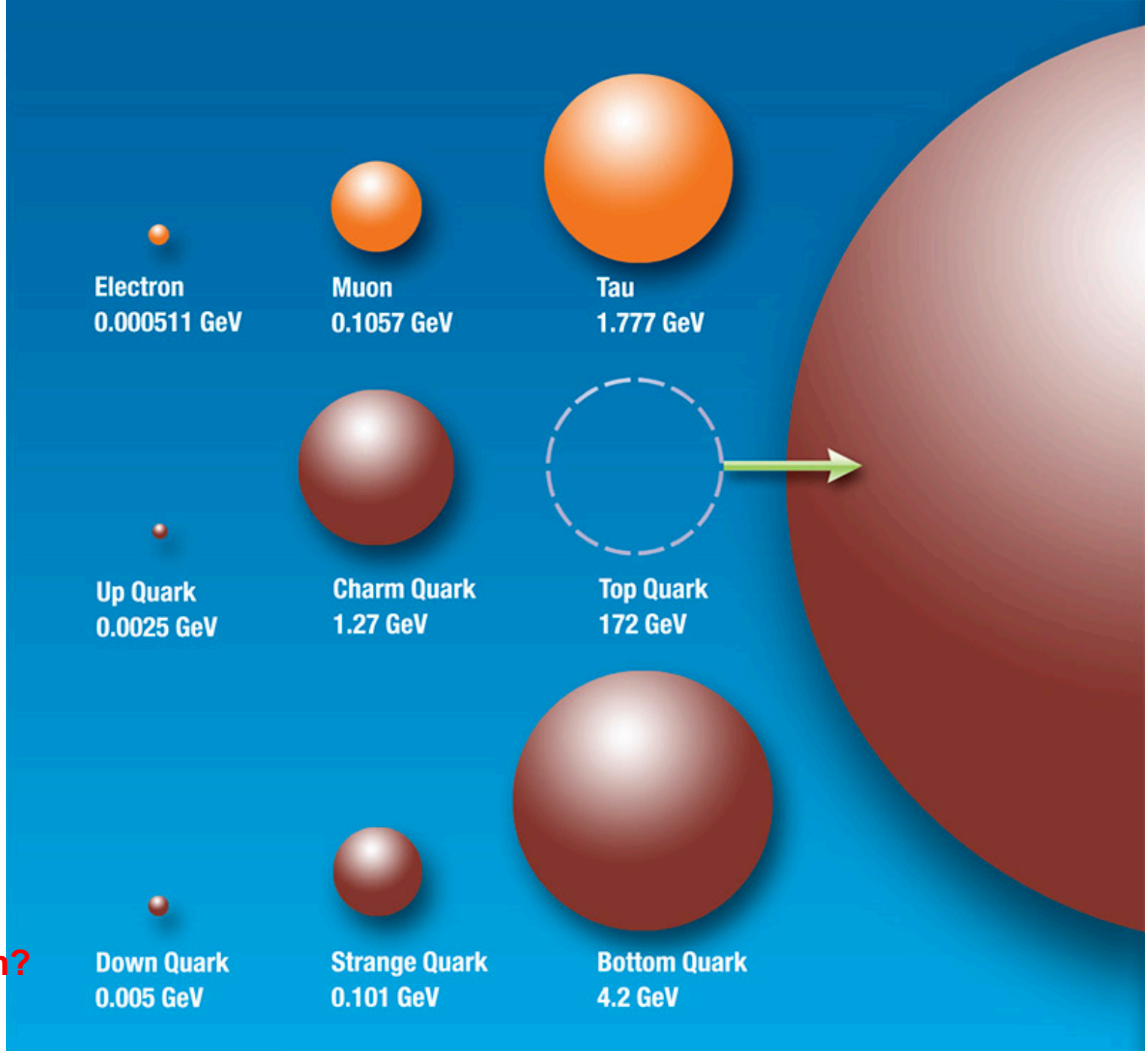
The three generations of matter particles and force carriers are all found.

Let us not forget the Higgs Boson!

Without it, the Standard Model does not work!

N_τ was discovered at Fermilab in 2000

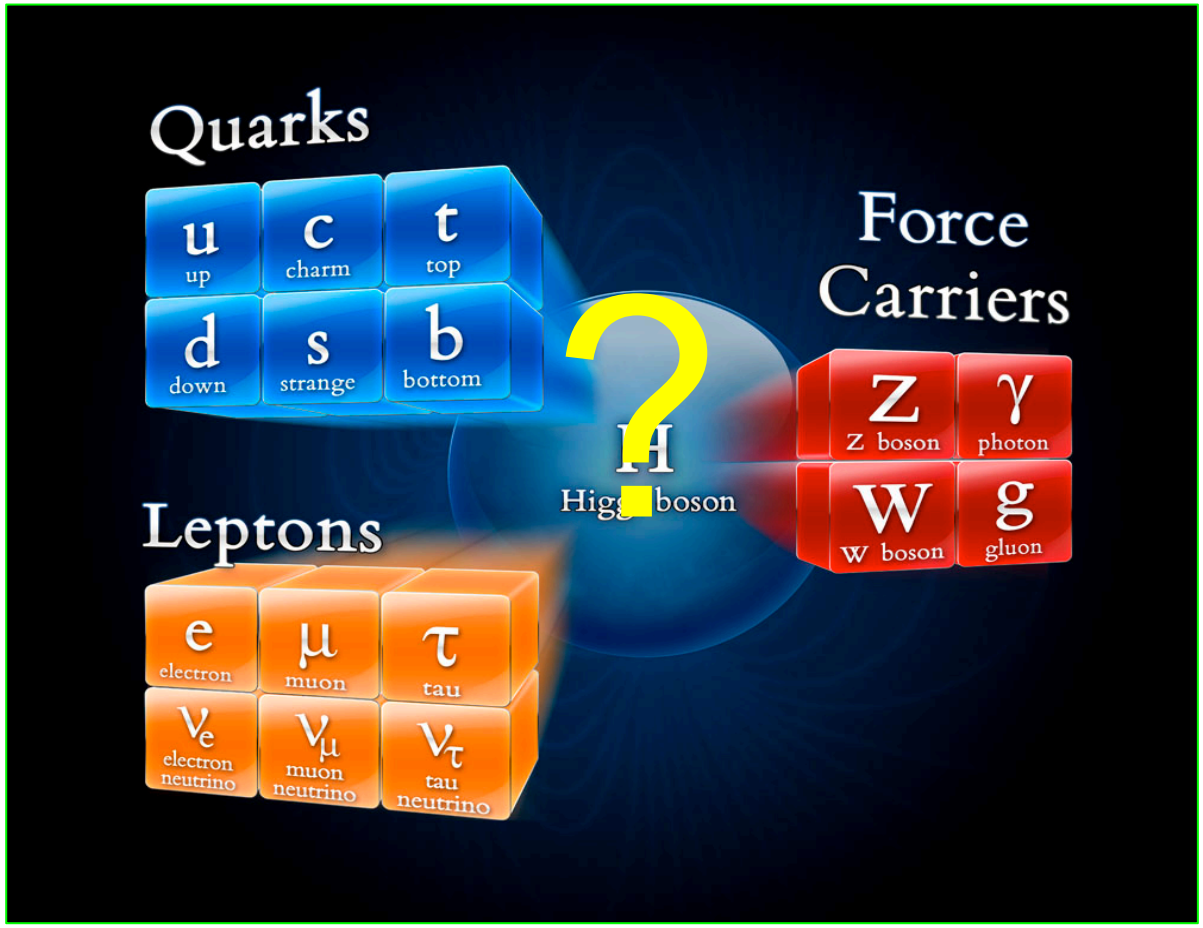
Quark/Lepton Masses



Where do these masses come from?

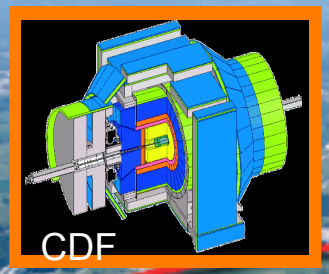
The Elusive "God" Particle!

The **Standard Model** is a remarkable theory!
Has been confirmed to great precision in hundreds of measurements.



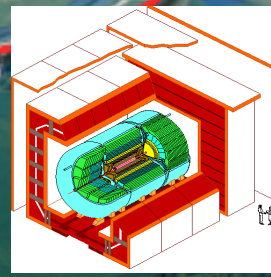
- But the Standard Model requires the **"Higgs field"** to break electroweak symmetry, giving masses to W,Z
- Quarks/leptons also get masses from the Higgs field
- Since the discovery of the top quark in 1995, the Higgs boson became the most wanted particle
- Intense pursuits at the LEP collider and the Tevatron before the LHC

The Tevatron Complex and experiments were upgraded to help find the Higgs: 2000 – 2006



Tevatron
6.5 km ring

Fermi National Accelerator Laboratory



Pursuing the Higgs at the Fermilab Tevatron

- Having discovered the top quark, Fermilab experiments hoped to discover the Higgs boson!
- Intense workshops yielded ideas and impetus for aggressive pursuit before the start of the LHC at CERN.
- It was found 100x more data for both experiments should allow clear evidence or observation of the Higgs boson.
- Extensive upgrades to the Tevatron complex, Run II Luminosity and Reliability Upgrades" followed.

Run II Higgs and SUSY Workshop

Strategy for discovering a low-mass Higgs boson at the Fermilab Tevatron

Pushpalatha C. Bhat, Russell Gilmartin, and Harrison B. Prosper
Phys. Rev. D **62**, 074022 – Published 12 September 2000

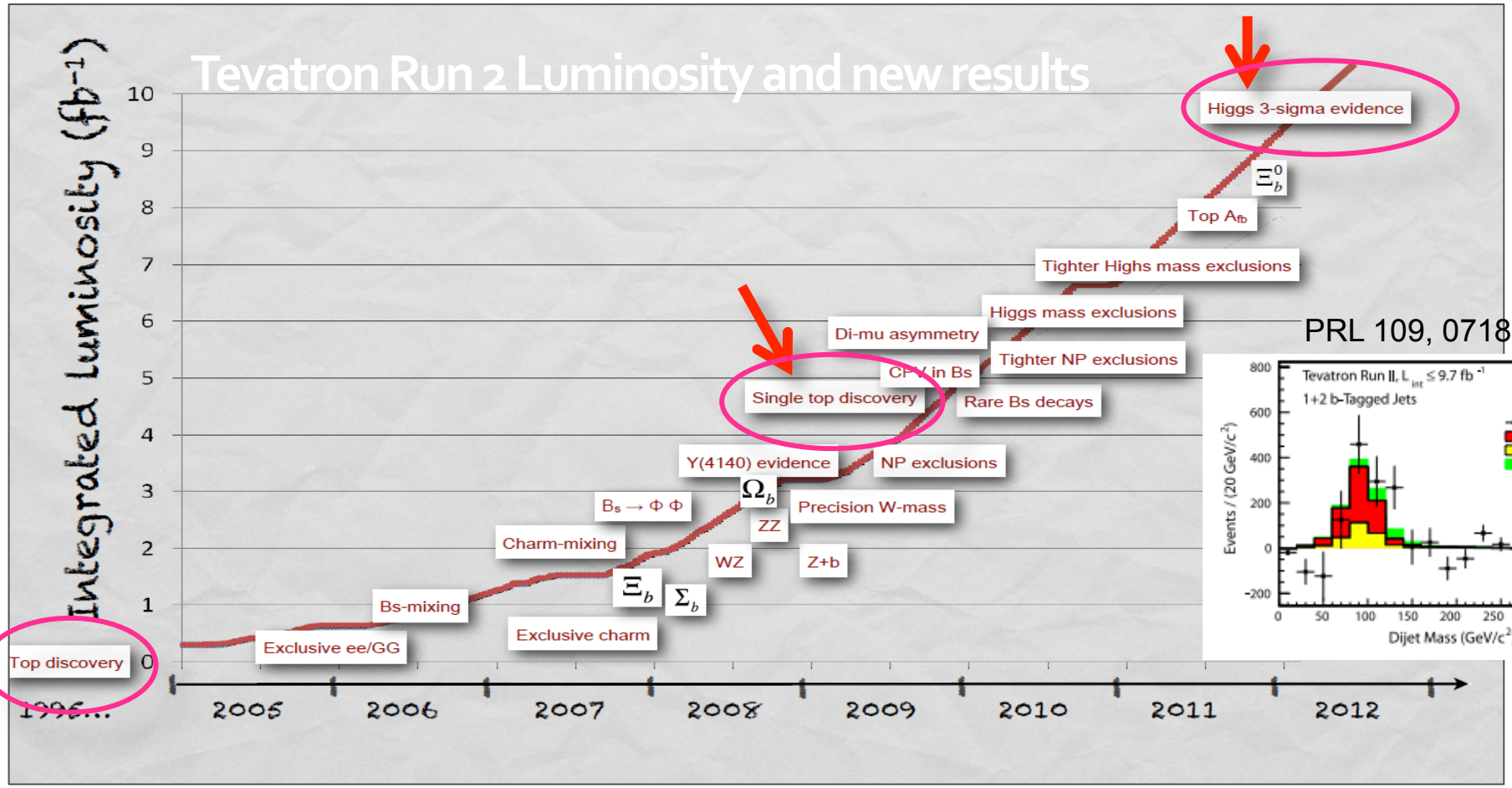
NEWS OF THE WEEK | HIGH-ENERGY PHYSICS

Higgs or Bust? Fermilab Weighs Adding 3 Years to Tevatron Run (beyond 2011)

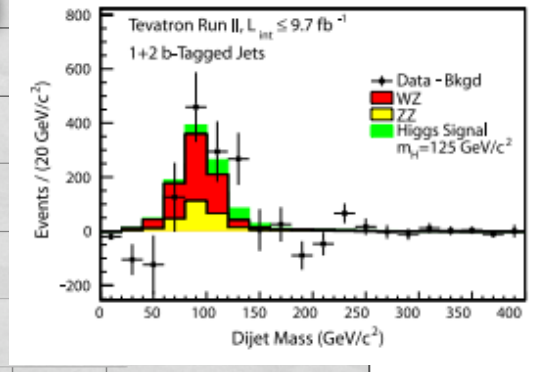
Adrian Cho
+ See all authors and affiliations

Science 10 Sep 2010:

Beyond the Top Discovery @Fermilab

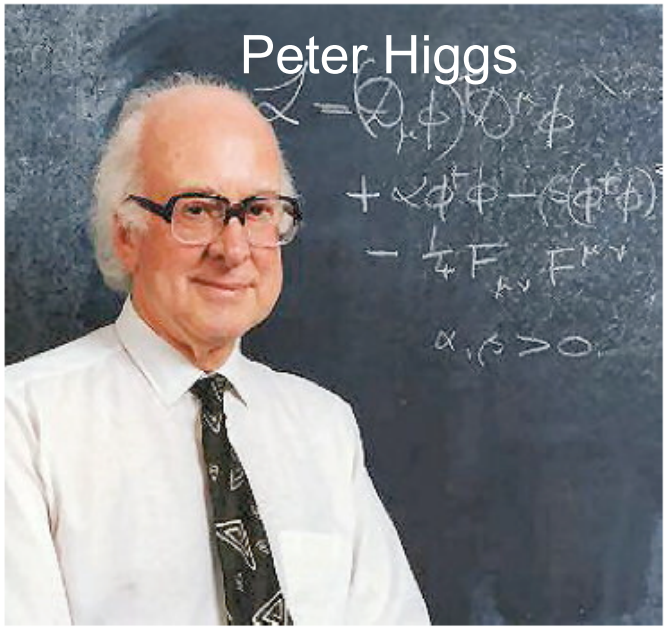


PRL 109, 071804 (2012)



- **Tevatron was shut down on September 30, 2011. ☹ A golden era ends.**
- **CDF and DØ had seen hints of Higgs in Run 2 and announced evidence for Higgs between masses of 120 and 135 GeV in July 2012.**

Higgs Theorists



Peter Higgs

Tom Kibble, Gerald Guralnik, Carl Hagen, Francois Englert, Robert Brout

The Higgs mechanism was proposed and the theory developed around 1964.

