The Large Hadron Collider
The Discovery Machine

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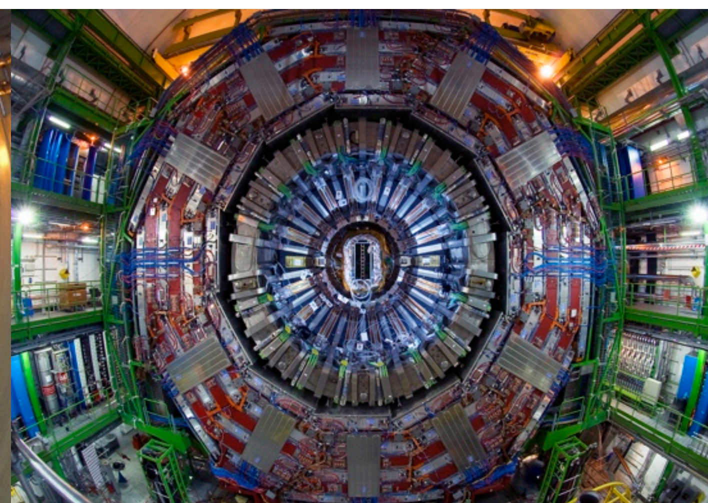



Purdue SURF Research Seminar, June 2009

Outline

- Introduction
  - What is Particle Physics
  - The Standard Model
  - Why do we go to the energy frontier
- CERN
- The Large Hadron Collider
  - The machine and the physics
- The Compact Muon Solenoid detector
  - Construction
  - Preparation for data taking
- Search for Physics Beyond the Standard Model
- Summary

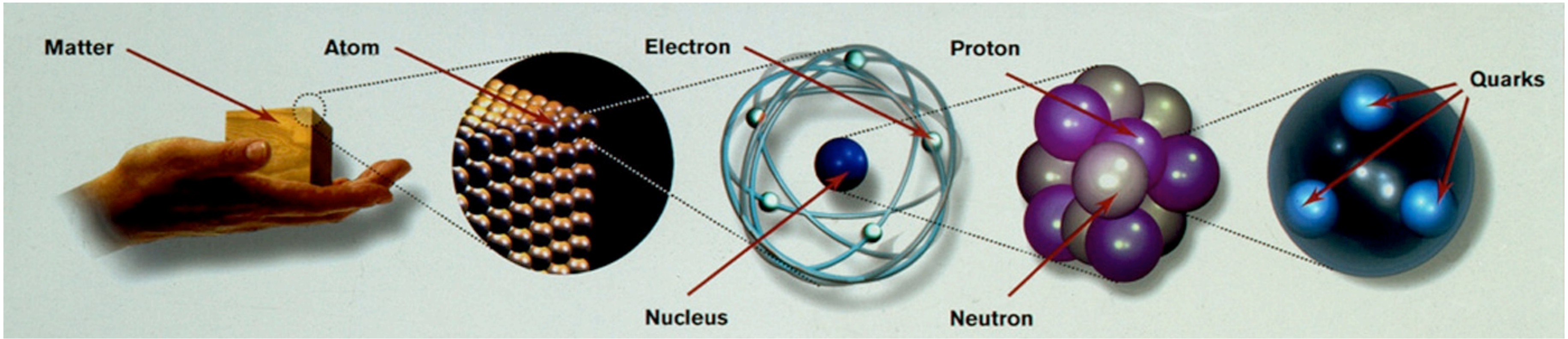
Particle Physics

Aim to answer the two following questions:

- What are the elementary constituents of matter?
- What are the fundamental forces that control their behavior at the most basic level?

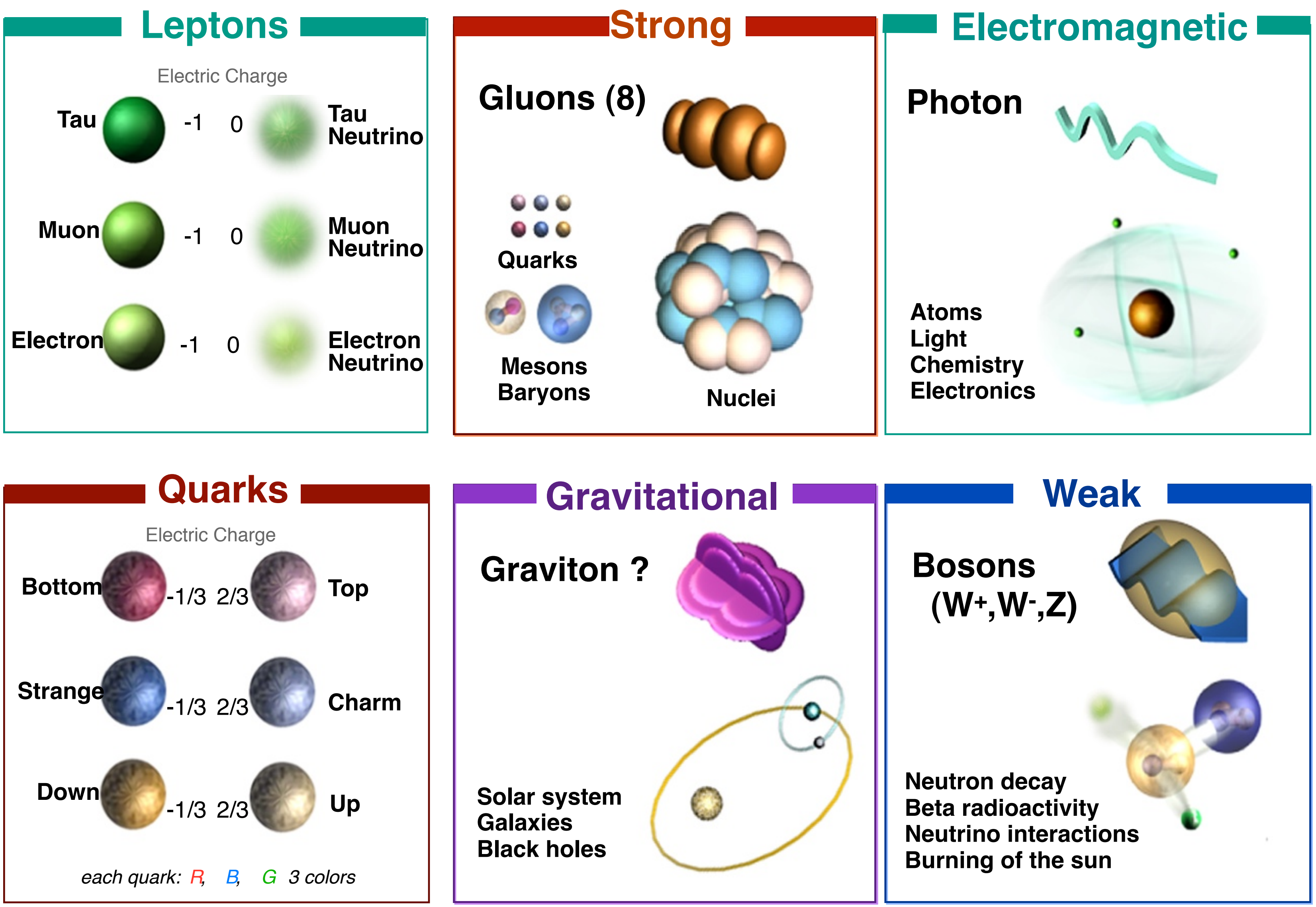
Tools:

Particle Accelerators, Particle Detectors, Computers

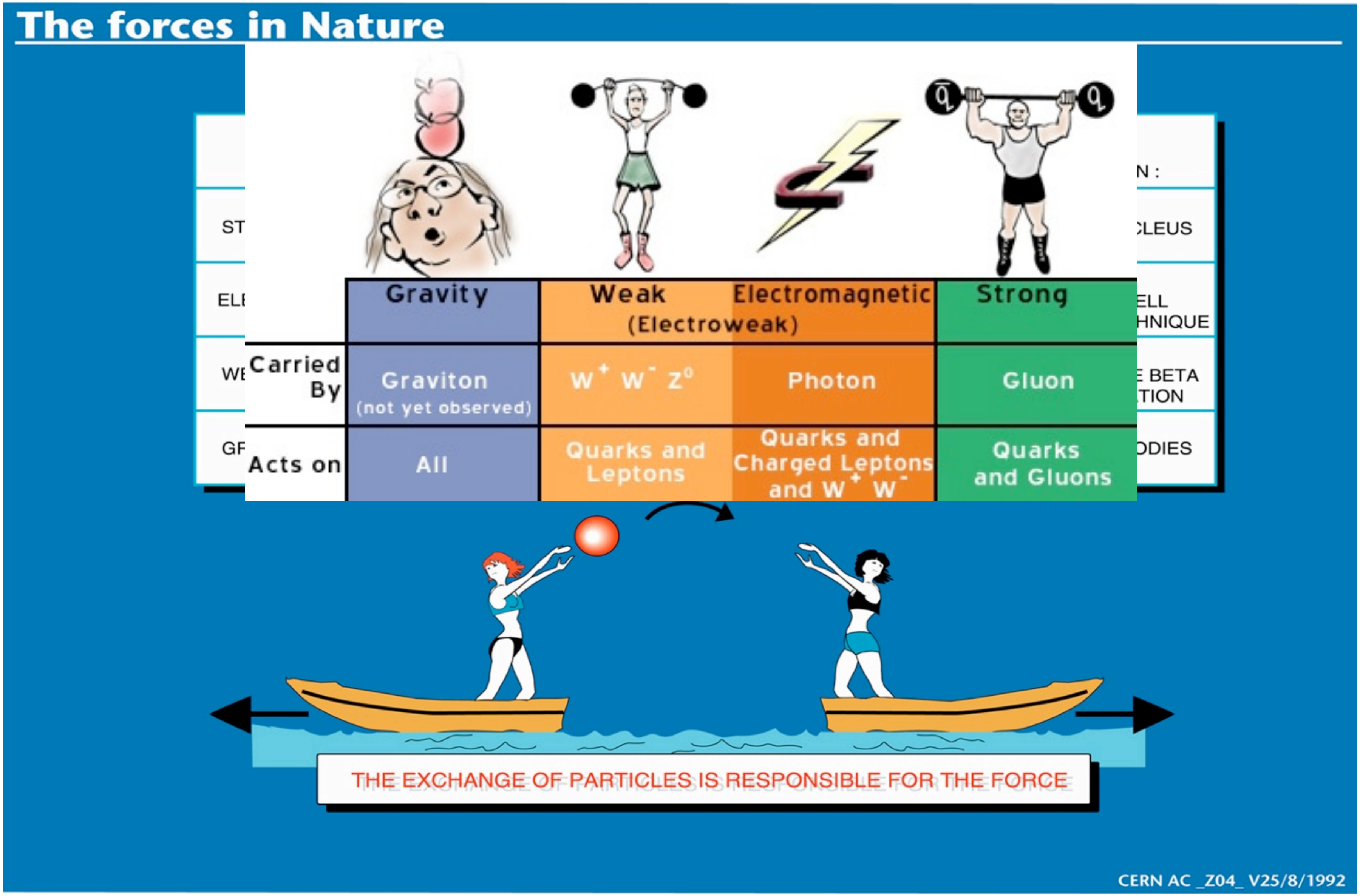


atom	nucleus	nucleon	quark
10^{-10} m	10^{-14} m	10^{-15} m	10^{-18} m

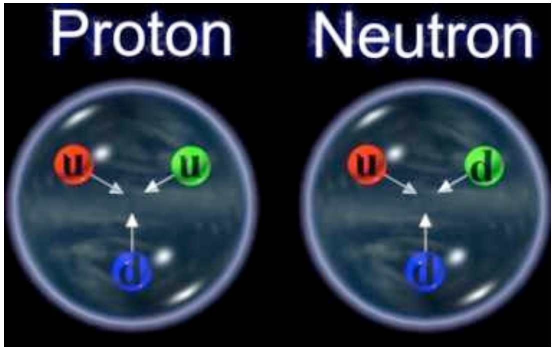
Particles and Forces



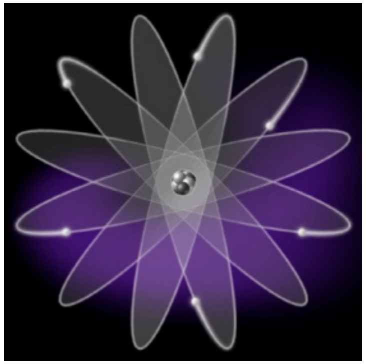
Hierarchy of Fields



Hierarchy of Structure



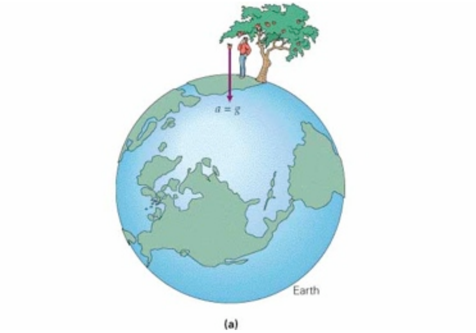
$R \sim 10^{-15}$ m (strong)



$R \sim 10^{-10}$ m (electromagnetic)

$R \sim 1/m_e$

The mass of the electron determines the size of atoms

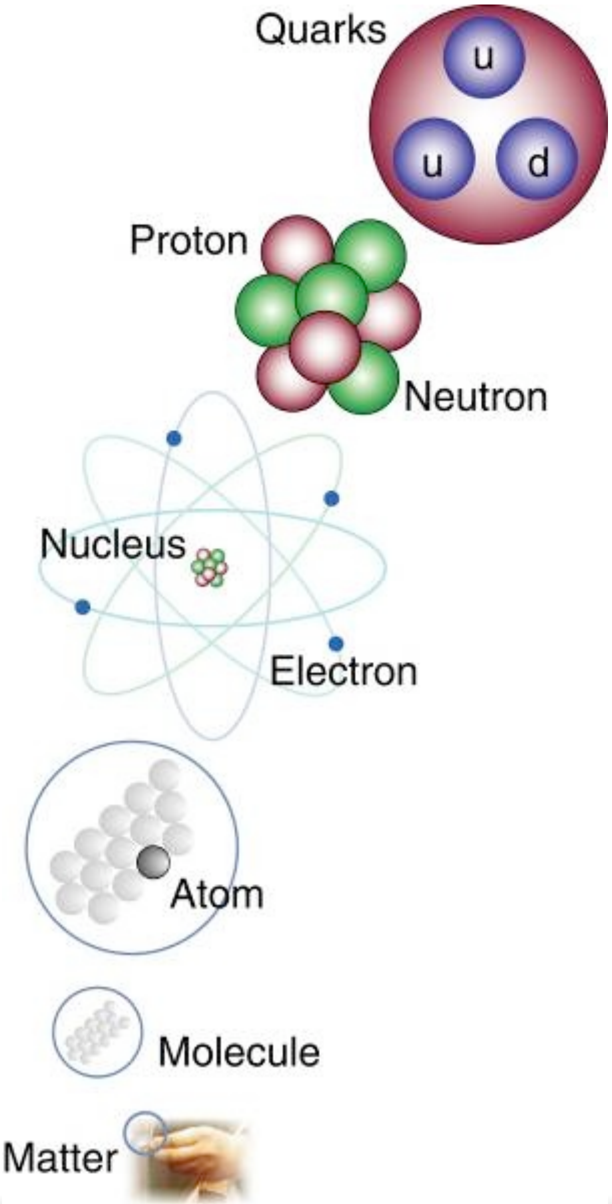


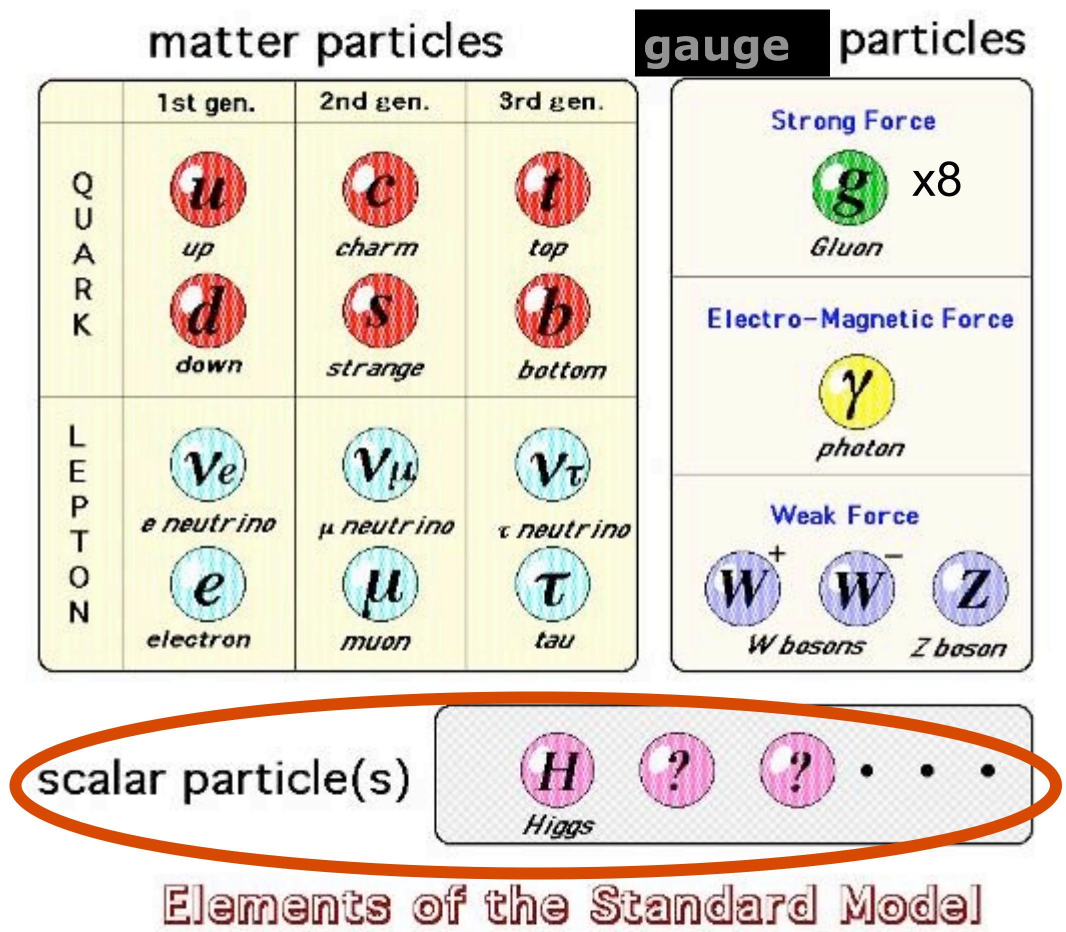
$R > 10^6$ m (gravitational)

The Standard Model

- Very successful model which contains all known particles in particle physics today.
- Describes the interaction between spin 1/2 particles (*quarks* and *leptons*) mediated by spin 1 *gauge bosons* (gauge symmetry).
- Electroweak physics tested up to per mill level.
- **BUT:** We know the Standard Model is incomplete:
  - One important element still missing: **The Higgs boson** (spin 0)
  - We know everything about the Higgs except for its mass
  - It is the last piece of the SM and also the key to understanding any beyond-the-SM physics
  - So we need to find the Higgs; and theory does NOT provide (precise) information on its mass!

The Standard Model





The Periodic Table

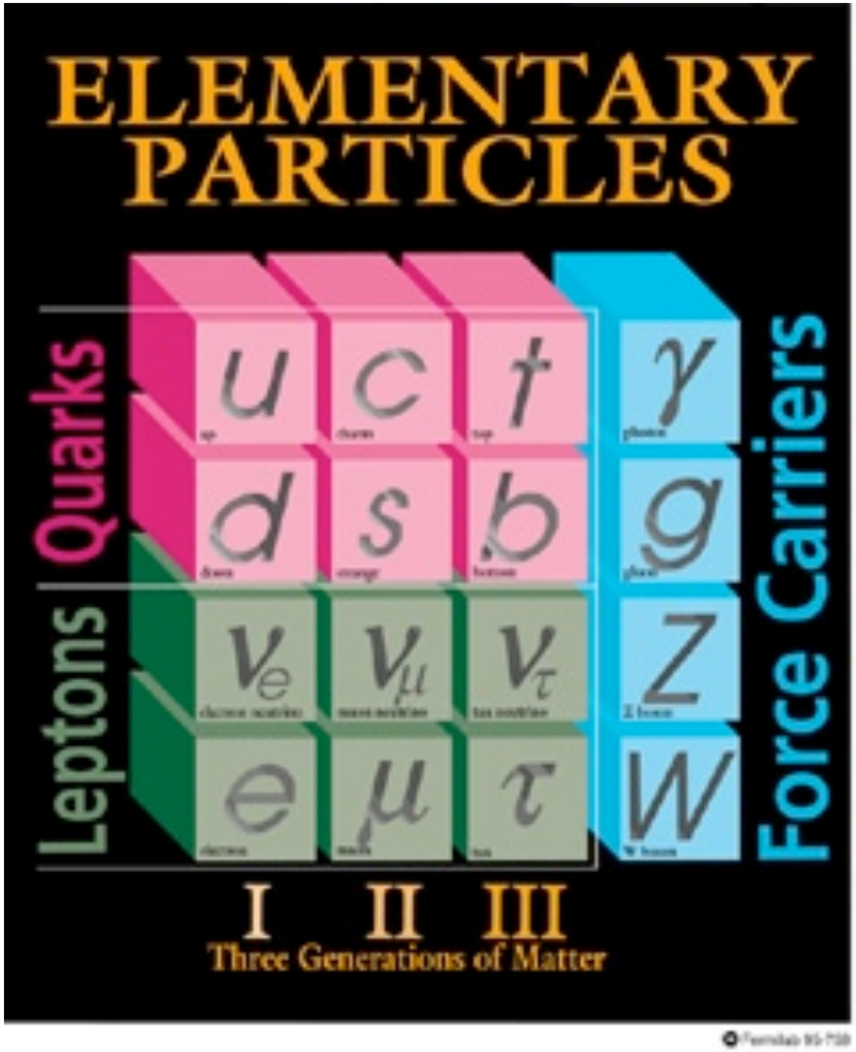
Key:

element name atomic number **symbol** atomic weight (mean relative mass)

1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
hydrogen 1 **H** 1.0079																		helium 2 **He** 4.0026
lithium 3 **Li** 6.941	beryllium 4 **Be** 9.0122												boron 5 **B** 10.811	carbon 6 **C** 12.011	nitrogen 7 **N** 14.007	oxygen 8 **O** 15.999	fluorine 9 **F** 18.998	neon 10 **Ne** 20.180
sodium 11 **Na** 22.990	magnesium 12 **Mg** 24.305												aluminium 13 **Al** 26.982	silicon 14 **Si** 28.086	phosphorus 15 **P** 30.974	sulfur 16 **S** 32.065	chlorine 17 **Cl** 35.453	argon 18 **Ar** 39.948
potassium 19 **K** 39.098	calcium 20 **Ca** 40.078		scandium 21 **Sc** 44.956	titanium 22 **Ti** 47.867	vanadium 23 **V** 50.942	chromium 24 **Cr** 51.996	manganese 25 **Mn** 54.938	iron 26 **Fe** 55.845	cobalt 27 **Co** 58.933	nickel 28 **Ni** 58.693	copper 29 **Cu** 63.546	zinc 30 **Zn** 65.39	gallium 31 **Ga** 69.723	germanium 32 **Ge** 72.61	arsenic 33 **As** 74.922	selenium 34 **Se** 78.96	bromine 35 **Br** 79.904	krypton 36 **Kr** 83.80
rubidium 37 **Rb** 85.468	strontium 38 **Sr** 87.62		yttrium 39 **Y** 88.906	zirconium 40 **Zr** 91.224	niobium 41 **Nb** 92.906	molybdenum 42 **Mo** 95.94	technetium 43 **Tc** [97.907]	ruthenium 44 **Ru** 101.07	rhodium 45 **Rh** 102.91	palladium 46 **Pd** 106.42	silver 47 **Ag** 107.87	cadmium 48 **Cd** 112.41	indium 49 **In** 114.82	tin 50 **Sn** 118.71	antimony 51 **Sb** 121.76	tellurium 52 **Te** 127.60	iodine 53 **I** 126.90	xenon 54 **Xe** 131.29
caesium 55 **Cs** 132.91	barium 56 **Ba** 137.33	57-70 *	lutetium 71 **Lu** 174.97	hafnium 72 **Hf** 178.49	tantalum 73 **Ta** 180.95	tungsten 74 **W** 183.84	rhenium 75 **Re** 186.21	osmium 76 **Os** 190.23	iridium 77 **Ir** 192.22	platinum 78 **Pt** 195.08	gold 79 **Au** 196.97	mercury 80 **Hg** 200.59	thallium 81 **Tl** 204.38	lead 82 **Pb** 207.2	bismuth 83 **Bi** 208.98	polonium 84 **Po** [208.98]	astatine 85 **At** [209.99]	radon 86 **Rn** [222.02]
francium 87 **Fr** [223.02]	radium 88 **Ra** [226.03]	89-102 **	lawrencium 103 **Lr** [262.11]	rutherfordium 104 **Rf** [263.11]	dubnium 105 **Db** [262.11]	seaborgium 106 **Sg** [266.12]	bohrium 107 **Bh** [264.12]	hassium 108 **Hs** [269.13]	meitnerium 109 **Mt** [268.14]	ununnilium 110 **Uun** [272.15]	unununium 111 **Uuu** [272.15]	ununbium 112 **Uub** [277]		ununquadium 114 **Uuq** [289]		ununhexium 116 **Uuh** [289]		ununoctium 118 **Uuo** [293]

*lanthanoids	lanthanum 57 **La** 138.91	cerium 58 **Ce** 140.12	praseodymium 59 **Pr** 140.91	neodymium 60 **Nd** 144.24	promethium 61 **Pm** [144.91]	samarium 62 **Sm** 150.36	europium 63 **Eu** 151.96	gadolinium 64 **Gd** 157.25	terbium 65 **Tb** 158.93	dysprosium 66 **Dy** 162.50	holmium 67 **Ho** 164.93	erbium 68 **Er** 167.26	thulium 69 **Tm** 168.93	ytterbium 70 **Yb** 173.04
**actinoids	actinium 89 **Ac** [227.03]	thorium 90 **Th** 232.04	protactinium 91 **Pa** 231.04	uranium 92 **U** 238.03	neptunium 93 **Np** [237.05]	plutonium 94 **Pu** [244.06]	americium 95 **Am** [243.06]	curium 96 **Cm** [247.07]	berkelium 97 **Bk** [247.07]	californium 98 **Cf** [251.08]	einsteinium 99 **Es** [252.08]	fermium 100 **Fm** [257.10]	mendelevium 101 **Md** [258.10]	nobelium 102 **No** [259.10]

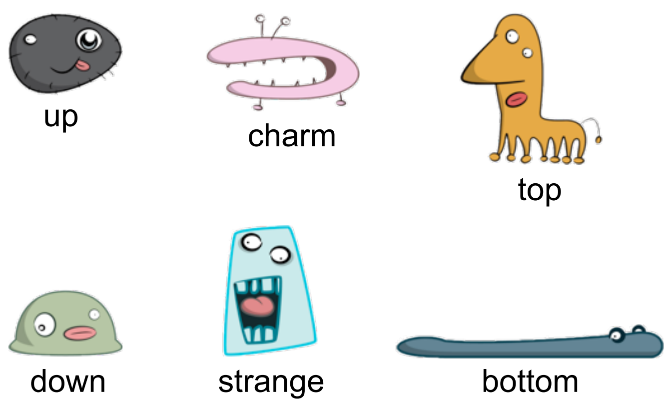
The "Newer" Periodic Table



What is Matter?

- Particles in various combinations

Quarks



Leptons

Building a Universe

electron

proton

neutron

Multiply by billions and billions and billions and billions…

Building a Universe

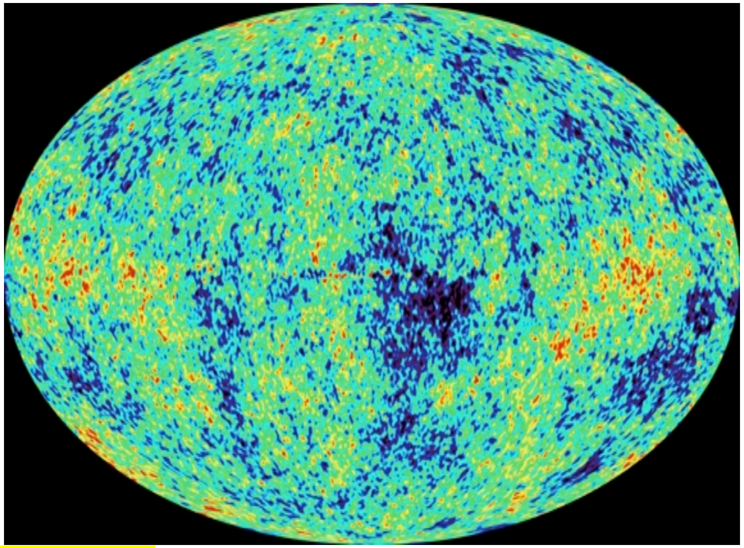
NASA, ESA/JPL-Caltech/B. Mobasher (STScI/ESA)

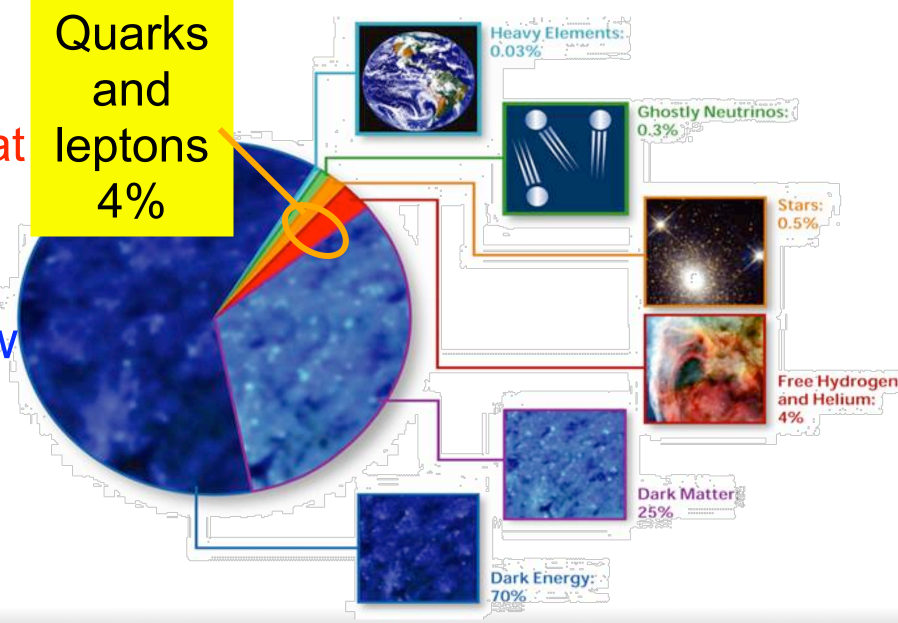
The Universe

- What shapes the cosmos?

