The Future of High Energy Physics: The Large Hadron Collider and the International Linear Collider

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ECLOUD workshop
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Overview

- What are the fundamental questions we are trying to answer with High Energy Physics experiments today (and tomorrow)
- What is the difference between the LHC and the ILC? Do we need both? How do these experiments work?
- What's the status now, and what is the prospect for the next few years?

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The “Standard Model”

- Over the last 4 decades we have developed a mathematical model that explains all known phenomena and has extraordinarily successful prediction power
  - Quantum Chromo Dynamics + Unified Electroweak Theory + Higgs mechanism

- *All* known particle processes (interactions, production,..) measured at SLAC, CERN, Tevatron, etc etc, agree with its predictions.

The Standard Model (SM)

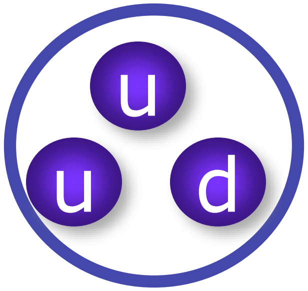
The Matter Particles (Fermions):

				Electric charge
6 leptons	e	μ	τ	Q= -1
	ν_e	ν_μ	ν_τ	Q=0
quarks **6 "flavors"**	u	c	t	Q=+2/3
	d	s	b	Q=-1/3

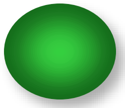
..plus antiparticles of opposite charge:

e^+, μ^+, $\tau+$, $\bar{u}$, $\bar{d}$, $\bar{c}$, $\bar{s}$, $\bar{t}$, $\bar{b}$

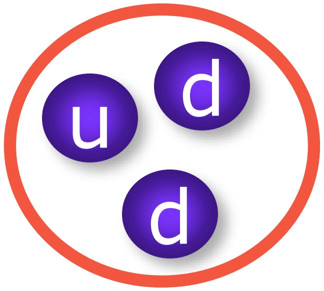
Building blocks of stable matter:
u quarks, d quarks & electrons



Proton
charge = +1
2/3 + 2/3 – 1/3



Electron
charge = -1



Neutron
charge = 0
2/3 - 1/3 – 1/3

Hundreds of other quark combinations
→ unstable Mesons ($q\bar{q}$) and Baryons (qqq)

The Masses

- electron: $M_e \approx 0.0005\ \mathrm{GeV}/c^2$ ($\approx 10^{-30}$kg)
- u-Quark: $M_u \approx 0.005\ \mathrm{GeV}/c^2$
- c-Quark: $M_c \approx 1.2\ \mathrm{GeV}/c^2$

- t-Quark: $M_t = 178 \pm 4.3\ \mathrm{GeV}/c^2$

→almost as heavy as an atom of gold!!

These are experimental observations--
masses cannot be predicted in the SM

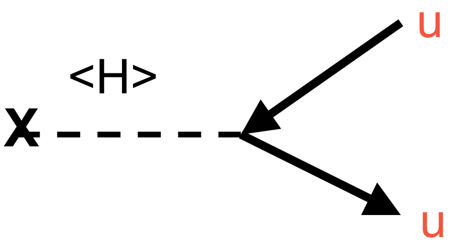
The Forces

transmitted by exchange of Spin 1 Gauge-Bosons between the Spin ½ Fermions

Force	Boson	Mass	Couples to
Strong (nucl.binding)	Gluons g	0	Quarks, gluons Strongly charged
Electro-magnetic	Photons γ	0	Leptons, … Electr. charged
Weak (nucl.decay)	W^{+-} Z^0	91 GeV 80 GeV	Quarks, leptons W,Z Weakly charged

Masses due to Higgs

- W, Z and the fermions acquire mass by interaction with the vacuum, the weak force becomes short range



Analogy: effective mass of electron moving through crystal lattice

- Photon doesn't interact with vacuum, remains mass-less and long-range
- Large Fermion mass hierarchy put in by hand via appropriate coupling constants spanning 5 orders of magnitude
- Higgs not (yet) observed. Too heavy to access with the experiments of the last 40 years.

Are we done?

Despite its huge success, the SM cannot be correct

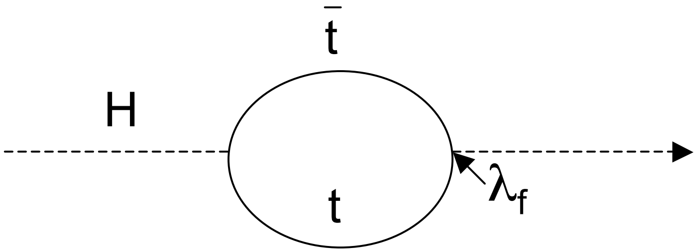
our explanation of how the particles get their mass must be wrong or incomplete!

- As is, the Higgs particle mass itself could be infinite
- We have not (yet) experimentally confirmed the Higgs

Plus, gravitational force not included and dark matter is not explained in the Standard Model!

“Hierarchy”-Problem

- As the Higgs propagates, it interacts virtually with all particles it can couple to, e.g. Fermion
- this will contribute to the Higgs mass (“radiative corrections”)



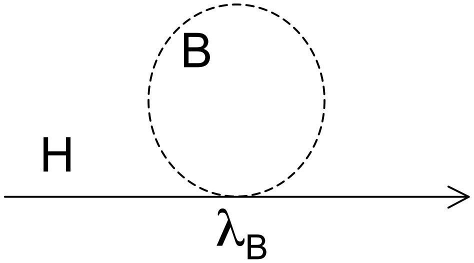
- Higgs mass can receive enormous corrections proportional to the largest scale in the theory (“Planck Mass”, 10^{19} GeV)

$$\Delta m_H^{\ 2} = \frac{|\lambda_t|^2}{16\pi^2}(-\Lambda_{UV}^{\ 2} + \ldots)$$

One way out

Many theories suggested, one of them is
Supersymmetry (SUSY)

- We know that a boson loop would contribute to Δm_H with opposite sign



$$\Delta m_H{}^2 = \frac{\lambda_B}{16\pi^2}(\Lambda_{UV}{}^2 + \ldots)$$

- Supersymmetry allows for systematic cancellation between Fermion and Boson loop contributions

Supersymmetry

- Implies that for every known Fermion there exists a new "superpartner" boson and vice-versa.
- If this is true, the superpartners must be heavier than the ordinary particles
- The lightest superpartner would be an ideal candidate for dark matter

Superpartners

name	spin	Super partner	spin
photon	1	photino	1/2
gluon	1	gluino	1/2
W+-	1	Wino	1/2
Z	1	Zino	1/2
Higgs	0	Higgsino	1/2

Transmission of forces

name	spin	Super partner	spin
lepton	1/2	slepton	0
quark	1/2	squark	0

Matter Particles

Summary: Part 1

- What are the fundamental questions we are trying to answer with High Energy Physics experiments today (and tomorrow)
  - Does the Higgs particle exist?
  - What is the complete picture? SUSY?
  - What is dark matter: lightest Superpartner?

Overview

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- What is the difference between the LHC and the ILC? Do we need both? How do the experiments work?
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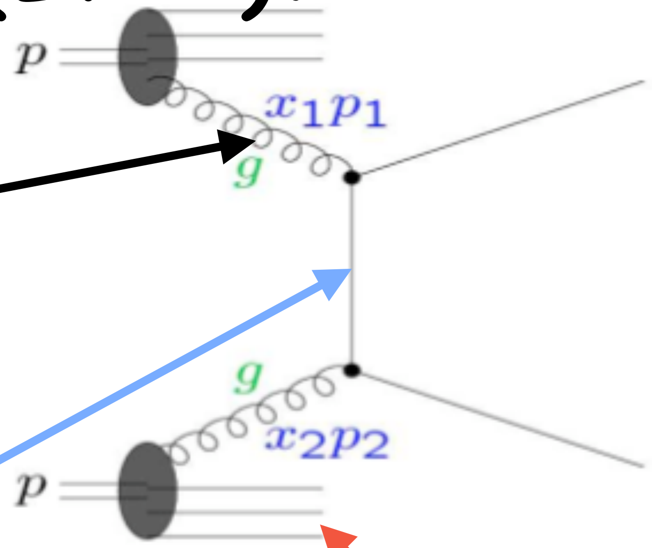
Difference between linear and circular accelerators

- Circular accelerators like the LHC "store" particles and increase their energy until ready for collisions
  - Unavoidable: energy loss due to synchroton radiation from the accelerated particles. Goes like $1/m^3$ and $1/r^2$. To reach ultra-high energies (TeV) need to use either *huge* rings or heavy particles, like protons.
- Linear accelerators do not suffer from the energy loss, can accelerate electrons, but need very long base (miles)

What happens during a proton collision (LHC)?

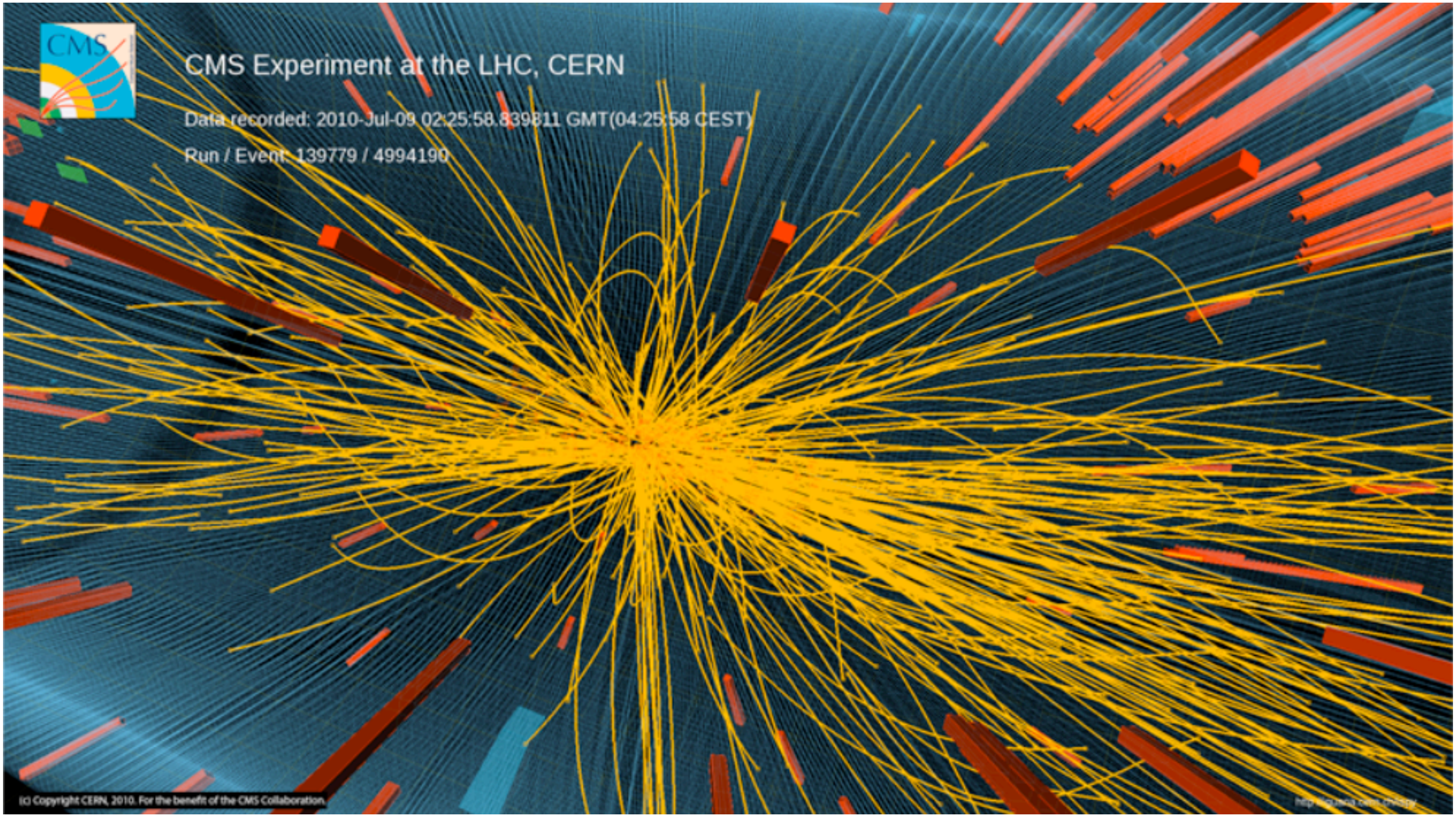
quarks and gluons interact at an unknown fraction of the proton energy. They may produce a Higgs!