The Higgs Mechanism

How Higgs boson manifests

How particles get mass moving in the Higgs field

Well before the LHC

The SSC

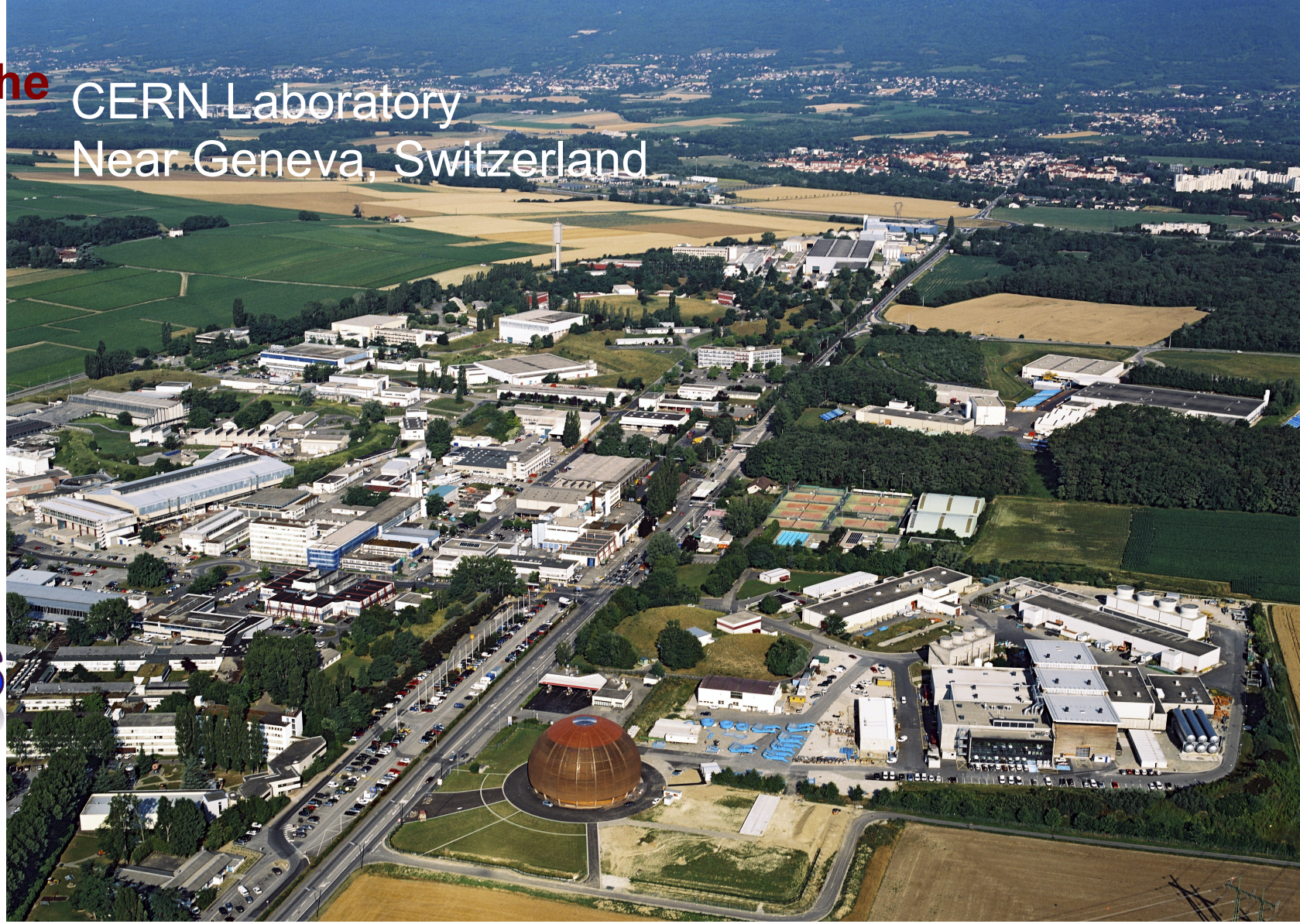
A Superconducting Super Collider was proposed to be built in Waxahachie, Texas, for the purpose of discovering the Higgs Boson

Endorsed and initiated in 1983
23.5 km of the 87 km tunnel bored.

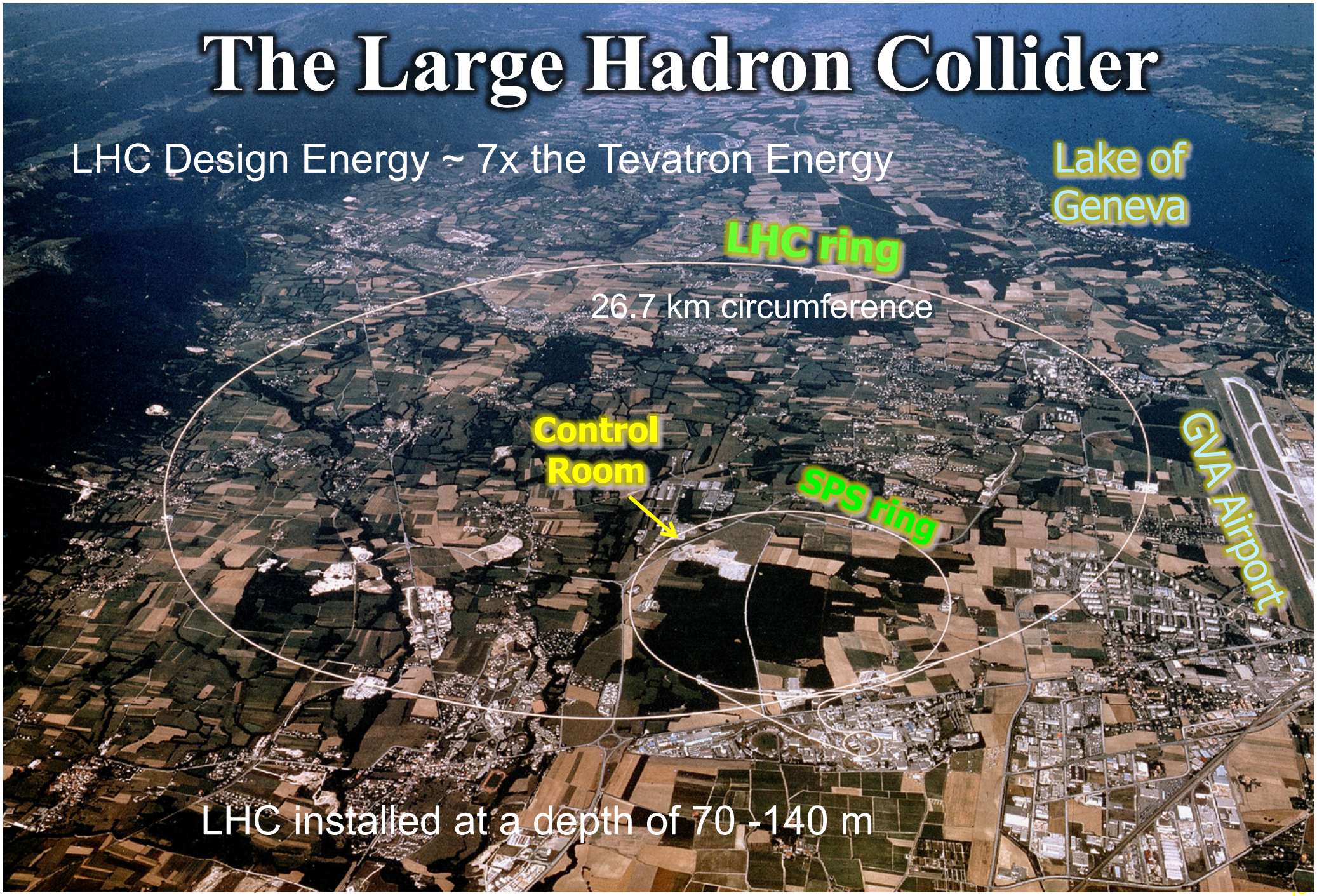
Cancelled by Congress in 1993

Torch from the Tevatron passed on to the LHC

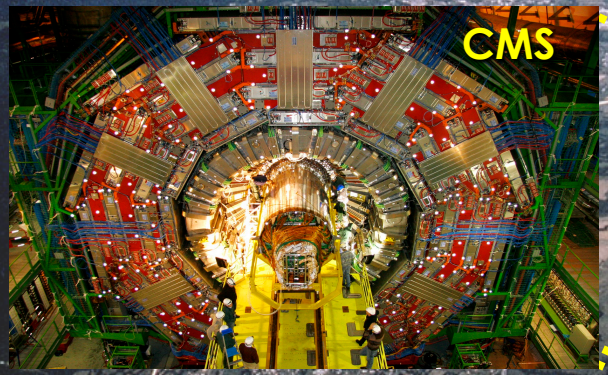
2008 THE LHC ERA BEGINS



Courtesy CERN


The Large Hadron Collider
LHC Design Energy ~ 7x the Tevatron Energy
Lake of Geneva
LHC ring
26.7 km circumference
Control Room
SPS ring
GVA Airport
LHC installed at a depth of 70 -140 m

The Large Hadron Collider

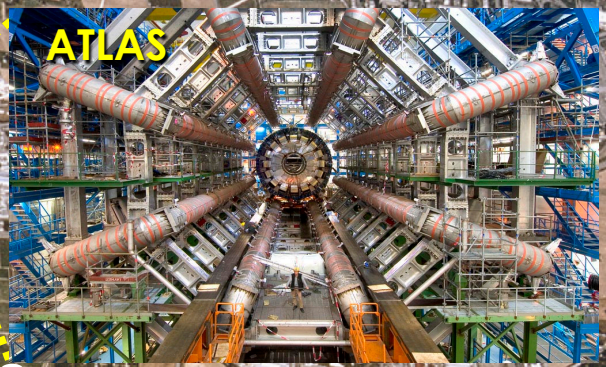


LHC ring

26.7 km circumference

Control Room

SPS ring



Beams circulate 11,245 times/sec
100 million collisions/sec in CMS, ATLAS

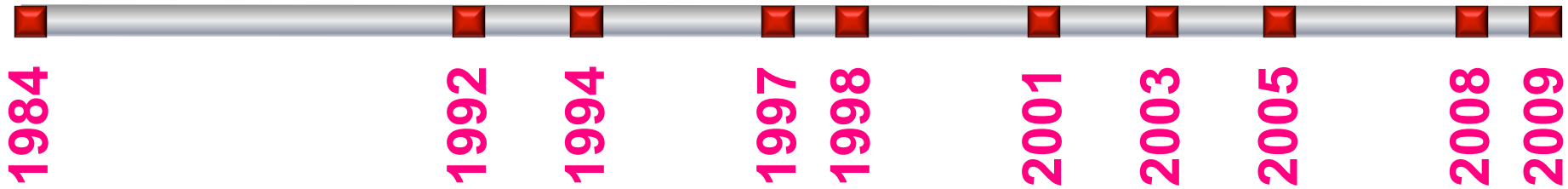
51

The Large Hadron Collider

A scientific & technological marvel!

- ~ 27 km circumference
- >10,000 Magnets
- Largest cryogenic system in the world
- Magnets cooled by superfluid helium to 1.9°K (523°F below RT

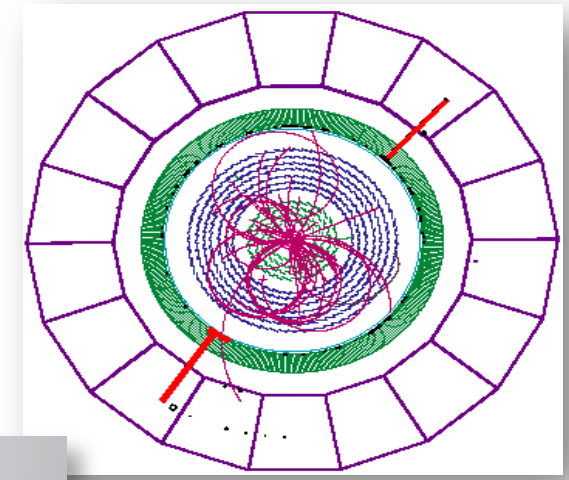
LHC Timeline

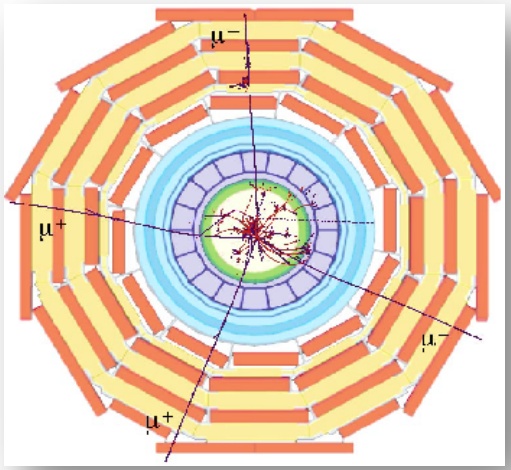


- 1984: Proposal
- 1992: Concepts for experiments
- 1994: CERN Council approval
- 1997: US Joins
- 1998: Construction begins
- 2001: LHC Computing Grid approved

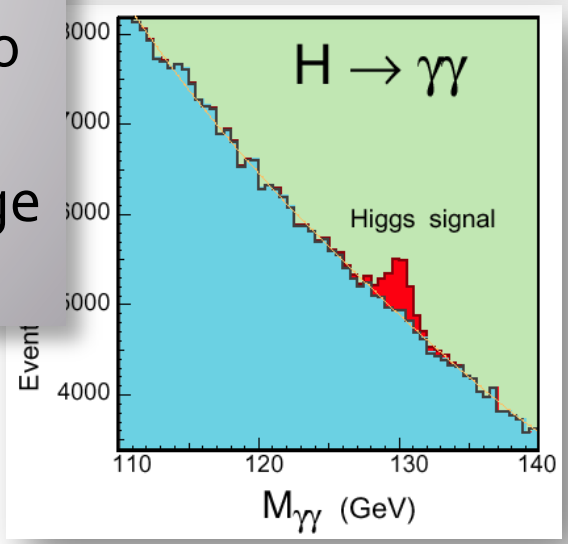
- 2003: ATLAS Construction begins
- 2005: CMS construction begins
- 2008: First beams in the LHC
- 2009: Restart
- 2010: First 7 TeV collisions (Highest on the Planet)

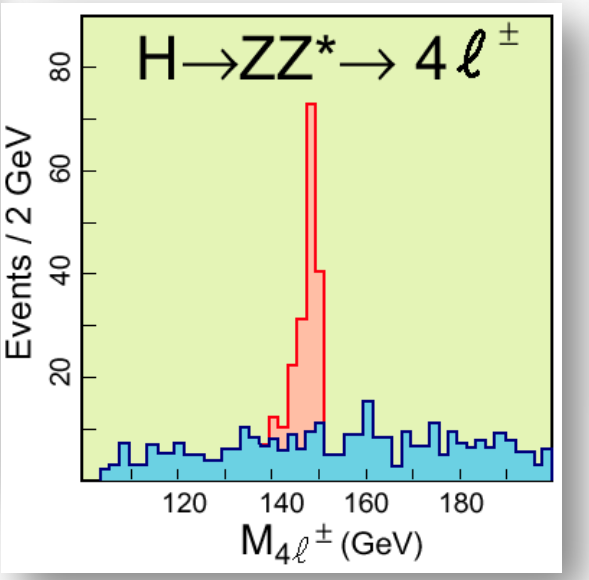
How would we *see* the Higgs Boson ?