  Old answer: Gravity – through mass and energy observed in the universe
- But now we know that:
  - ❖ There is much more mass than we expect from just the stars we see, or from the amount of helium that was formed in the early universe... Solution: **Dark matter**
  - ❖ The velocity of distant galaxies indicates that, in addition to the mass that slows down expansion of the universe, there is also some new kind of energy driving that expansion outward!

    Solution: **Dark Energy**
- So, if we're so smart, why don't we know what 96% of the universe is made of?
  - – Back to the accelerators!

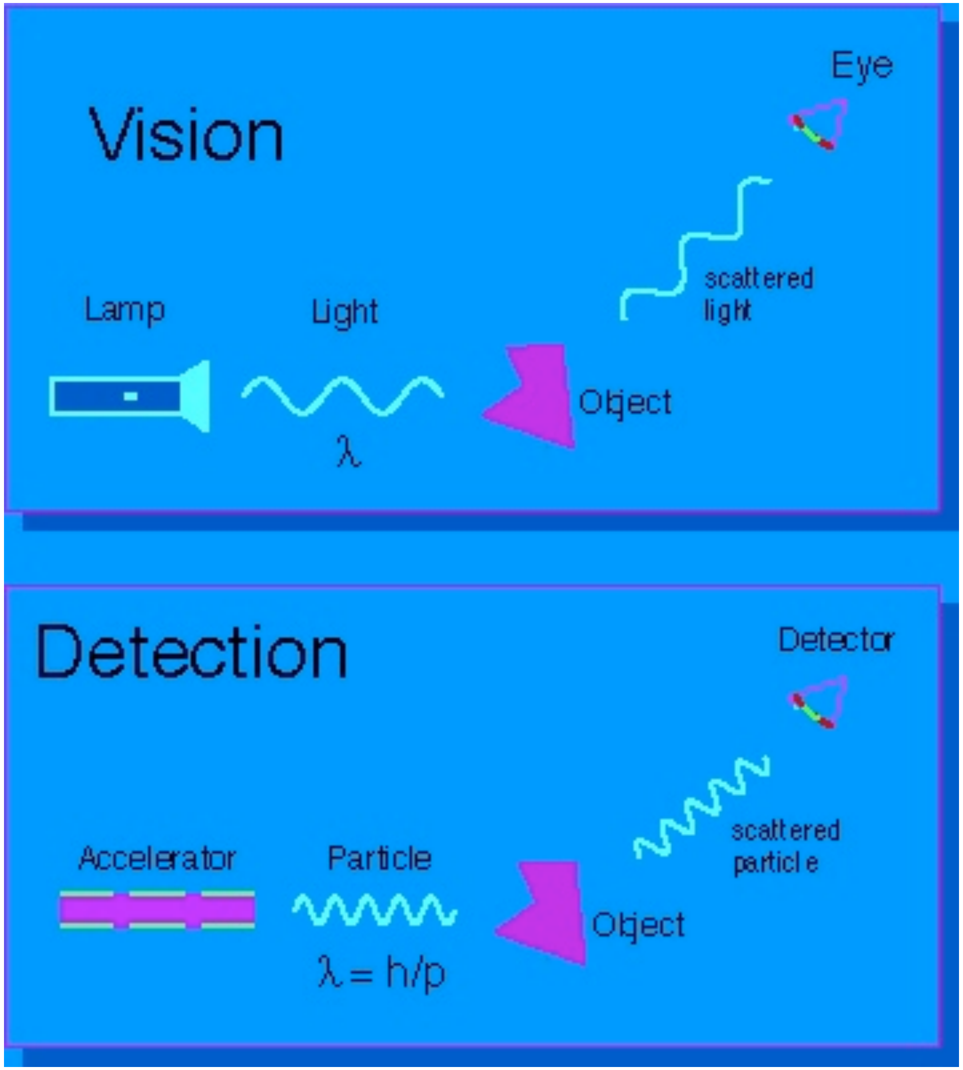




Probing the TeV Energy Scale

- Higher energy: Reproduce conditions of early Universe
- TeV energy scale: Expect breakdown of current calculations unless a new interaction or phenomenon appears
- Many theories, but need data to distinguish between them
- **What might we find:**
  - The mechanism that generates mass for all elementary particles
    - In Standard Model, masses generated through interaction with a new particle the Higgs boson
    - Other options possible, but we know that the phenomena occurs somewhere between 100 and 1000 GeV
  - A new Symmetry of Nature
    - Supersymmetry gives each particle a partner
    - Would provide one source of the Dark Matter observed in the Universe
  - Extra Space-Time Dimensions
    - String theory inspired
    - This would revolutionize Physics!
  - These are only some of the possibilities

Why Accelerate Particles (1)

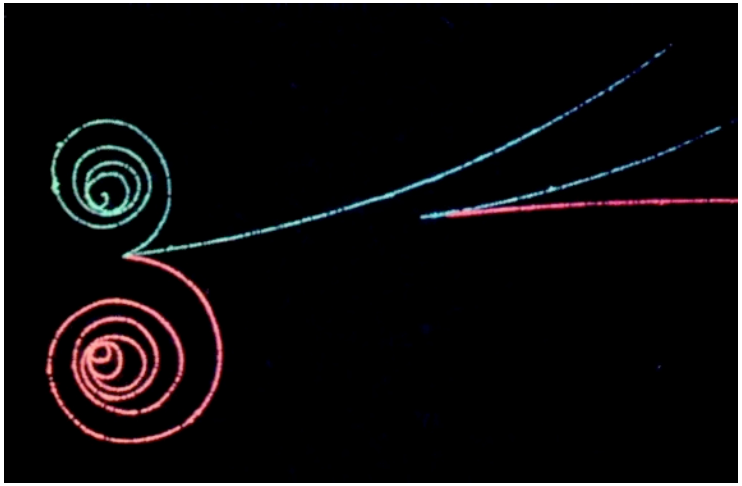


To look inside

Why Accelerate Particles (2)

- $E = mc^2$: “Mass is condensed energy”
- Concentrate energy on one particle

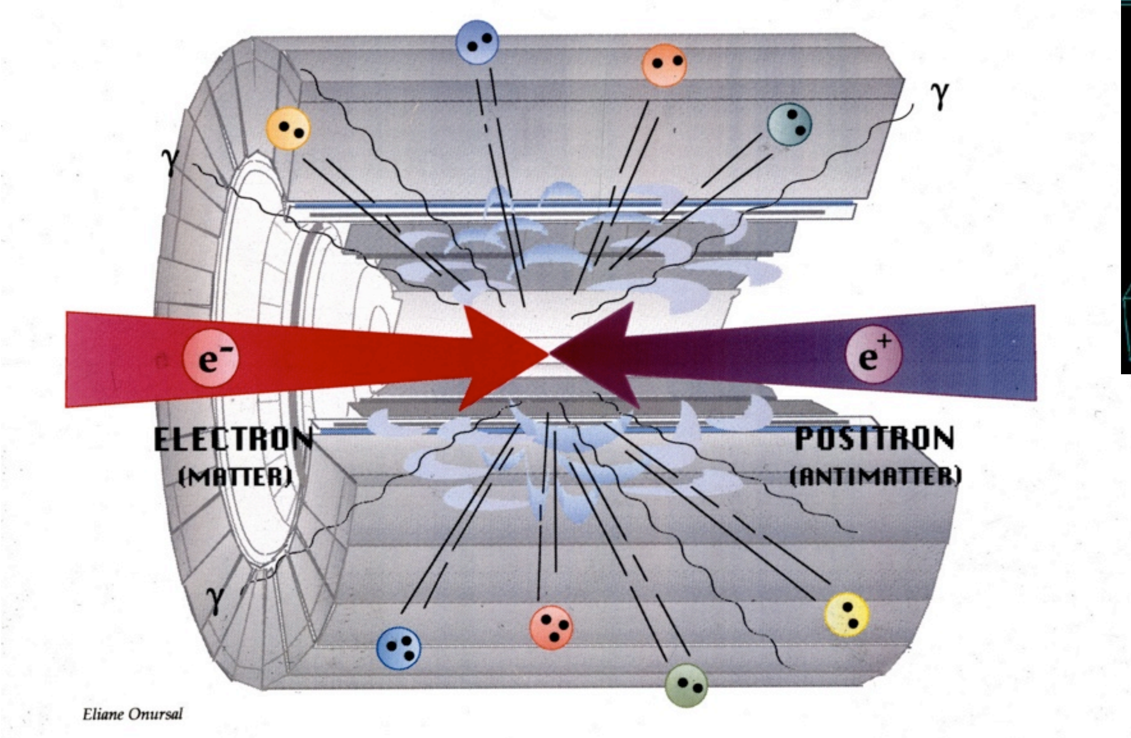
Photon ------

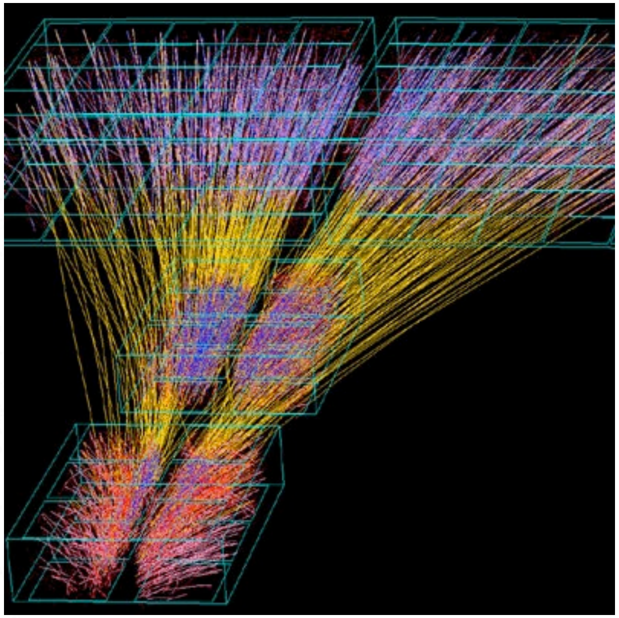


Creation of new particles

Particles from Energy

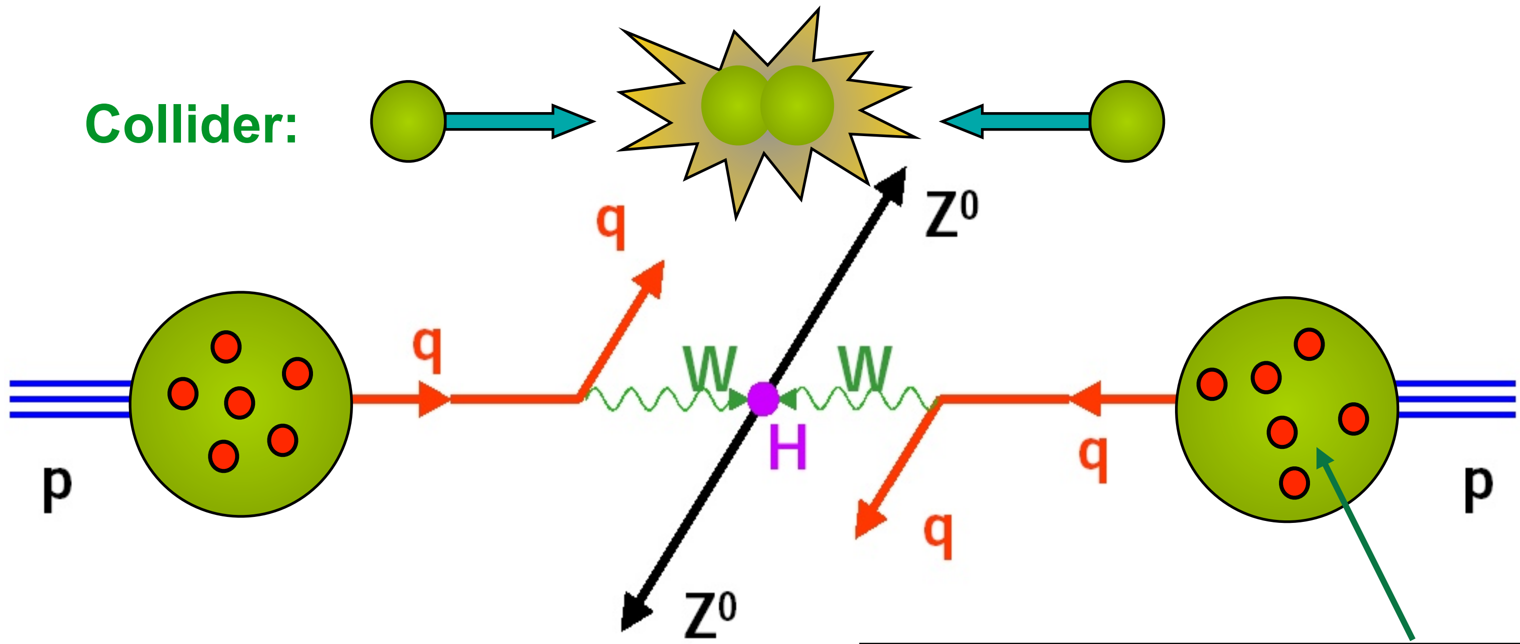
More energy - more (and new) particles are created

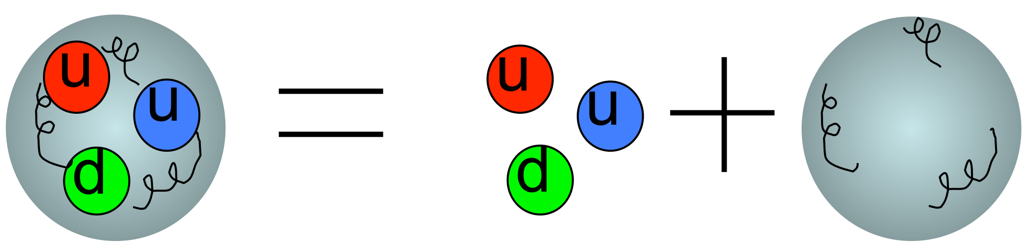




Particle collisions

Higgs Production in pp Collisions





E_{beam} = ½E_{beam} + ½E_{beam}

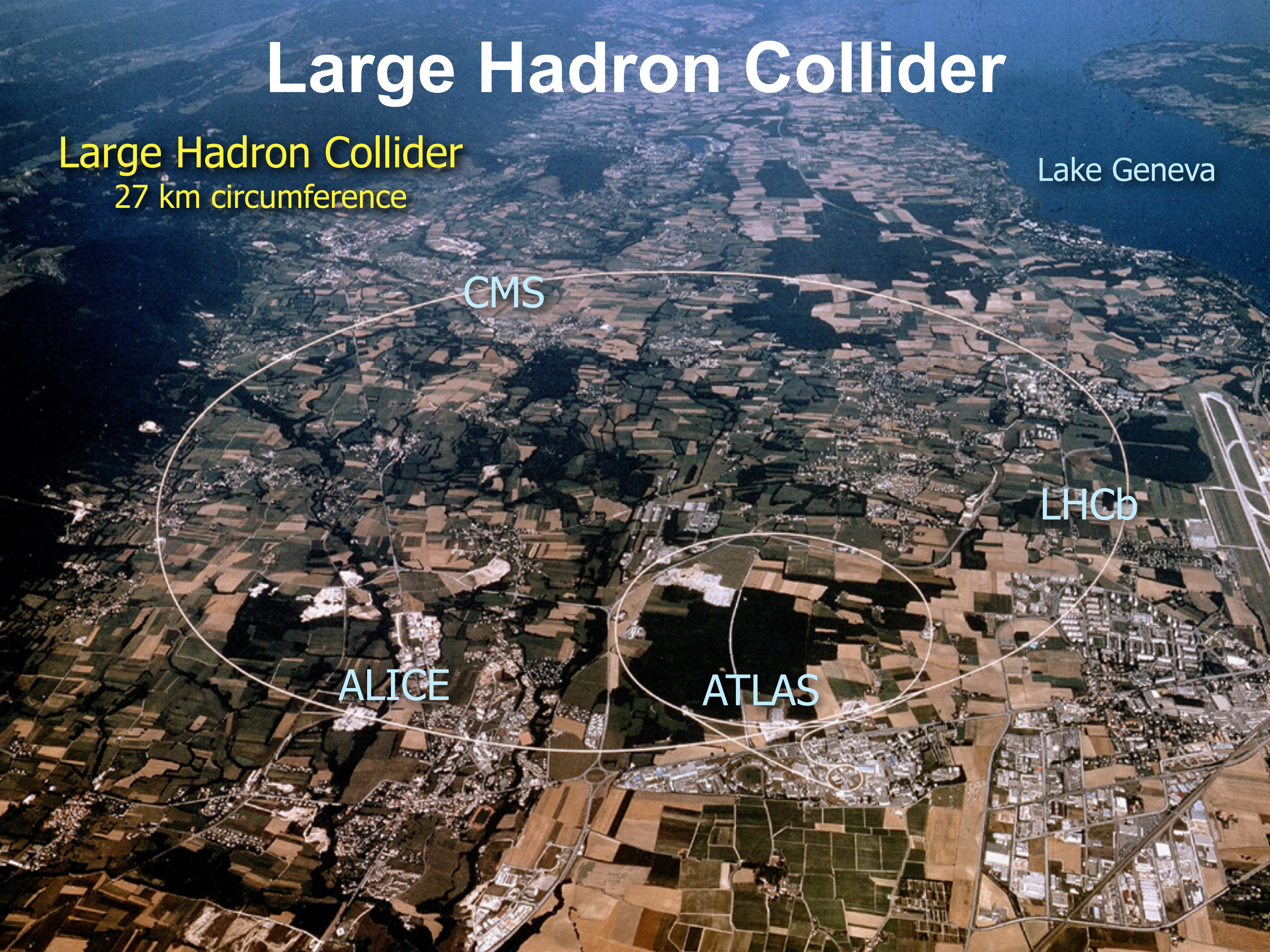
Really colliding 'partons': **qg, qq, gg**

E_{Quark} is on average only 1/6 of E_{Proton}

E_{CM} ~ 1/3 E_{beam}

→ Proton-proton collider with $E_p \geq 7$ TeV

Large Hadron Collider



Conseil Européen pour la Recherche Nucléaire

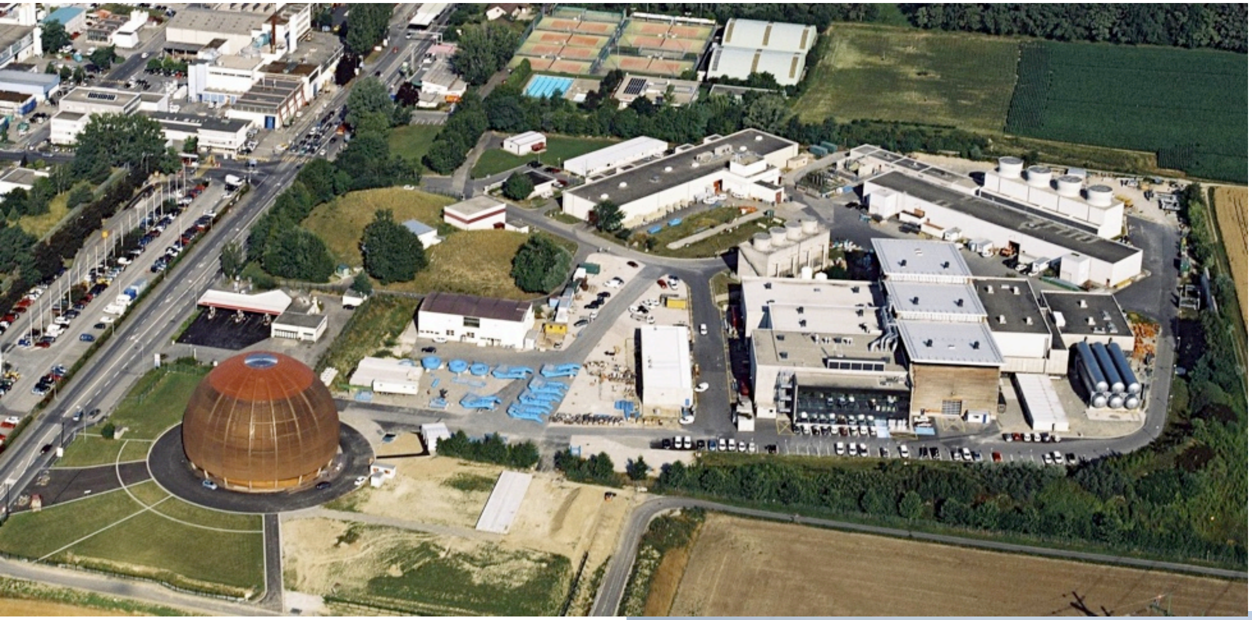
European Laboratory for Particle Physics
Founded in 1954

- 2415 staff*
- 730 Fellows and Associates*
- 9133 users*
- Budget (2007) $900M (610M Euro)

*5 February 2008

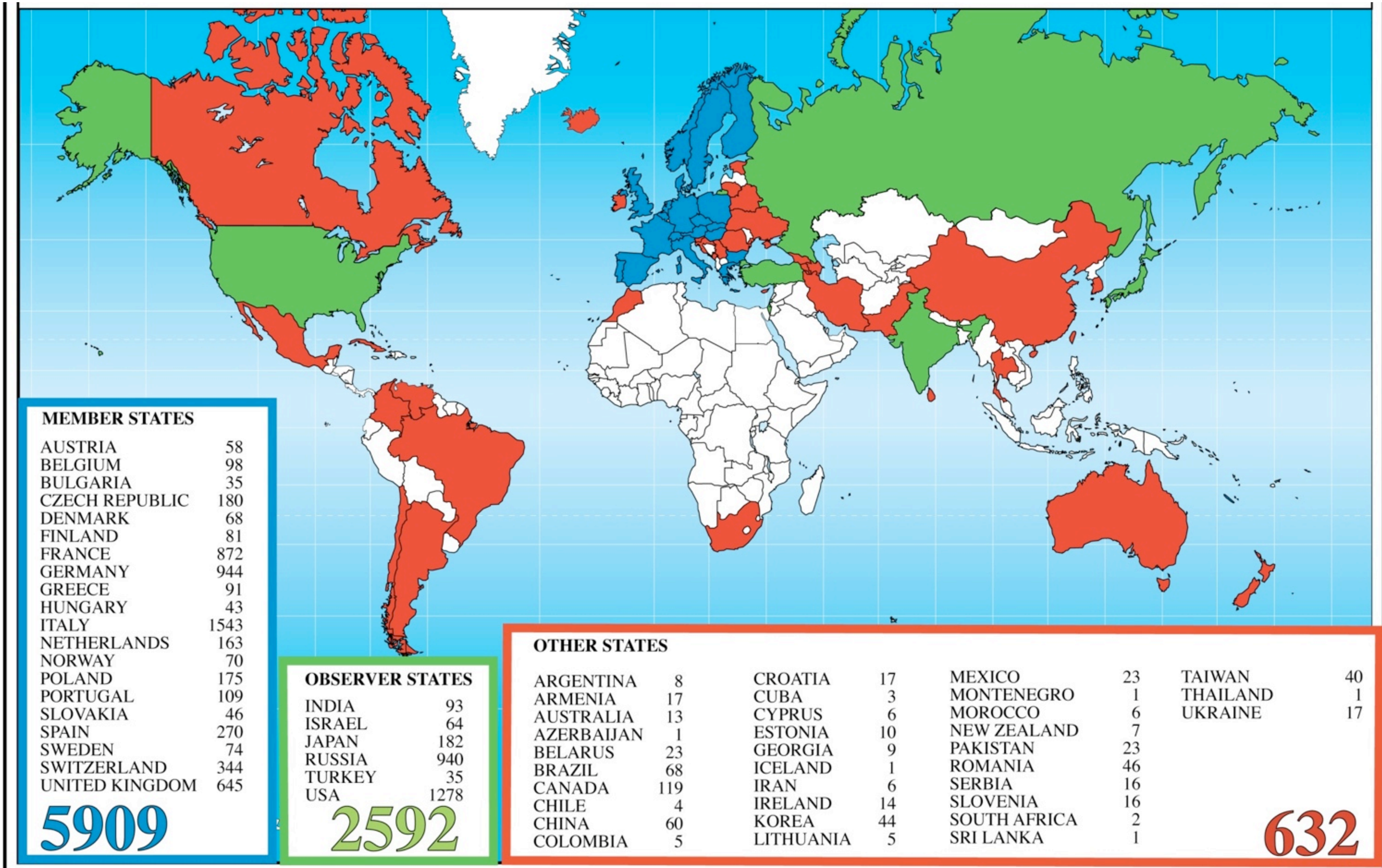
- Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.
- Observers to Council: India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and Unesco

CERN



Near Geneva, Switzerland

CERN in Numbers



MEMBER STATES

AUSTRIA	58
BELGIUM	98
BULGARIA	35
CZECH REPUBLIC	180
DENMARK	68
FINLAND	81
FRANCE	872
GERMANY	944
GREECE	91
HUNGARY	43
ITALY	1543
NETHERLANDS	163
NORWAY	70
POLAND	175
PORTUGAL	109
SLOVAKIA	46
SPAIN	270
SWEDEN	74
SWITZERLAND	344
UNITED KINGDOM	645

5909

OBSERVER STATES

INDIA	93
ISRAEL	64
JAPAN	182
RUSSIA	940
TURKEY	35
USA	1278

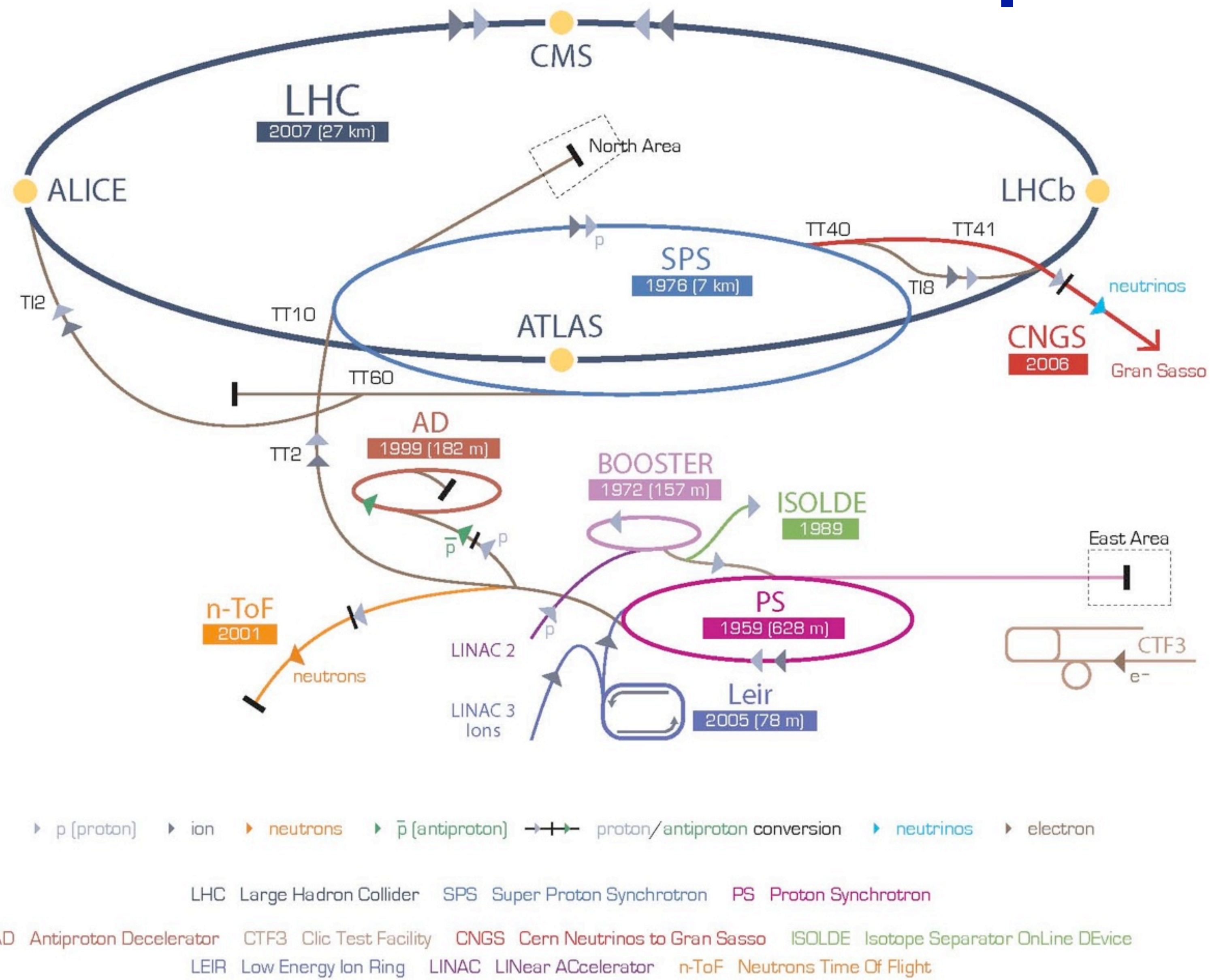
2592

OTHER STATES

ARGENTINA	8	CROATIA	17	MEXICO	23	TAIWAN	40
ARMENIA	17	CUBA	3	MONTENEGRO	1	THAILAND	1
AUSTRALIA	13	CYPRUS	6	MOROCCO	6	UKRAINE	17
AZERBAIJAN	1	ESTONIA	10	NEW ZEALAND	7		
BELARUS	23	GEORGIA	9	PAKISTAN	23		
BRAZIL	68	ICELAND	1	ROMANIA	46		
CANADA	119	IRAN	6	SERBIA	16		
CHILE	4	IRELAND	14	SLOVENIA	16		
CHINA	60	KOREA	44	SOUTH AFRICA	2		
COLOMBIA	5	LITHUANIA	5	SRI LANKA	1		