They interact via the strong force, and the Higgs will be buried under HUGE backgrounds from other strong processes.

we have to deal with remnants of protons in addition to the Higgs..

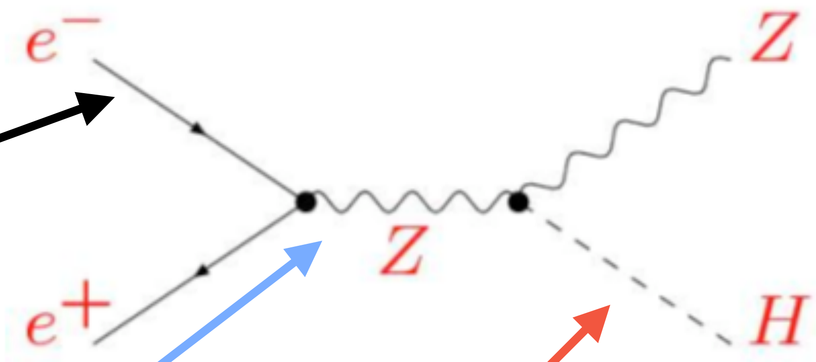
Collision recorded at CMS July 2010



Experimental Challenges

- High Interaction rate
  - data for only ~10 out of 1 million bunch crossings can be recorded.
  - Need to make quick decision if event should be recorded ("Trigger")
- 20 superimposed proton collisions in each bunch crossing
  - ~1000 tracks stream into detector every 25 ns
  - need high granularity of detector -> large number of readout channels
- High radiation levels

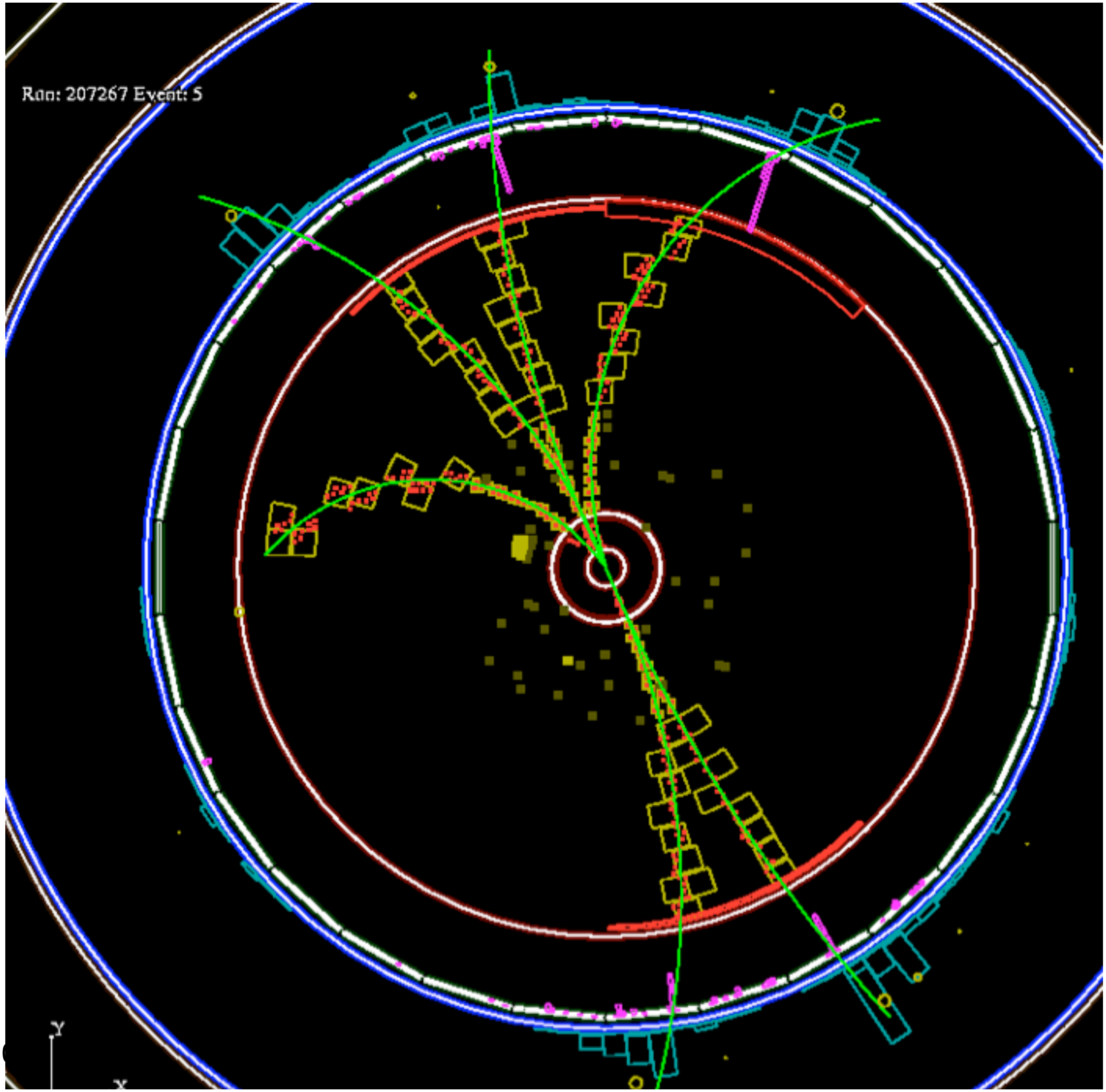
What happens during an electron collision (ILC)?



Electrons collide at exactly the energy they are accelerated to and annihilate. They may produce a Higgs!

electrons interact via the electroweak force, and the backgrounds are very well understood.

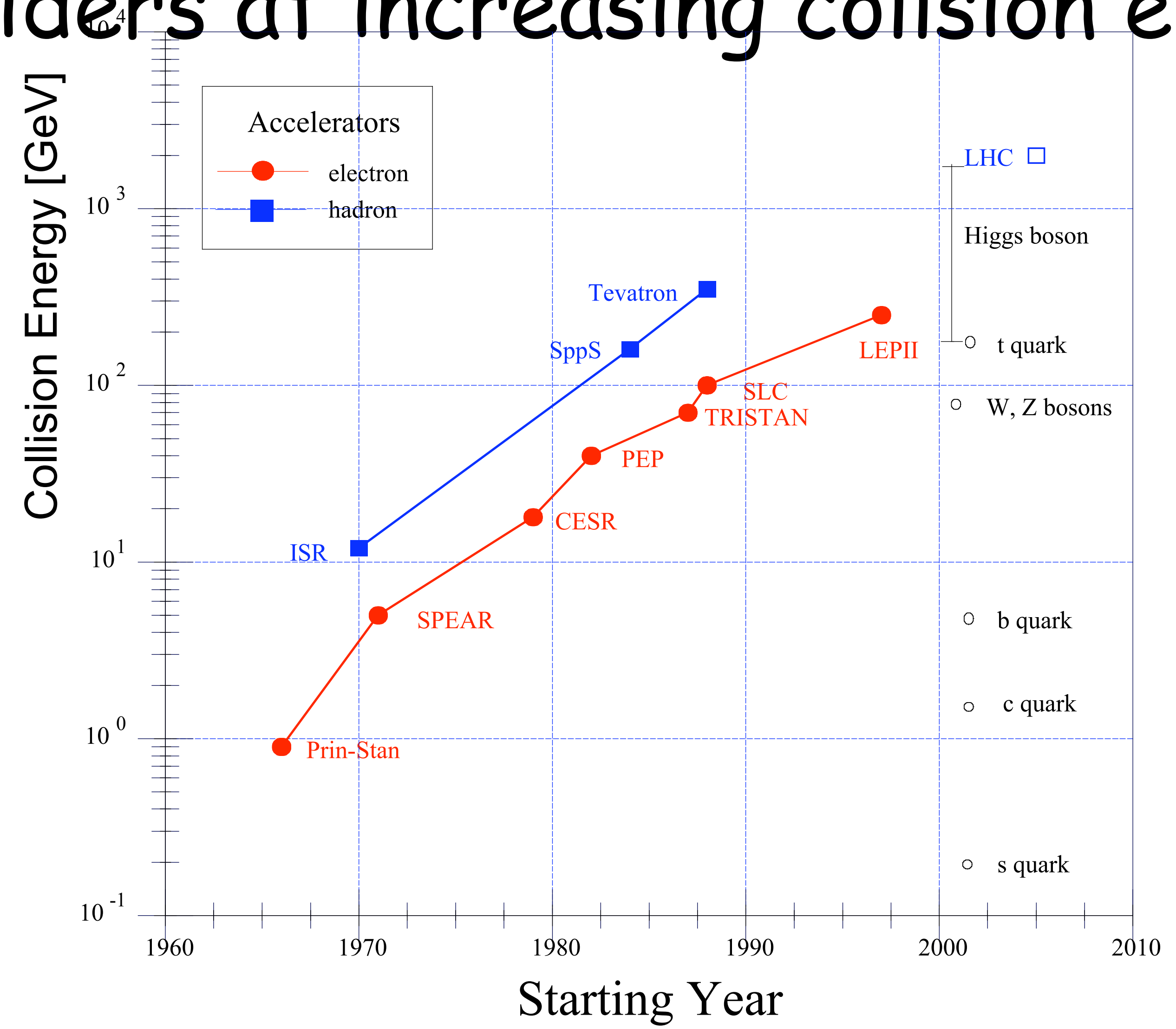
In the detector we see ONLY the products of the weak interaction


Run: 207267 Event: 5
Y
X

Why do we need both?

- The high energy proton collisions will enable us to discover new particles
  - BUT high backgrounds, proton remnants and unknown collision energy make it extremely difficult to determine the properties of these new particles (spin, mass,...). It may for example be impossible to determine if the origin is SUSY or something else..
- ILC with precision electron collision data will allow us to study new phenomena in detail
- ILC and LHC are complementary. We need both if we are to get to the bottom of the fundamental questions.