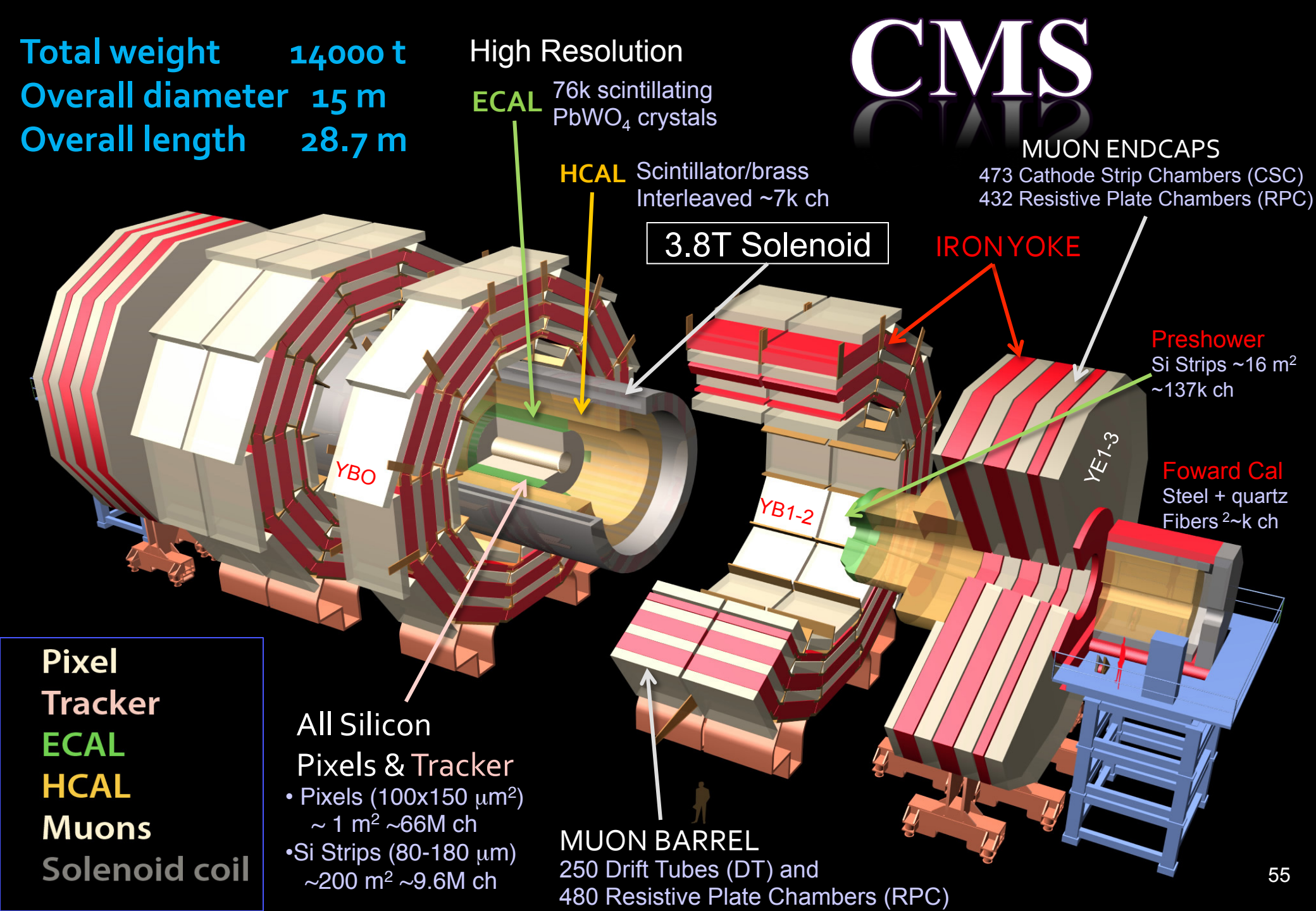


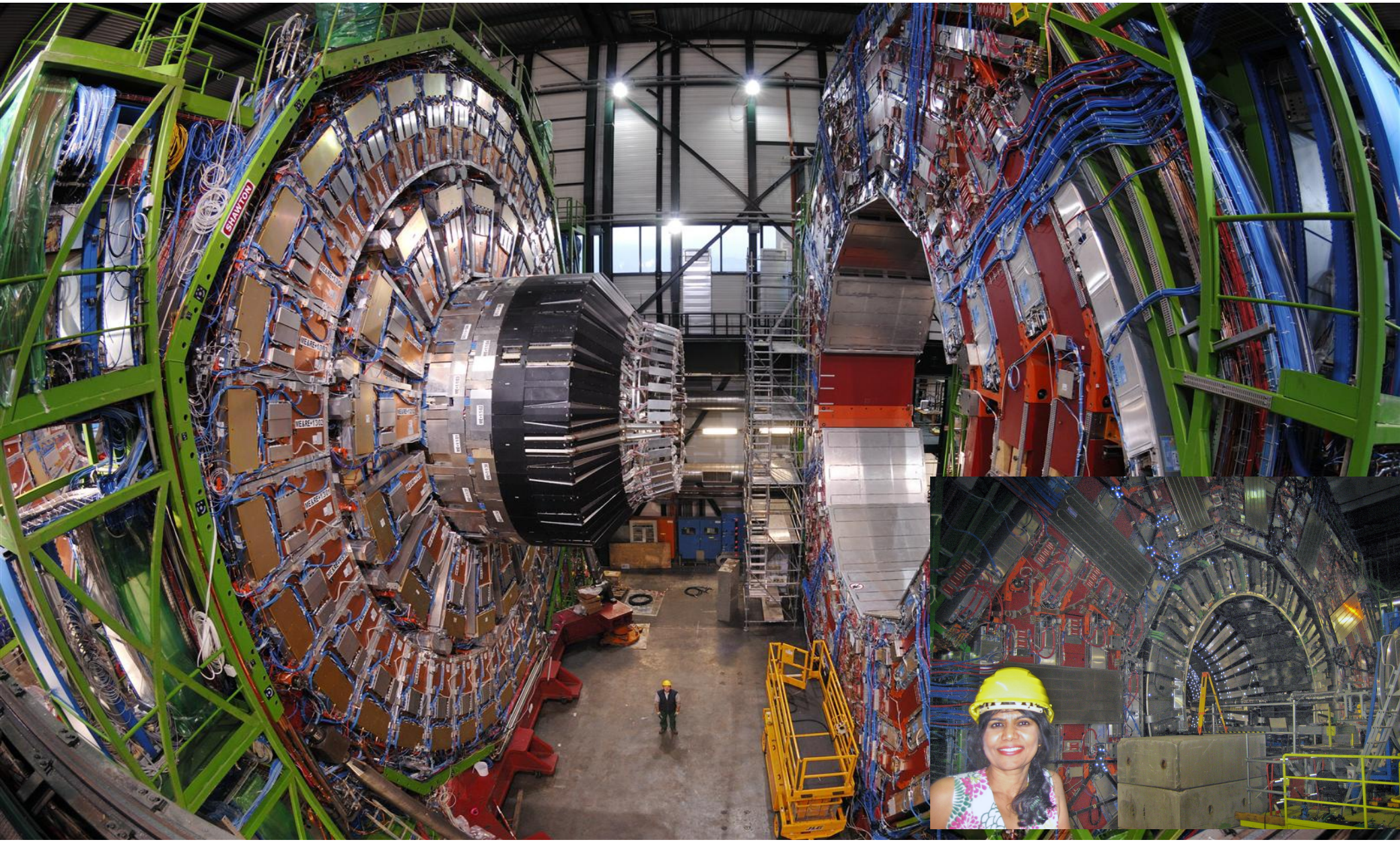
Simulated data for Higgs m~130 decaying to γγ and various large backgrounds



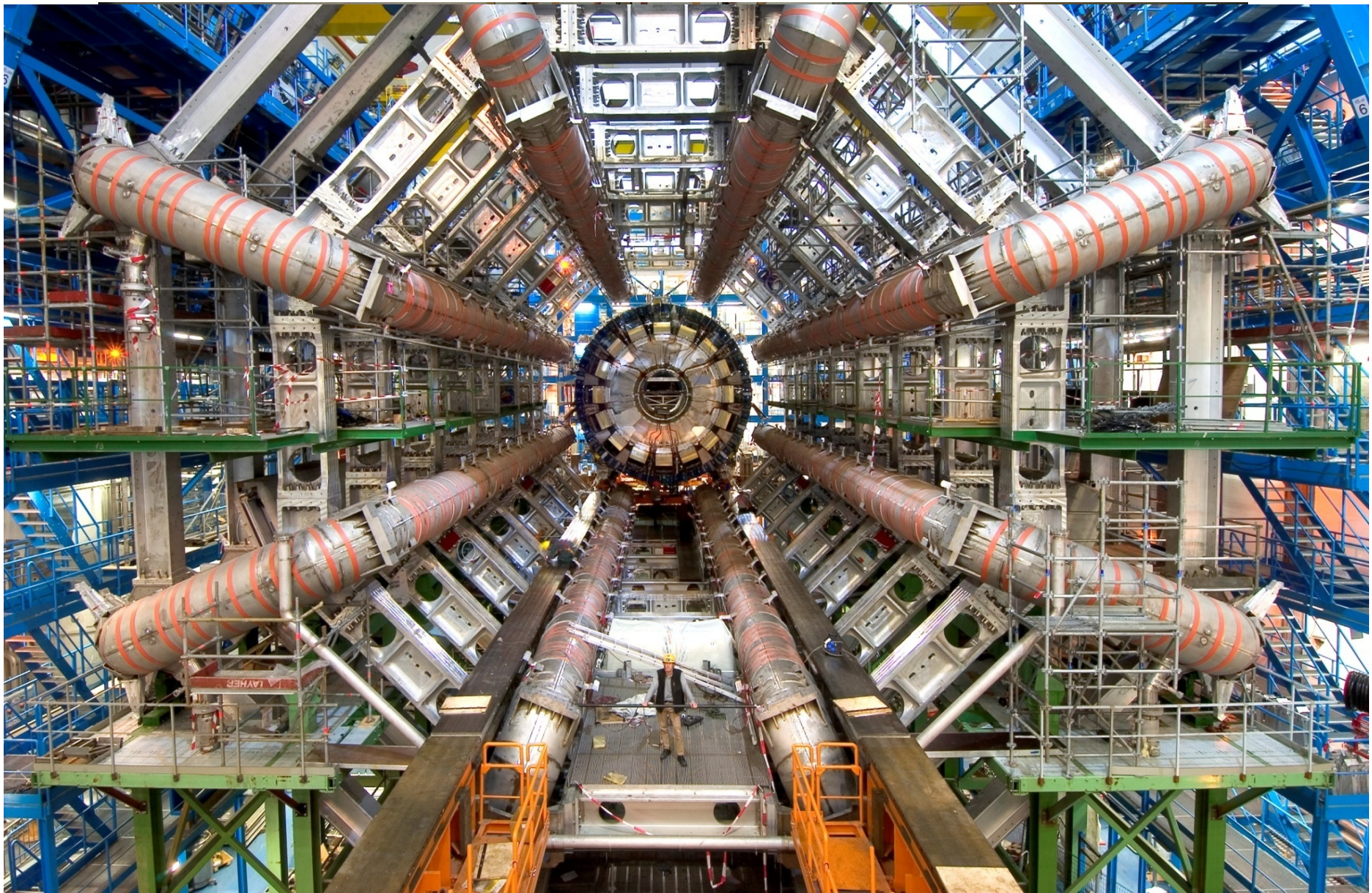


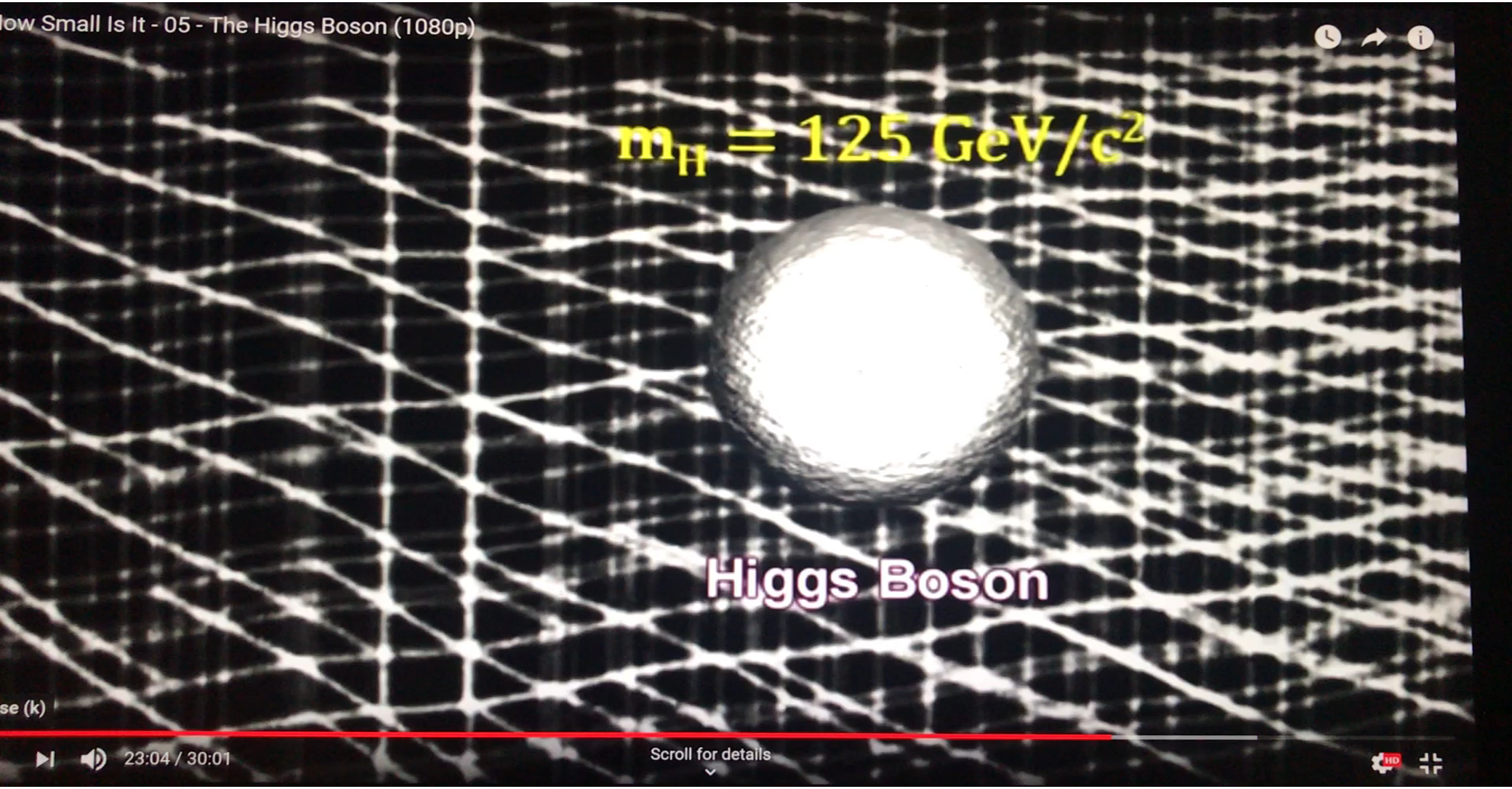
Simulated data for Higgs m~145 decaying to ZZ to 4 leptons with various sm backgrounds


Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
High Resolution
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass Interleaved ~7k ch
CMS
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
3.8T Solenoid
IRON YOKE
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers ²~k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
All Silicon
Pixels & Tracker
• Pixels (100x150 μm²)
~ 1 m² ~66M ch
•Si Strips (80-180 μm)
~200 m² ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

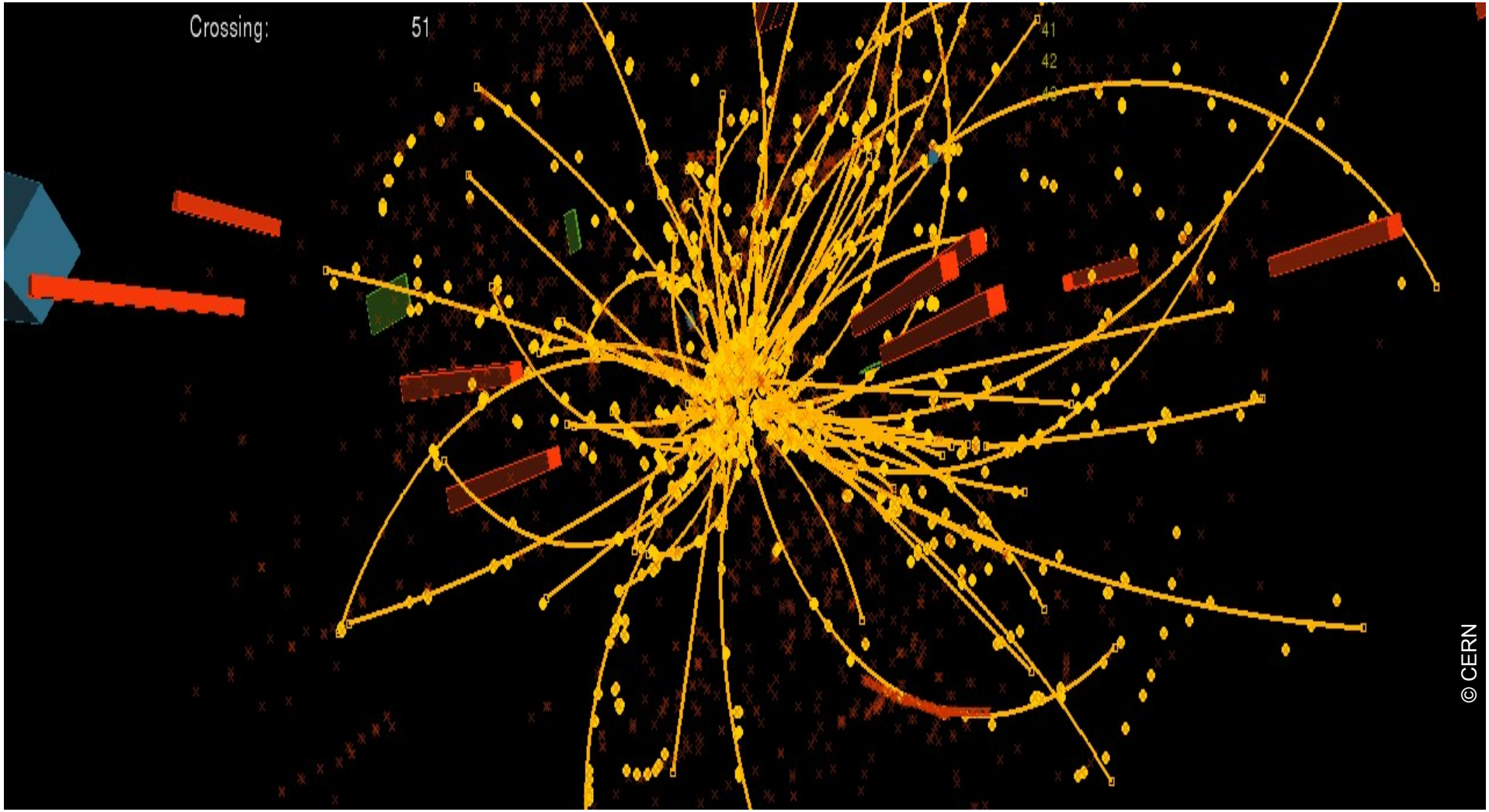


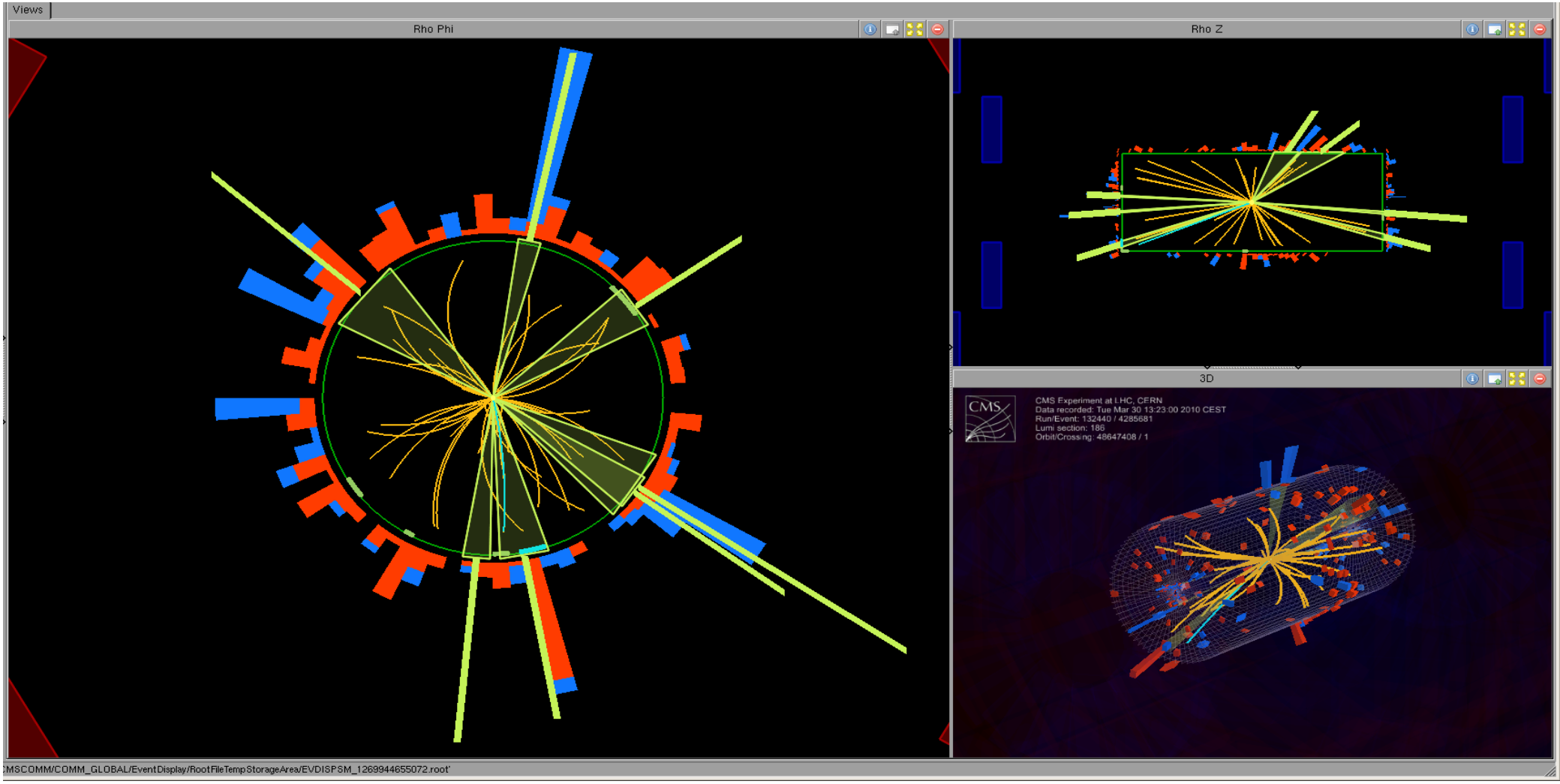
The ATLAS Detector



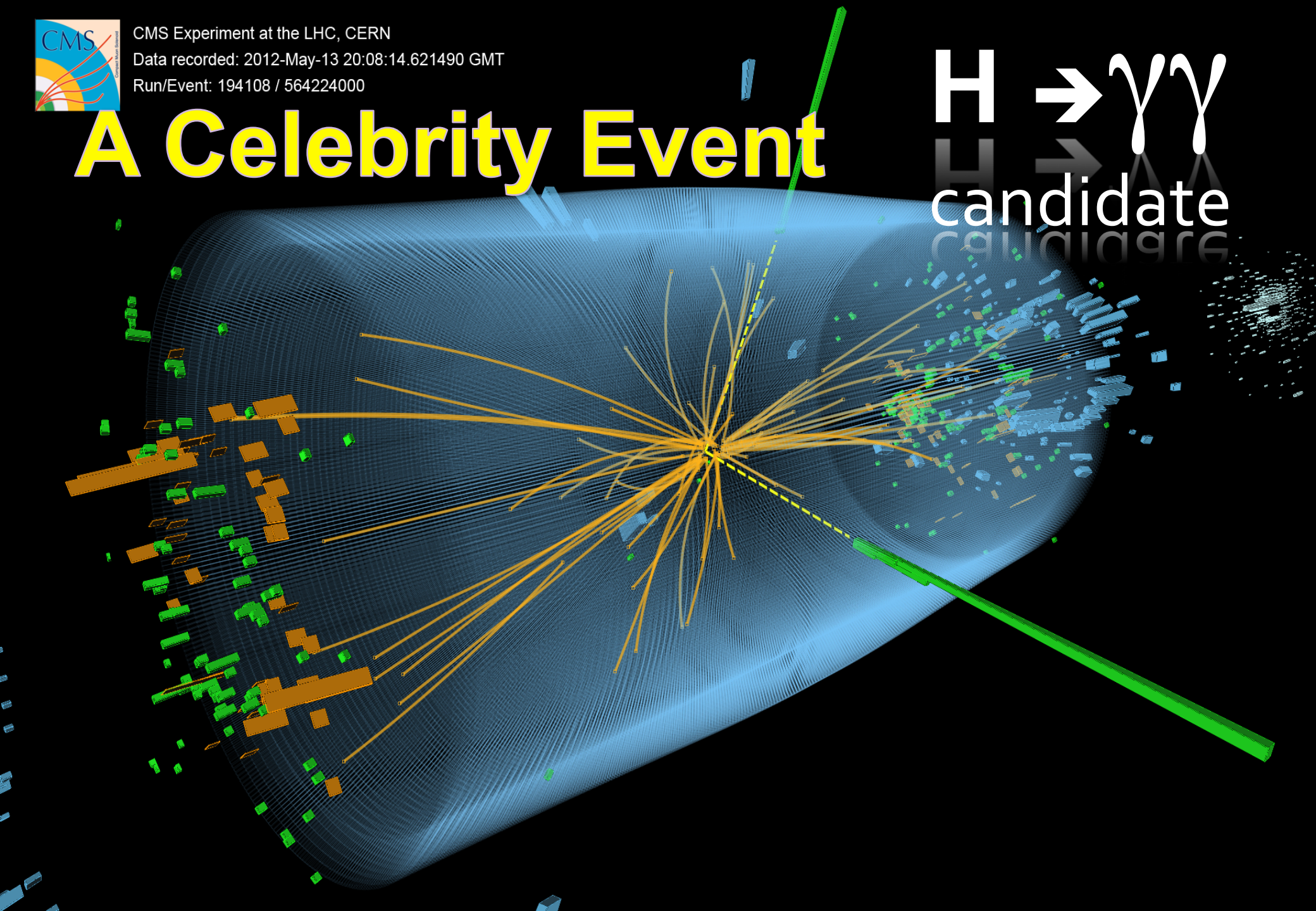

low Small Is It - 05 - The Higgs Boson (1080p)
$m_H \cong 125\ GeV/c^2$
Higgs Boson
se (k)
23:04 / 30:01
Scroll for details
HD

Colliding protons generate temperatures one billion times hotter than the center of the sun

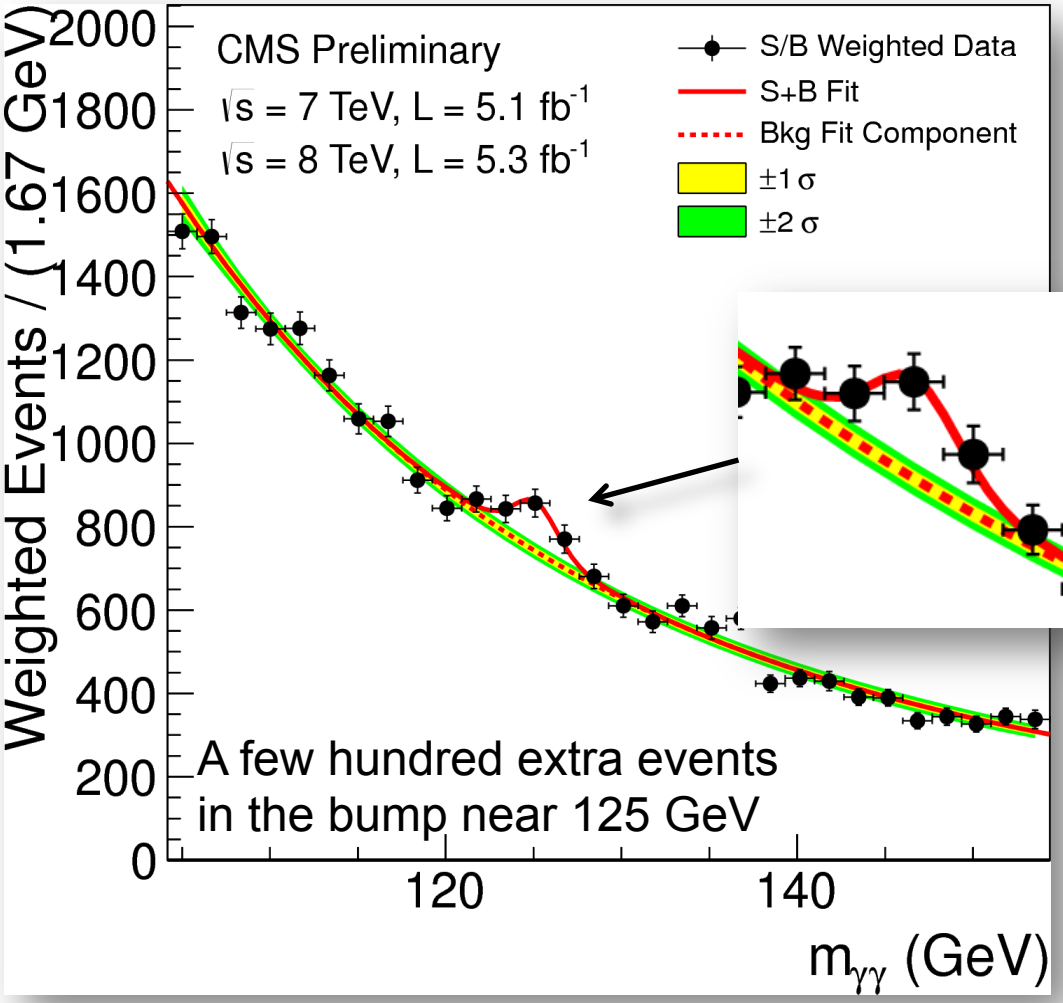




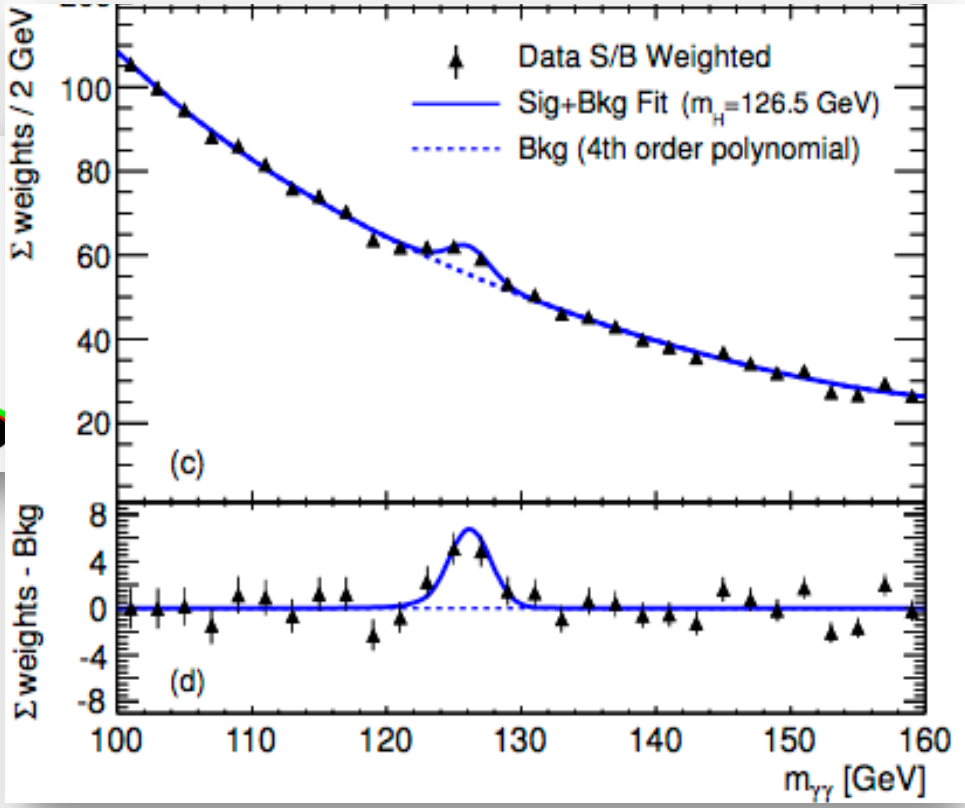
First 7 TeV collisions in CMS – 30 March 2010