632

CERN Accelerator Complex

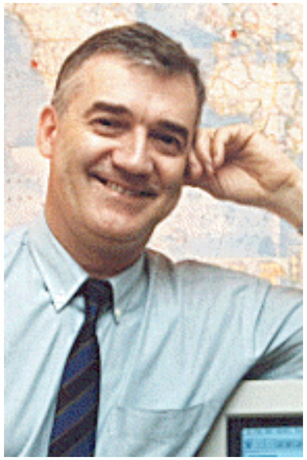


The World Wide Web

1990: Tim Berners-Lee, a CERN computer scientist invented the World Wide Web

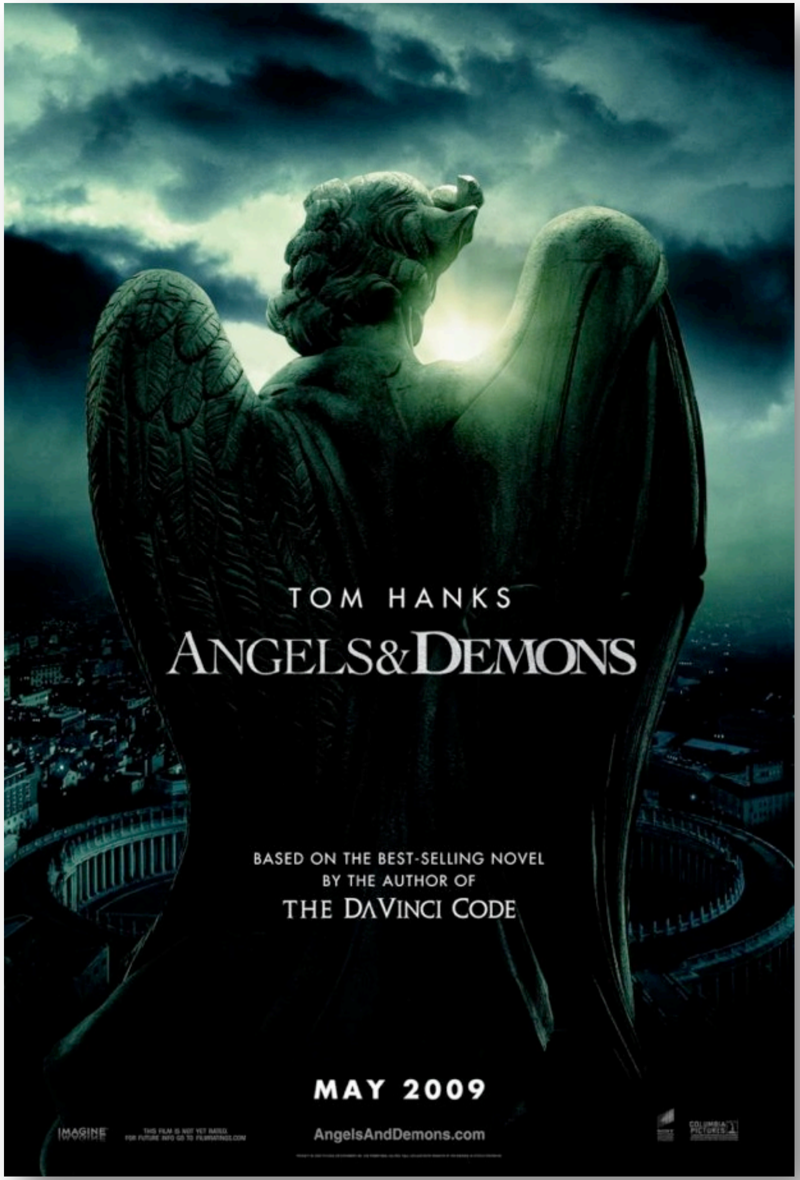
The "Web" as it is affectionately called, was originally conceived and developed for the large high-energy physics collaborations which have a demand for instantaneous information sharing between physicists working in different universities and institutes all over the world. Now it has millions of academic and commercial users.

Tim together with Robert Cailliau, another CERN computer scientist, wrote the first WWW client (a browser-editor running under NeXTStep) and the first WWW server along with most of the communications software, defining URLs, HTTP and HTML.



In December 1993 WWW Tim received the IMA award and in 1995 Tim and Robert shared the Association for Computing (ACM) Software System Award for developing the World-Wide Web.

CERN and Hollywood



Angels and Demons

The plot:

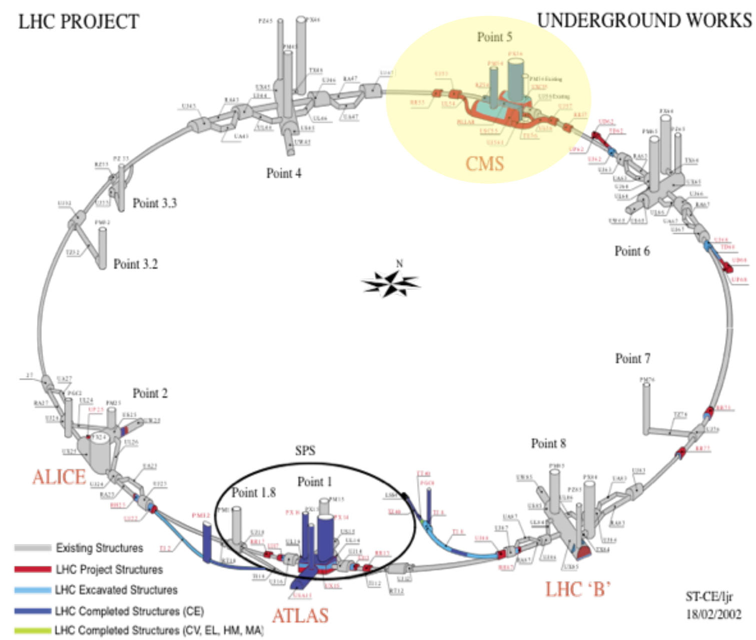
- Antimatter is stolen from CERN's Large Hadron Collider (LHC) and hidden in Vatican City.
- Countdown to Vatican annihilation begins.
- Race through Rome to avert death and destruction.

The real LHC

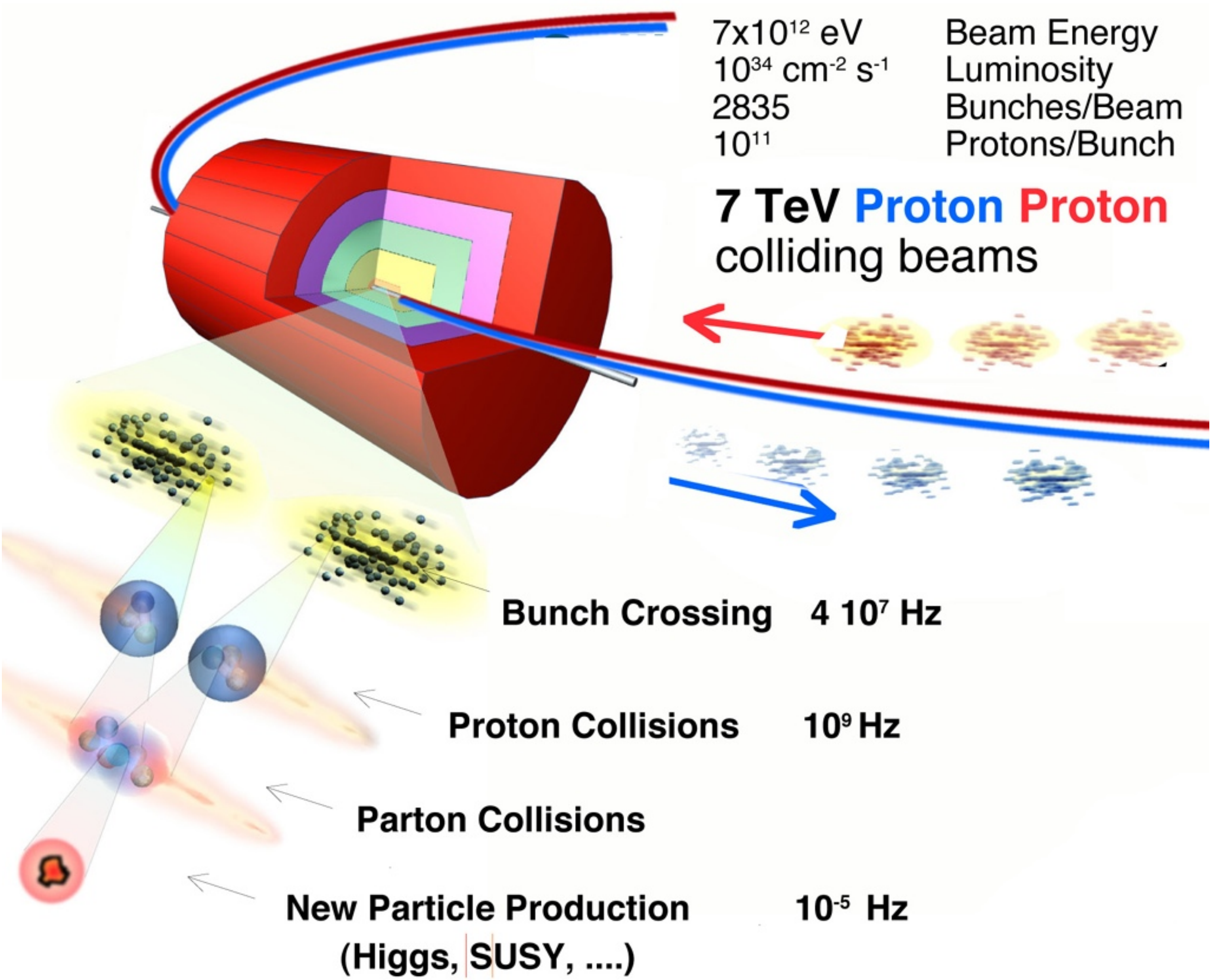
- The world's most powerful particle accelerator
- 16.8 miles around, 330 feet underground

The Large Hadron Collider

- 7 TeV on 7 TeV proton-proton collider, 27 km ring
  - 7 times higher energy than the Tevatron at Fermilab
  - 100 times higher design luminosity than Tevatron ($L=10^{34}\ cm^{-2}s^{-1}$)
- 1232 superconducting 8.4 T dipole magnets @ T=1.9º K
  - Largest cryogenic structure, with 40 ktons of mass to cool
- 4 experiments
  - ATLAS
  - CMS
  - LHCb
  - ALICE



Collisions at the LHC



Selection of 1 event in 10,000,000,000,000

Stored Energy

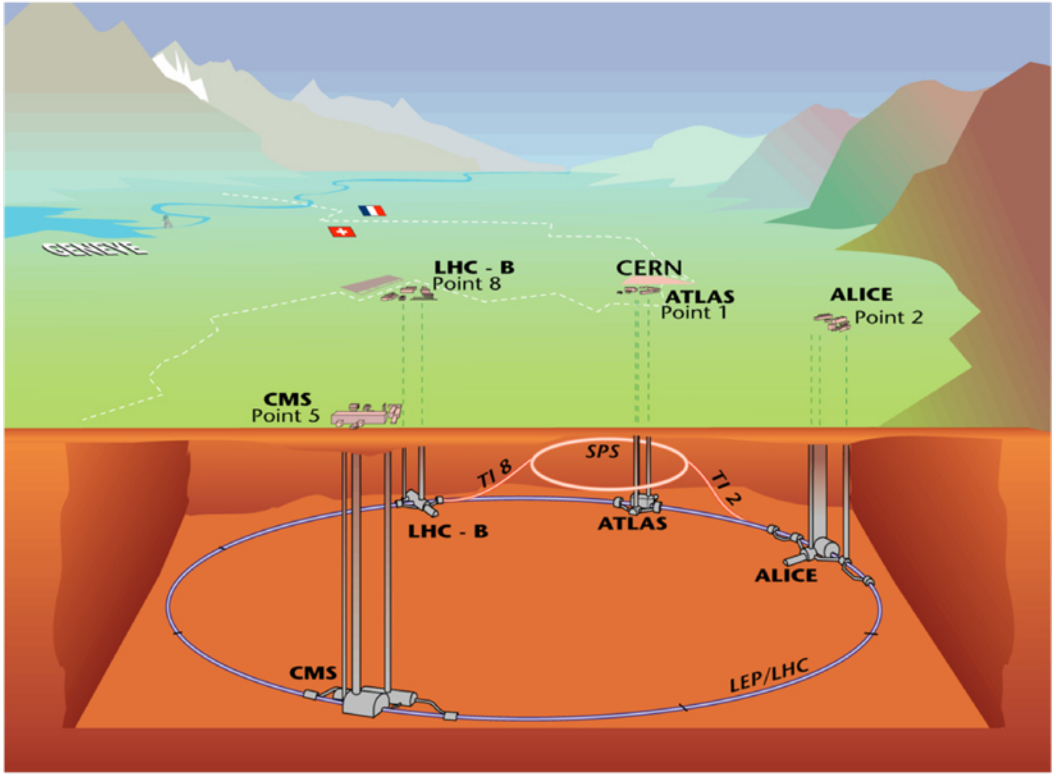
$$E = 2E_{\text{proton}} N_{\text{bunches}} N_{\text{protons}}$$

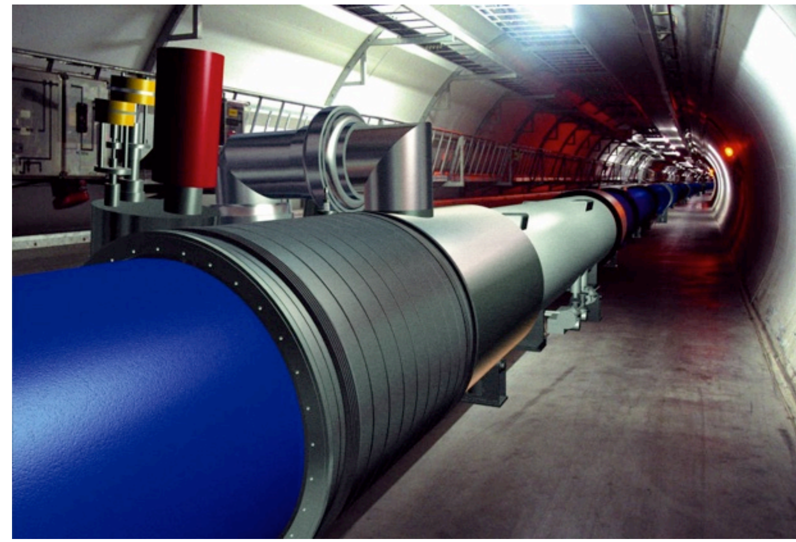
$$E = 2(7 \times 10^{12}\text{eV})(1.6 \times 10^{-19}\text{J/eV})(2808)(1.1 \times 10^{11}) \sim 700\ \text{MJ}$$

350 MJoule per beam: unprecedented!

- Kinetic energy
  - 1 small aircraft carrier of 10^4 tonnes going 15 knots
  - 450 automobiles of 2 tonnes going 100 kph
- Chemical energy
  - 80 kg of TNT
  - 70 kg of (swiss?) chocolate
- Thermal energy
  - melt 500 kg of copper
  - raise 1 cubic meter of water 85 C

LHC tunnel, magnets



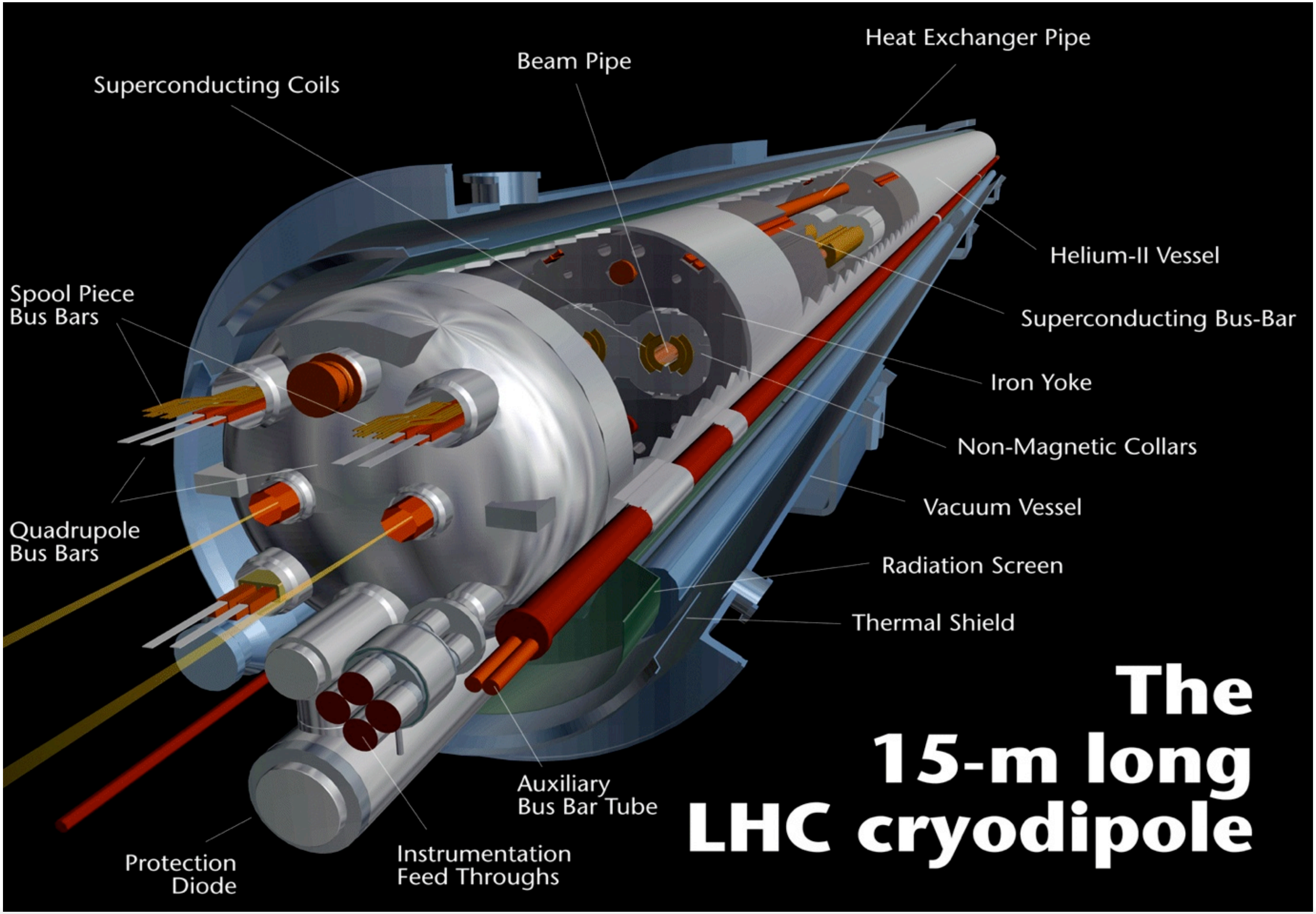


Proton-proton collisions
E = 7000 + 7000 GeV
800 million collisions/sec

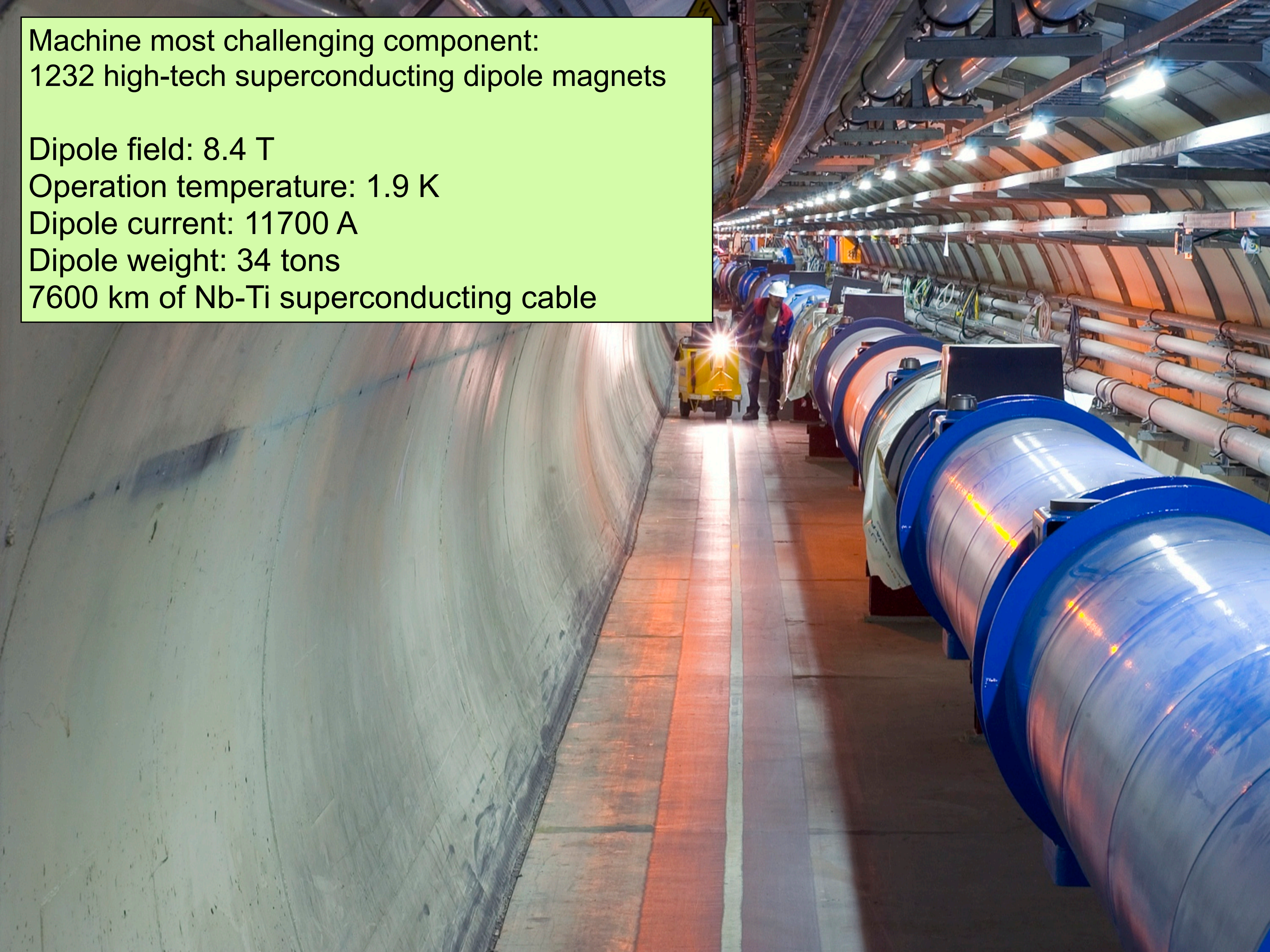
Largest cryogenic system
(1.8 K, suprafluid helium)

27 km of 8 T magnets
100 m below surface

The LHC Dipole Magnets



The LHC Dipole Magnets


Machine most challenging component:
1232 high-tech superconducting dipole magnets
Dipole field: 8.4 T
Operation temperature: 1.9 K
Dipole current: 11700 A
Dipole weight: 34 tons
7600 km of Nb-Ti superconducting cable

LHC Installation

Final dipole magnet (of more than 1700 LHC magnets) being lowered for placing in the tunnel ~50 - 100 meters below ground.
(April 26, 2007)
(Coils of NbTi superconductor cable - 1Mkg of material in all - operated at 2K.)