Progress in HEP: electron and hadron colliders at increasing collsion energy



Overview

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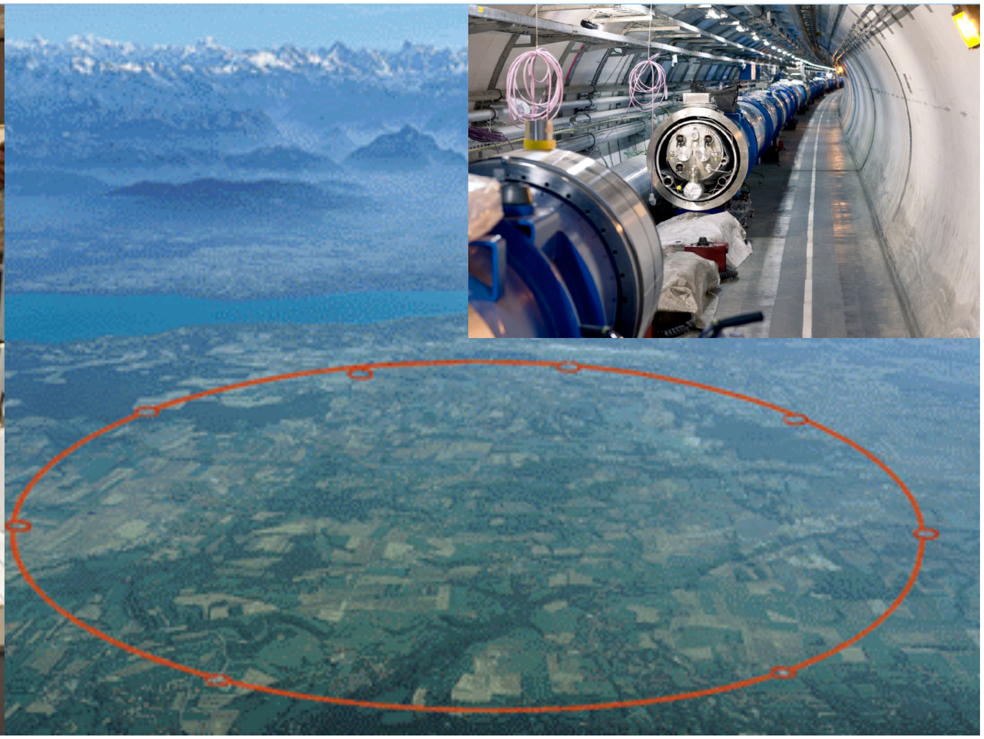
- How do these experiments work? What is the difference between the LHC and the ILC? Do we need both?

- What's the status now, and what is the prospect for the next few years?
  - Large Hadron Collider is taking data
  - ILC is in design phase

Proton Collisions at 7 TeV

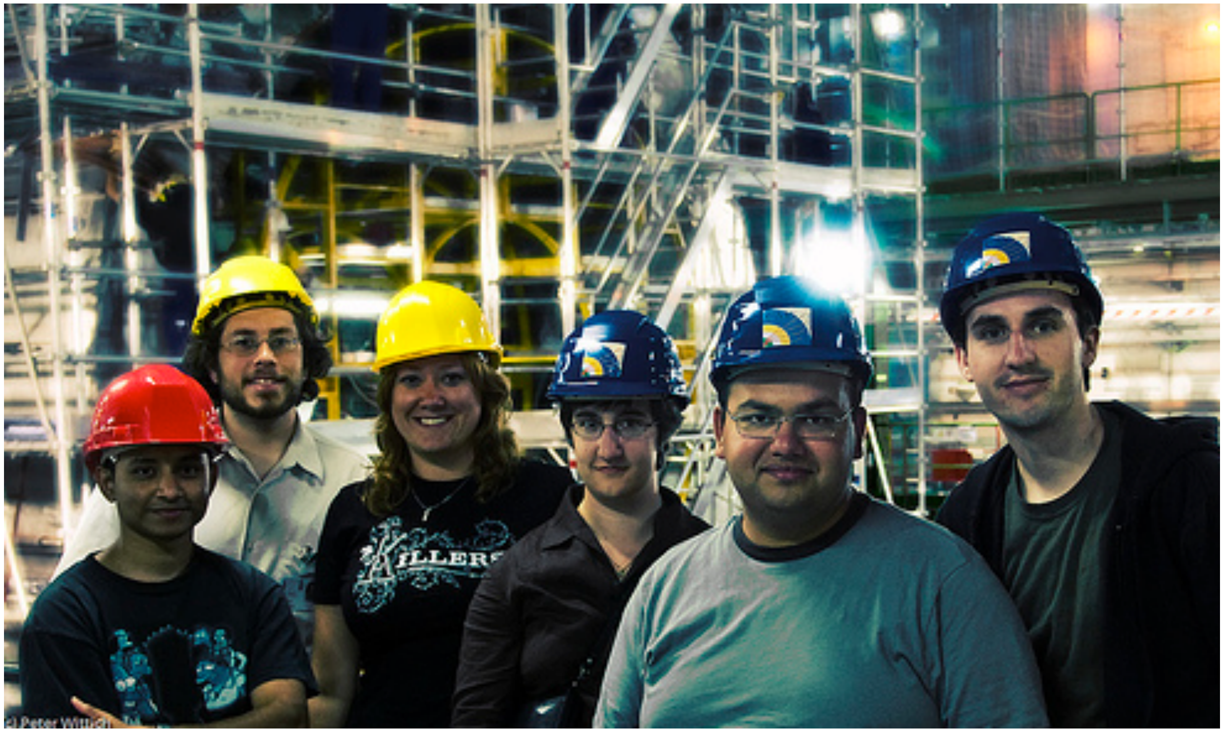
- Colliding two beams of 3.5 TeV protons at the LHC as of March 30th, 2010
- 200k collisions recorded in first hour
- Run will last 18 months. In 2013: 14 TeV




CMS
LHCb
ALICE
ATLAS

Cornell's experimental HEP group at the Large Hadron Collider

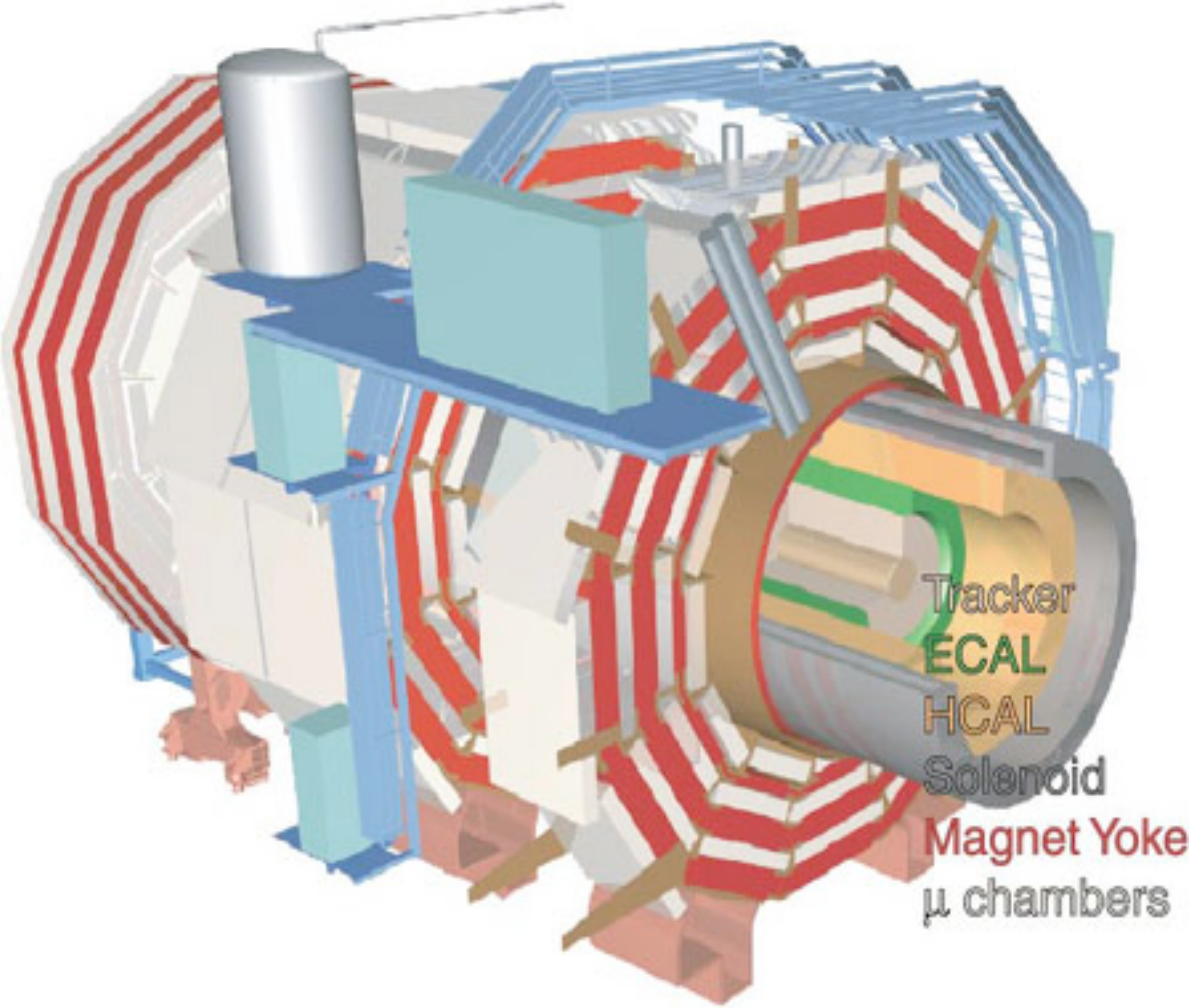
- 7 faculty, 7 postdocs, 8 graduate students and 10 undergraduate students, working at CERN and CU
- Our contribution to the Compact Muon Solenoid (CMS) Experiment
  - Software
  - Pixel Detector
  - Trigger
  - Calorimeter
  - Physics analysis
  - Tracker Upgrade