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

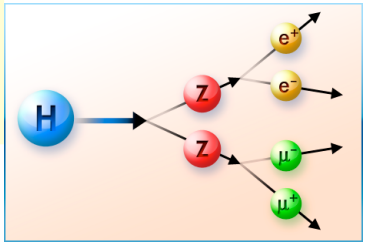
Di-photon ($\gamma\gamma$) Mass Distribution



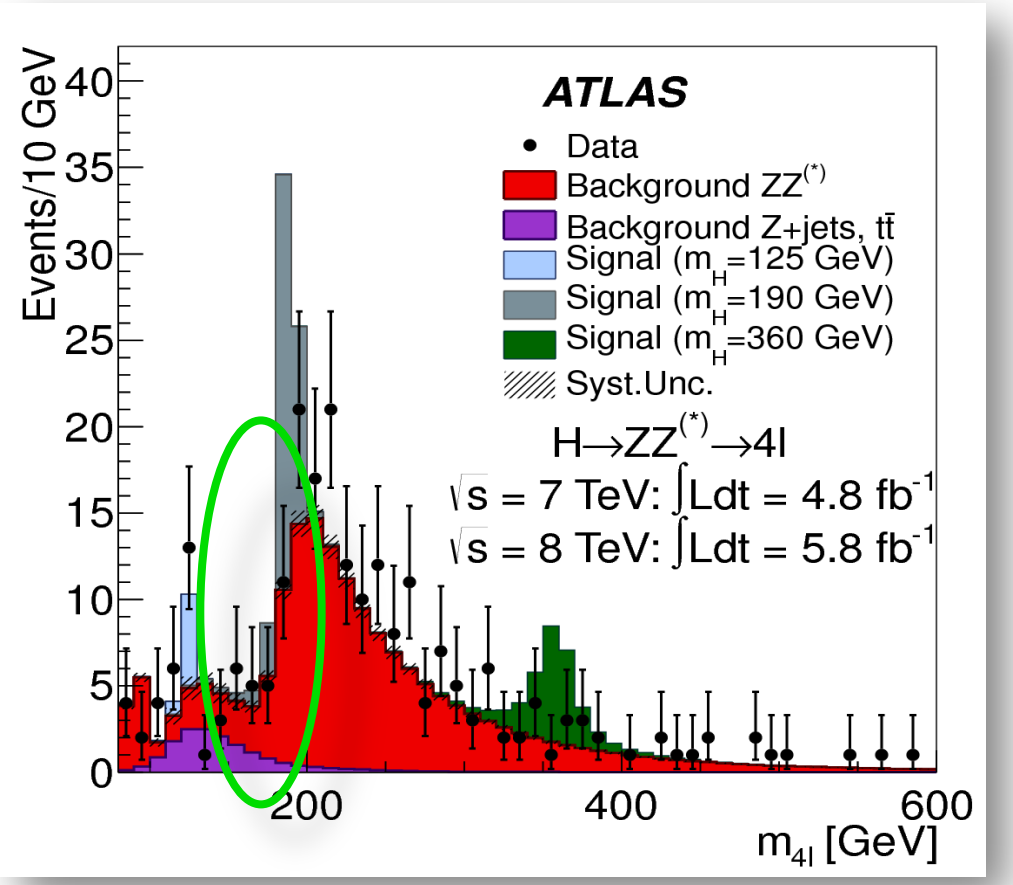
ATLAS $\gamma\gamma$

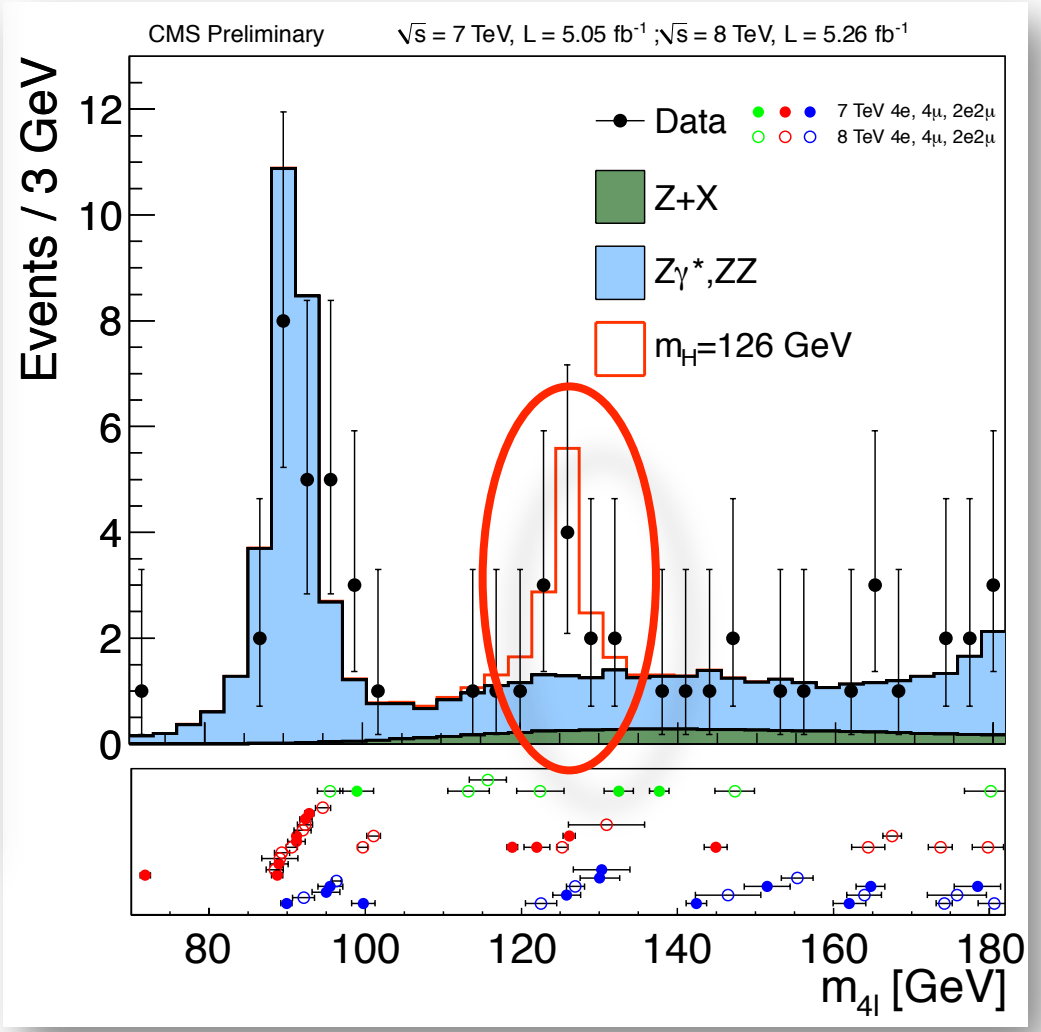


Data from ~10^{15} Collisions



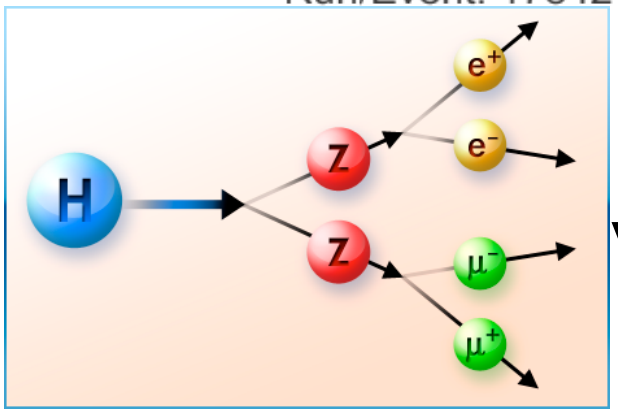
$H \rightarrow ZZ \rightarrow 4\ell$





H → ZZ → 4ℓ

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902



7 TeV DATA

4μ+γ Mass : 126.1 GeV

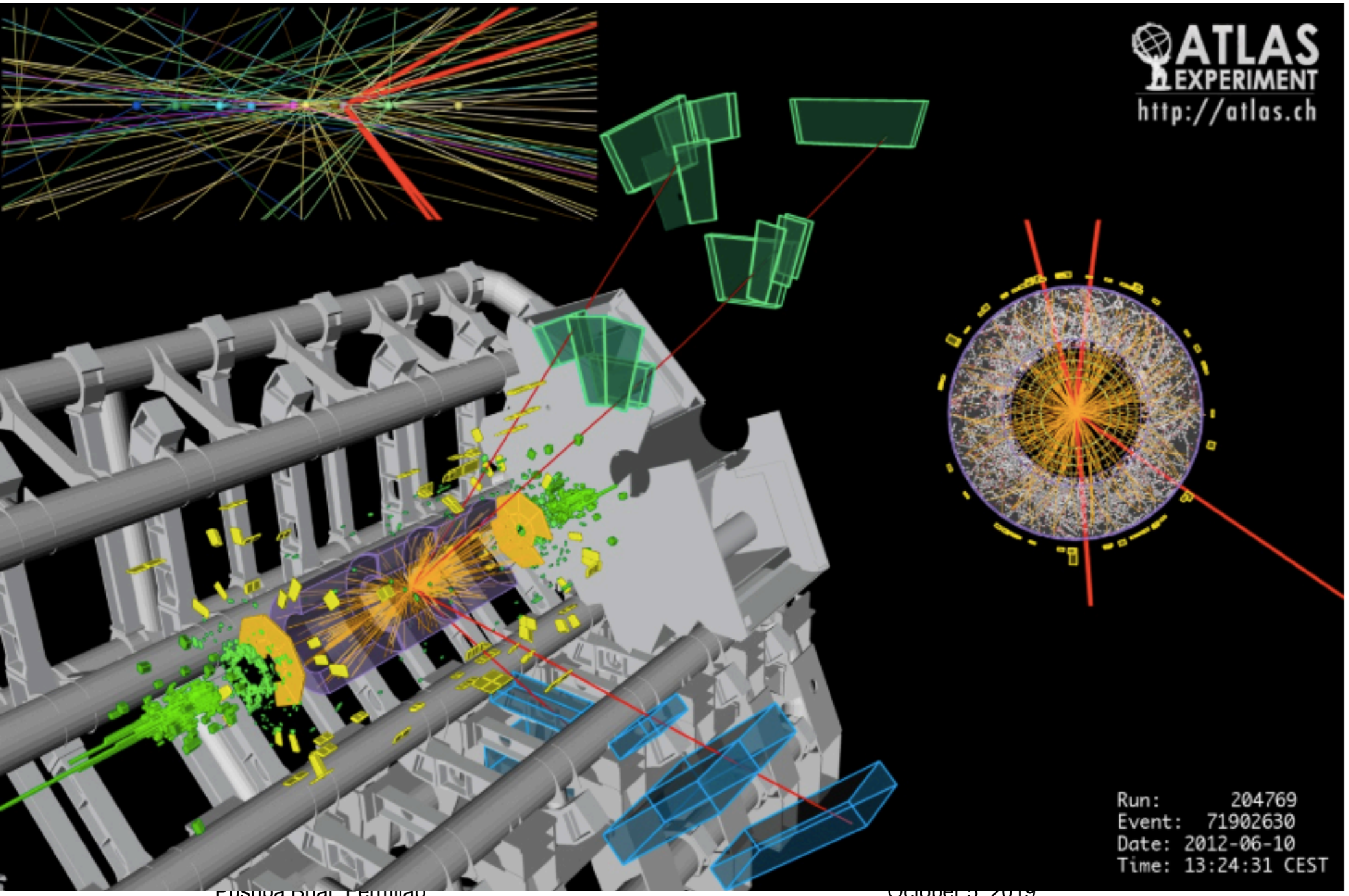
γ(Z_1) E_T : 8 GeV

$\mu^-(Z_1)$ p_T : 28 GeV

$\mu^-(Z_2)$ p_T : 14 GeV

$\mu^+(Z_2)$ p_T : 6 GeV

$\mu^+(Z_1)$ p_T : 67 GeV


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

CERN Auditorium July 4, 2012

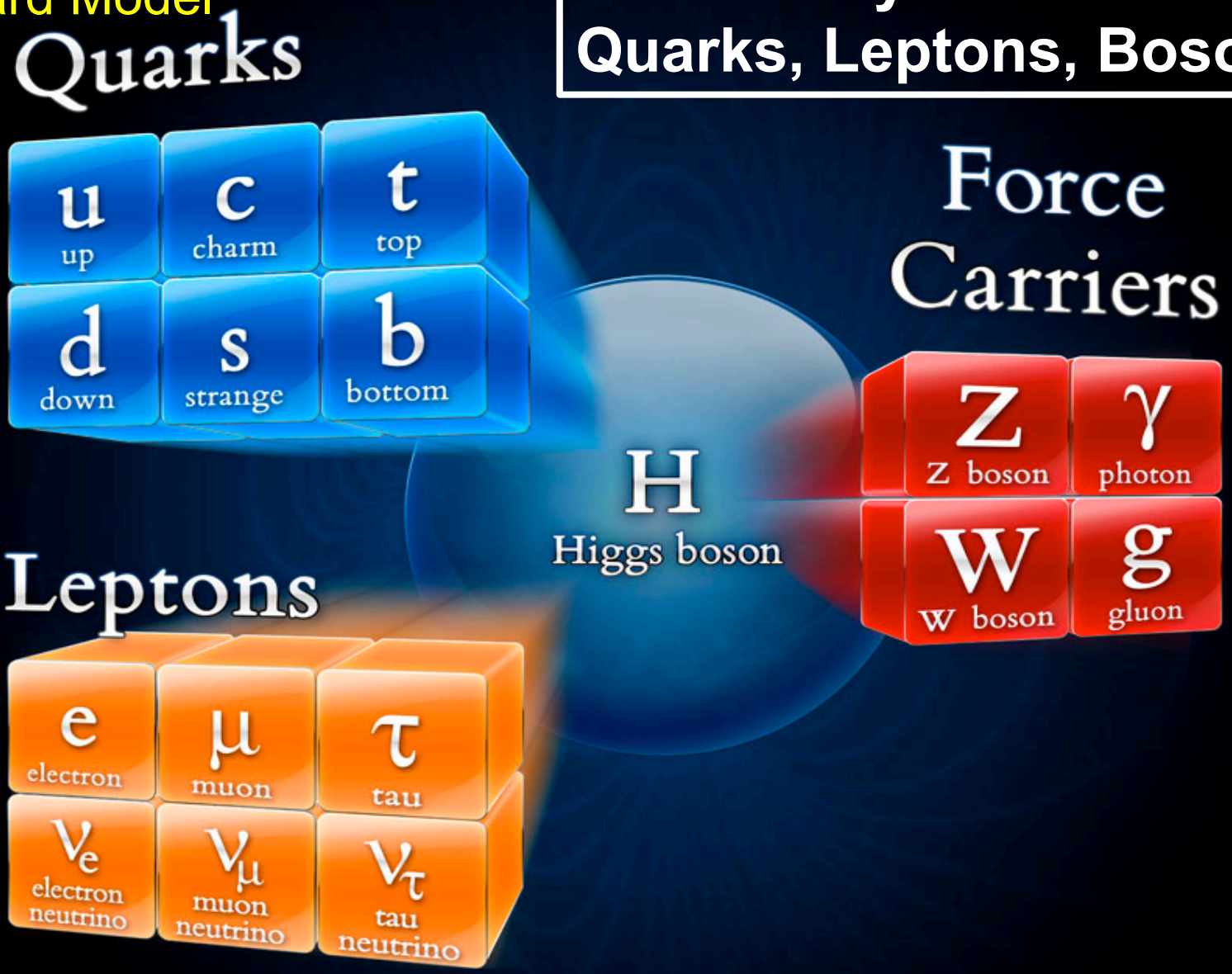
July 4, 2012
CERN

The Economist
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
JULY 7TH–13TH 2012
Economist.com
A giant leap for science
Finding the Higgs boson