LHC History

The most ambitious project in high-energy physics ever, and one of the most ambitious in science more generally

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne

1987 Rubbia “Long-Range Planning Committee” recommends Large Hadron Collider as the right choice for CERN’s future

1990 ECFA LHC Workshop, Aachen

1992 General Meeting on LHC Physics and Detectors, Evian les Bains

1993 Letters of Intent (ATLAS and CMS selected by LHCC)

1994 Technical Proposals approved

1996 Approval to move to construction (ceiling of 475 MCHF)

1998 Memorandum of Understanding for construction signed

1998 Construction begins (after approval of Technical Design Reports)

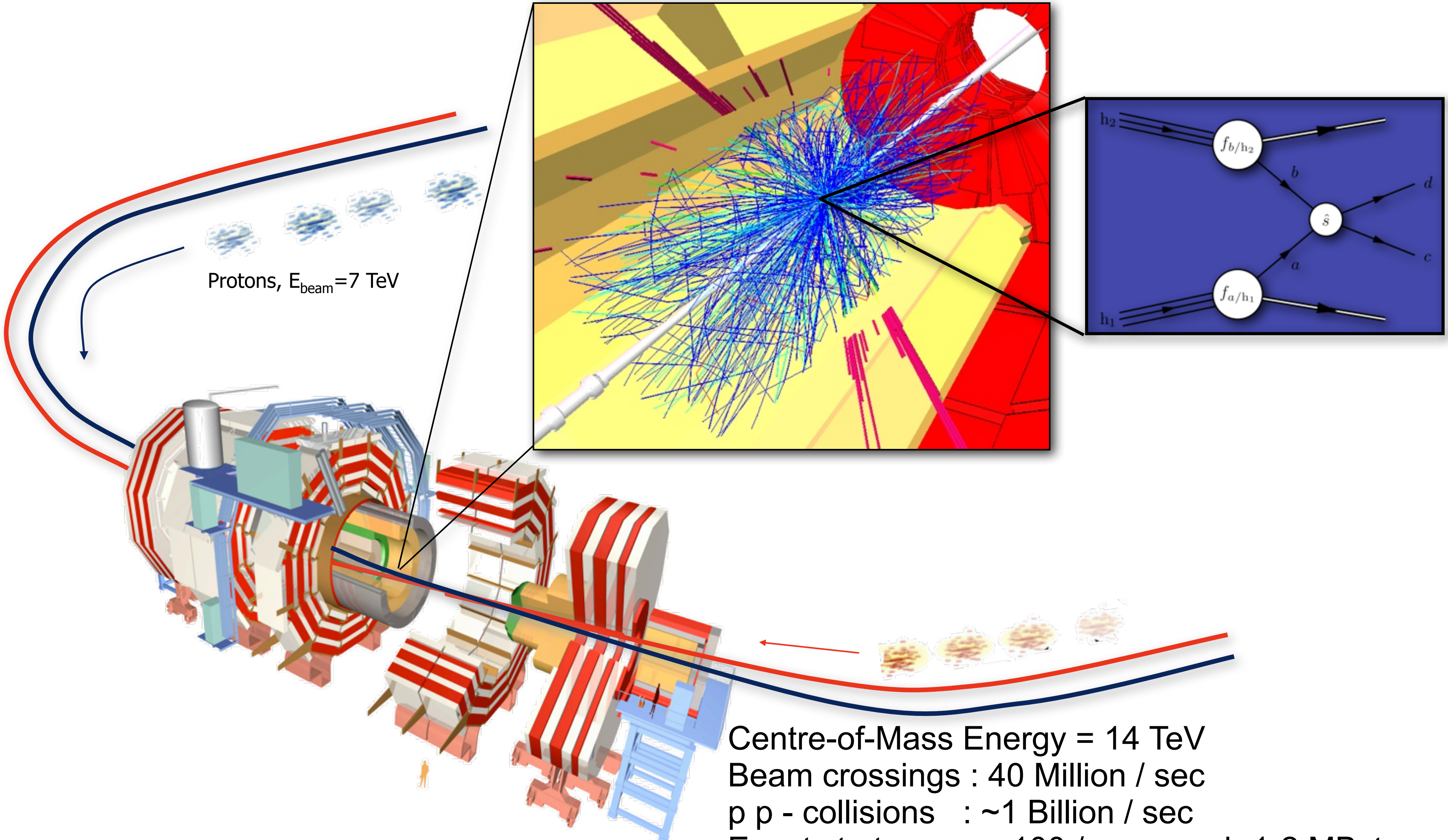
2000 CMS assembly begins above ground. LEP closes

2004 CMS underground caverns completed

2008 CMS ready for first proton-proton Collisions

2008 Official LHC inauguration: 21 Oct 2008

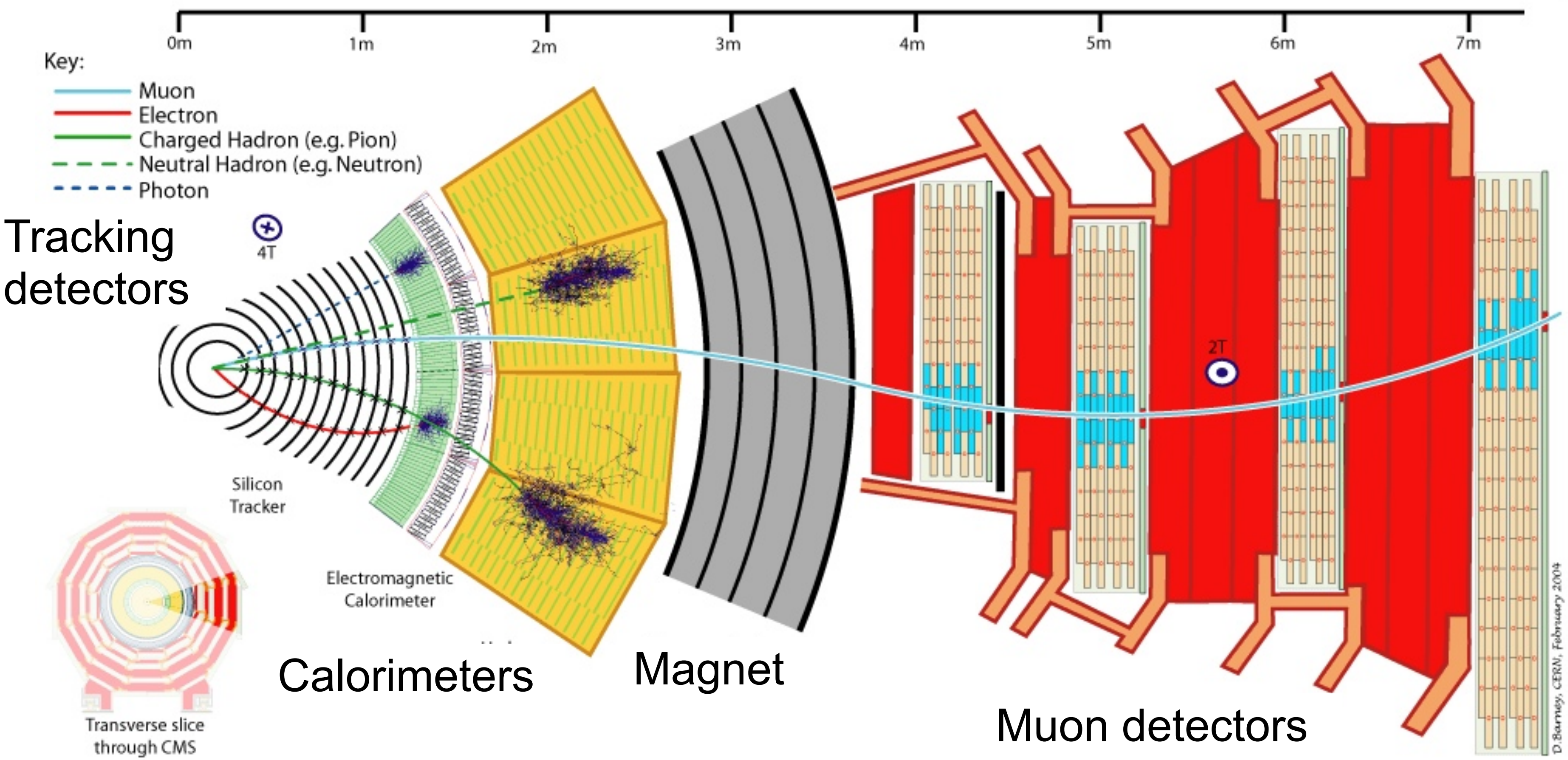
Collisions at the LHC



Centre-of-Mass Energy = 14 TeV
Beam crossings : 40 Million / sec
p p - collisions : ~1 Billion / sec
Events to tape : ~100 / sec, each 1-2 MByte

Particle Detection

- Surround the collision point with instruments in order to identify the types of particles and their energy or momentum to reconstruct collisions



Detector Design

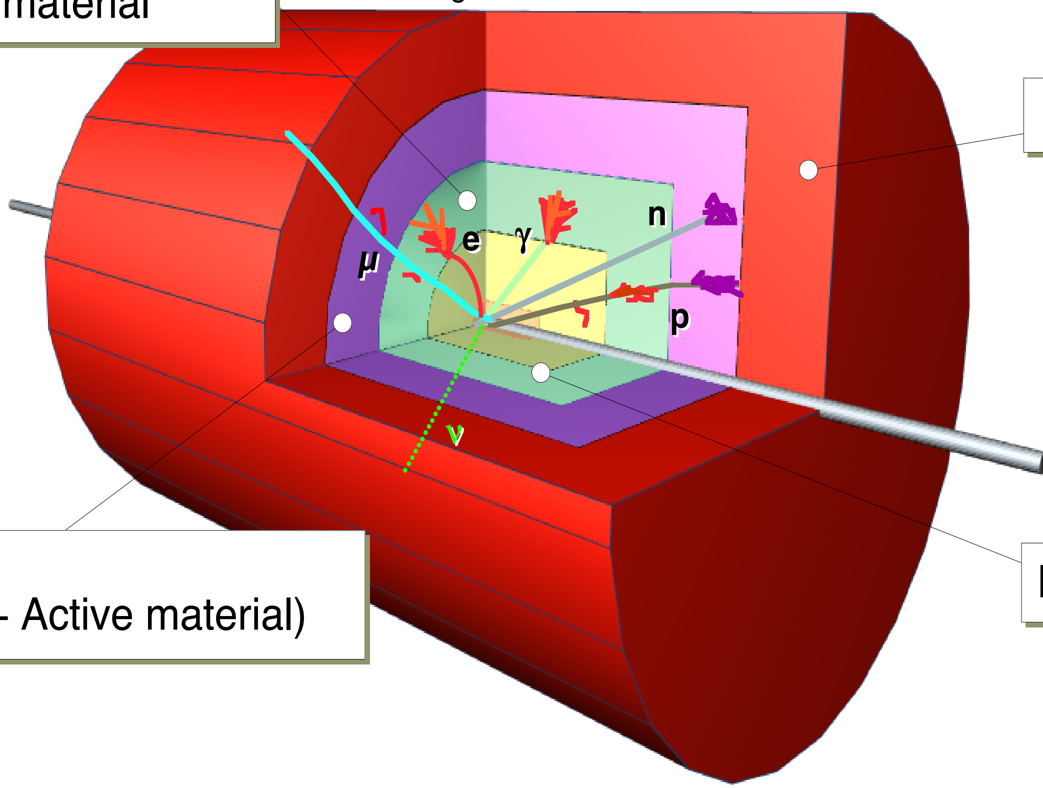
- LHC detectors must have fast response:
  - otherwise will integrate over many bunch crossings
  - typical response time: 20-40 ns
    - integrate over 1-2 bunch crossings → pile-up of 25-50 minimum bias events
    - very challenging readout electronics
- LHC detectors must be highly granular:
  - minimize probability that pile-up particles be in the same detectors element as interesting object
    - large number of readout channels ≈ O(107)
    - high cost
- LHC detectors must be radiation resistant:
  - high flux of particles from pp collisions → high radiation environment
  - up to 1017 n/cm2 in 10 years of LHC operation
  - up to 10 Gy (1 Gy = unit of absorbed energy = 1 Joule/kg)
- Can store data at ≈100 Hz:

Detectors at the LHC

Materials with high number of protons + Active material

Hermetic calorimetry
• Missing Et measurements

Electromagnetic and Hadron calorimeters
• Particle identification (e, γ Jets, Missing E_T)
• Energy measurement



Heavy materials

Muon detector
• μ identification

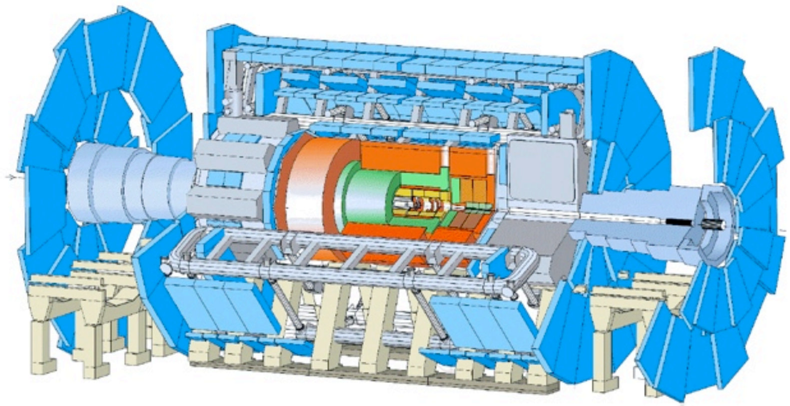
Heavy materials
(Iron or Copper + Active material)

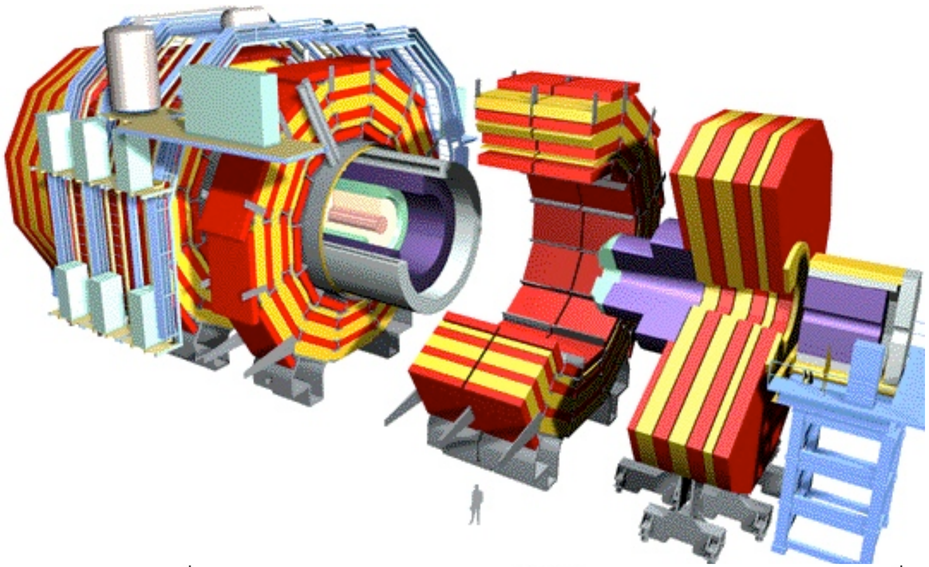
Light materials

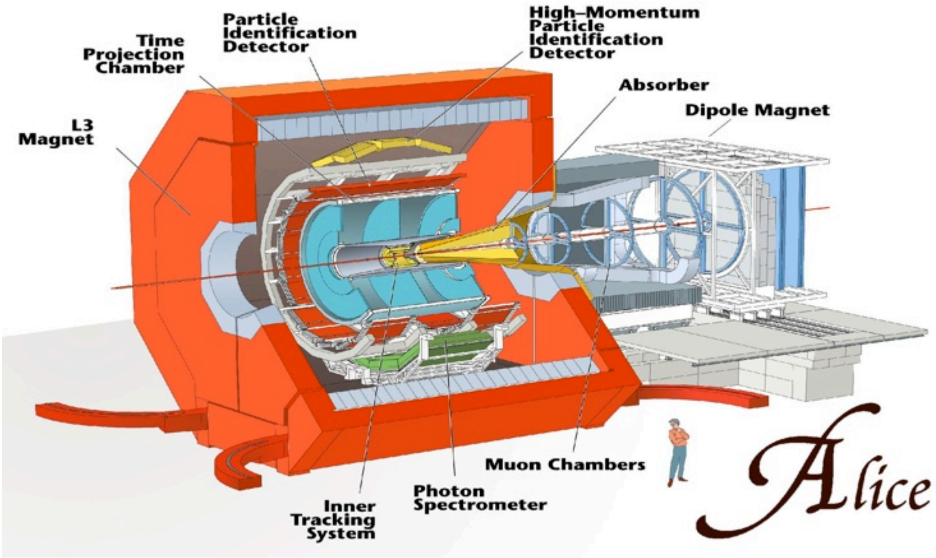
Central detector
• Tracking, p_T, MIP
• Em. shower position
• Topology
• Vertex

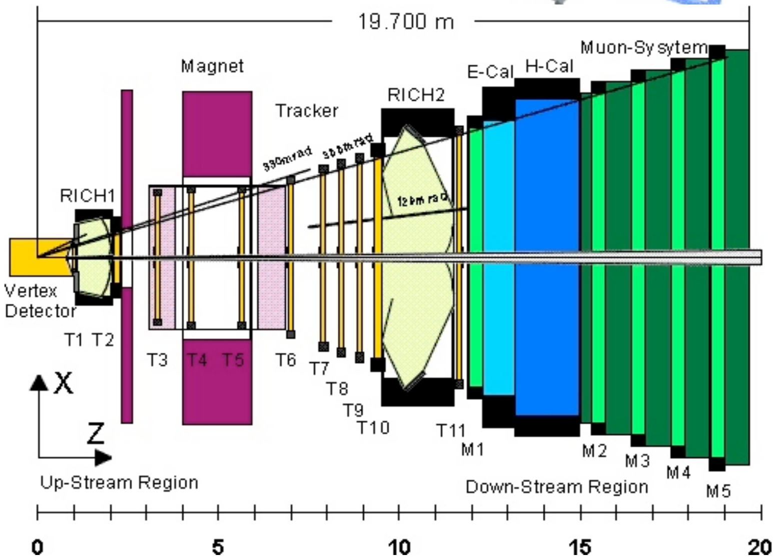
Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

LHC Experiments









Compact Muon Solenoid Detector

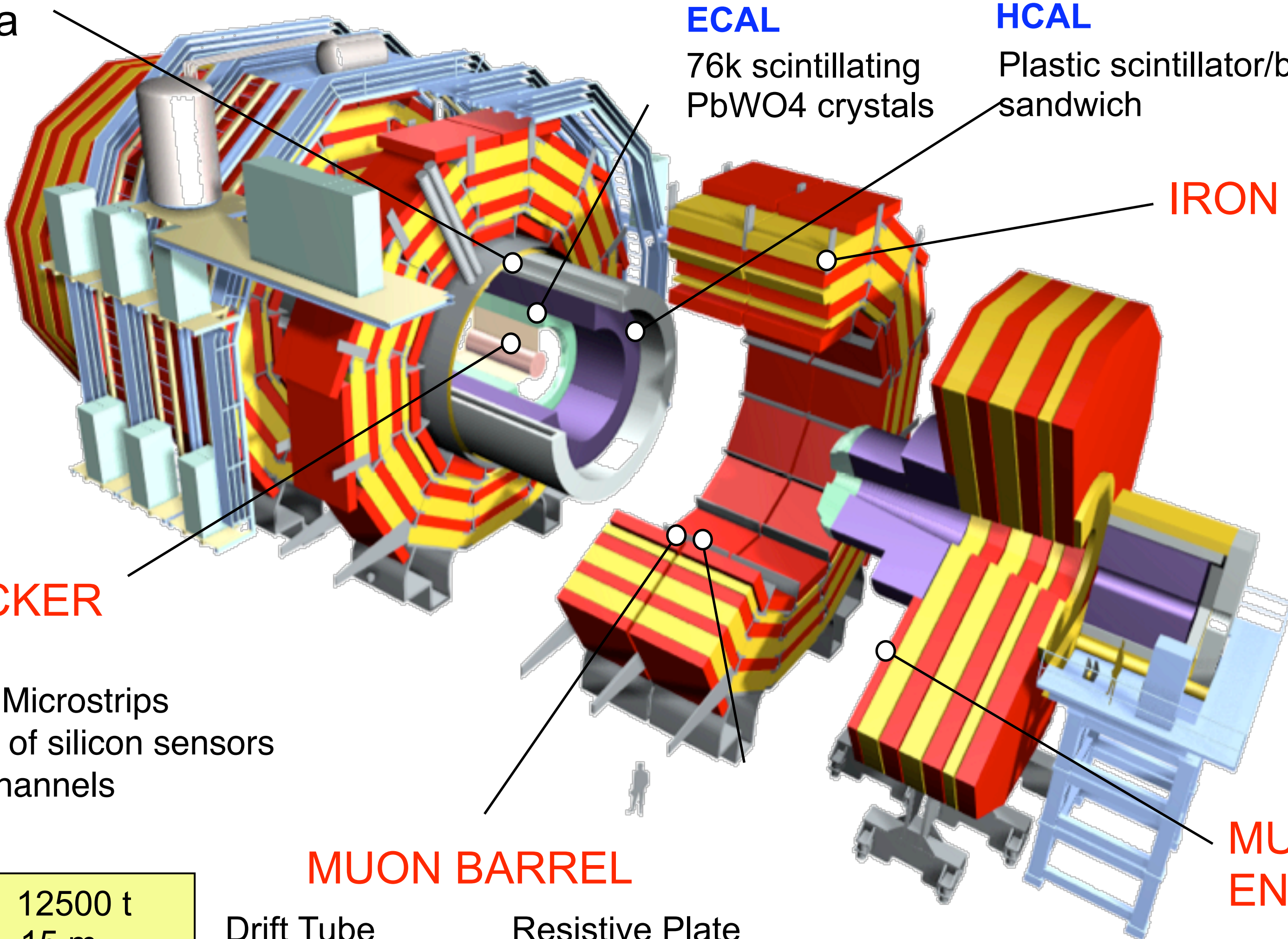
Superconducting Coil, 4 Tesla

CALORIMETERS

ECAL
76k scintillating PbWO4 crystals

HCAL
Plastic scintillator/brass sandwich

IRON YOKE



TRACKER

Pixels
Silicon Microstrips
210 m² of silicon sensors
9.6M channels

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

MUON BARREL

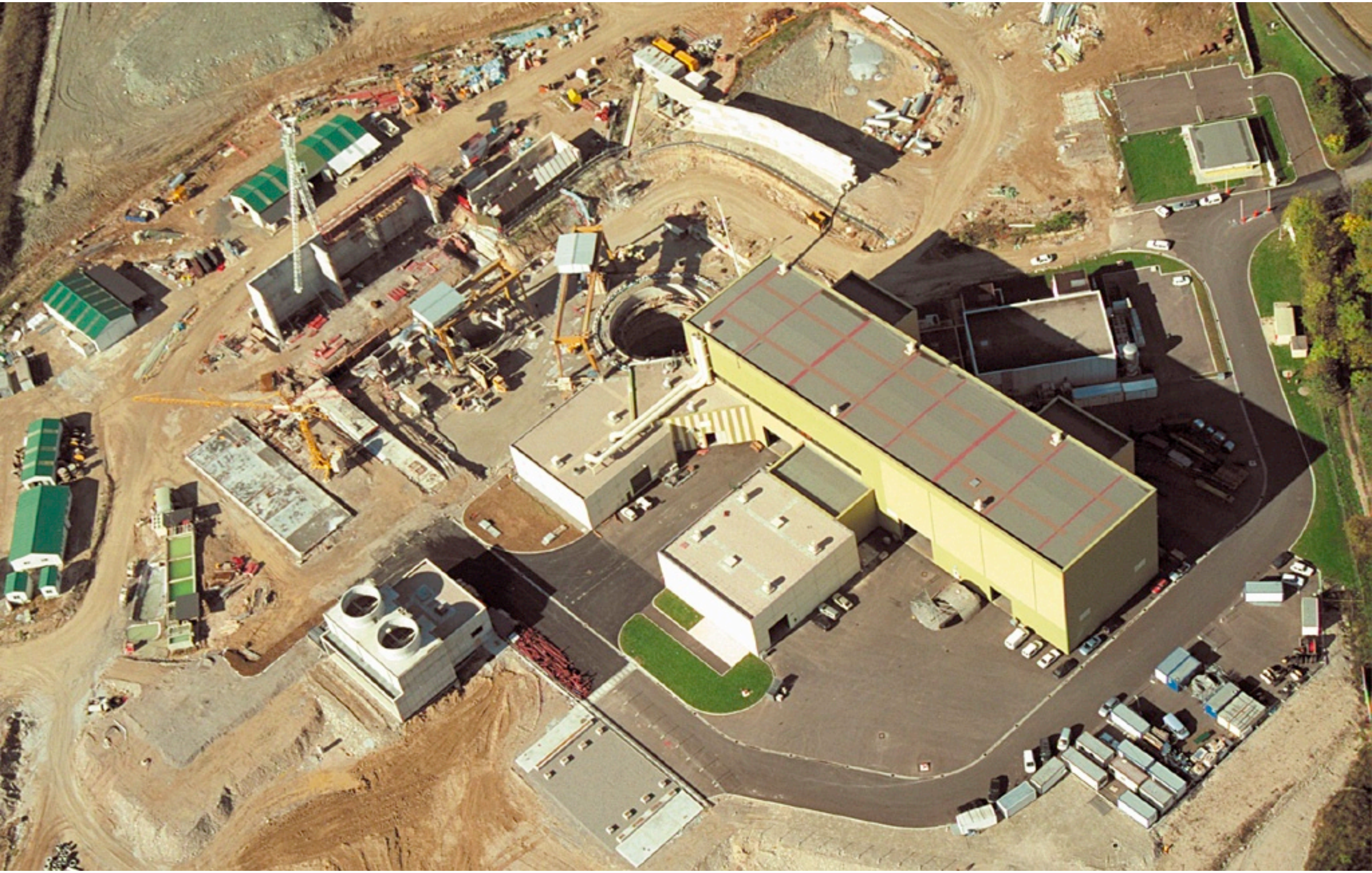
Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