Elements of Particle Detectors

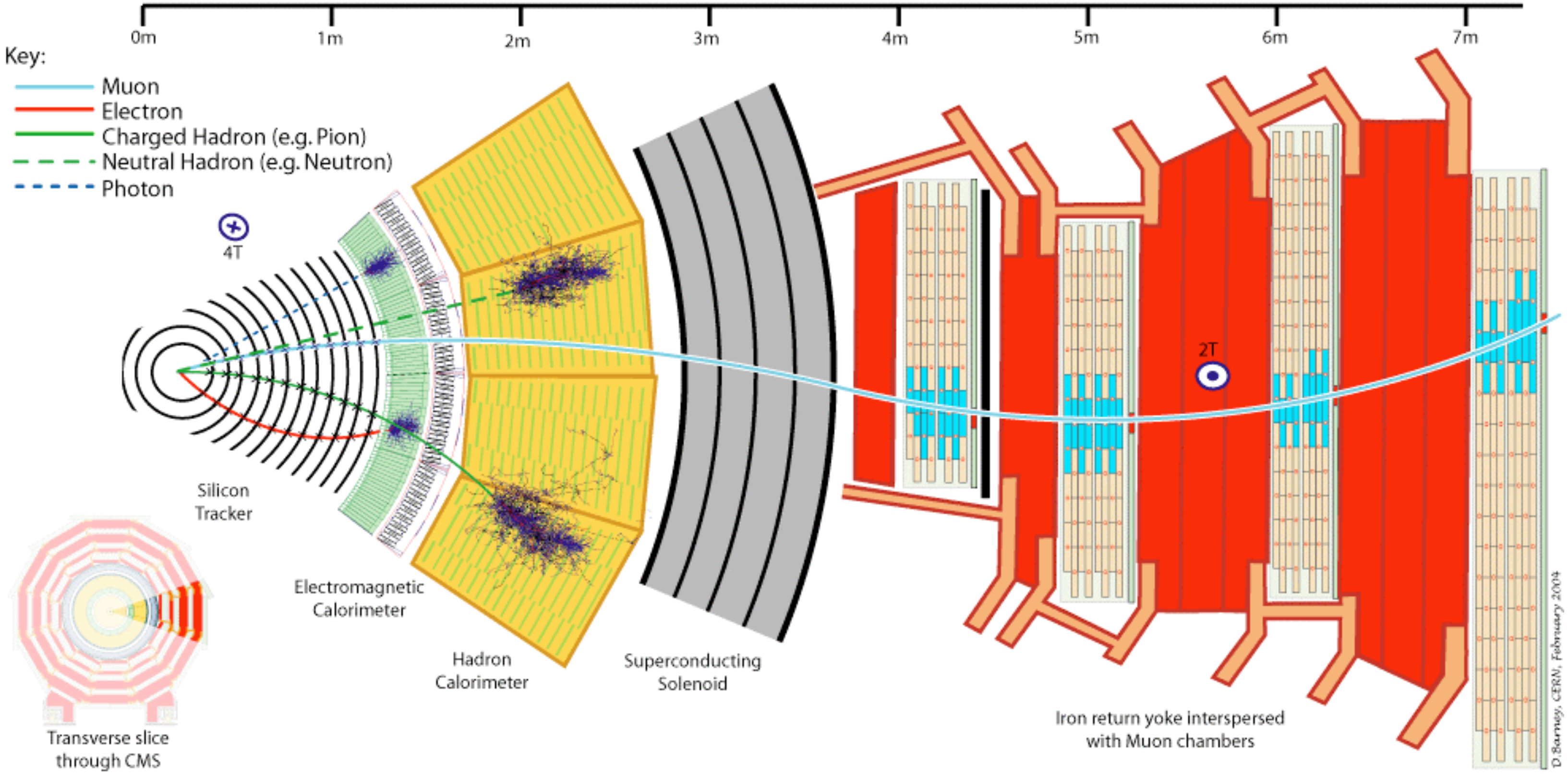
- Momentum measurement of charged particles
  - path radius of charged particles in Magnetic Field
- Measure tracks of charged particles through charge deposition on silicon microstrips and silicon pixels (3D)
- Measure Energy (Calorimeters)
  - Through electromagnetic and hadronic interactions
- Identify muons from tracks and hits in muon drift chambers