Science
21 December 2012 | $10
BREAKTHROUGH of the YEAR
The HIGGS BOSON
AAAS

The Triumphant Standard Model

Elementary Particles: Quarks, Leptons, Bosons

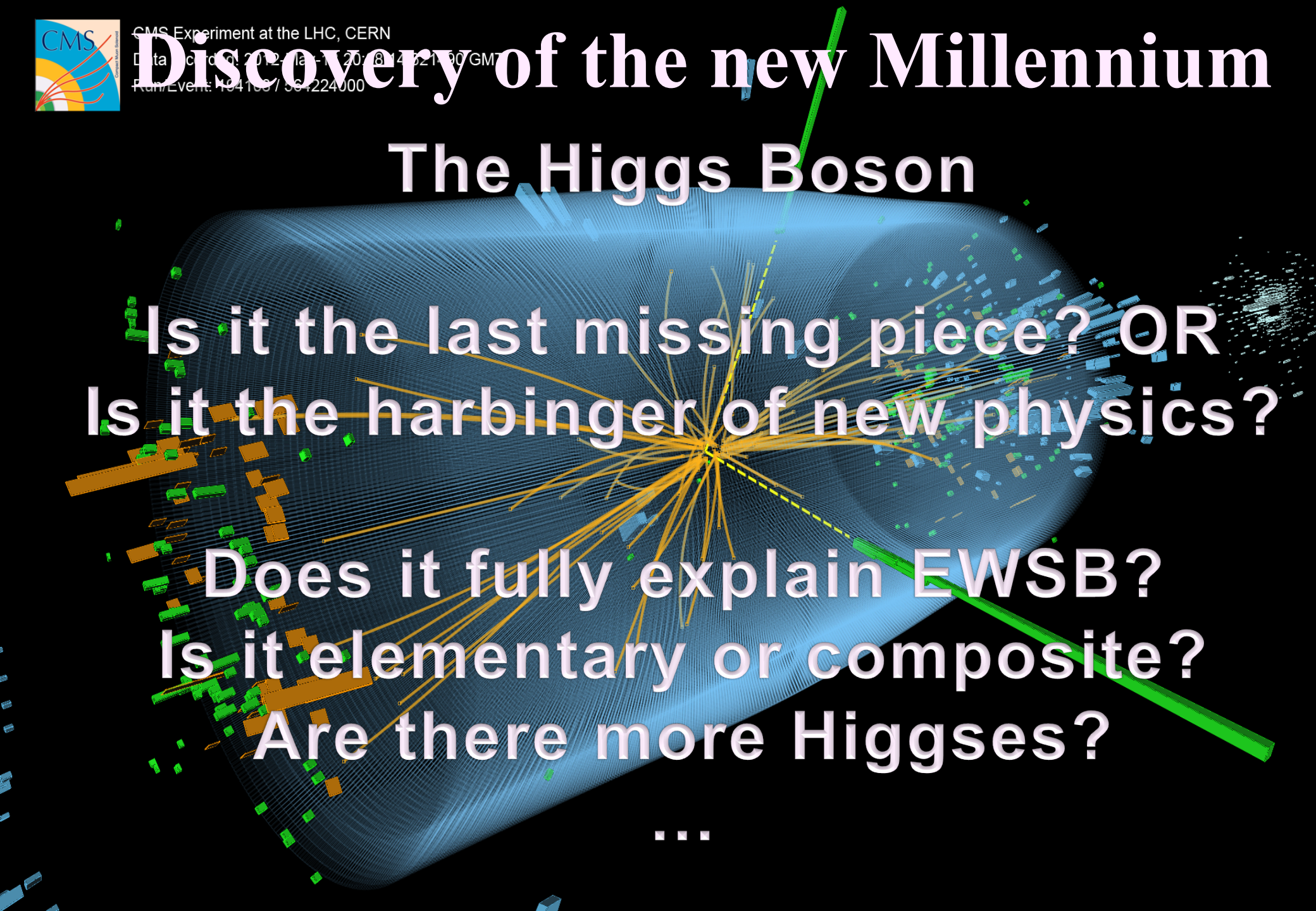


Englert & Higgs win the Nobel Prize

Announcement: October 8, 2013

"*for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider*"

Higgs Boson Celebrated on Capitol Hill
November 20, 2013


CMS Experiment at the LHC, CERN
Data Recorded: 2012-Jul-1 20:18:14.621900 GMT
Run/Event: 194108 / 364224000
Discovery of the new Millennium
The Higgs Boson
Is it the last missing piece? OR
Is it the harbinger of new physics?
Does it fully explain EWSB?
Is it elementary or composite?
Are there more Higgses?
...

Why is the Higgs Boson so special?

- The Higgs is central to our very existence!
- The Higgs gives masses to the heavy electroweak force carriers and to other fundamental matter particles.
- Without the Higgs field, electron, for example, will be massless, and so atoms cannot form, therefore no chemical bonds, no chemistry, and so no life forms.
- The Higgs field is also very special and unique! It is a scalar field, i.e., has only a value at every point in space but no direction. Higgs boson is the only scalar fundamental particle (spin=0) that we know.

What's Next?

- The LHC is being upgraded for higher luminosity to produce 100x more data than we had for the Higgs discovery.

- An **electron-positron collider** (**a Higgs Factory**) for making precision measurements of the Higgs Boson properties is critical for the field.

- A **Very Large Hadron Collider** at ~100 TeV would be awesome!

Global Competition for the Future Machine

- CERN (Europe) has an ongoing effort to plan building the next large collider, a Future Circular Collider (FCC): first e^+e^- (90 GeV – 350 GeV) and then pp collider at 100 TeV
- Japan has proposed to build an International Linear Collider (ILC), an e^+e^- machine ($\sqrt{s}$ = 0.5 TeV, 1 TeV)
- China is preparing to build circular collider in 50 – 100 km ring, first an e^+e^- (CEPC) and then a pp (SPPC)

- What about the US?

Building for Discovery

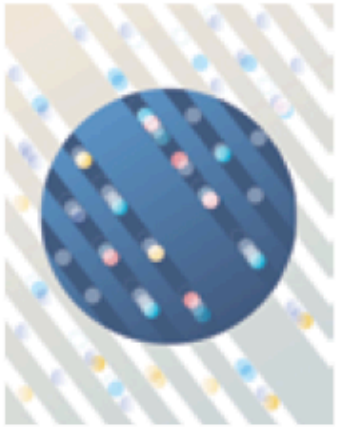
Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

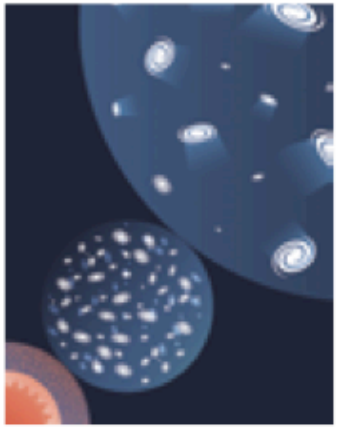
- Use the Higgs boson as a new tool for discovery ← LHC, HL-LHC
- Pursue the physics associated with neutrino mass ← LBNF and other neutrino program
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

Higgs boson



Neutrino mass

Dark matter



Cosmic acceleration

Explore the unknown

Summary

- The race for the Top Quark and pursuit of the Higgs boson, particularly at Fermilab and CERN, had been breathtaking and their discoveries monumental.
- The saga of elementary particles that began at the turn of the 20th century culminated in the development of the Standard Model and the discovery of all it particles about a century later.
- The Standard Model (SM) of Particle Physics is one of mankind's magnificent intellectual achievements!
- New physics beyond the SM to solve many other mysteries such as the hierarchy problem, neutrino masses/mixing, and to explain dark matter, baryon asymmetry in the universe, etc.
- We are working towards the next big machine -- an e^+e^- Higgs Factory and/or a 100 TeV pp collider or a $\mu^+\mu^-$ collider.

Back-up

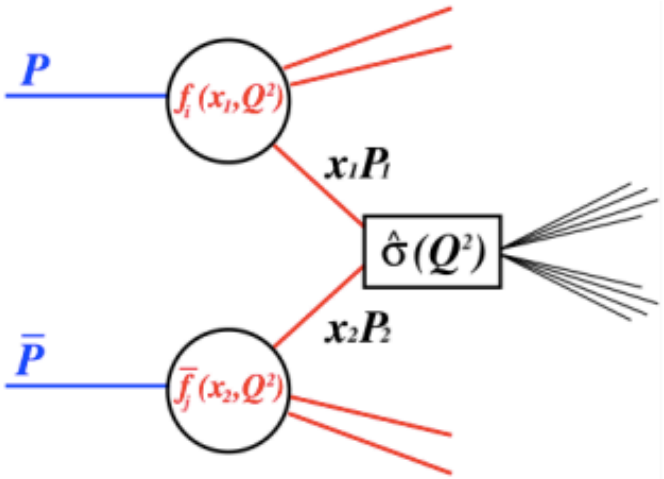
Particle discoveries

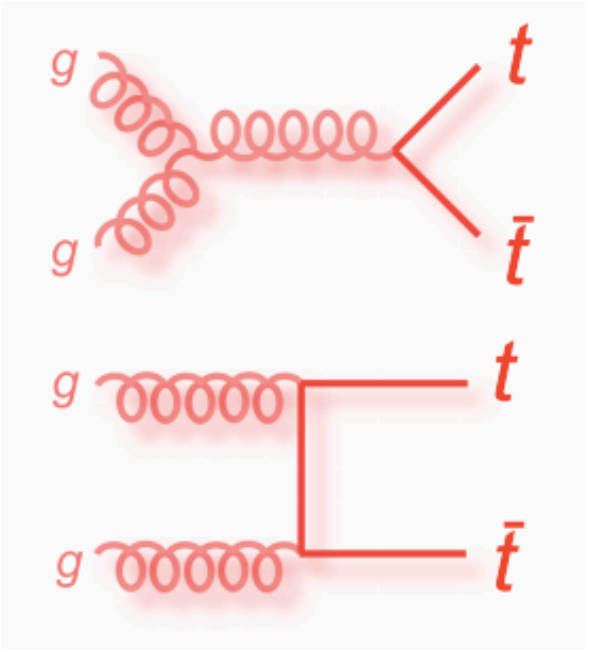
- Electron 1897, Thompson
- Nucleus, 1911, Rutherford
- Model of the modern atom, 1913, Bohr
- Proton 1919, Neutron 1932
- Muon 1937
- Strange particles 1949
- Charm: The November Revolution, 1974
- Tau lepton, 1975, SPEAR/SLAC
- Beauty/Bottom quark, 1977, Fermilab
- W & Z, 1983, CERN (UA1, UA2)
- Top quark, 1995, Fermilab
- Tau neutrino, 2000, Fermilab
- Higgs boson, 2012, CERN

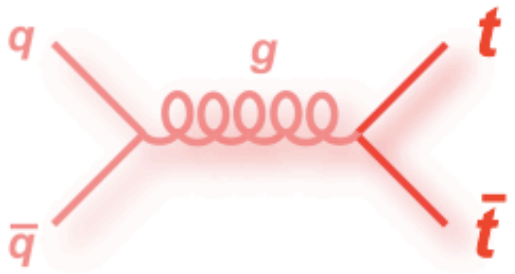
Top Quark Searches Timeline

Year	Collider	Particles	References	Limit on m_t
1979-84	PETRA (DESY)	e^+e^-	[45]-[58]	$> 23.3\ \mathrm{GeV/c^2}$
1987-90	TRISTAN (KEK)	e^+e^-	[59]-[63]	$> 30.2\ \mathrm{GeV/c^2}$
1989-90	SLC (SLAC), LEP (CERN)	e^+e^-	[64]-[67]	$> 45.8\ \mathrm{GeV/c^2}$
1984	SpS̄pS (CERN)	$p\bar{p}$	[70]	$> 45.0\ \mathrm{GeV/c^2}$
1990	SpS̄pS (CERN)	$p\bar{p}$	[71, 72]	$> 69\ \mathrm{GeV/c^2}$
1991	TEVATRON (FNAL)	$p\bar{p}$	[73]-[75]	$> 77\ \mathrm{GeV/c^2}$
1992	TEVATRON (FNAL)	$p\bar{p}$	[76, 77]	$> 91\ \mathrm{GeV/c^2}$
1994	TEVATRON (FNAL)	$p\bar{p}$	[79, 80]	$> 131\ \mathrm{GeV/c^2}$
1995	TEVATRON (FNAL)	$p\bar{p}$	[37]	$= 174 \pm 10^{+13}_{-12}\ \mathrm{GeV/c^2}$
			[38]	$= 199^{+19}_{-21} \pm 22\ \mathrm{GeV/c^2}$