MUON ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

CMS Site Under Construction



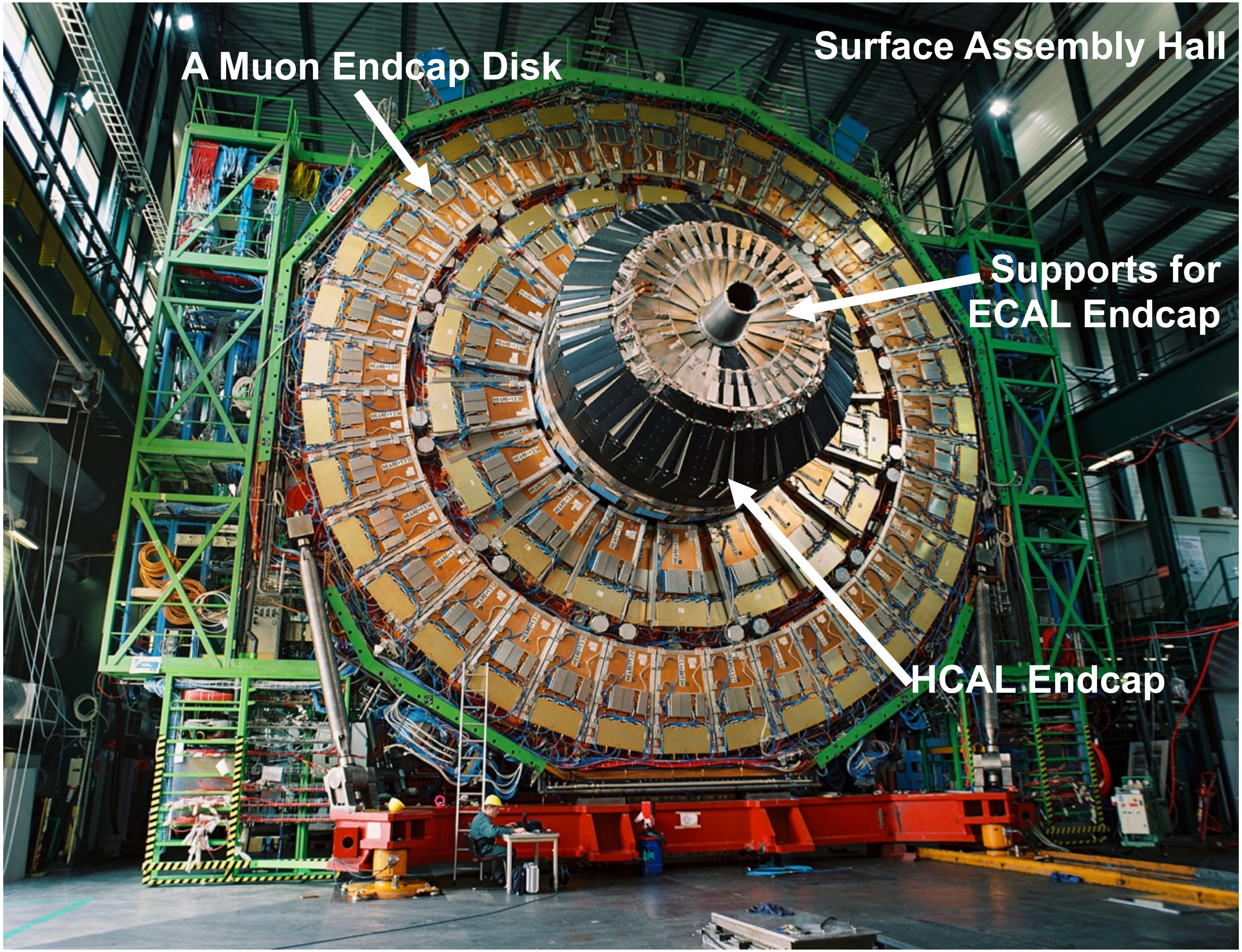
Experiment Cavern

2003

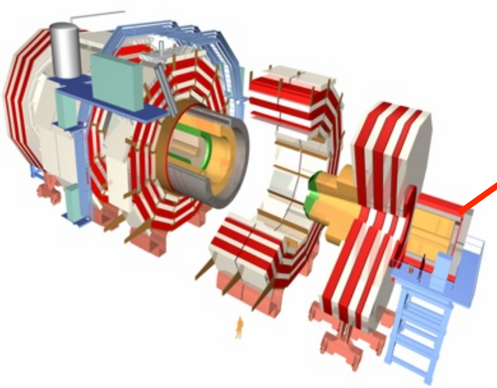
2004

CMS

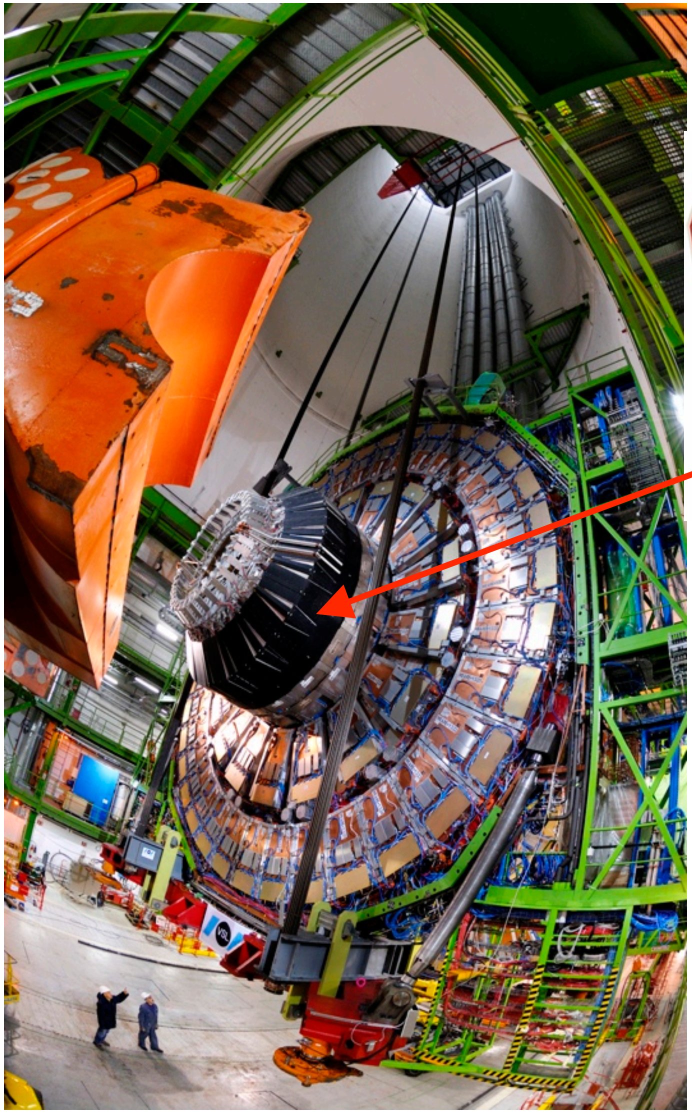
CMS Assembled & Tested on Surface

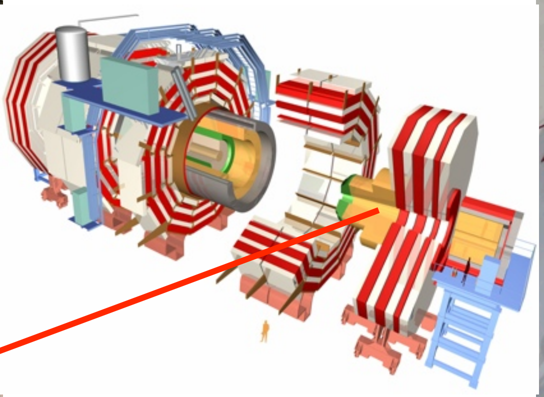


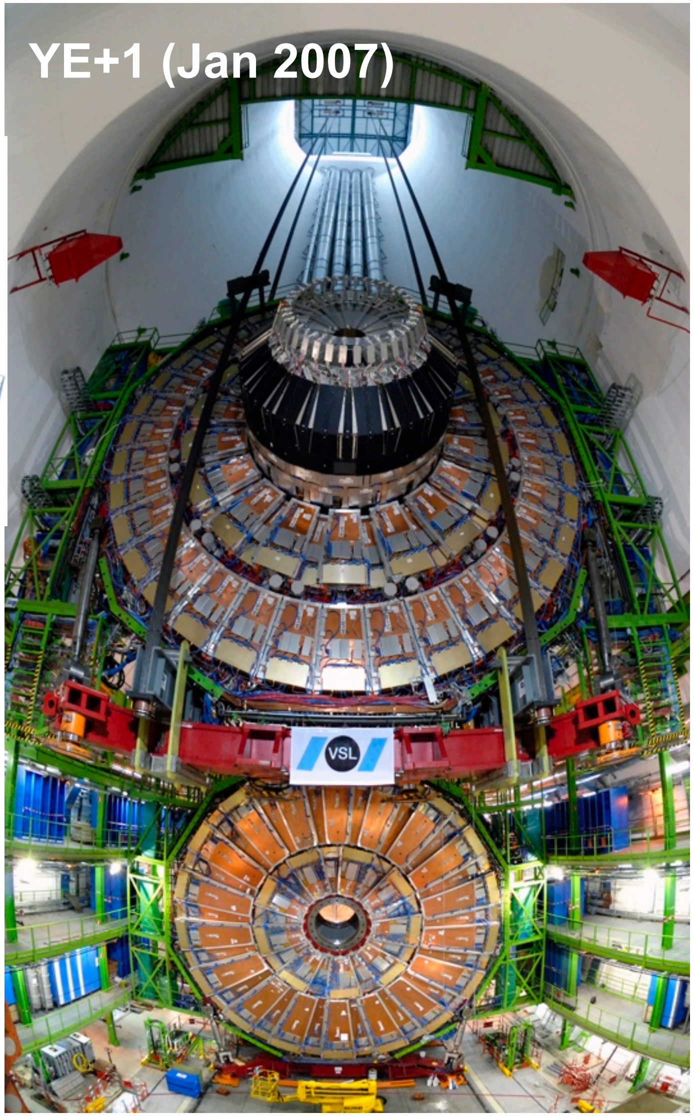
Lowering the Detector



Lowering the Detector

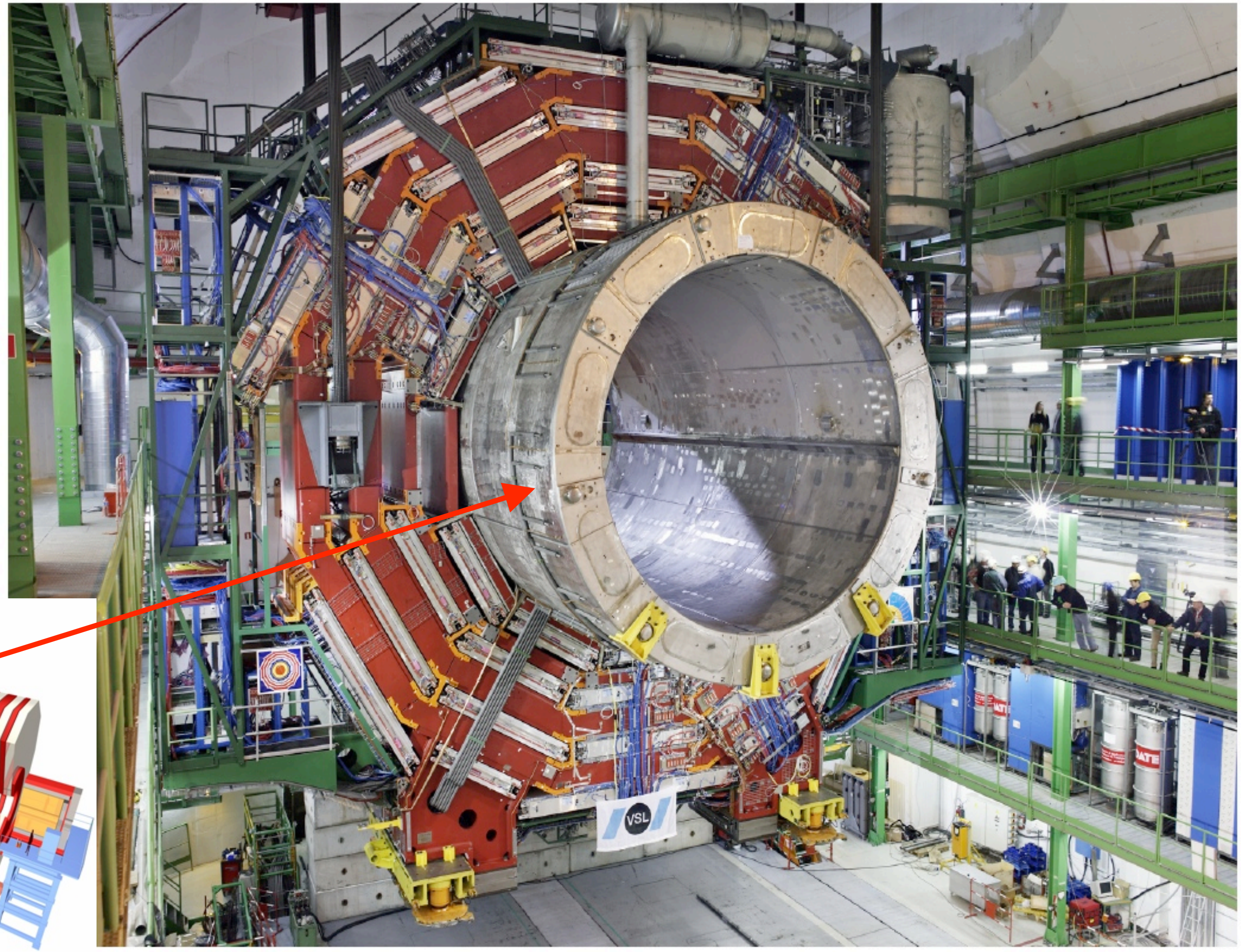


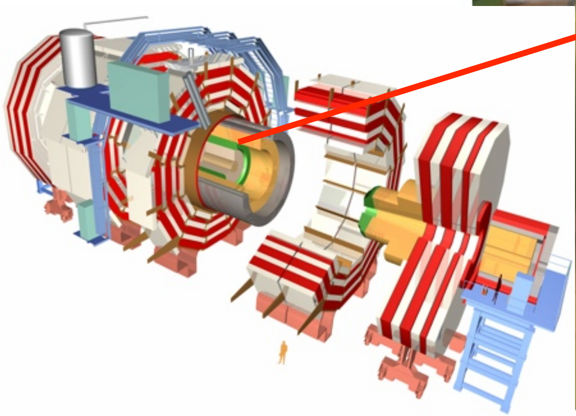




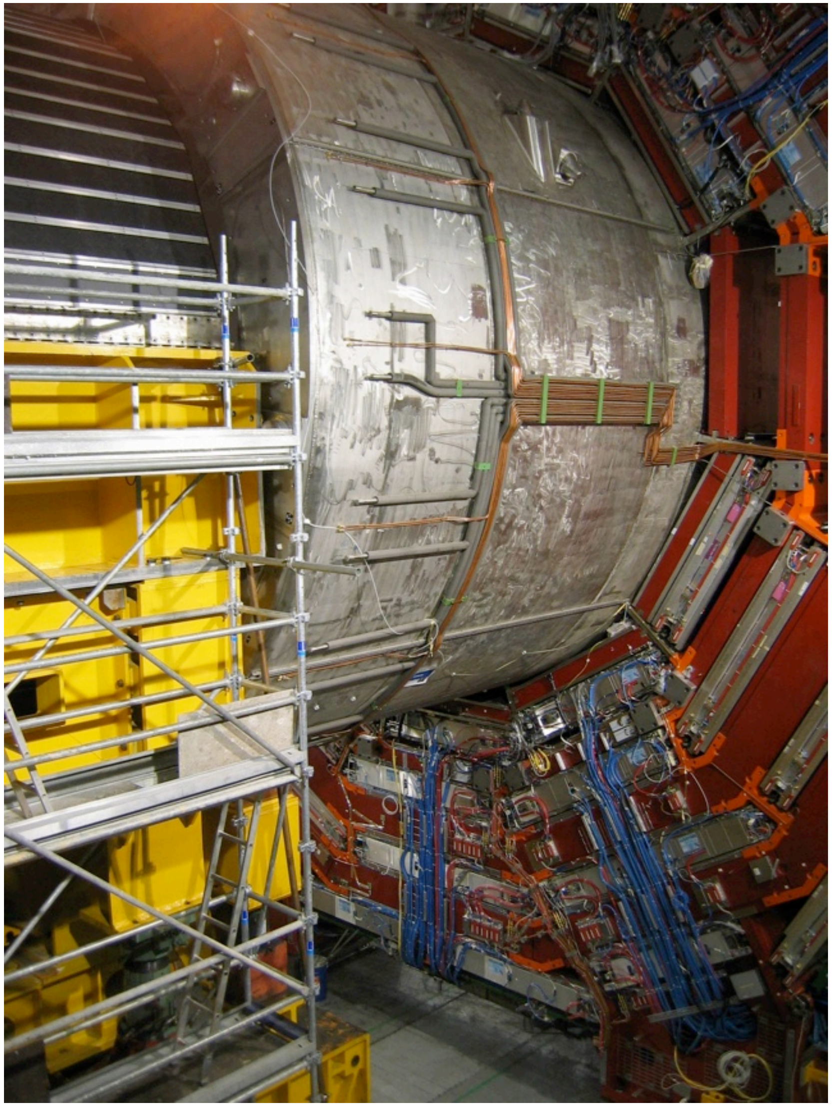
Lowering the Detector

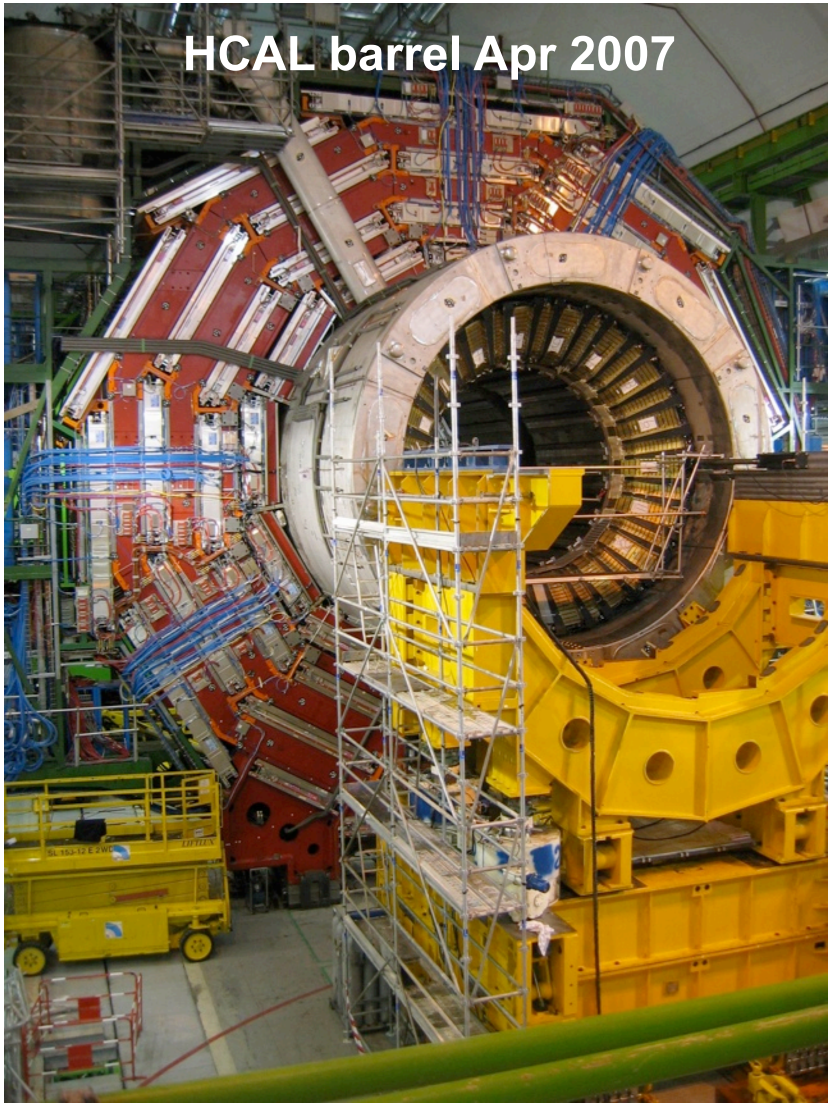
YB0 lowering



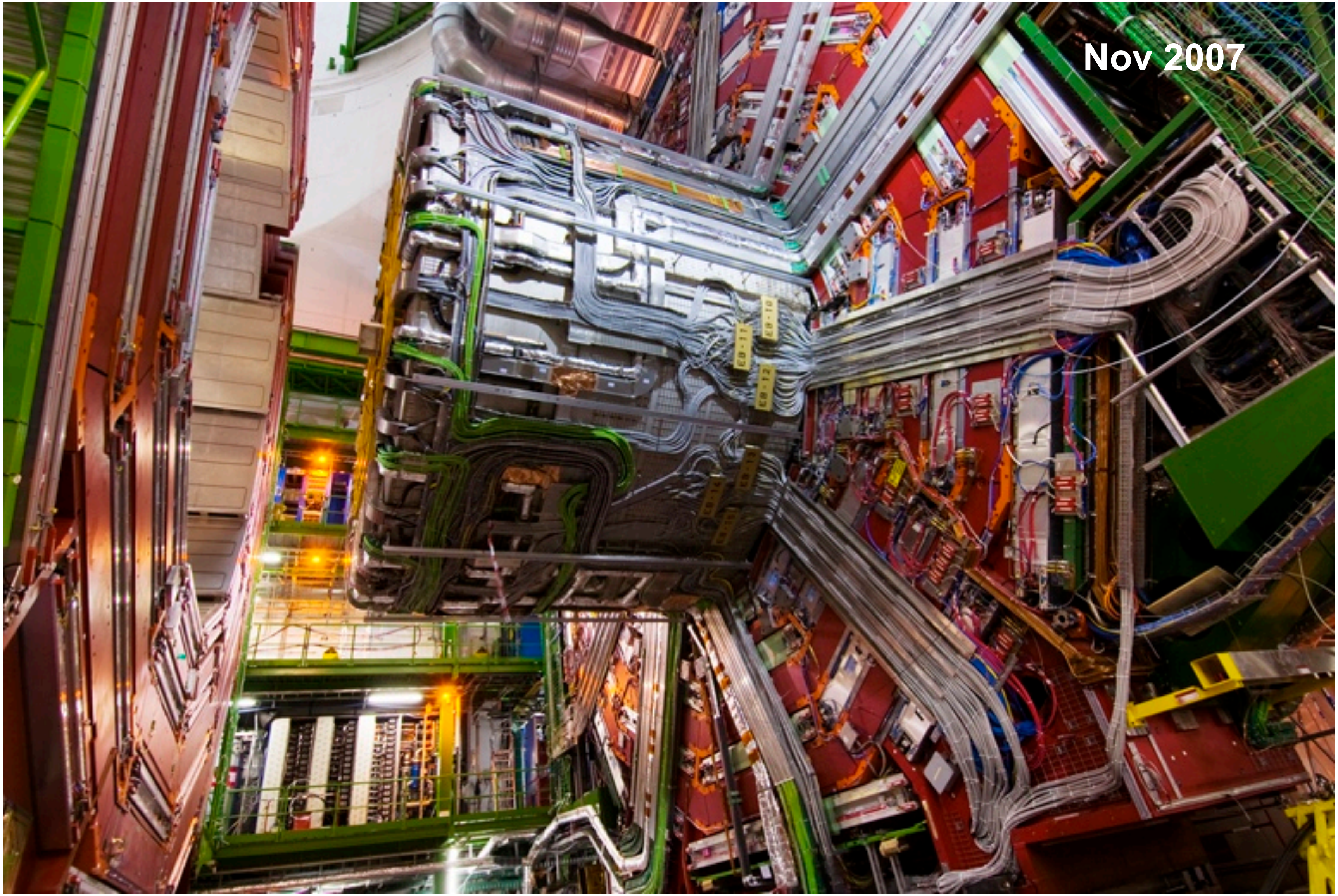


Putting the Detector in Place

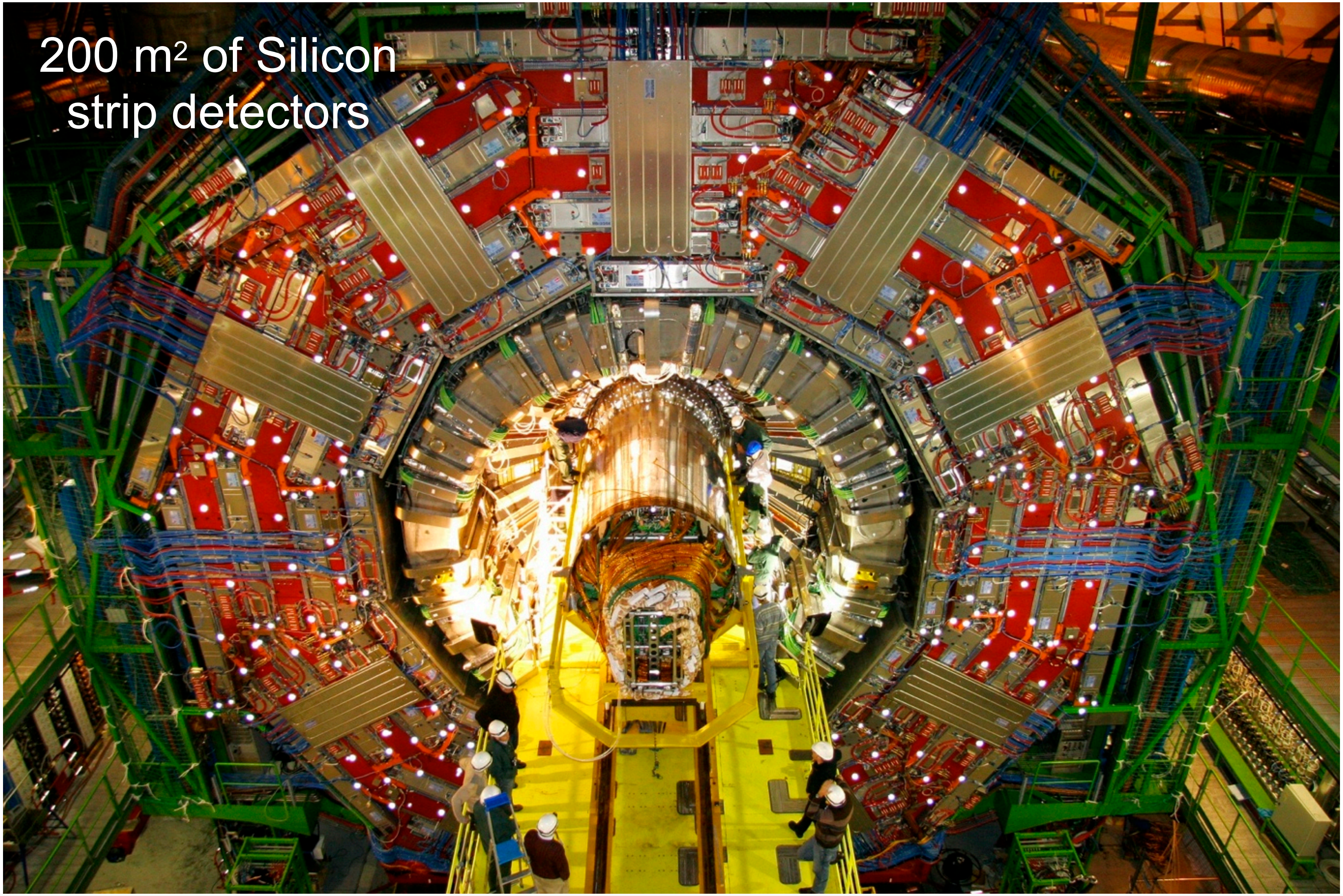




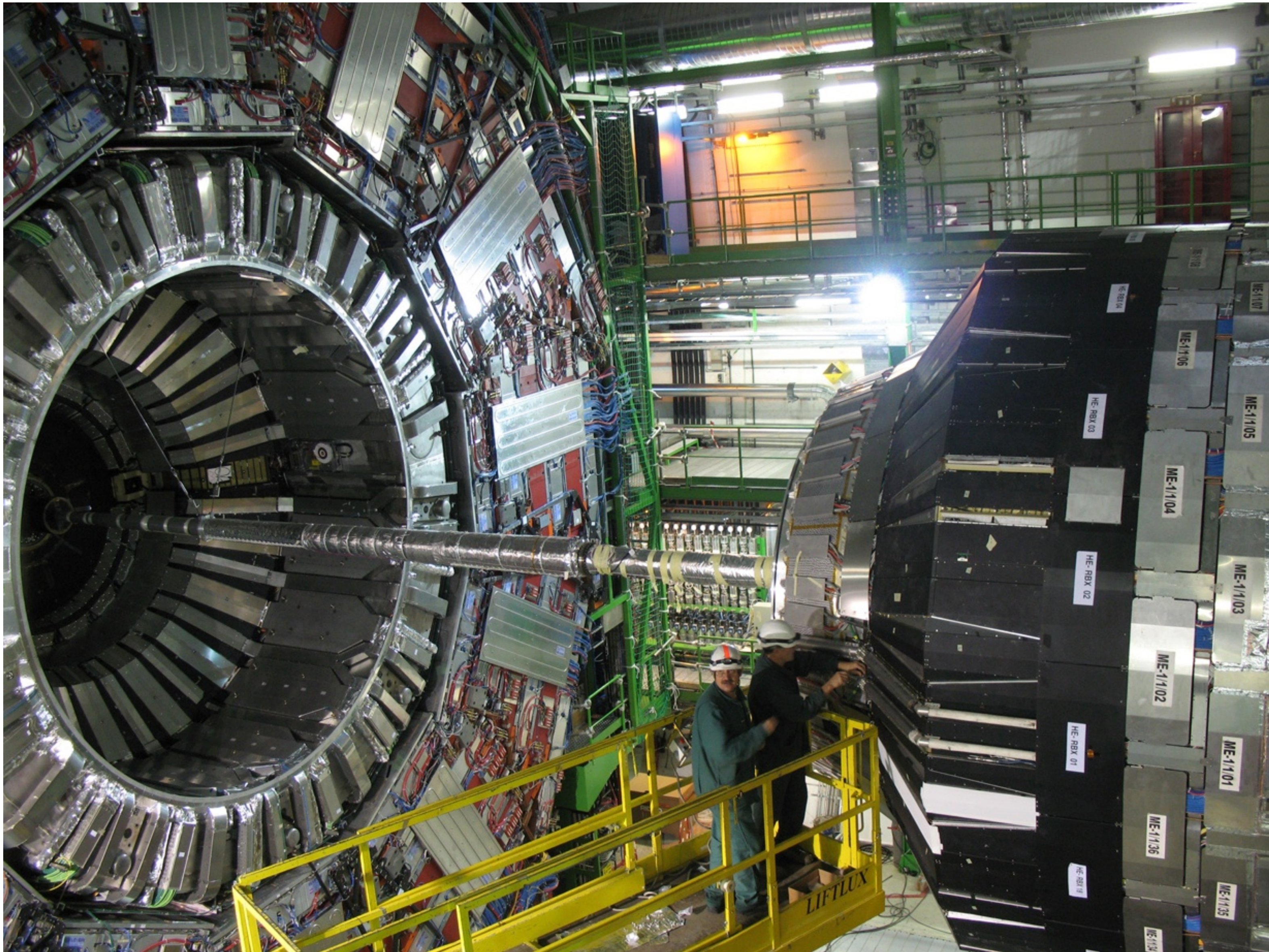
Completion of Services on YB0



Silicon Strip Tracker, Dec 2007



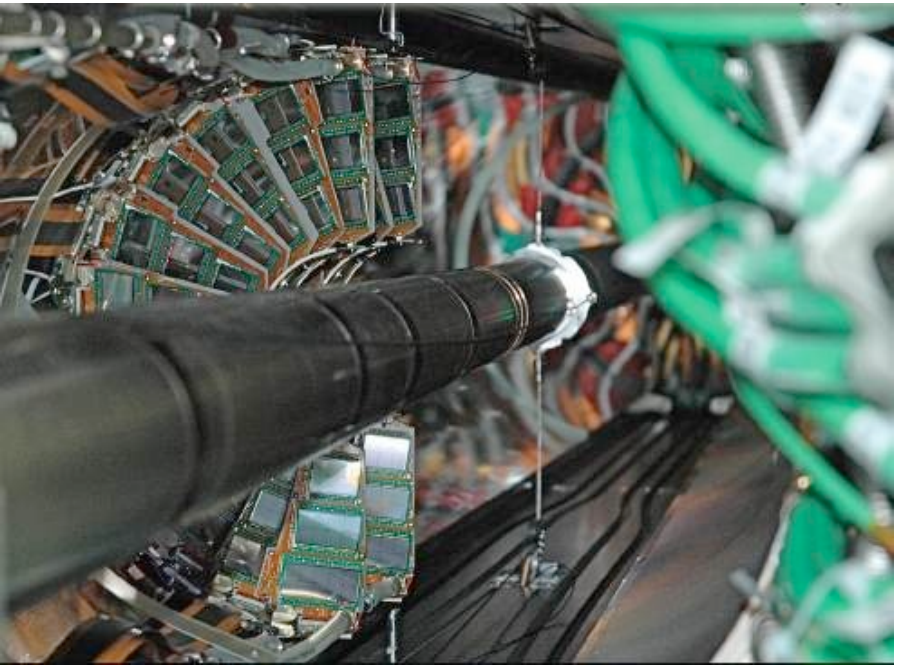
Beam-pipe Installed, May 2008



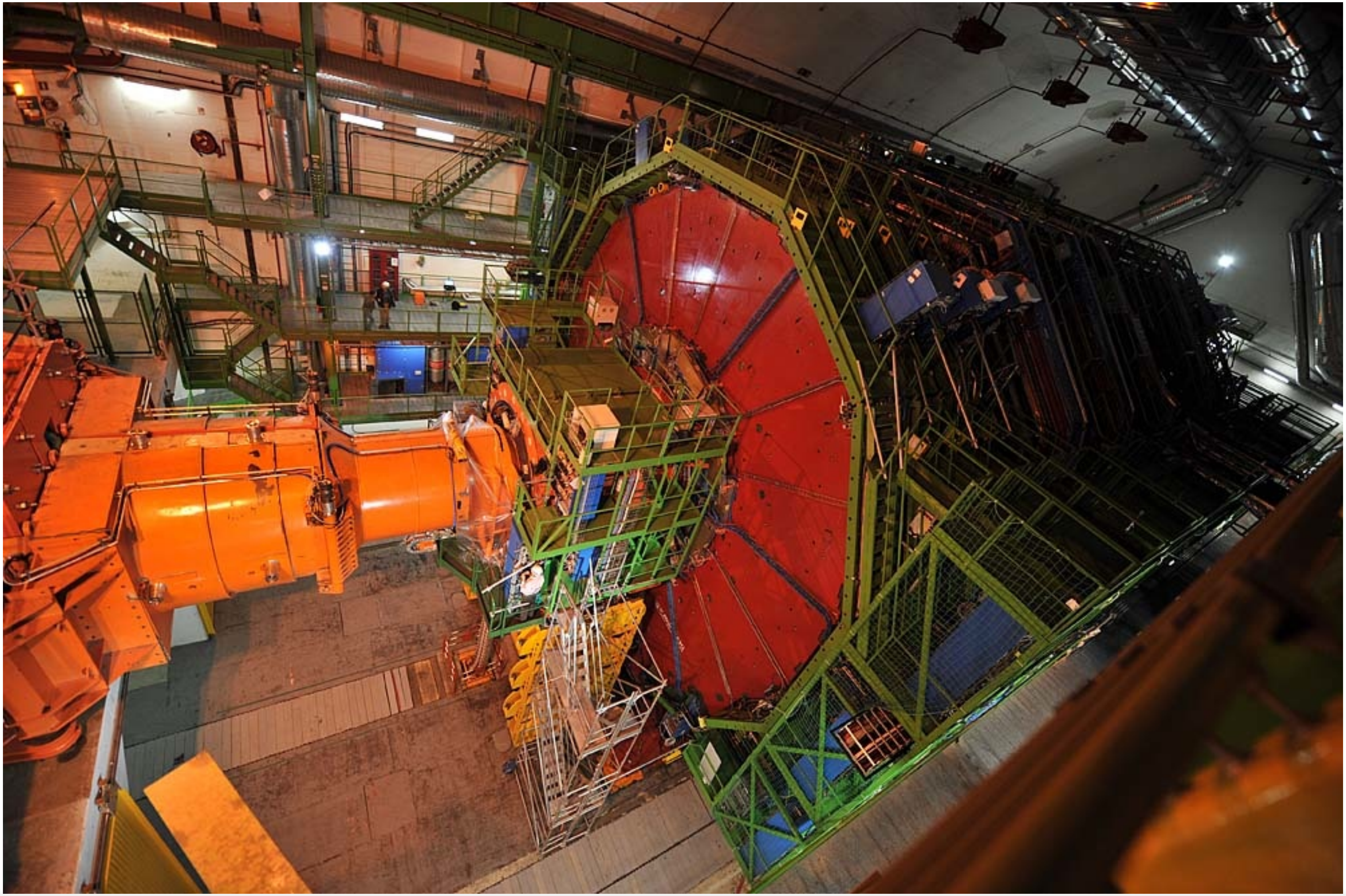
Installation of the Pixel System, Aug 2008

A 66 megapixel "camera"

- Makes precise measurements of charged particle impact parameters to tag particles with a small but finite lifetime



Final Closure – Sep 2008



Cosmic Ray Muons

…while waiting for LHC collisions
Cosmic ray muons used as probe of detector performance during no beam!