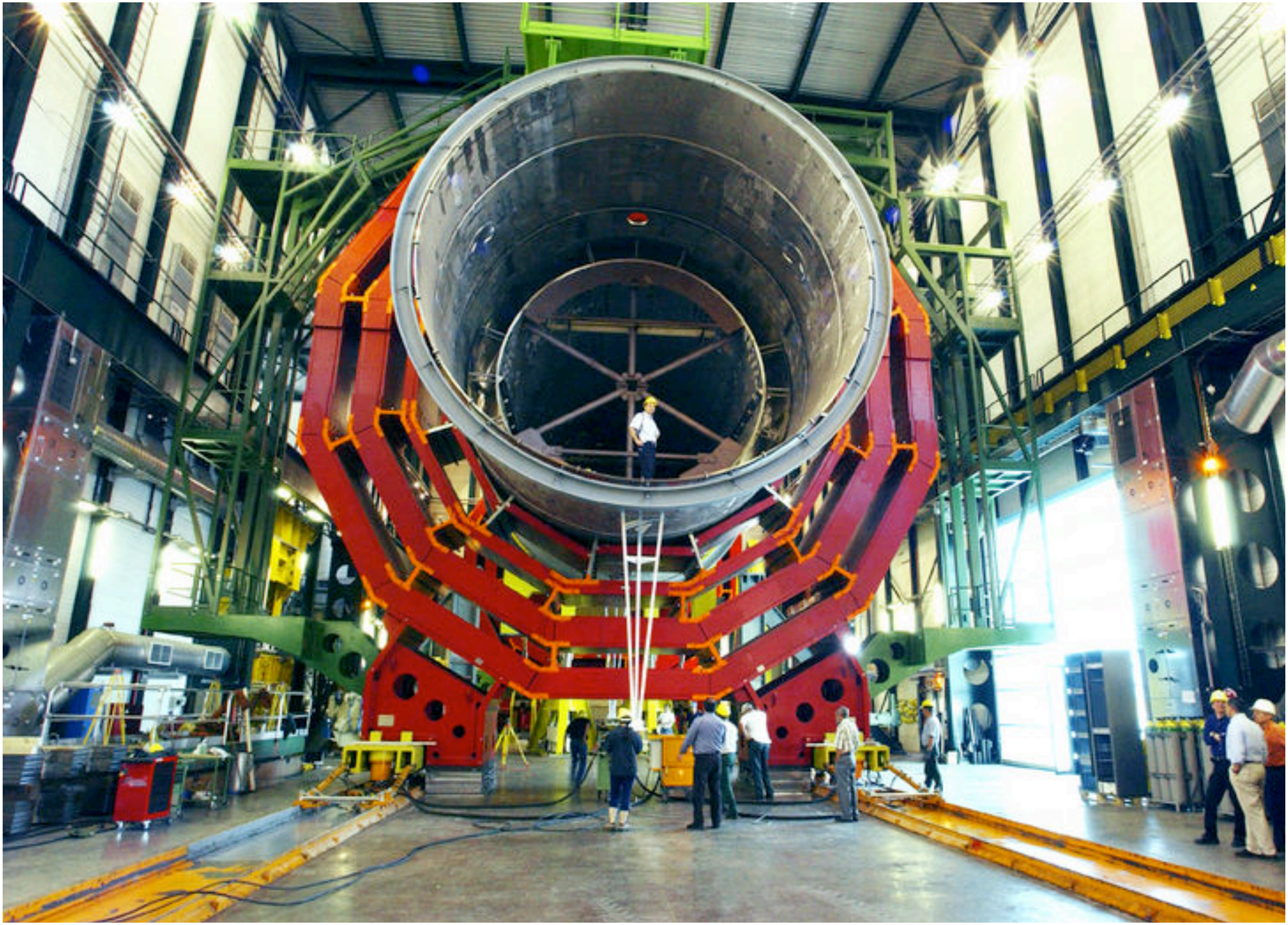
Detection Devices for Particles



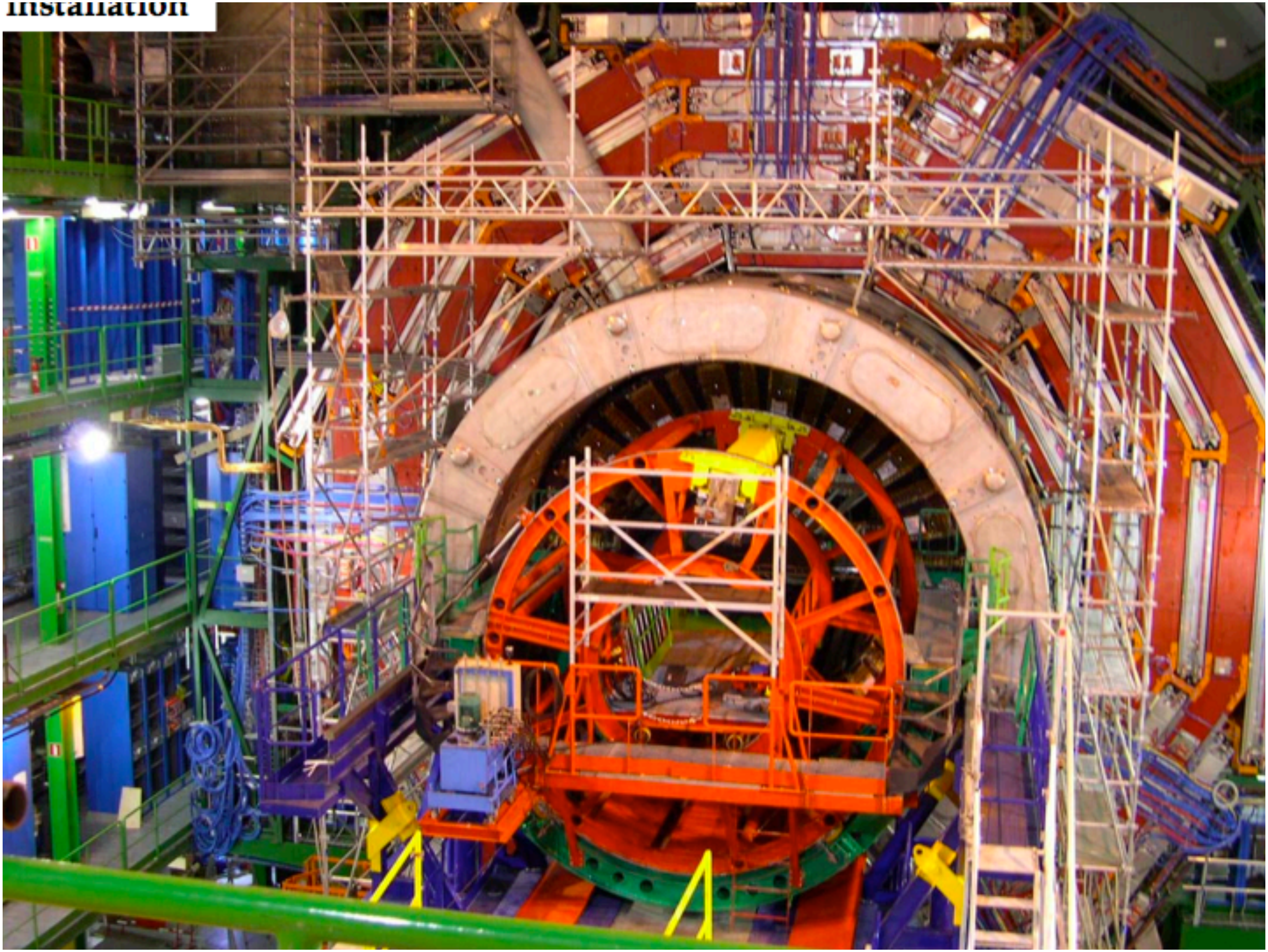
Compact Muon Solenoid (CMS) at CERN

Particle Tracks



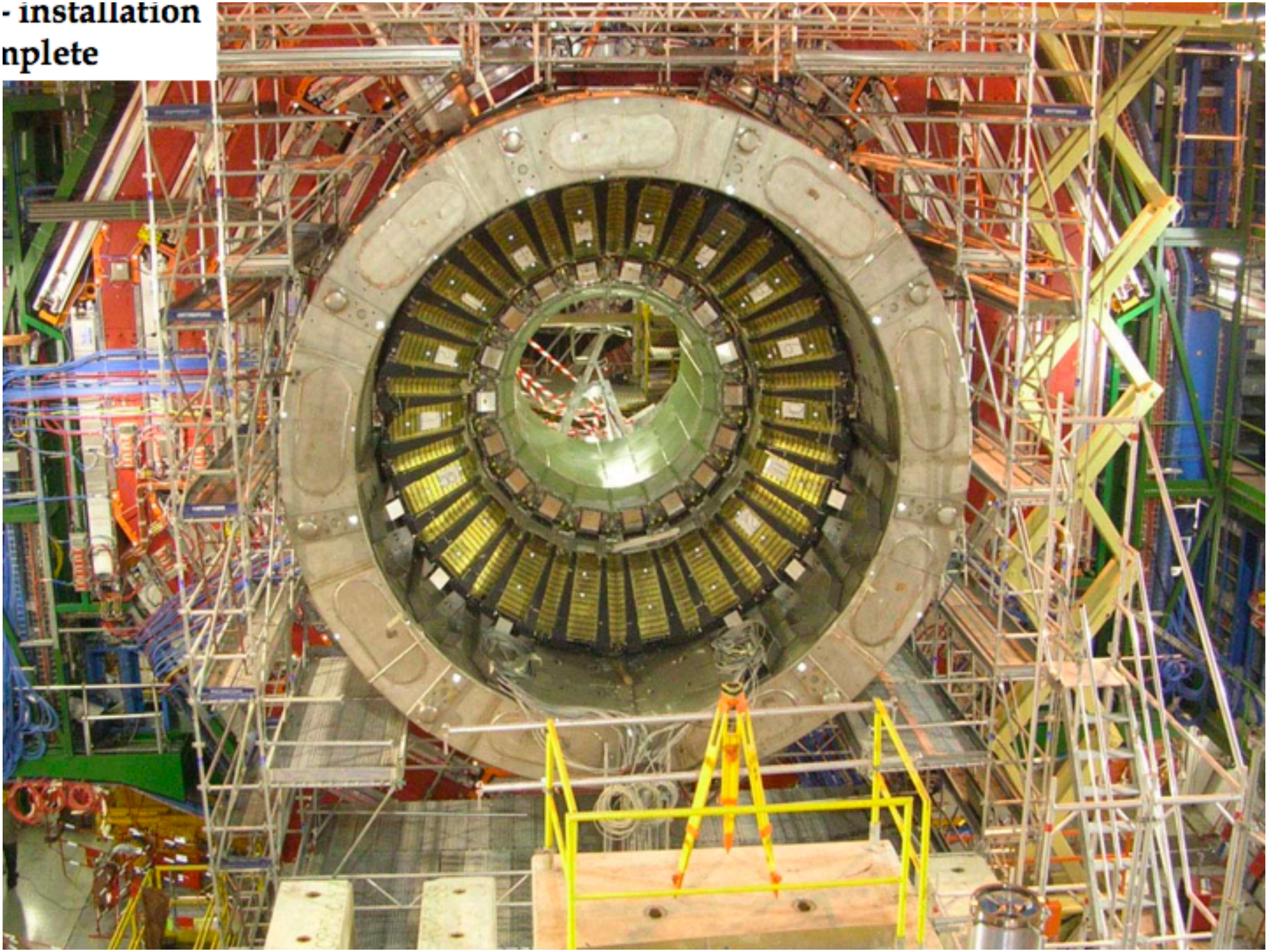


Installation



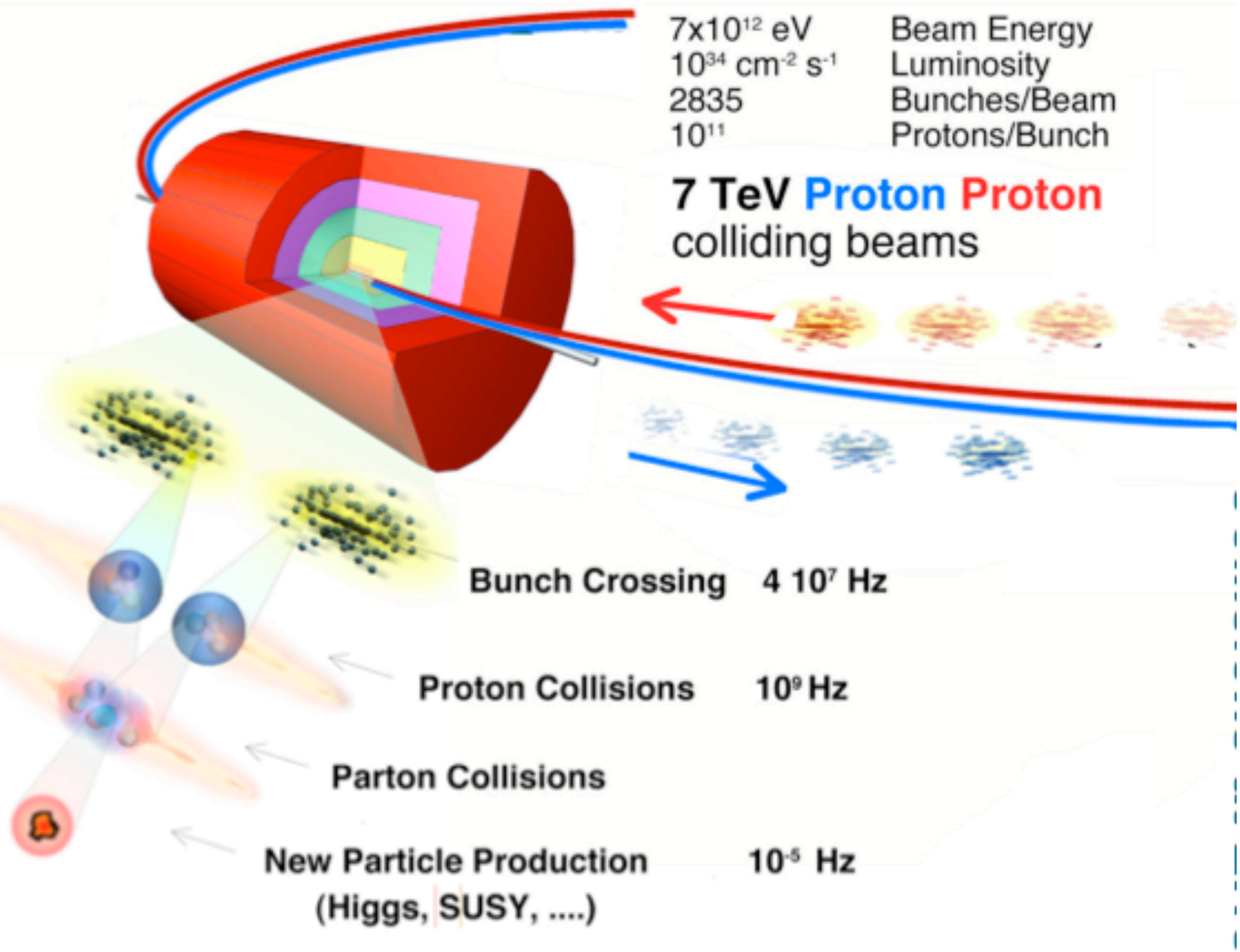

A
B

- installation
nplete



We are colliding protons at the highest energy ever: are we creating Higgs and SUSY particles already?

- Probably, but they will be buried under enormous backgrounds: production probability is much smaller than that of ordinary gluon or quark production
- That's why we have to collect huge amounts of data before we can hope to "see" a statistically significant signal



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

Higgs Production at LHC

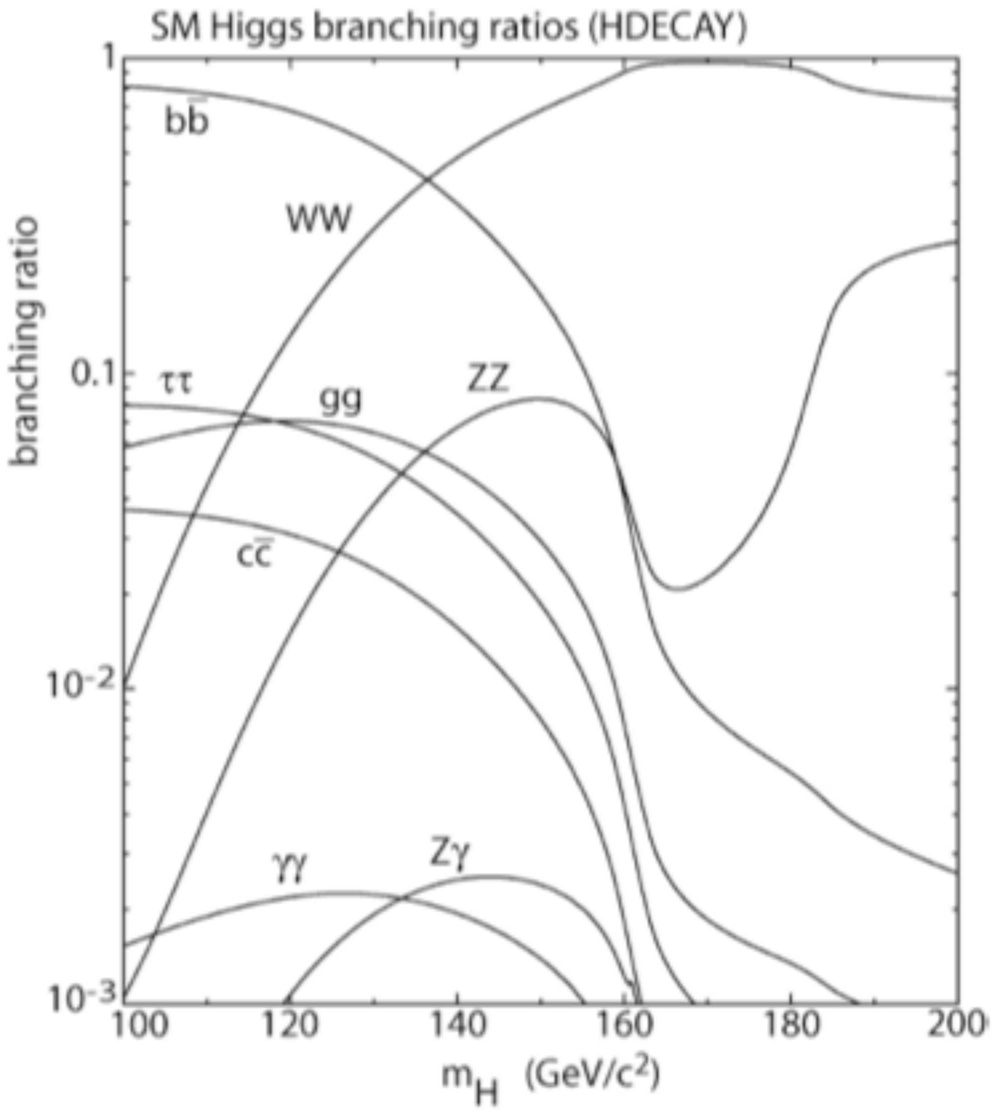
- Proton Collision Center of Mass Energy is 7 TeV

- Probability to produce Higgs is ~1 in 10^{13}

- That's ~100 Higgs Bosons per day*
- detect them through their (stable) decay products

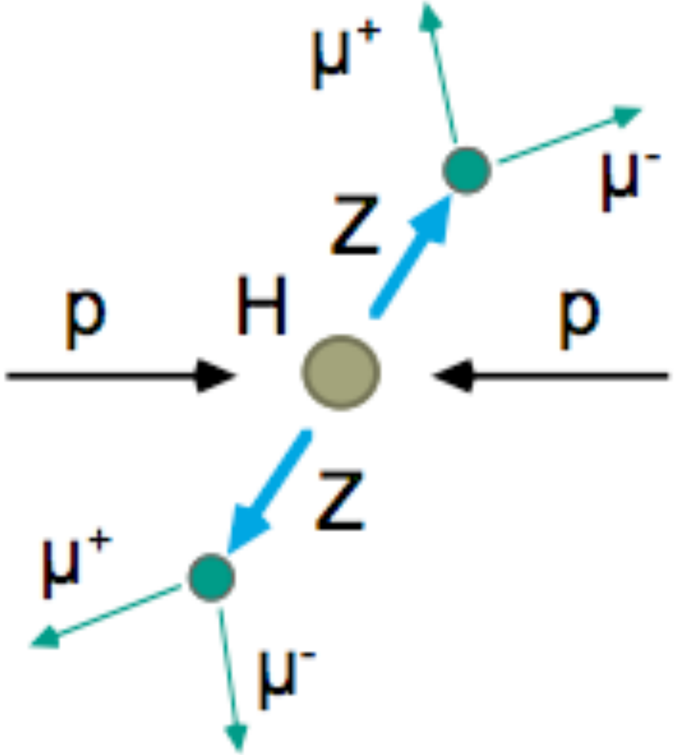
* Not necessarily recorded!