Top Quark Production



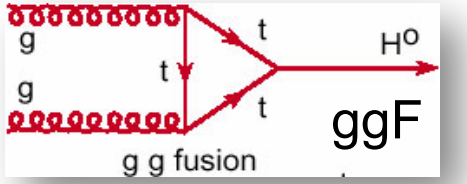


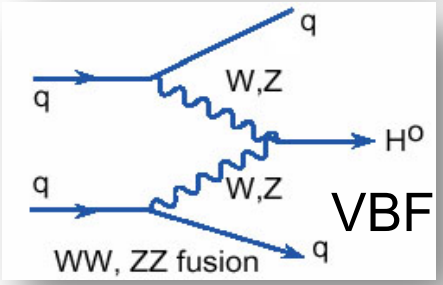


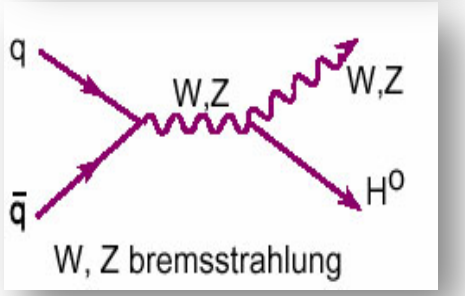
$$\sigma^{t\bar{t}}(\sqrt{s}, m_t) = \sum_{i,j=q,\bar{q},g} \int dx_i\, dx_j\, f_i(x_i,\mu^2) \cdot \bar{f}_j(x_j,\mu^2) \cdot \hat{\sigma}^{ij\to t\bar{t}}\left(\rho, m_t^2, \alpha_s(\mu^2), \mu^2\right)$$

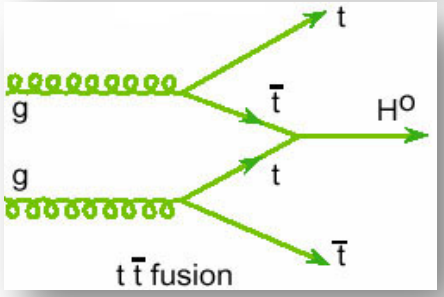
Higgs Production & Decay

Production

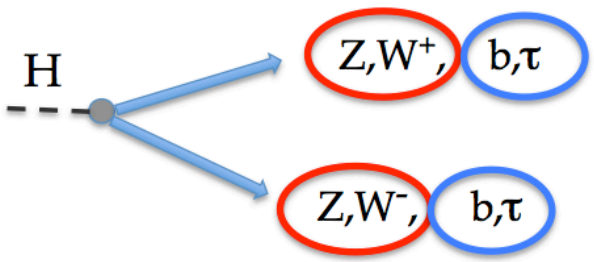


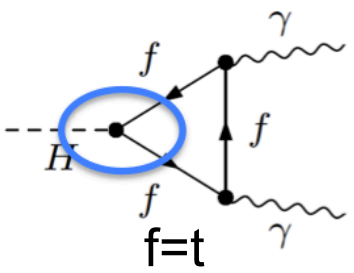


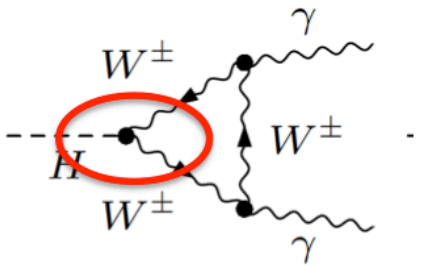




Decays







- Decay modes to be exploited: bb, ττ, WW, ZZ, γγ
- High (mass) resolution Channels:

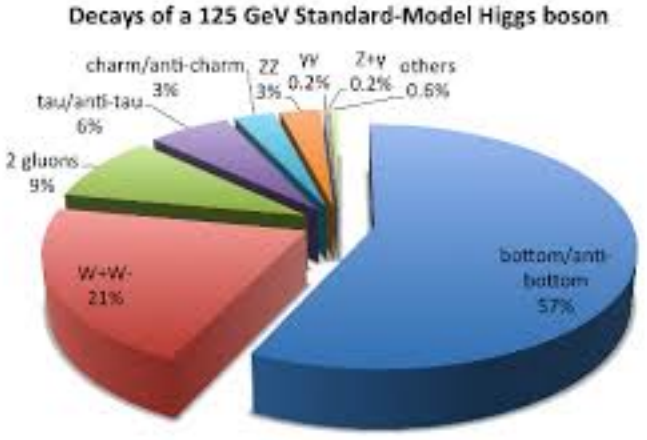
  H→γγ and H→ZZ→4l ← should see bumps in mass spectra

  Each Z decays to e+e- or μ+μ-

  so expect, 4e, 2e2μ or 4μ

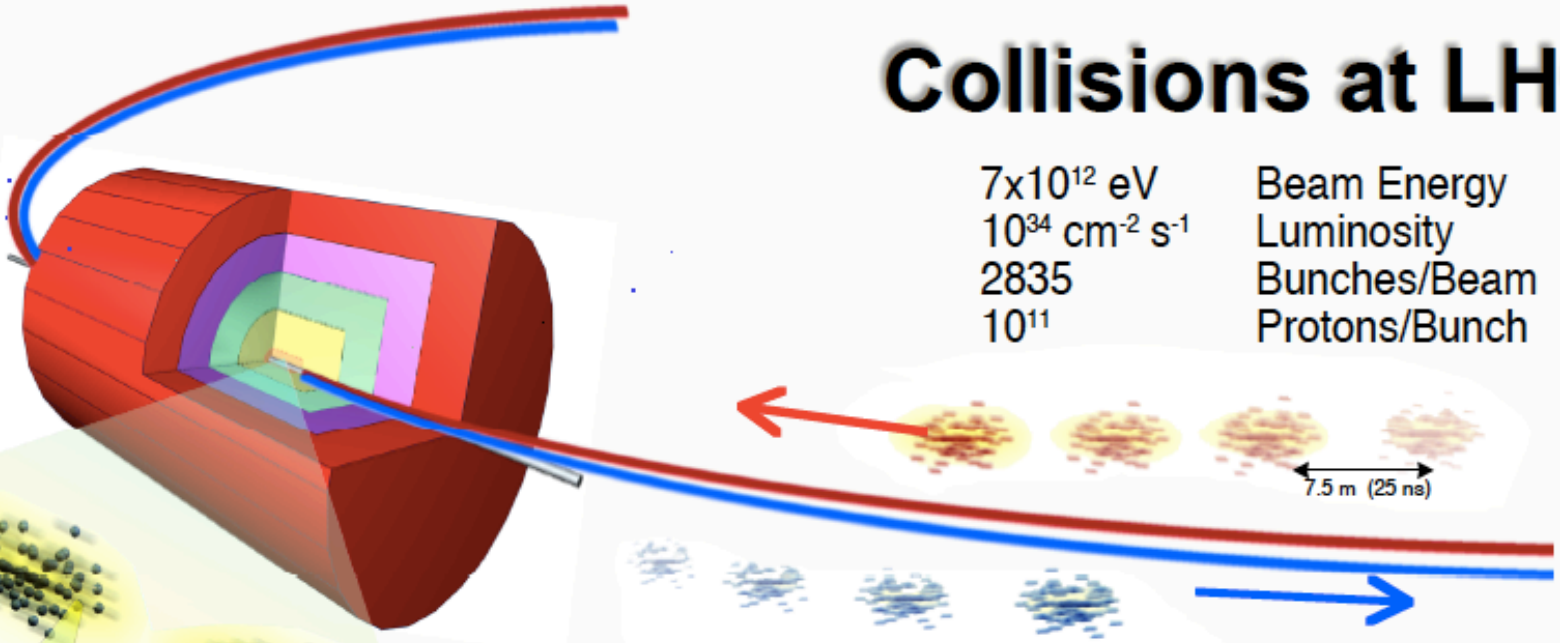
Decay branching fractions @ m_H = 125 GeV

$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.3%
$H \to ZZ^*$	2.6%
$H \to \gamma\gamma$	0.23%



Collisions at LHC

7×10^{12} eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch



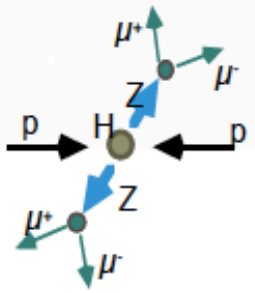
7 TeV Proton Proton
colliding beams

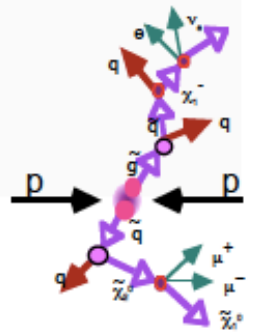
Bunch Crossing **4 10^{7} Hz**

Proton Collisions **10^{9} Hz**

Parton Collisions

New Particle Production **10^{-5} Hz**
(Higgs, SUSY, ...)

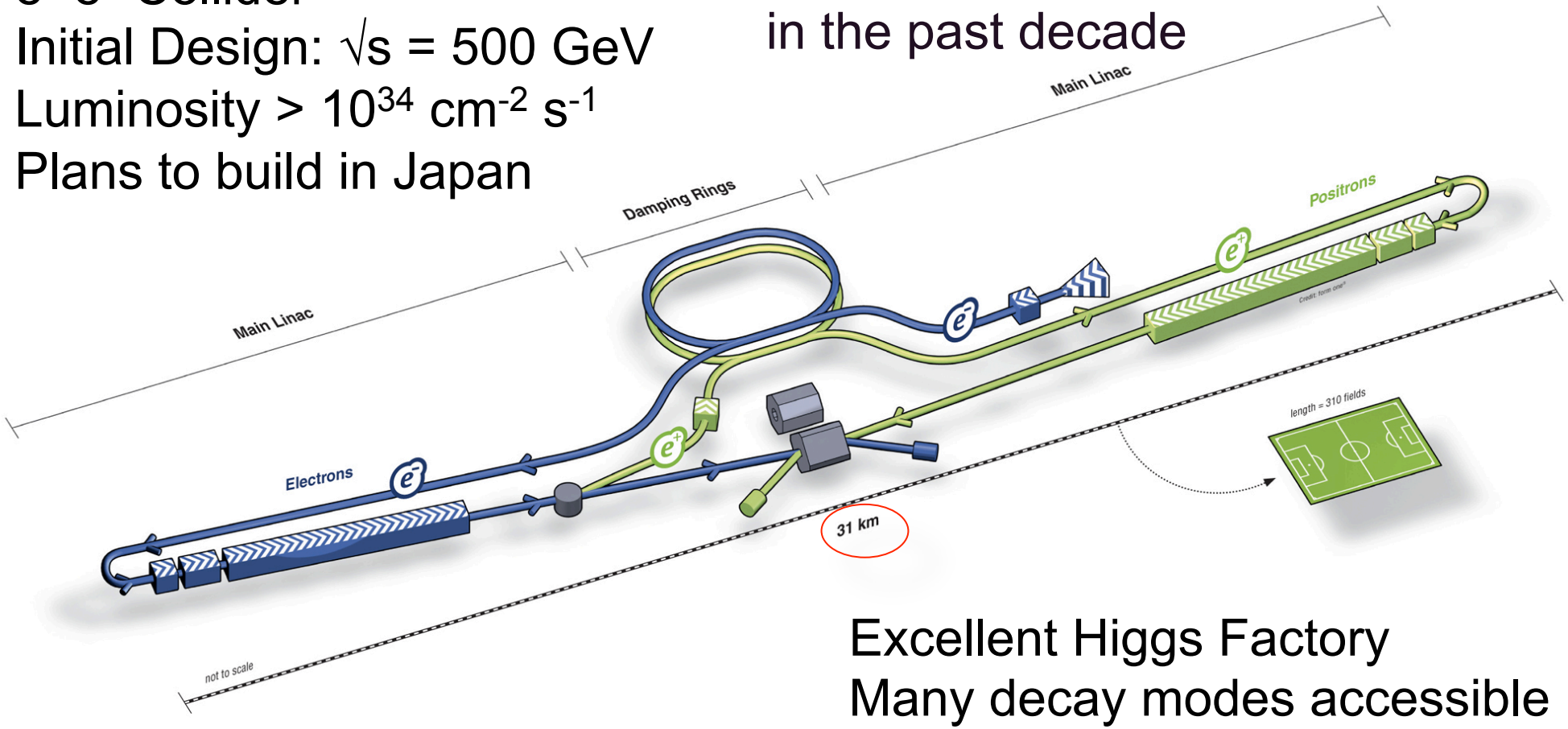




The International Linear Collider

e+e- Collider
Initial Design: $\sqrt{s}$ = 500 GeV
Luminosity > 10^{34} cm^{-2} s^{-1}
Plans to build in Japan

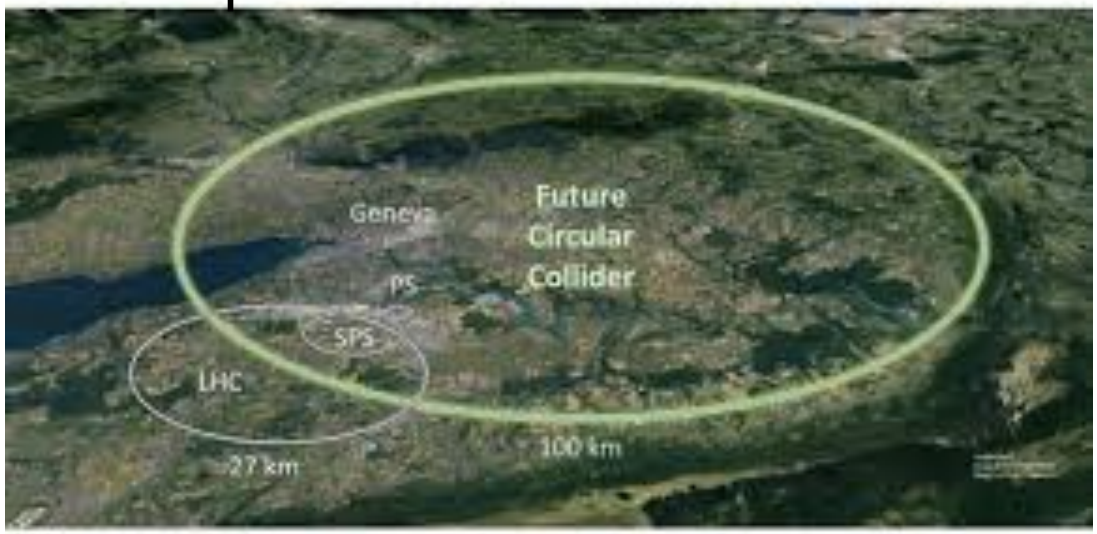
Global Design Effort led by the US in the past decade



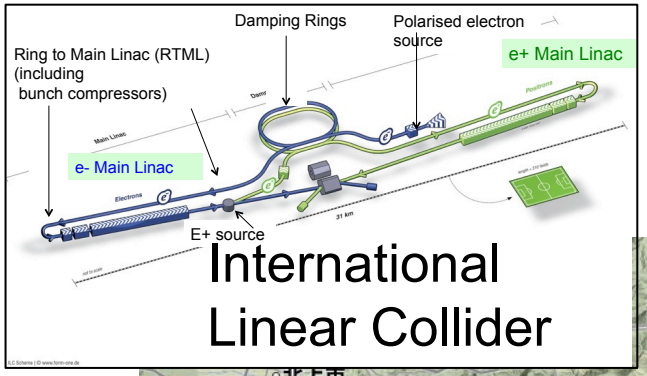
Japan working on garnering International support

Excellent Higgs Factory
Many decay modes accessible
Precision measurements of Higgs couplings