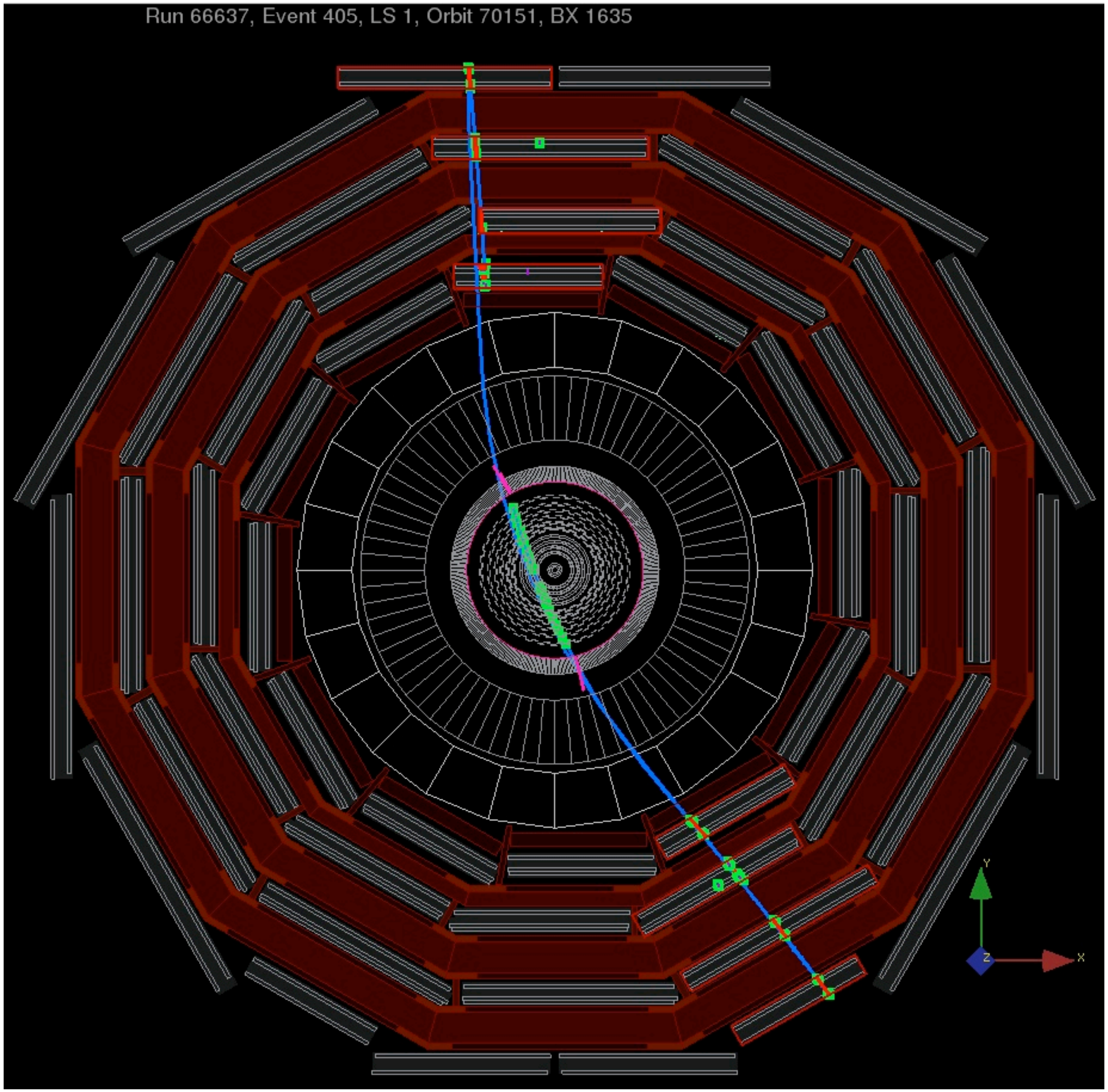
Total rate is about 350 Hz at 100 m depth (about 1% of rate on surface of Earth)

Cosmic rays are continuously bombarding Earth's atmosphere with far more energy than protons will have at the LHC, so cosmic rays would produce everything LHC can produce.

They have done so throughout the 4.5 billion years of the Earth's existence, and the Earth is still here!

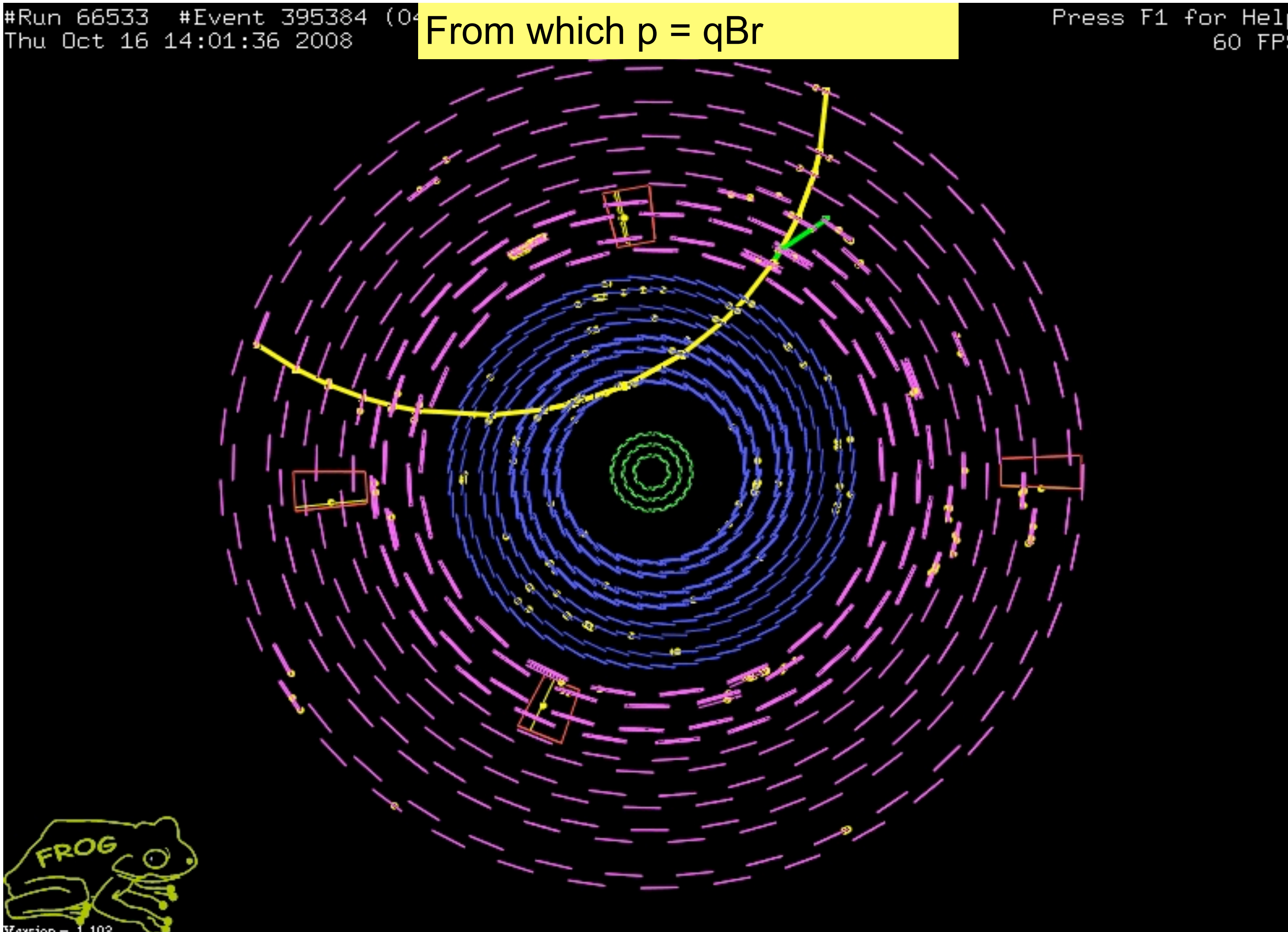
The LHC just lets us see these processes in the lab (though at a much lower energy than some cosmic rays).

Cosmic Muons

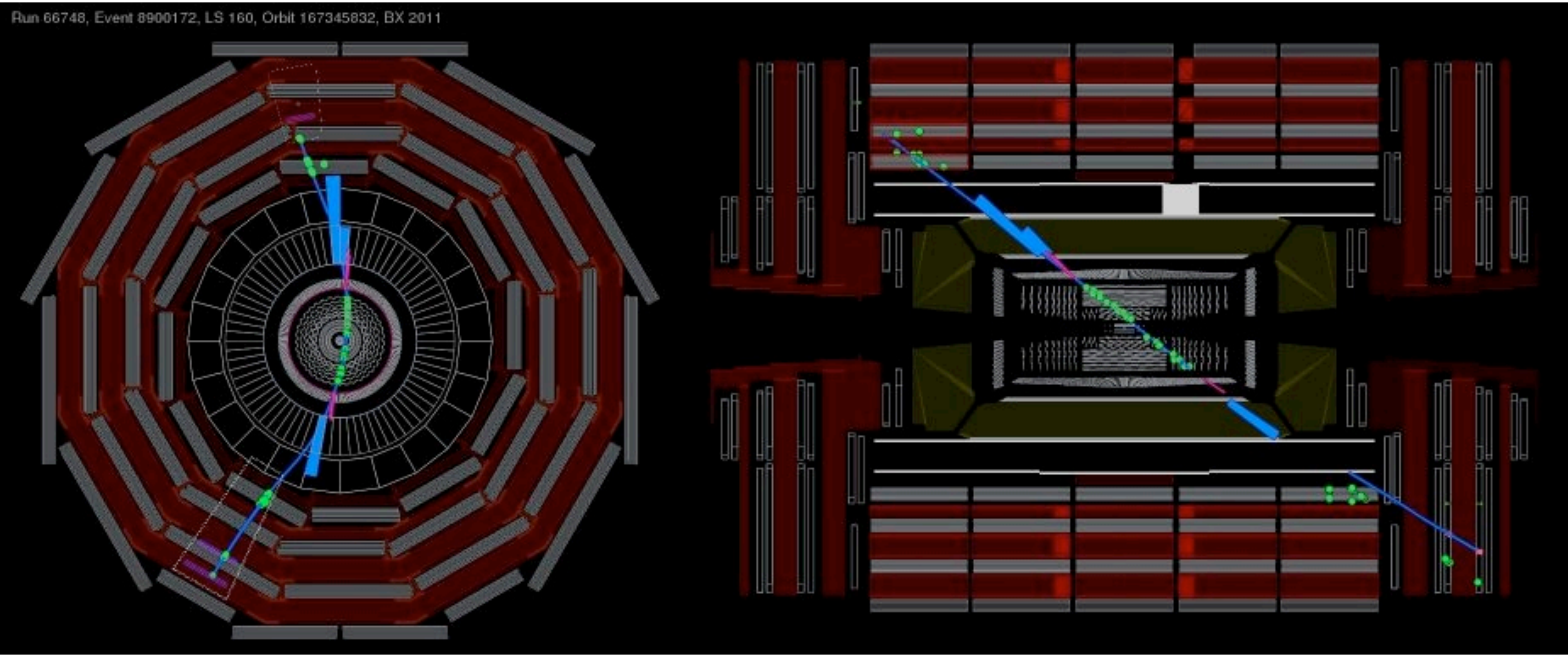


$F=q(v\times B)$

From which $p = qBr$



Cosmic Muons



LHC Start-up: Sep. 10, 2008

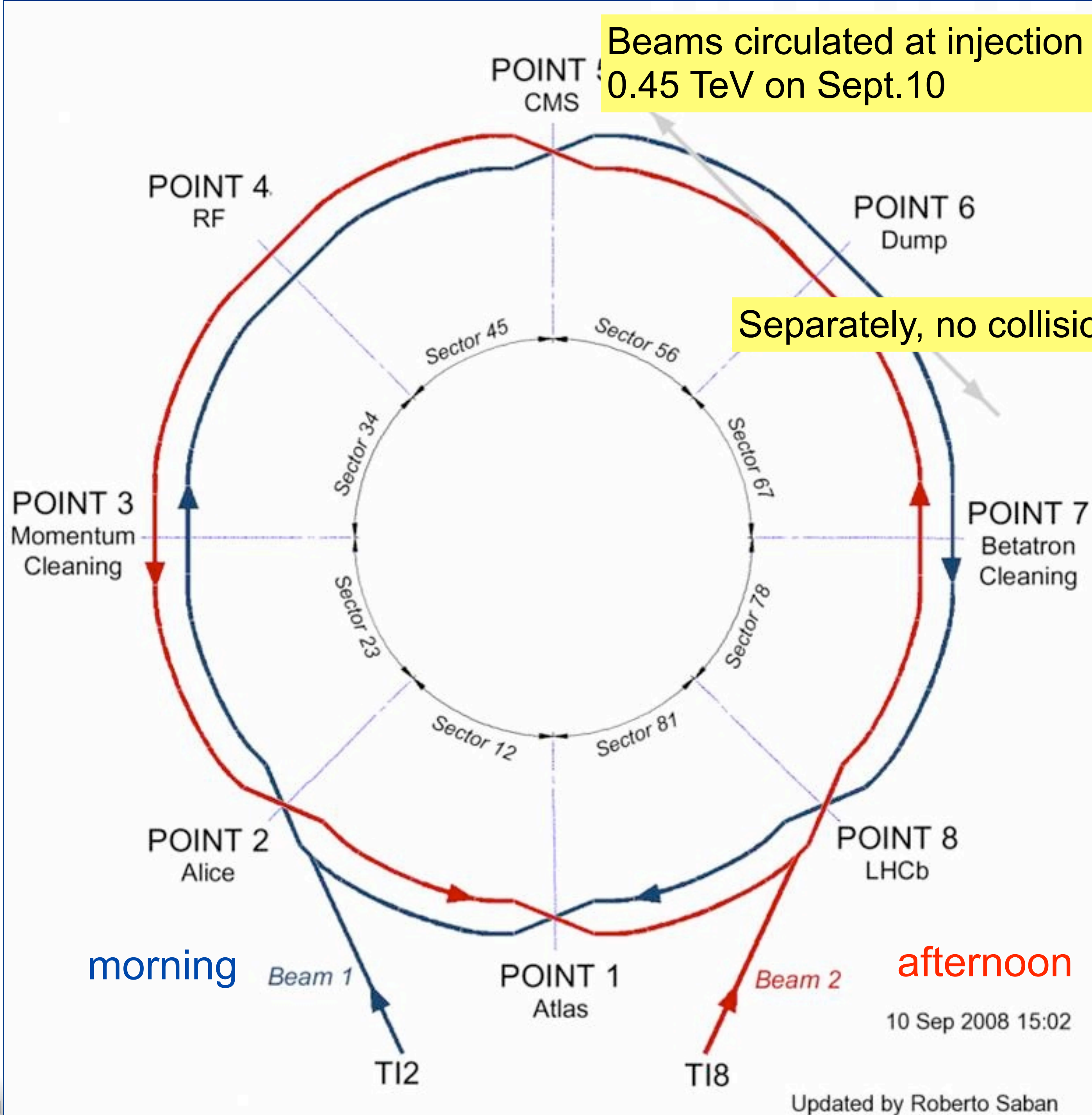
Sep.10 – Big Media Day

A Brief Diary of LHC Events

- Aug. 8 and Aug. 22 weekends
  - "Synchronization tests" sent protons through the first arcs of the LHC in both directions, past ALICE and then LHCb experiments
  - By Aug.22, alternate injections of beam 1 and 2: "…pretty blooming amazing…"
- Sun/Mon, 7-8 Sep.
  - Single shots of beam 1 onto a collimator 150m upstream of CMS.
- Tues, 9. Sep.
  - Additional single shots of beam 1 onto a collimator at CMS
- Wed., 10 Sep. (Media Day!)
  - Beam 1 circulated in the morning, 3 turns by 10:40am (1 hour)
  - Beam 2 circulated by 3:00pm
  - 300 turns of beam 2 by 11:15pm
- Thurs., 11 Sep.
  - RF system captures beam at 10:30pm (millions of orbits)

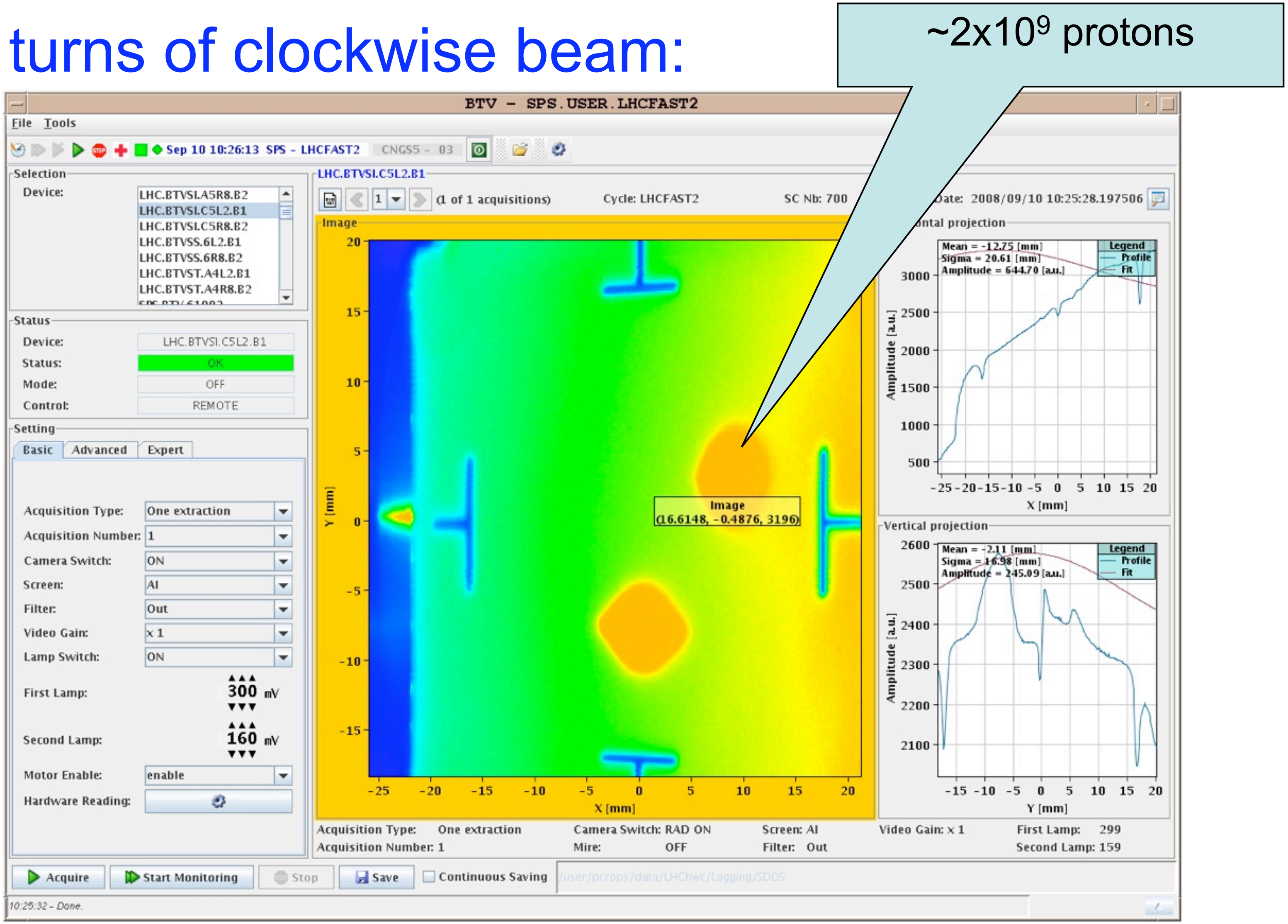
Beams circulated at injection energy of 0.45 TeV on Sept.10

Separately, no collisions



Sep. 10 Orbits

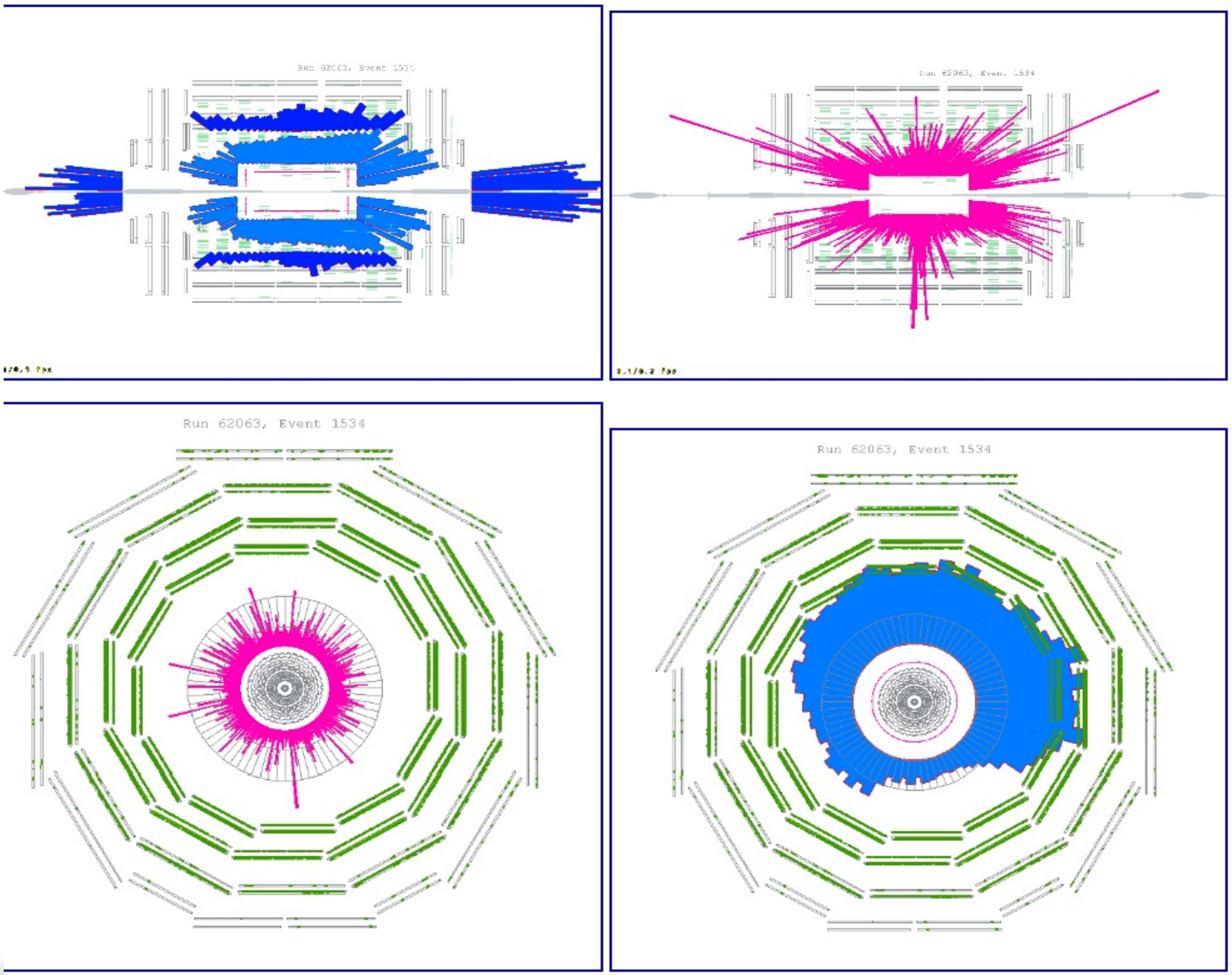
- 2 turns of clockwise beam:



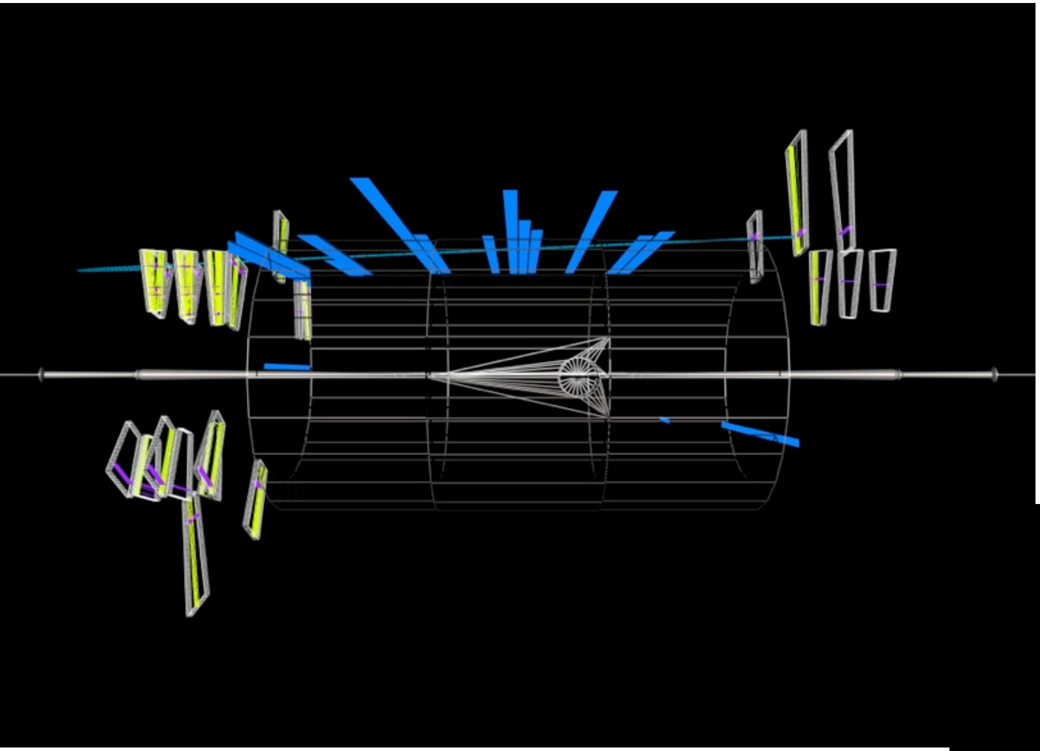
First Events: Collimators Closed

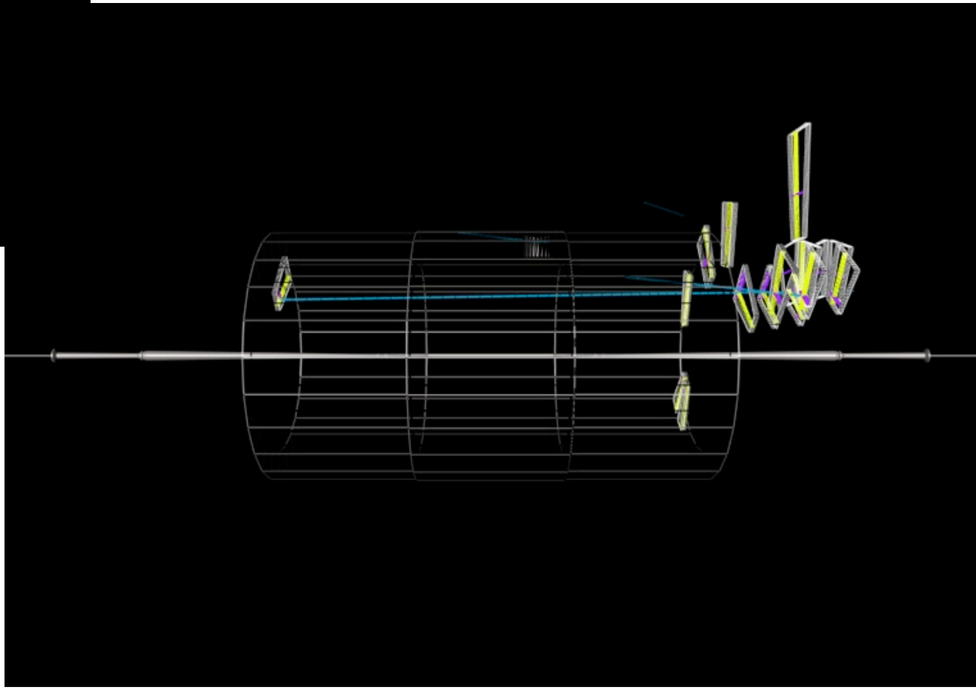
~2×10⁹ protons on collimator ~150 m upstream of CMS