Higgs Decay Modes



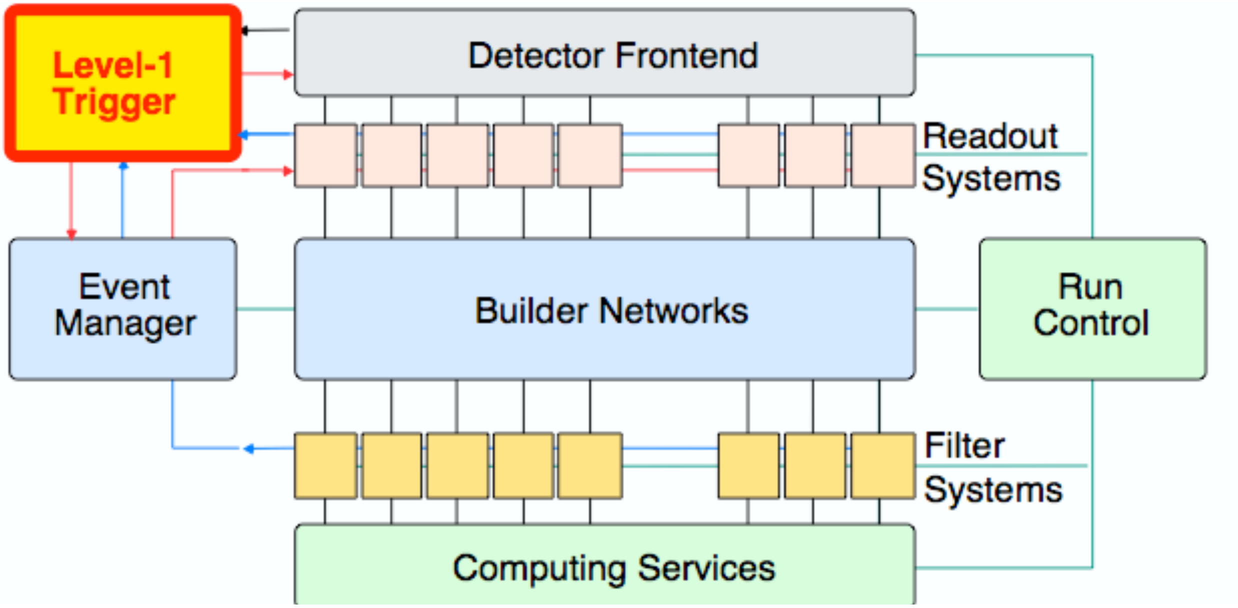
Higgs decays

- assuming m_H~ 200 GeV
- Can decay into two Z bosons, each of which decay into 2 muons,
- Final State: 4 muons



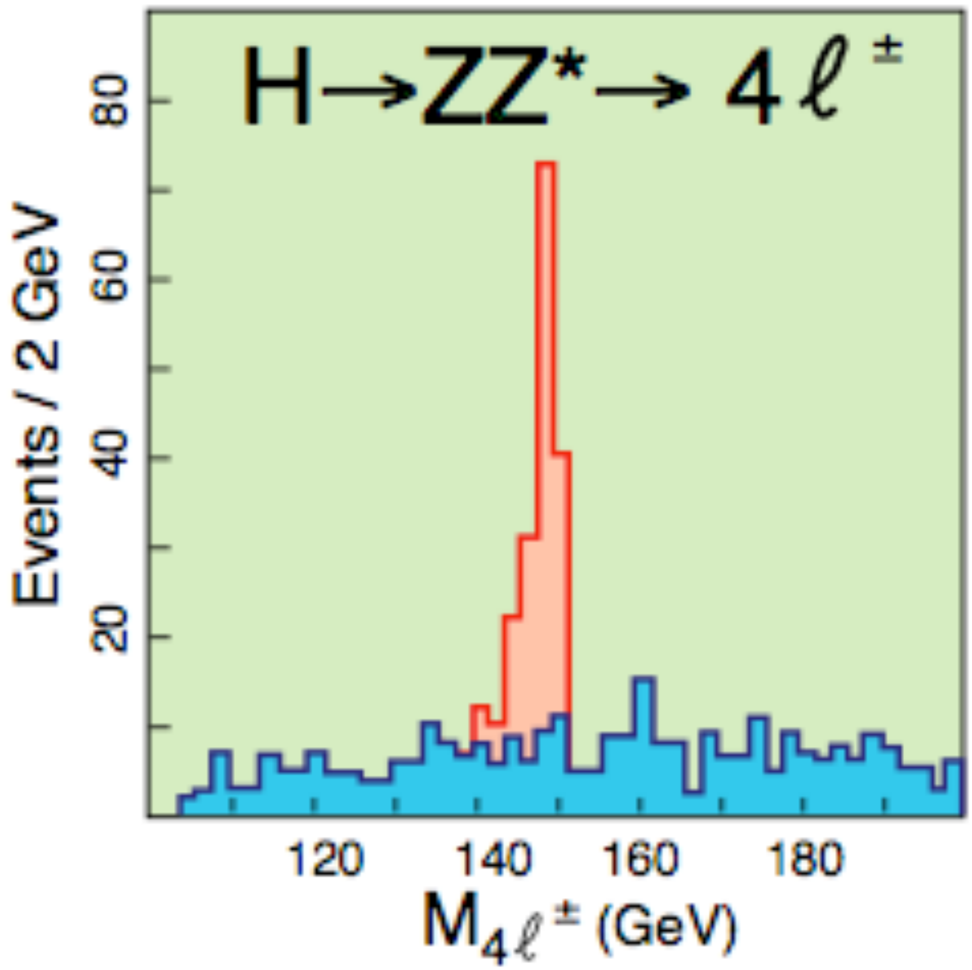
Computing Power

- Average event size 1Mbyte
- Data production: 1TByte/day
- 300 readout crates, 10000 electronics boards



Have found 4 muons..are we done?

- Background from
  - 4 unrelated muons from other decays
  - Particles that look like muons
- Need other characteristics of H->ZZ->4μ to reject these and estimate remaining background events
- use energy measurement of the muons: they have to add up to to a Higgs mass



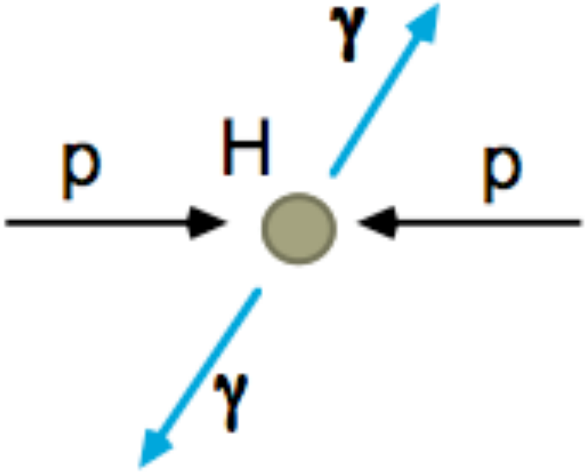
Red: simulated muons from Higgs

Blue: backgrounds from b, cosmics, …

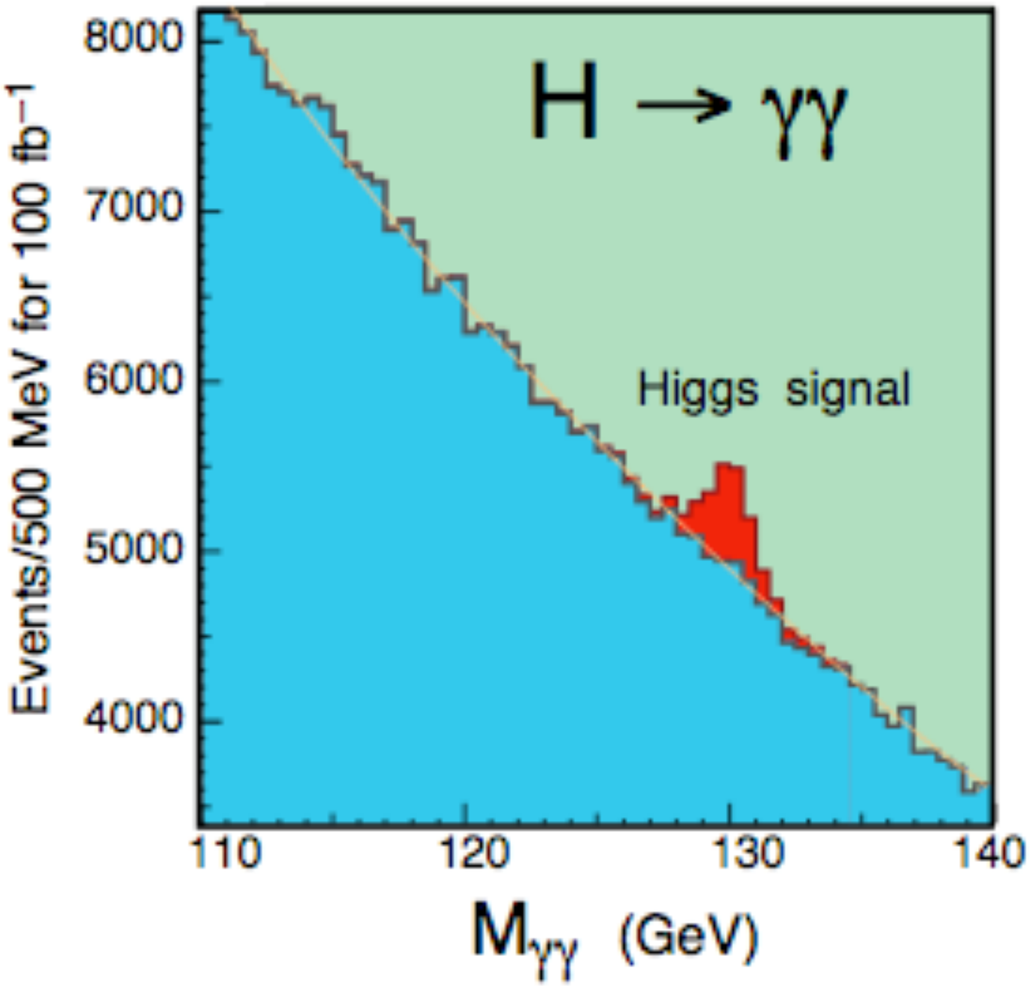
More realistically..