Future Circular Collider in Europe/CERN

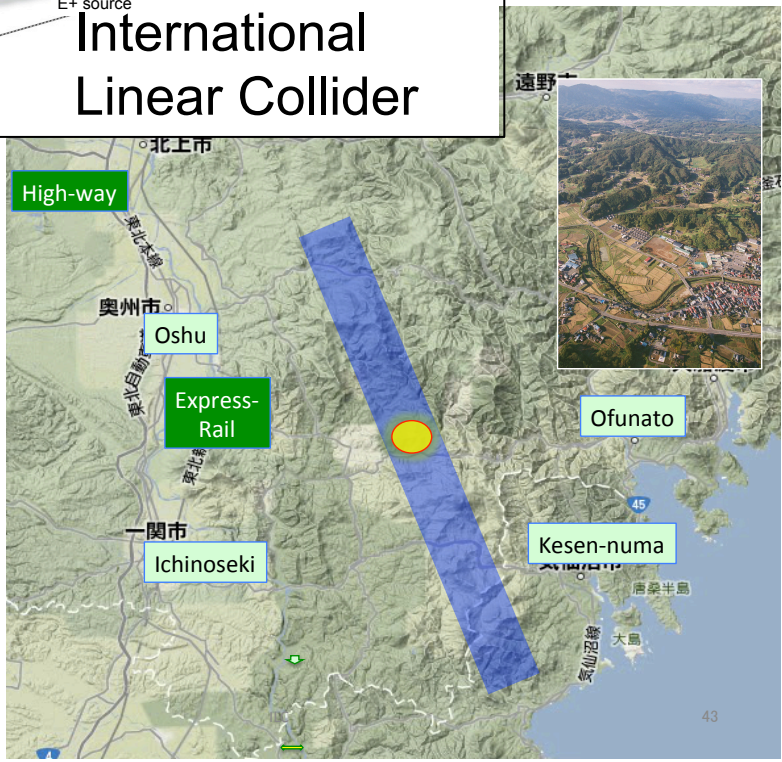


CepC China



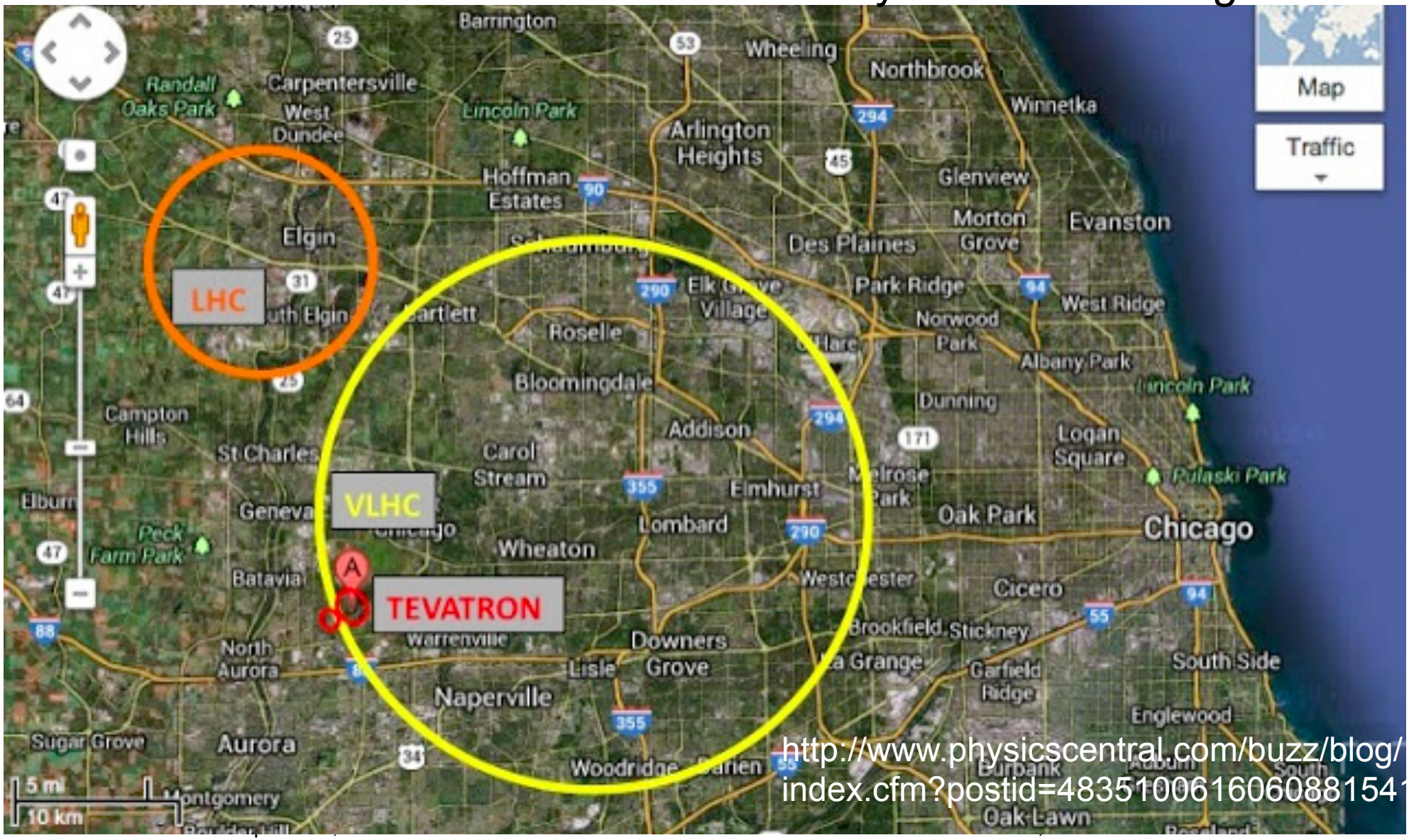
Japan

International Linear Collider

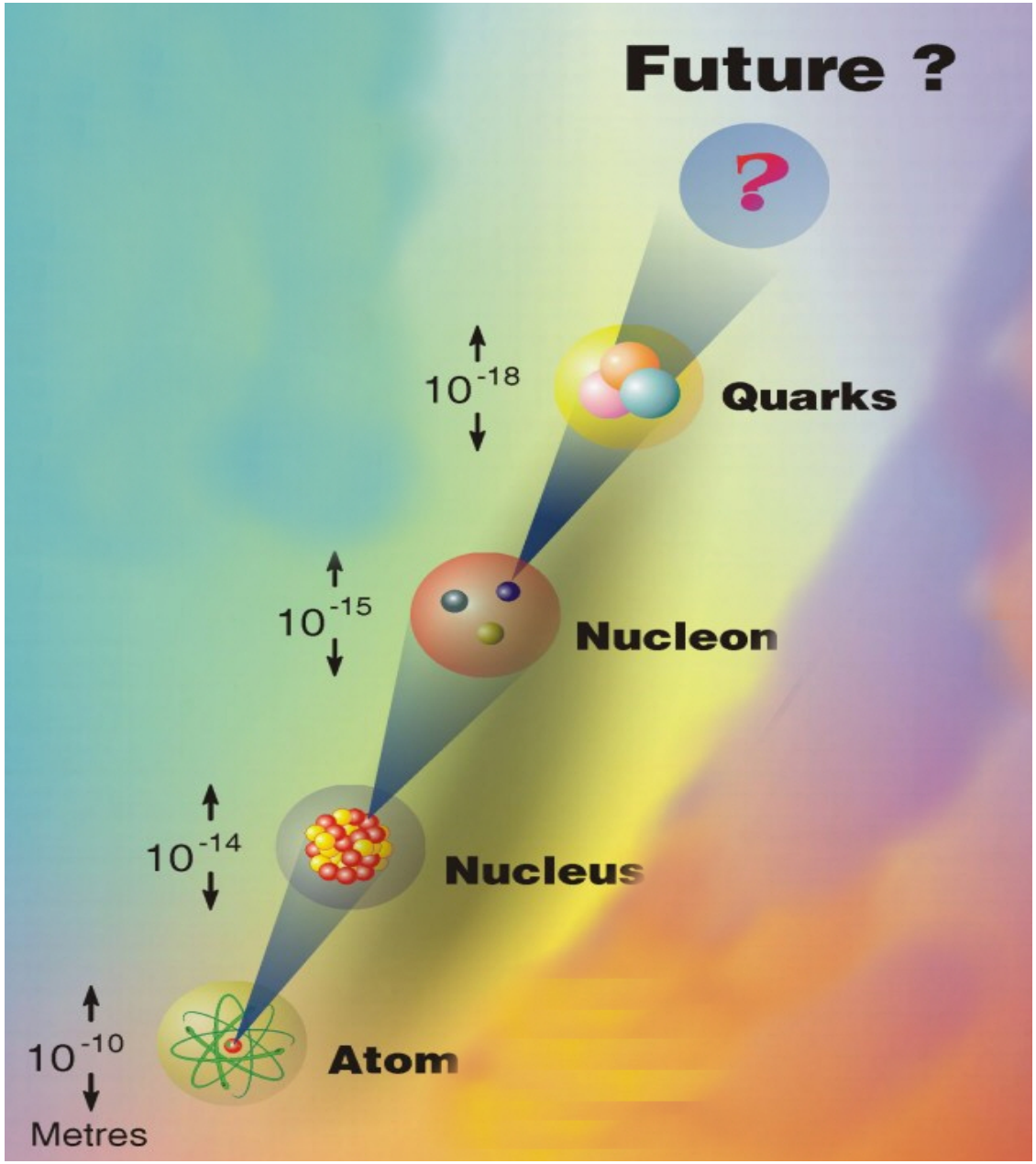


100 km ring for VLHC/VLEP

http://arxiv.org/pdf/1306.2369v1.pdf PhysicsCentral Blog



http://www.physicscentral.com/buzz/blog/index.cfm?postid=48351006160608815


Future ?
?
10^{-18}
Quarks
10^{-15}
Nucleon
10^{-14}
Nucleus
10^{-10}
Metres
Atom

The Dark Side of the Universe

Universe
=4% SM +30%DM+66% DE

"Dark Matter and Dark Energy"

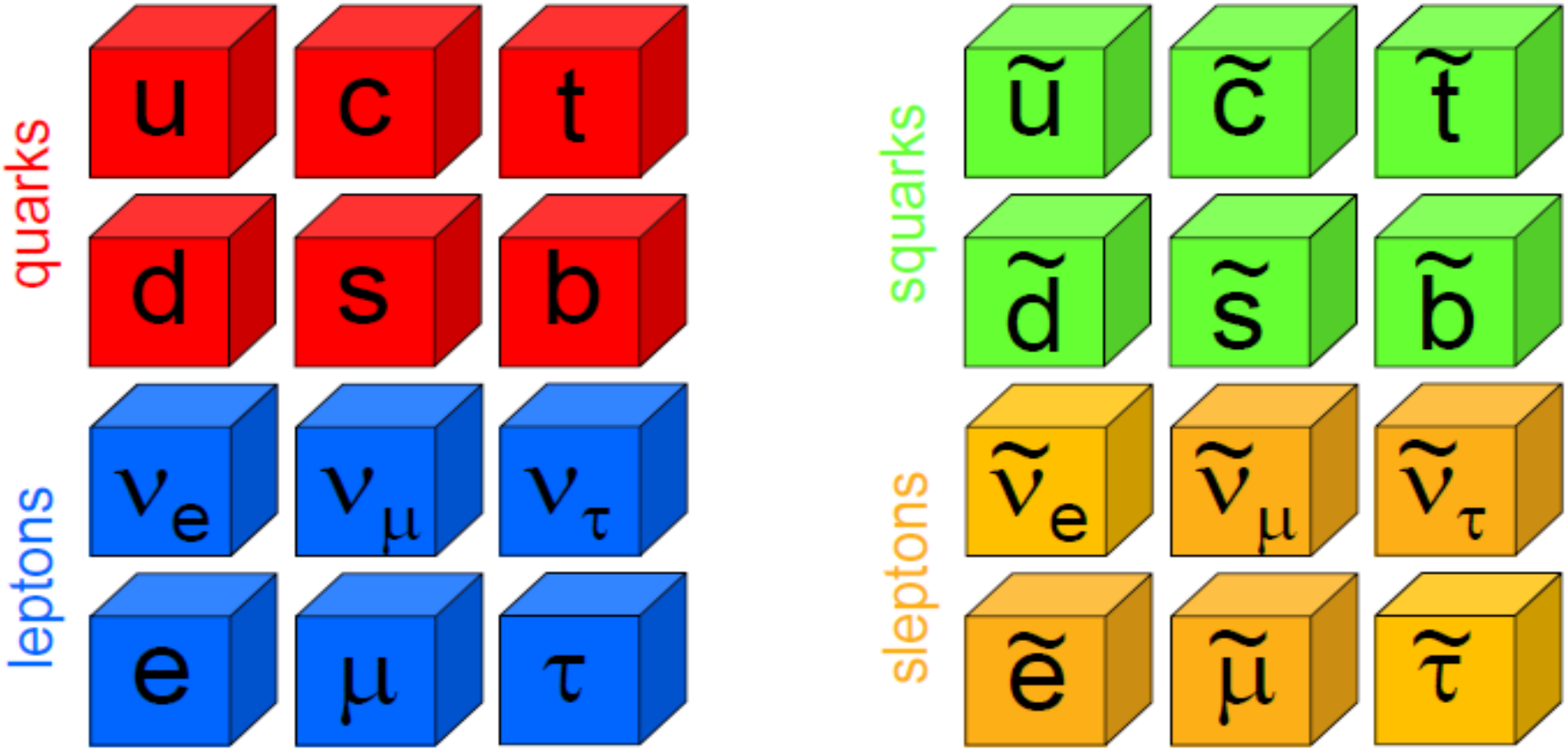
Dark Matter:
Galaxies rotation inconsistent with visible mass

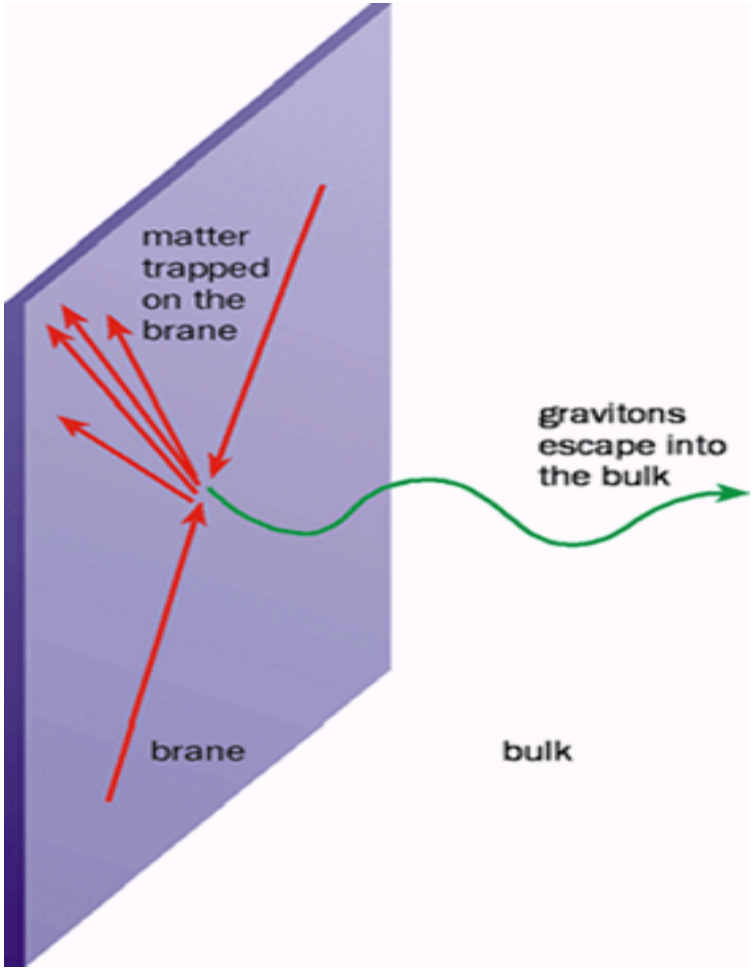
Dark Energy:
The expansion of the Universe is accelerating

Physics [particles] beyond the Standard Model !

Supersymmetry (SUSY)

A symmetry between bosons and Fermions



Hidden Dimensions?
Are there Extra Spatial Dimensions?

- Extra dimensions can explain why gravity is so weak.
- Maybe we are trapped on a 3-D membrane in a higher dimensional space-time
- Only gravity acts in the extra dimensions