ECAL- pink; HB,HE - light blue; HO,HF - dark blue; Muon DT - green; Tracker Off



Beam Halo Events

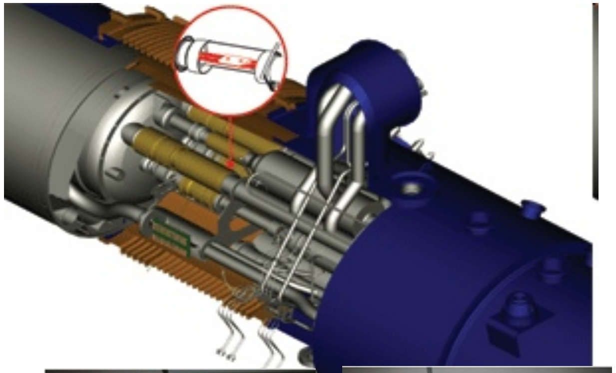




The Excitement of the First LHC Beam Measurements at CMS (September 2008)

Setback: Friday, Sep. 19

- An incident occurred during a powering test of one LHC sector for commissioning beam operation to 5 TeV
  - Massive helium loss in one arc of the tunnel (2 tons initially), cryogenics and vacuum lost
- The cause of the incident was determined to be a faulty electrical connection ("bus bar") between a dipole and a quadrupole
  - Mechanical damage occurred
  - Need to extract and repair dipole and quadrupole magnets in the region



Not enough time to make repairs before winter shutdown
→ Aim to restart LHC operations Fall 2009

Arc and Helium Released

Physics Selection

Interactions/s:

- Lum = 10^{34} $cm^{-2}s^{-1}$ = 10^{7} mb^{-1} Hz
- $\sigma_{inel}(pp)$ = 70 mb
- Interaction Rate, R = 7×10^{8} Hz

Events/ beam crossing:

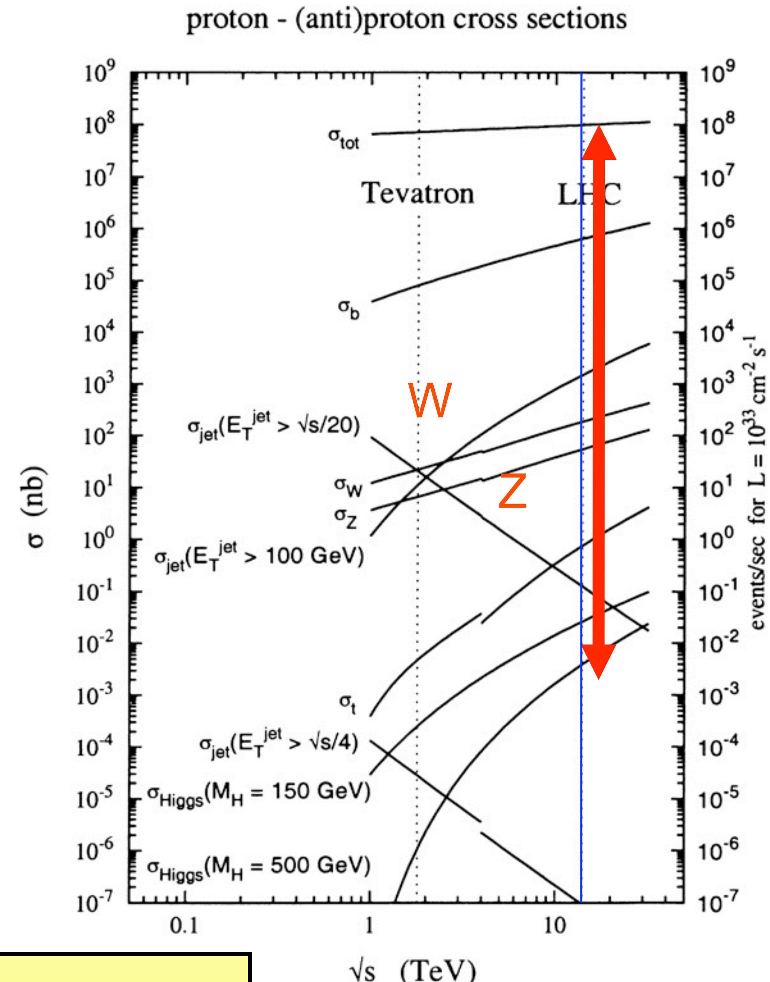
- Δt = 25 ns = 2.5×10^{-8} s
- Interactions/crossing = 17.5

Cross-section of physics processes:

- inelastic: 10^{9} Hz
- Higgs (600 GeV) : 10^{-2} Hz

Selection needed: $1:10^{10\ -11}$

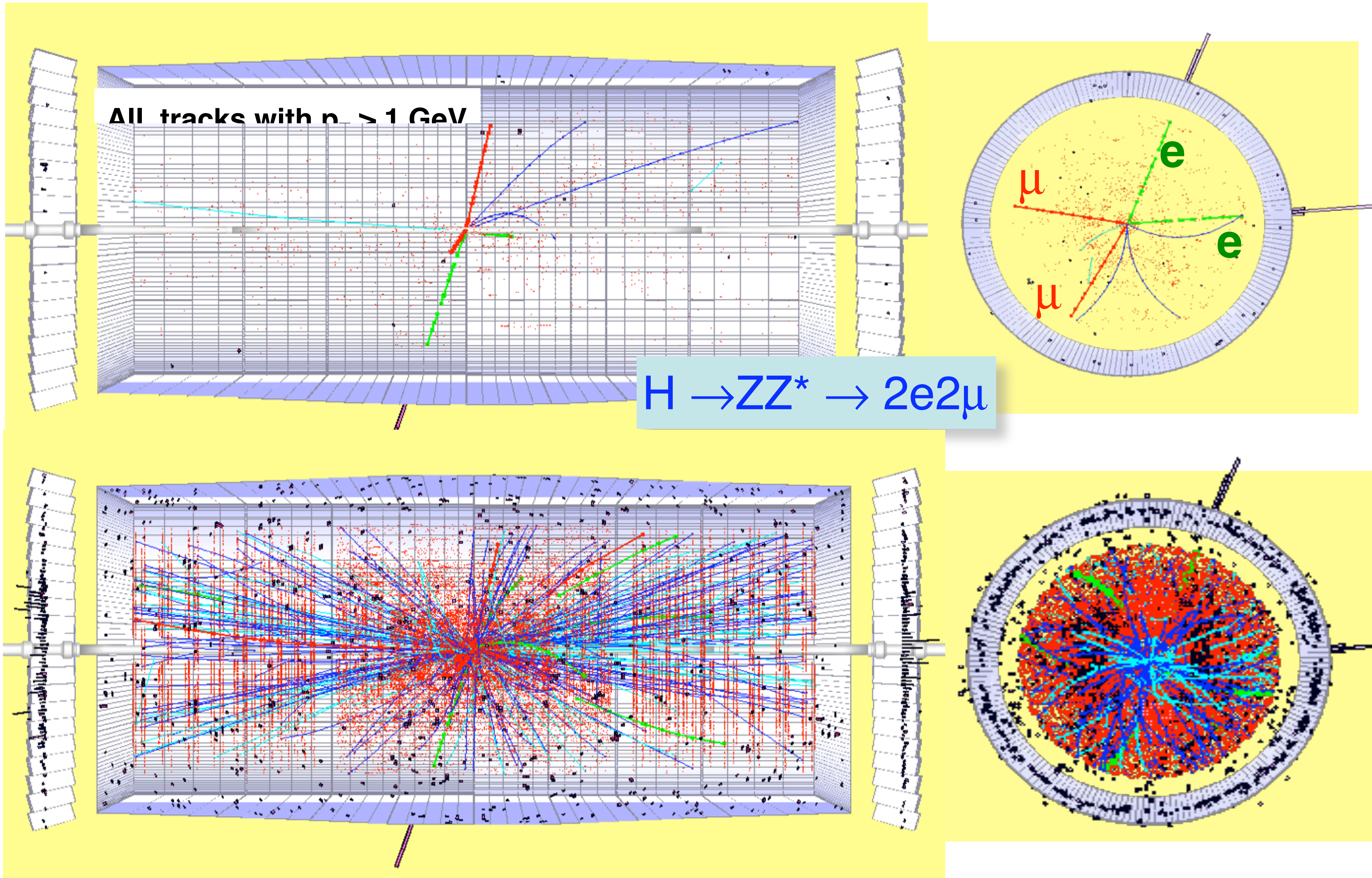
- before branching fractions



Operating conditions:

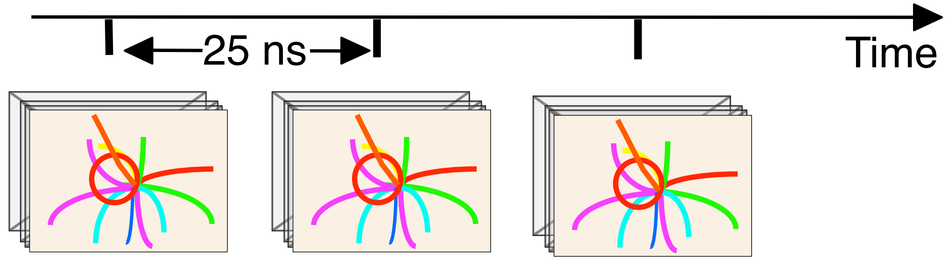
1) A “good” event containing a Higgs decay +
2) ~20 extra “bad” (minimum bias) interactions

pp Collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}



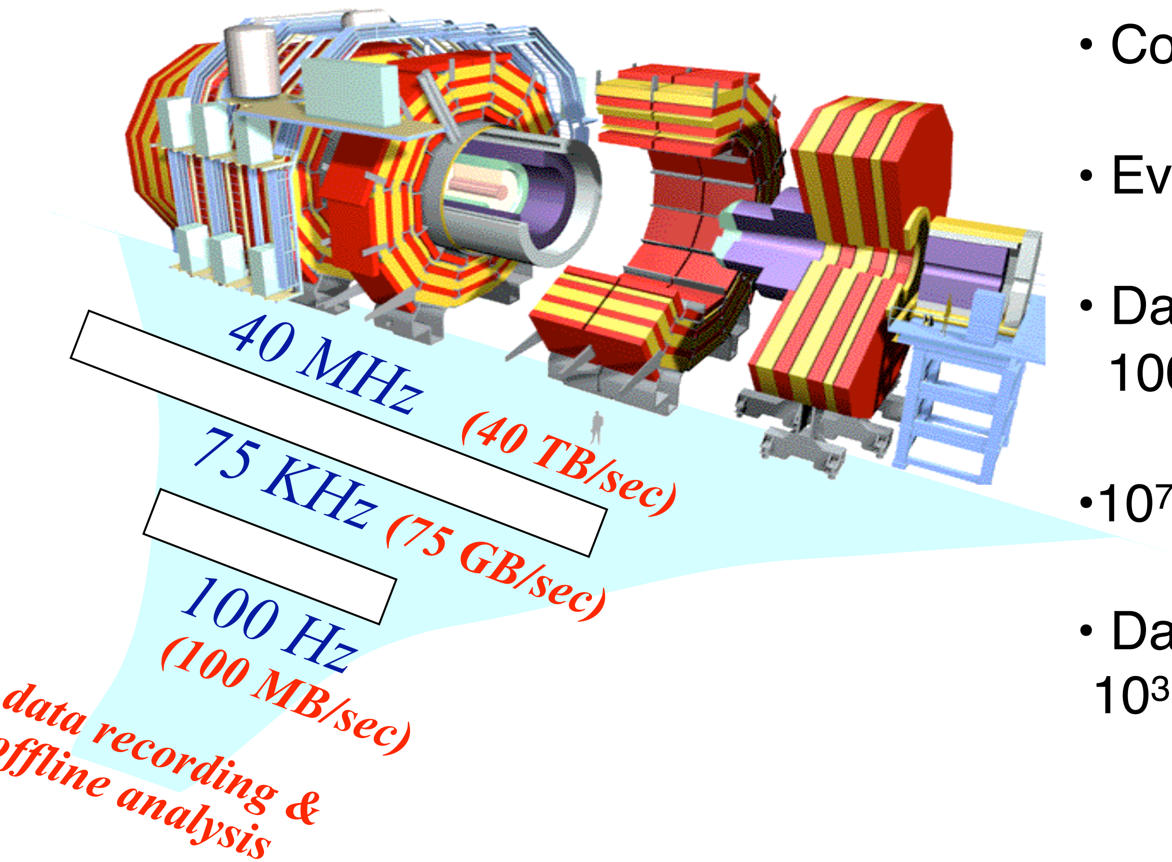
Event Selection

~20 collisions/25ns
(10^9 event/sec)
10^7 channels
(10^{16} bit/sec)



- The challenge is the identification of the most interesting (and potentially entirely new) physics processes amidst the much more copious occurrence of well-understood and studied processes.
- On-line event selection
  - Costume electronics (FPGAs, ASICs)
  - Online computing farm
    - A **single processor** analyzes one event at a time
- Out of a billion interactions/sec select one hundred for further analysis
  - Need to reject most interactions
  - Can store data at ≈100 Hz (= 100 events/s)

Data Recording



- Collision rate: 40 MHz
- Event size: ≈ 1 MByte
- Data size: 1 MByte/event
  100 events/s → 100 MByte/s
- 10^7 s data taking per year (30%)
- Data size: 1 PetaByte =
  10^3 TByte = 10^6 GByte per year

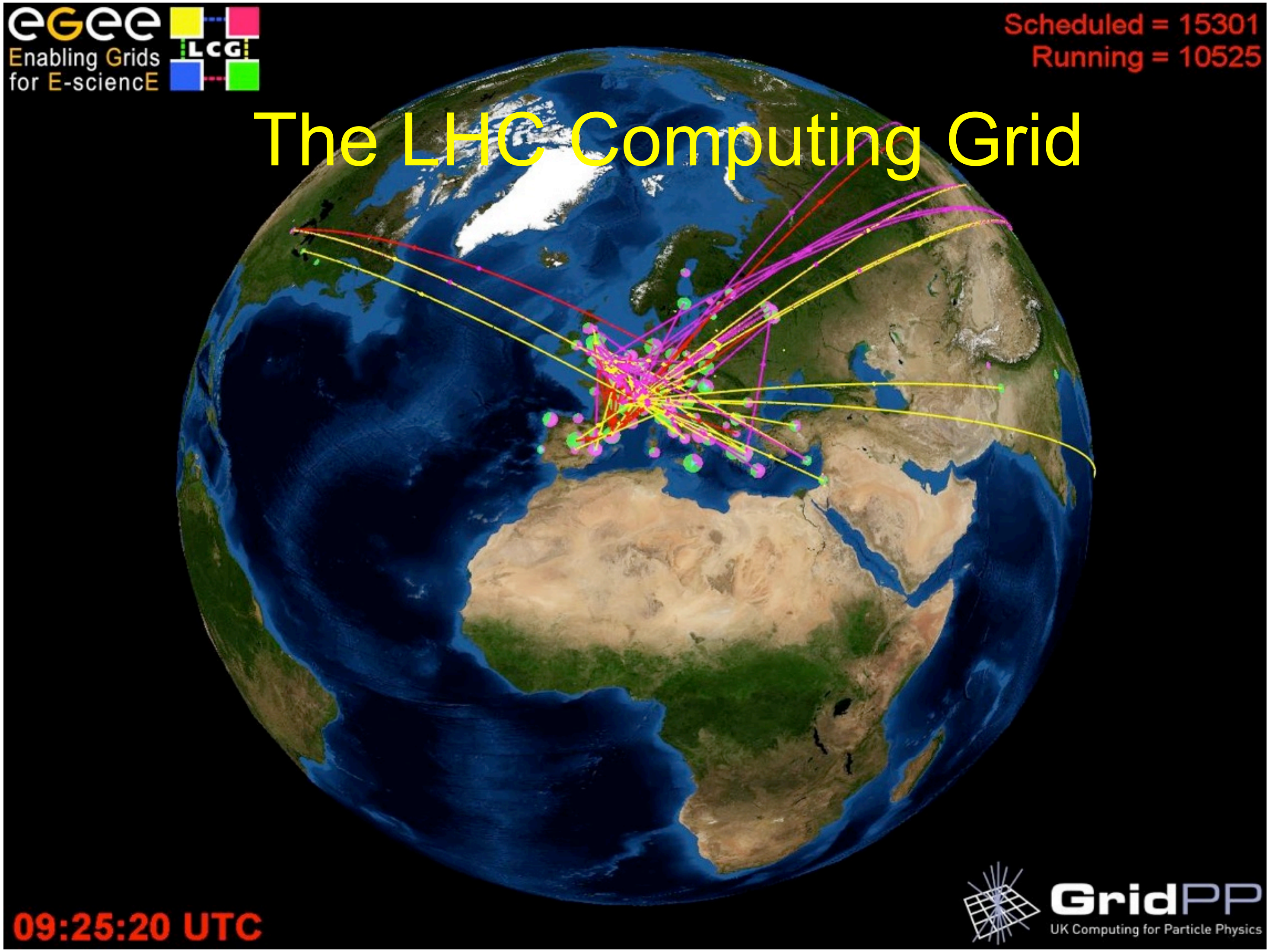
~ PetaBytes/year
~10^9 events/year
~10^3 batch and interactive users

LHC Data Challenge

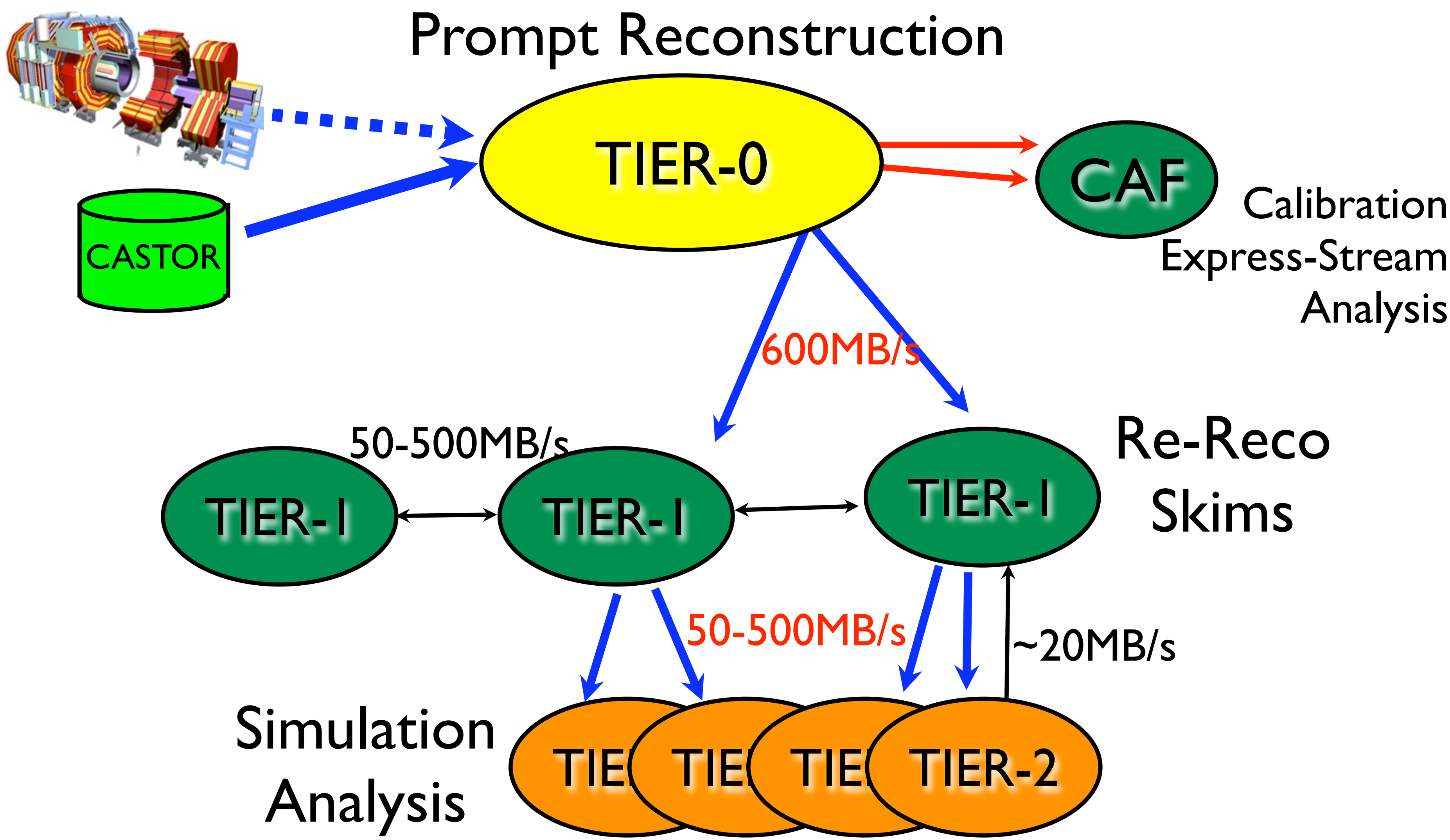
- The LHC generates 40×10^6 collisions / s
- Combined the 4 experiments record:
  - 100 interesting collision per second
  - 1 ÷ 12 MB / collision $\Rightarrow$ 0.1 ÷ 1.2 GB / s
  - ~ 10 PB (10^{16} B) per year (10^{10} collisions / y)
  - LHC data correspond to 20×10^6 DVD's / year!
    - Space equivalent to 400,000 large PC disks
  - Computing power ~ 10^5 of today's PC

Using parallelism is the only way to analyze this amount of data in a reasonable amount of time

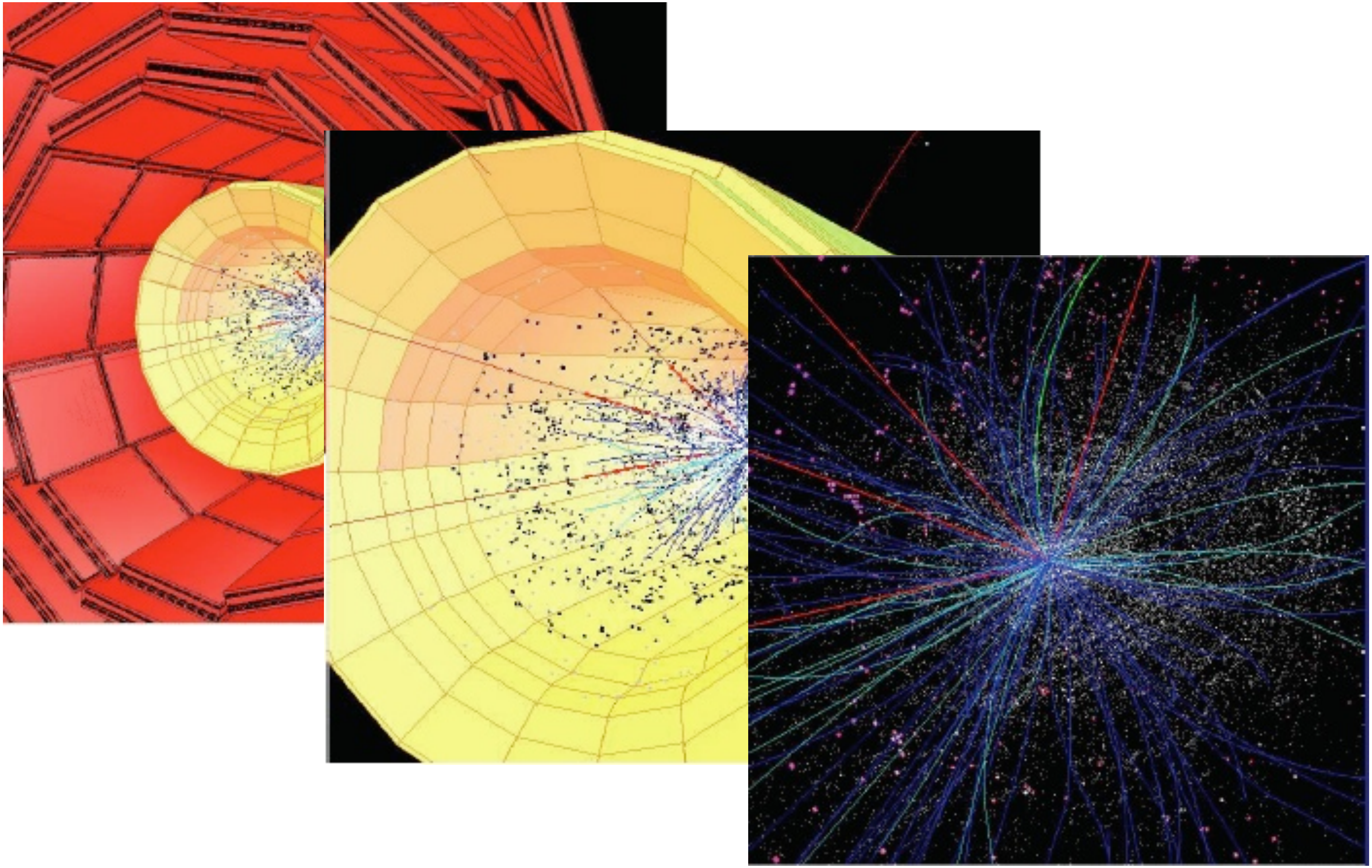
Computing and Software



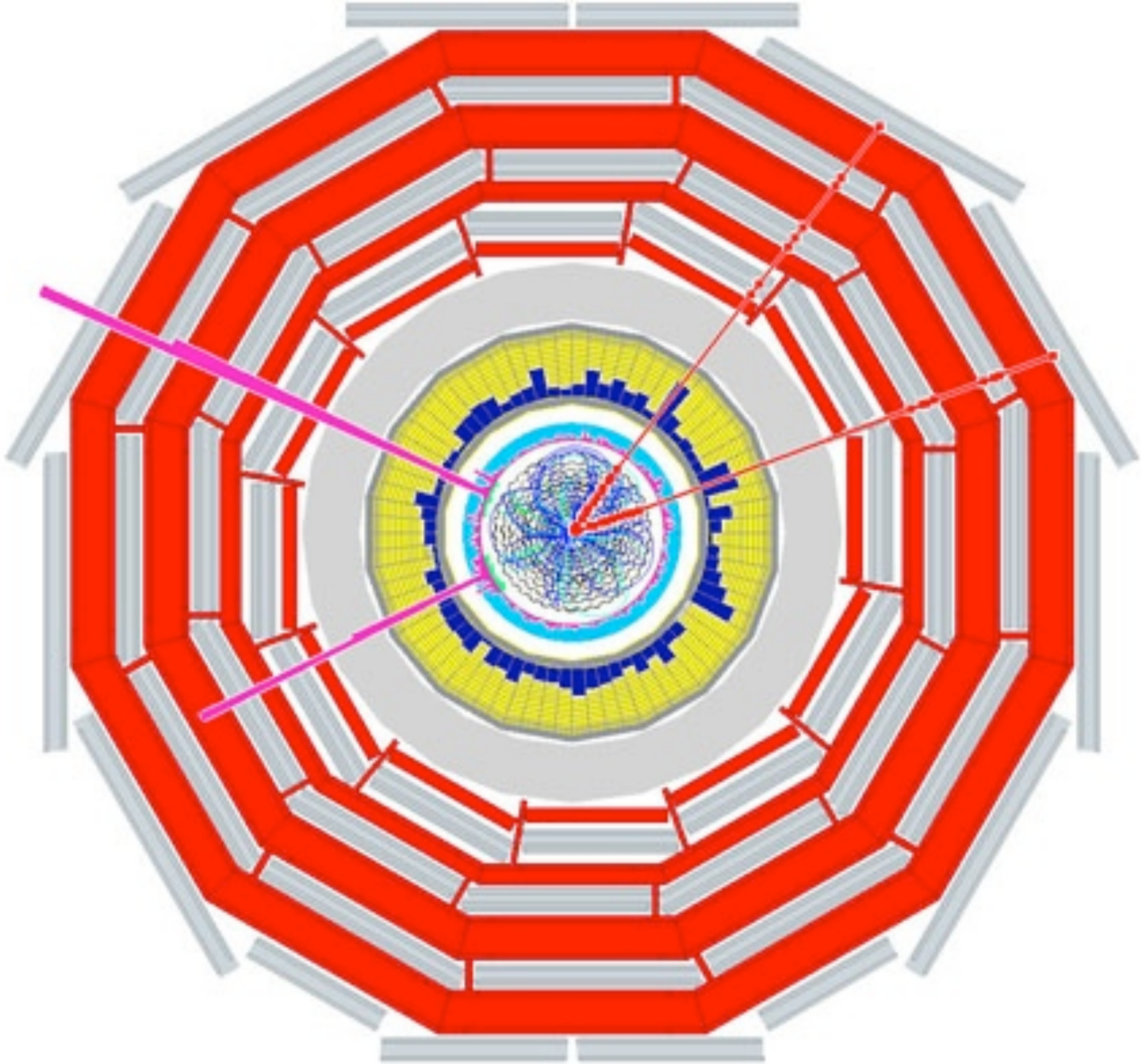
CMS Data Flow



Event Reconstruction



A Higgs Boson

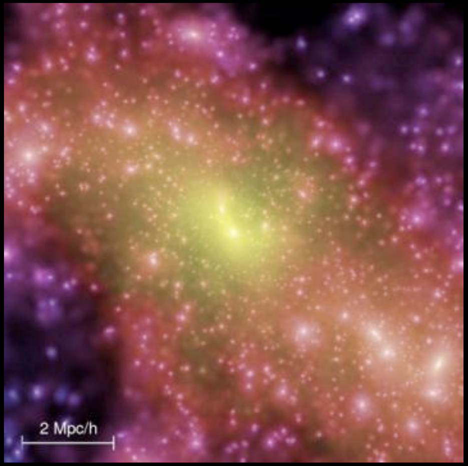


Dark Matter

In galaxies and galaxy clusters

There is not enough visible mass in rotating spiral galaxies to hold them together

Separation of dark matter and ordinary matter in the collision of two clusters of galaxies



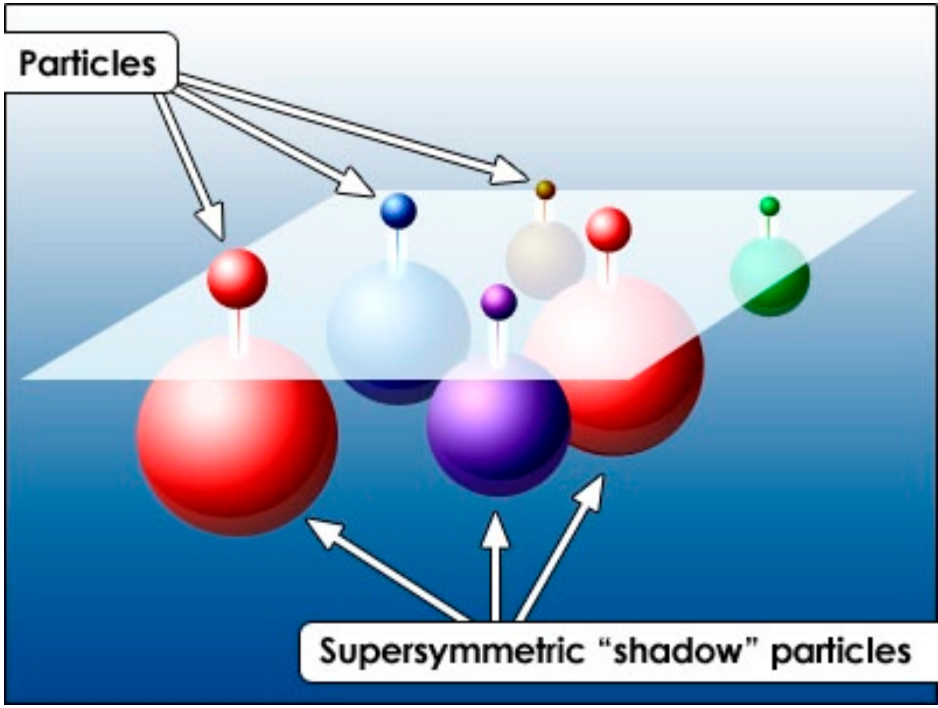
Photos courtesy of NASA

Supersymmetry

For fundamental particles, Supersymmetry says:

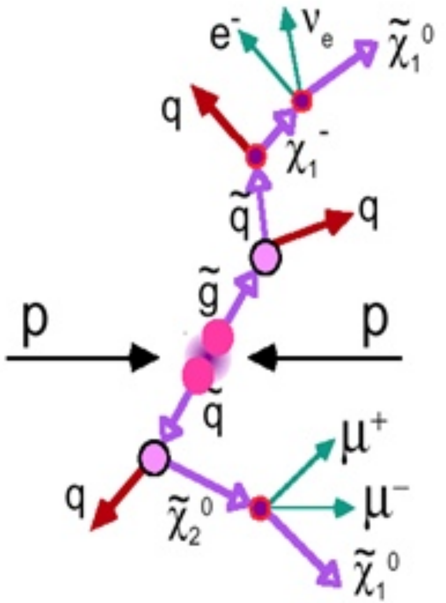
Every matter particle (*fermion*) should be associated with a massive "shadow" force carrier particle (*boson*).