We know that Higgs mass is <200GeV

Most probable detection mode is H->γγ



Very difficult measurement..



Summary

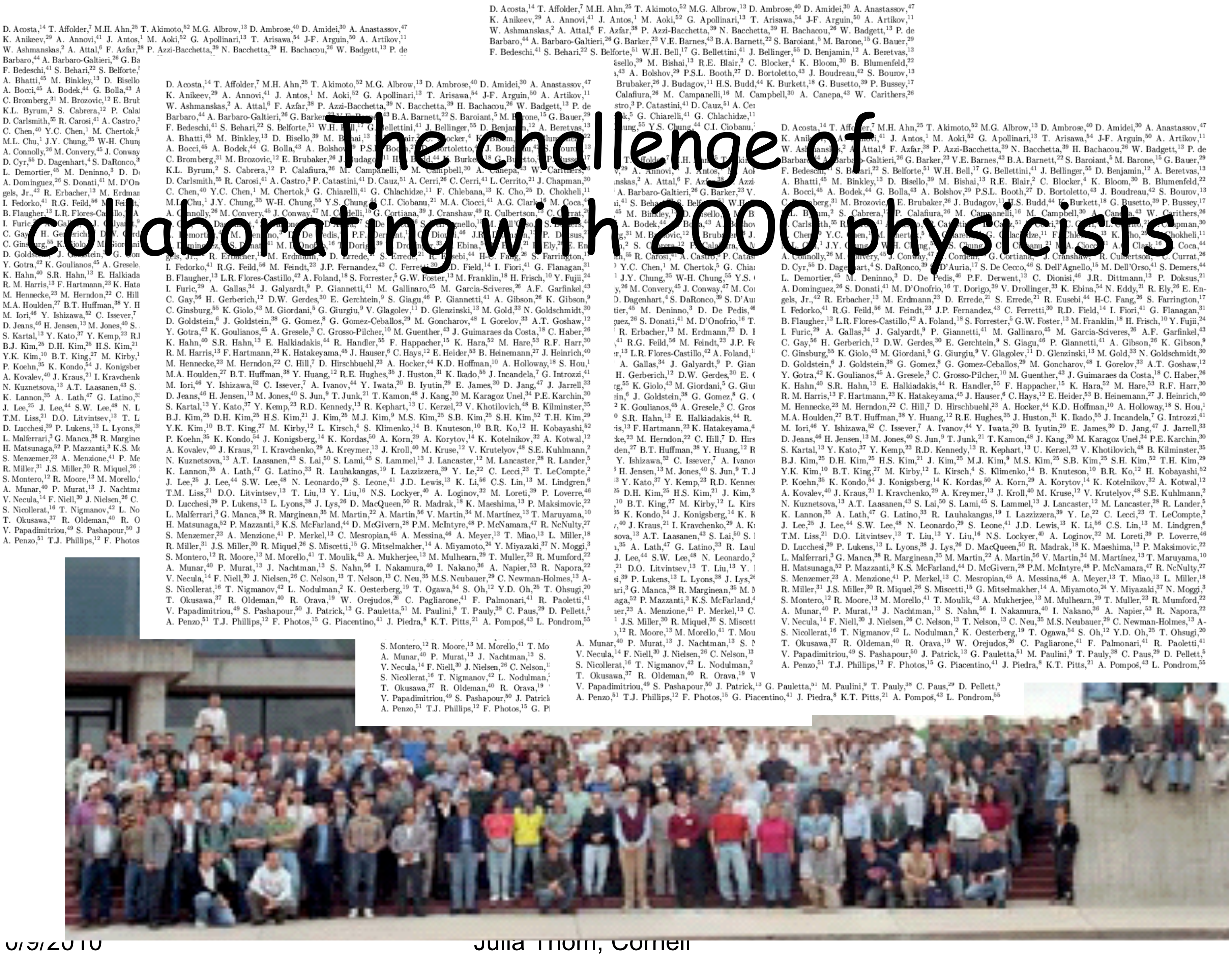
- We believe that we're just around the corner of a revolution in particle physics- LHC and ILC are our tools for the next decades of experiments
- The LHC is a powerful discovery machine, but a Linear Collider can measure quantum numbers with precision. We need it to understand the origin of the new phenomena that we expect to see soon.
- LHC has started taking data and is reaching the critical point where we could make discoveries any day now. Stay tuned!

Resources

- The CMS TIMES: http://cmsinfo.cern.ch/outreach/CMSTimes.html

  contains all news, results, updates, links to outreach pages, etc.
- To stay tuned on ILC developments: http://www.linearcollider.org/
- Colloquium tonight by Barry!
- My email address: jt297@cornell.edu

The challenge of collaborating with 2000 physicists



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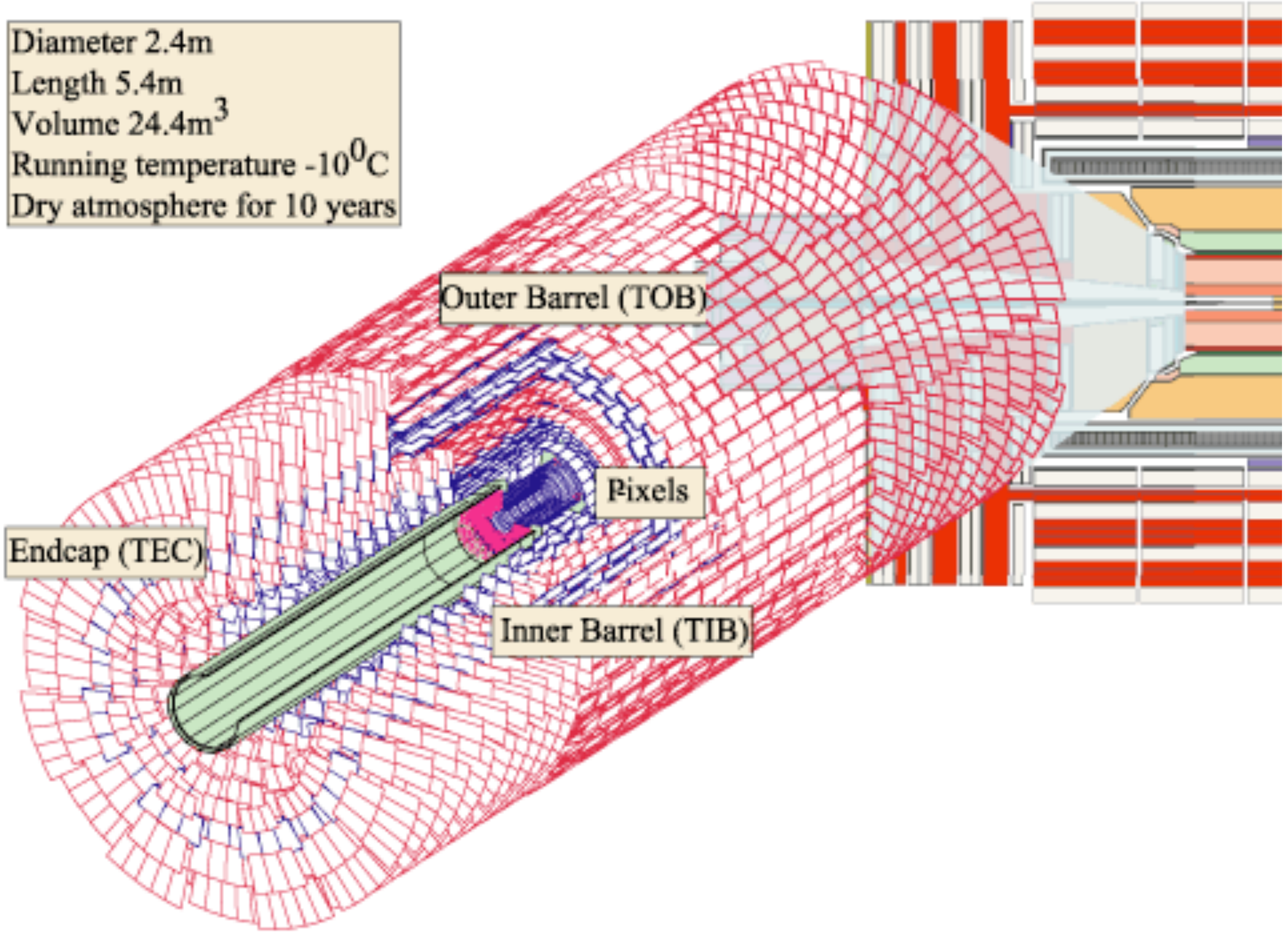
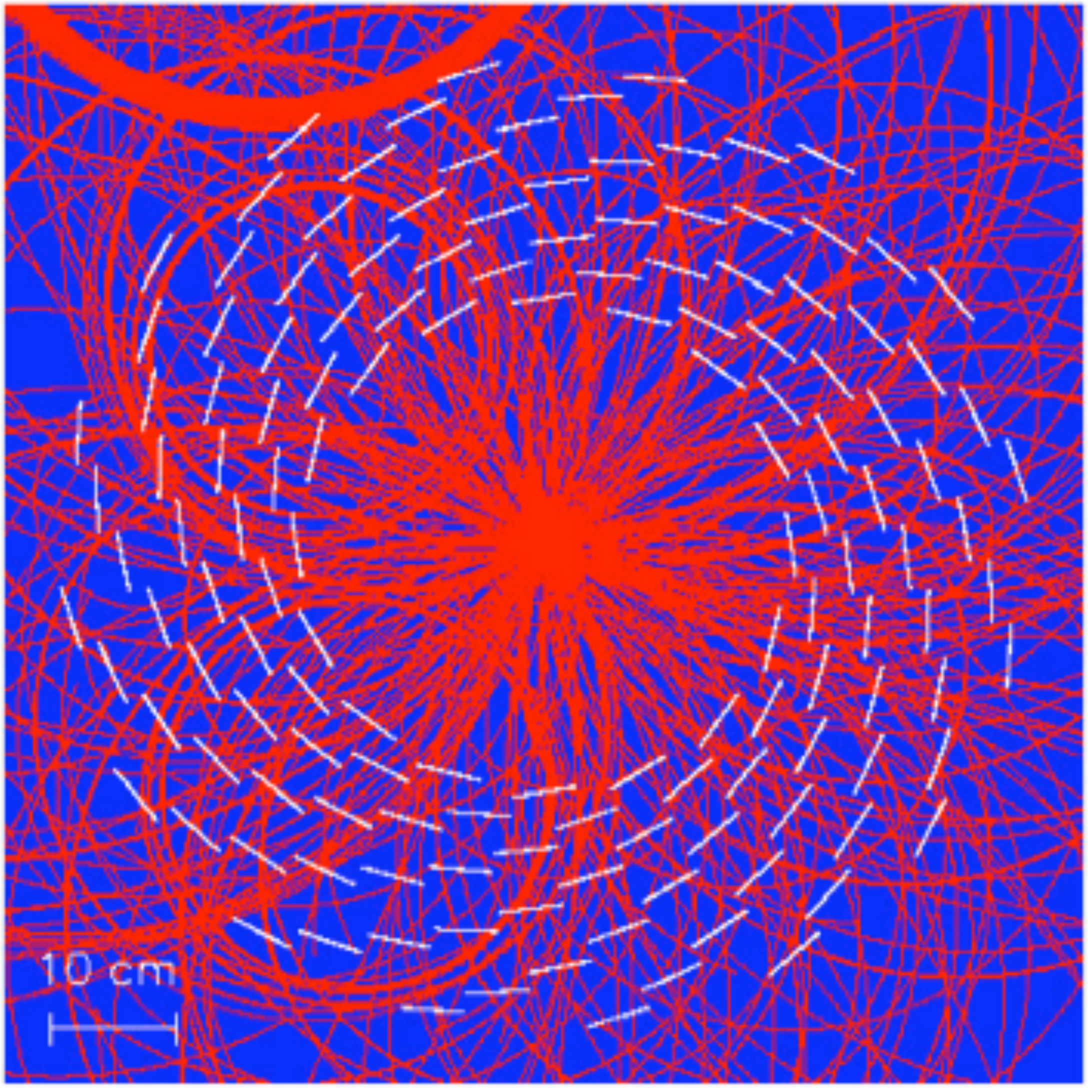


Diameter 2.4m
Length 5.4m
Volume 24.4m^3
Running temperature -10^{0}C
Dry atmosphere for 10 years

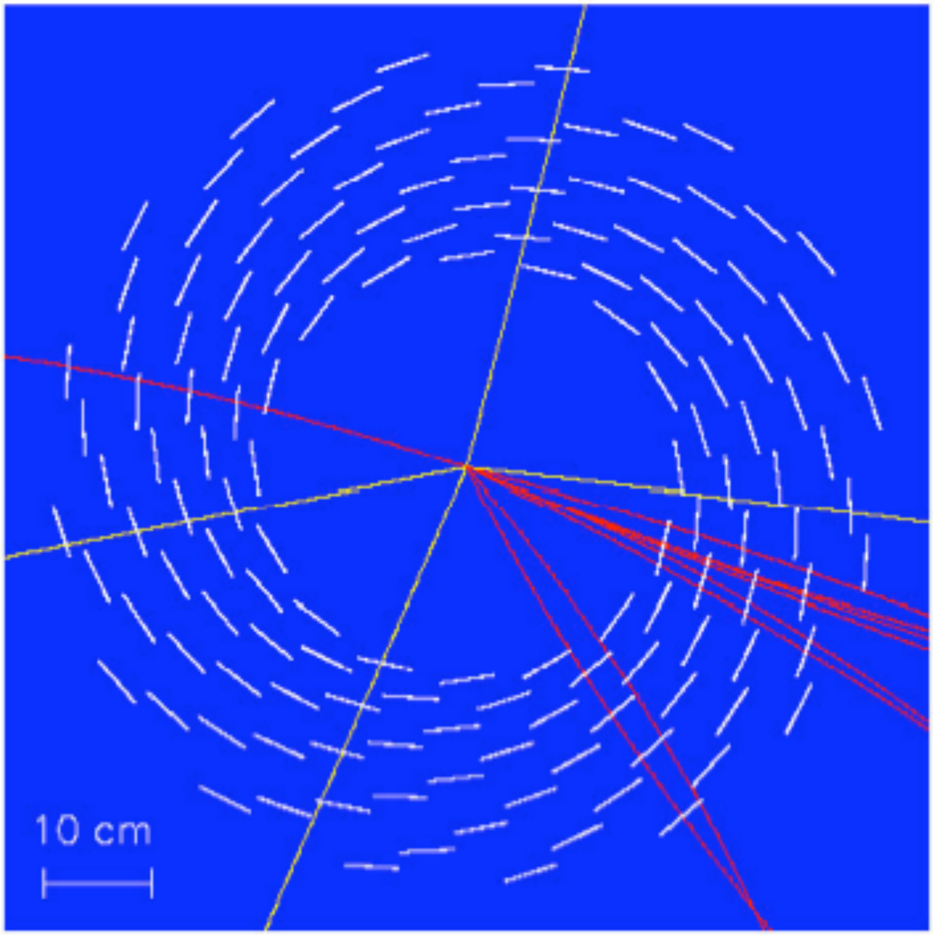
25000 silicon strip sensors covering an area of 210 m^2. Have to control 9600000 electronic readout channels (26 million microbonds).

18 superimposed pp collisions,
as seen by internal part of CMS silicon central tracker.
Among them 4 muons from a higgs decay.



Reconstructed tracks of $p_t > 2$ GeV.

Among them well visible 4 muons from the higgs decay.

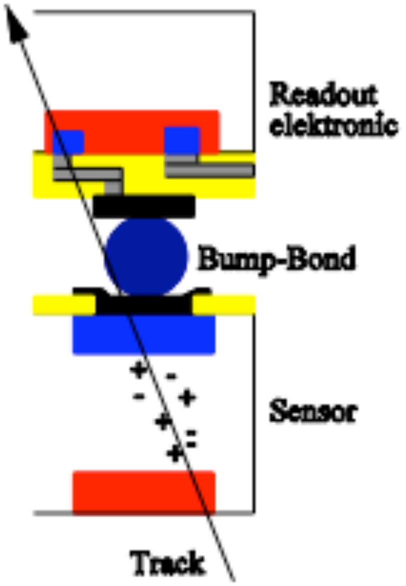


The solution is possible if detector occupancy ~1%

→ microstrip area ~1mm^2

→ >10^7 readout channels

CMS pixel detector

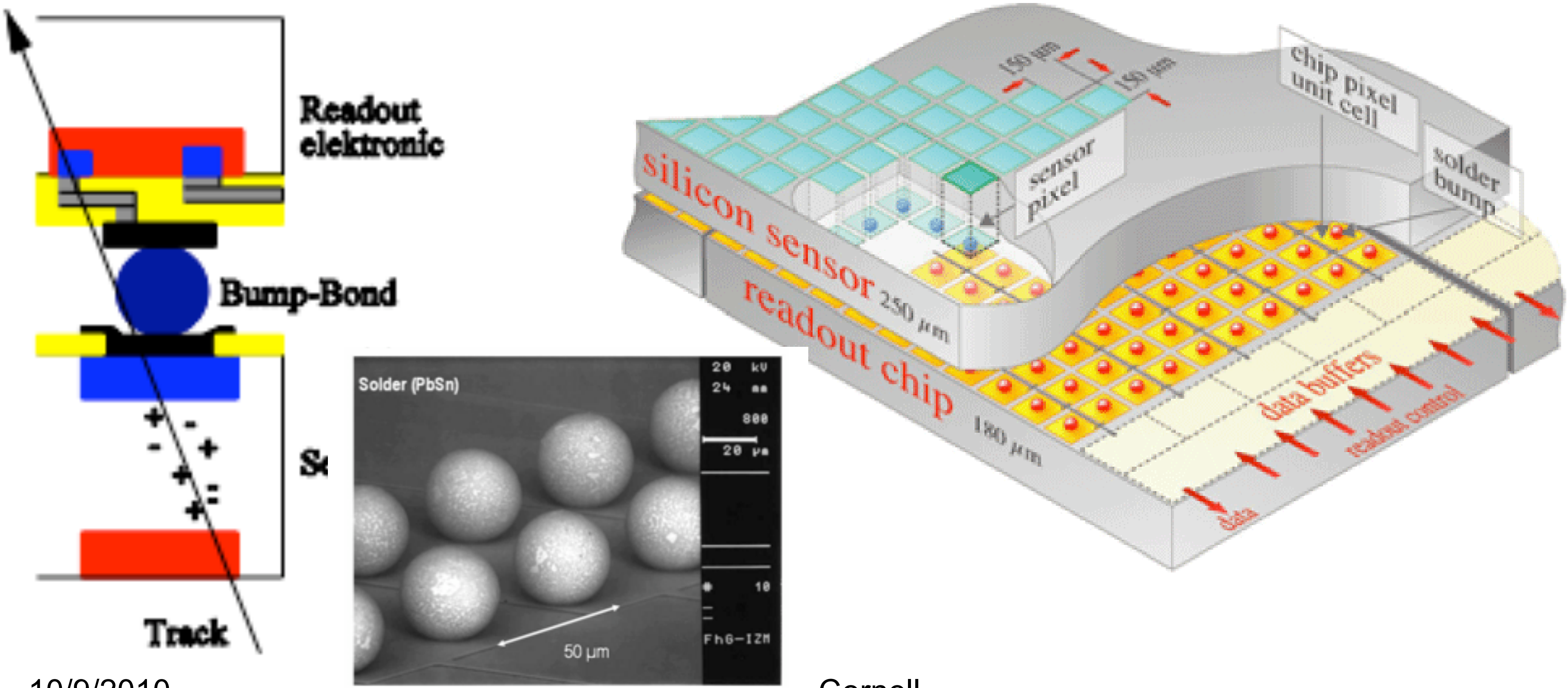


- "Hybrid active pixels". Presently only technology for LHC application
- Need pixels because of huge track multiplicity
  - Readout chip has same pixelation as sensor, bump-bonded onto sensor
  - pixel size limited by readout circuit and heat/power dissipation limit (150x150μm)
  - 2% X0 per layer (3 pixel layers 4, 7, 11cm, material budget driven by COOLING)
  - Readout chip:0.25μ CMOS technology
    - rad hard "Complemetary metal oxide semiconductor", Field effect Transistor circuit (fast)

- Vertexing and track reconstruction in a harsh environment!
  - Radiation:
    - dose: 3×10^{14}pcm^{-2}yr
  - Rate
    - up to 20MHz/cm^2 of particles
- For b-tagging, vertex reconstruction: 100GeV B jet, flight path ~100μ
  - need ~20 μ resolution, 3D space point
  - All hit information has to be stored until L1 decision
  - Trigger latency: 3μs, 10Tbit/sec stored and transferred by ROC
- Also want low cost, easy cooling & cabling, low material budget

CMS pixel detector

- 66 Million Pixels, 1m^2 of silicon
- pixel size limited by readout circuit and heat/power dissipation limit (150x150μm)



Higgs Mechanism

- Introduce weak doublet spin 0 “higgs field” H with classical potential

$$V = m_H^2 \, |H|^2 + \lambda \, |H|^4$$

- H acquires non-vanishing vacuum-expectation value if Higgs mass $m_H^2 < 0$

$$\langle H \rangle = \sqrt{\frac{-m_H^2}{2\lambda}}$$

- If superpartners too heavy introduce a mini-hierarchy problem (Δm_H proportional to m_S^2)

$$\Delta m_H = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \dots\right]$$

Higgs mass constraints

"Indirect":

- Top and Higgs loops contribute to W and Z mass

- We have measured W and Z masses with high precision, can indirectly constrain Higgs mass

$m_H^{SM} < 200$ GeV

Direct searches in current experiments:

$m_H^{SM} > 115$ GeV

How are the masses generated: Electroweak Symmetry Breaking

- High energy: electromagnetic and weak forces are unified, i.e. equal couplings; gauge bosons mass-less
- Observation: $M_\gamma=0$ but M_Z, M_W ~100 GeV
- How does this difference arise?

The Higgs Field

- Introduce Spin 0 Higgs field
- Introduce classical potential for Higgs field such that at minimum Higgs acquires "vacuum expectation value" $\langle H \rangle \neq 0$
- Higgs is electrically neutral (doesn't couple to photons) but weakly charged
- "Spontaneous symmetry breaking"