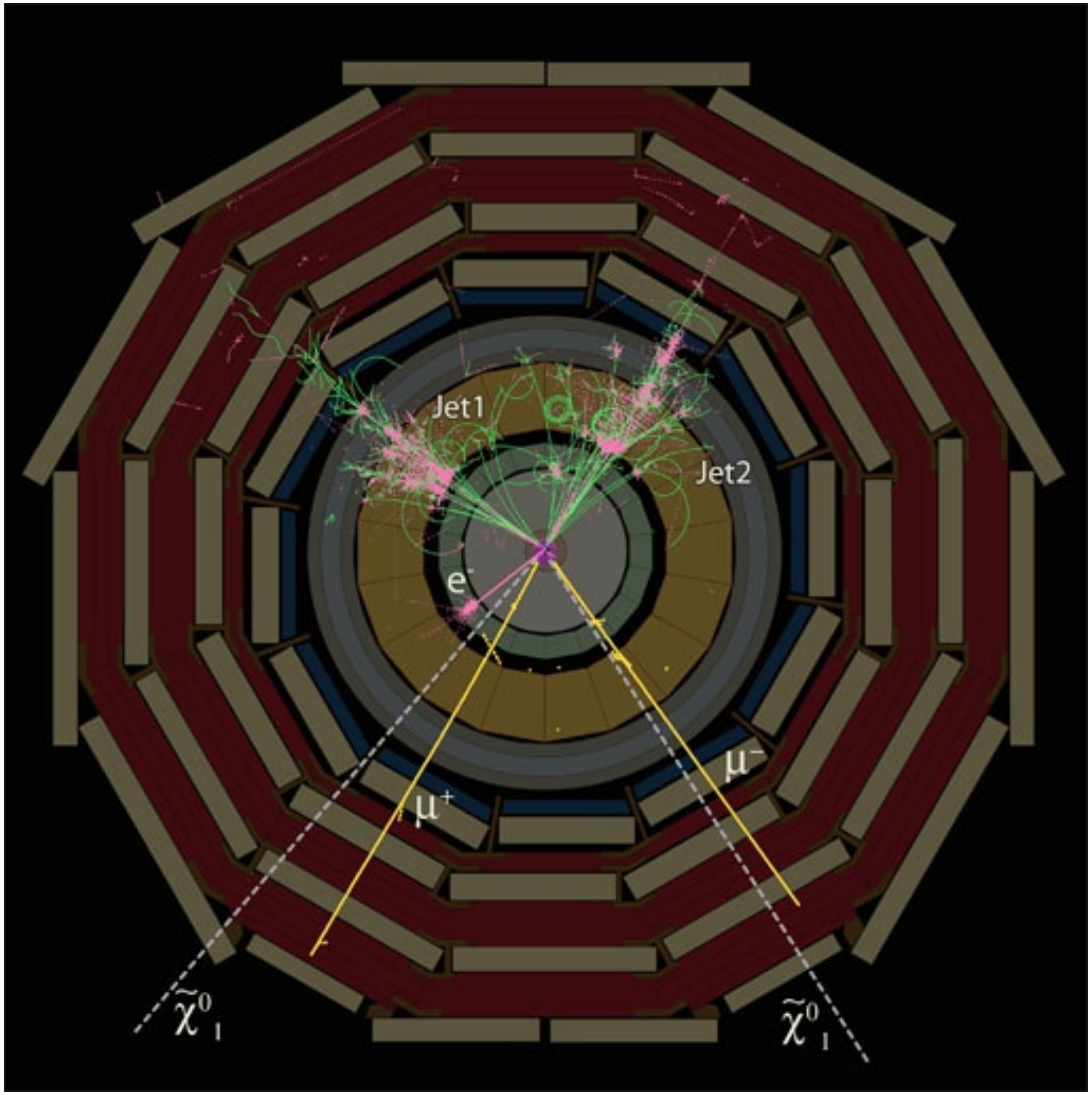
Every force carrier particle should have a massive "shadow" matter particle.



This has possible implications for <u>Dark Matter</u>

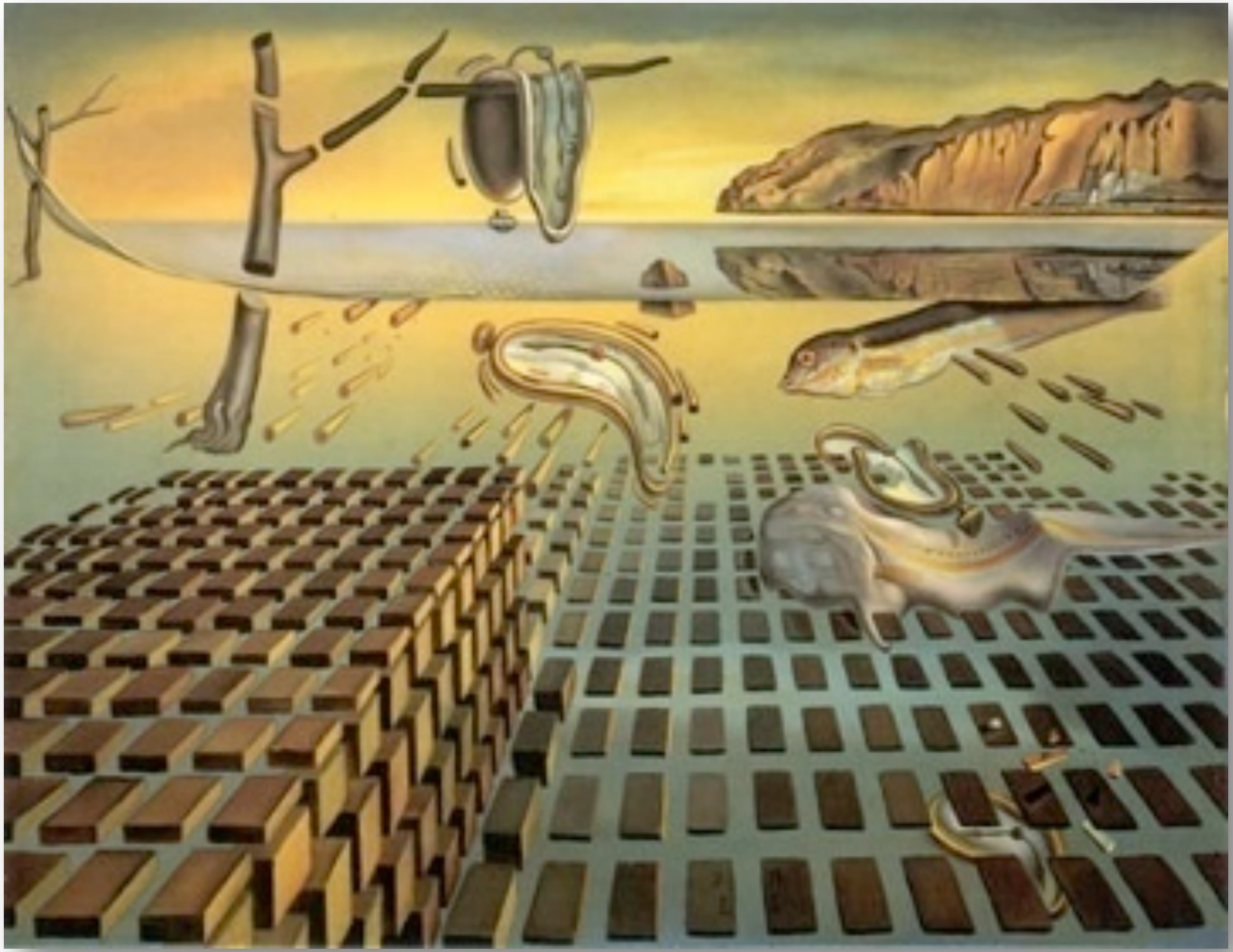
Supersymmetry in CMS





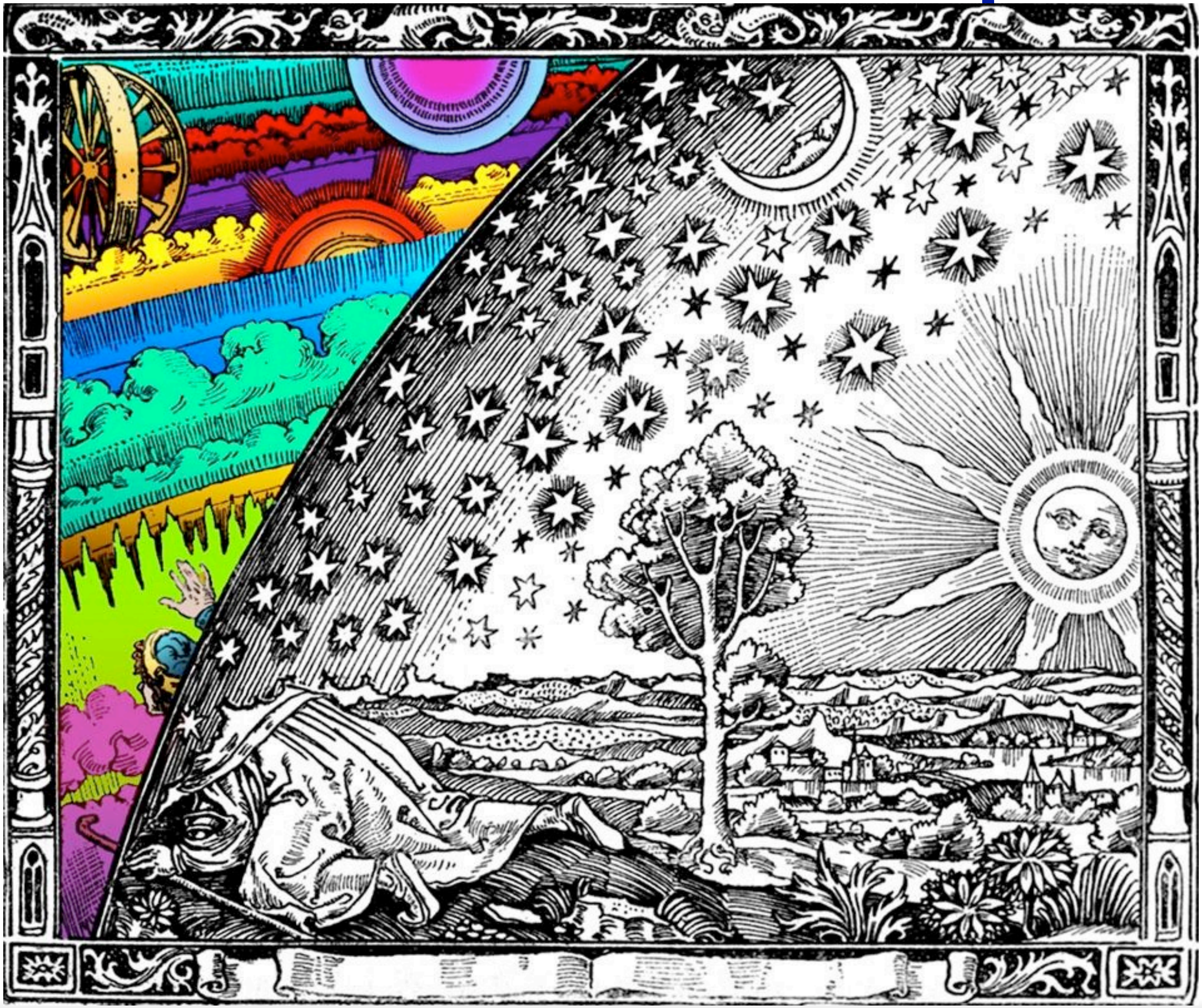
Is Matter also in Other Dimensions?

Are there extra dimensions of space that we cannot see?



(Dali, The Disintegration of the Persistence of Memory, 1954)

Extra Dimensions of Space



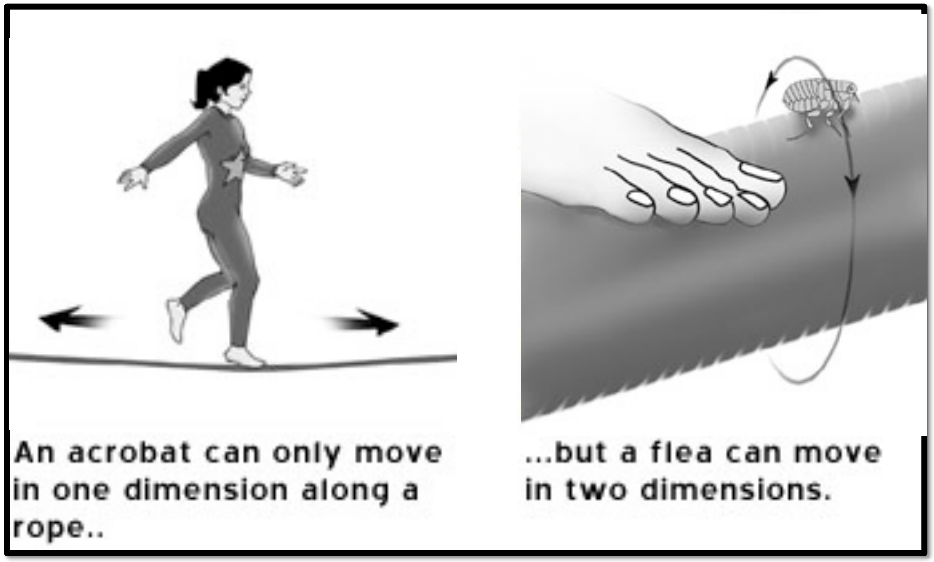
Extra Dimensions of Space

Think about an acrobat and a bug on a tight rope.

The acrobat can move forward and backward along the rope.

But the bug can also move sideways around the rope.

If the flea keeps walking to one side, it goes around the rope and winds up where it started.

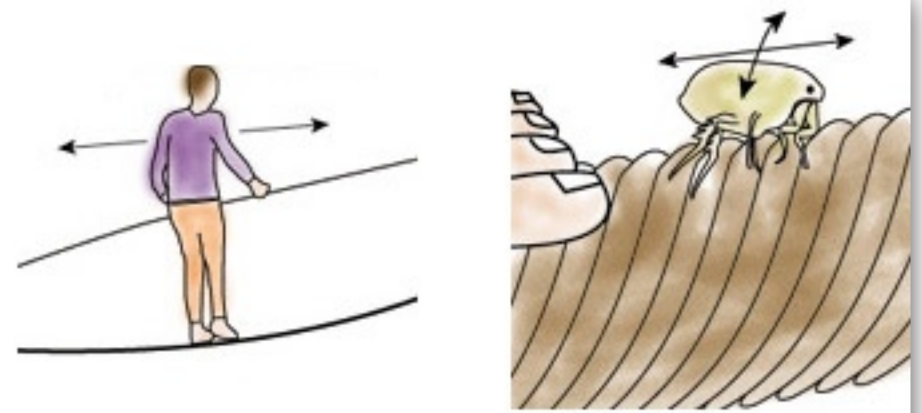


Extra Dimensions of Space

So the acrobat has one dimension, and the flea has two dimensions, but one of these dimensions is a small closed loop.

The acrobat can only detect the one dimension of the rope, just as we can only see the world in three dimensions, even though it might well have more.

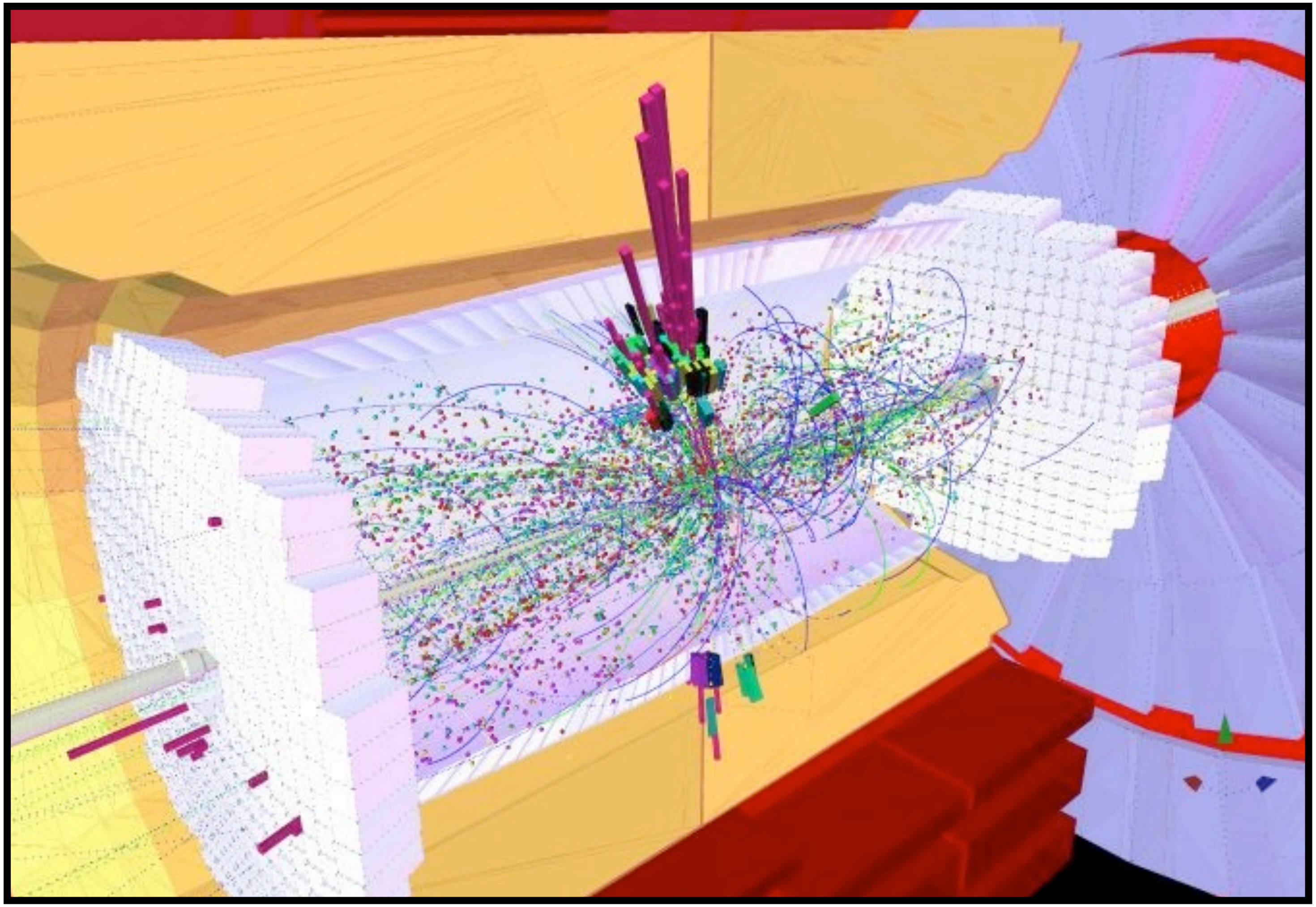
This is impossible to visualize, precisely because we can only visualize things in three dimensions!



An acrobat can only move in one dimension along a rope..

...but a flea can move in two dimensions.

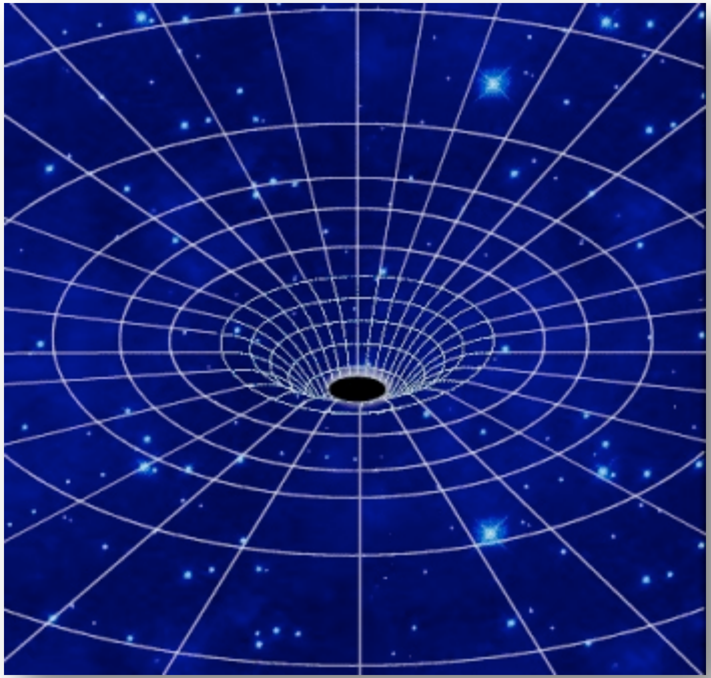
A hypothesized new particle Z'



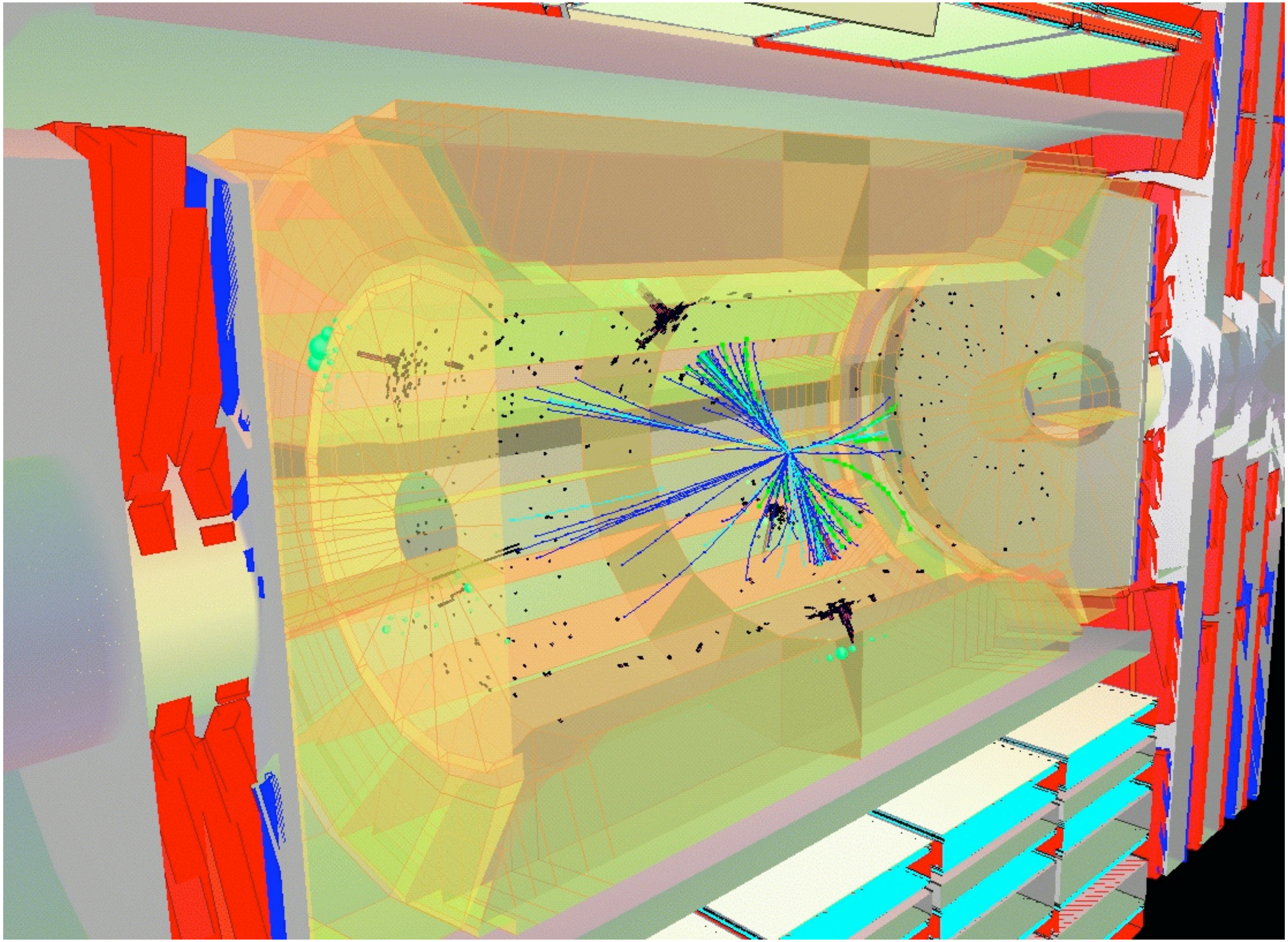
Microscopic Black Holes

According to some theoretical models, tiny black holes could be produced in collisions at the LHC.

They would then very quickly decay and be detected by experiments (the tinier the black hole, the faster it evaporates).



Black Hole



Summary

- LHC will provide proton-proton collisions at 10 TeV soon
- LHC will provide access to conditions not seen since the early Universe
  - Analysis of LHC data has potential to change how we view the world
  - But LHC analysis will require finesse and care
- LHC is likely to provide answers to many key questions in Physics
- All expectations are based on a detailed understanding of particles and forces within the SM that we have garnered over the past several decades
- With the expected clarifications, we will address some very major issues pertaining to the universe, for example:
  - What is cosmic dark matter? Is it made of SUSY neutralinos?
  - Is the universe filled with a Higgs field? Is it related to dark energy?
  - What is the structure of space-time? Are there extra space dimensions?
- CMS is eagerly awaiting data

Exciting times ahead – stay tuned!

The Unknowns!