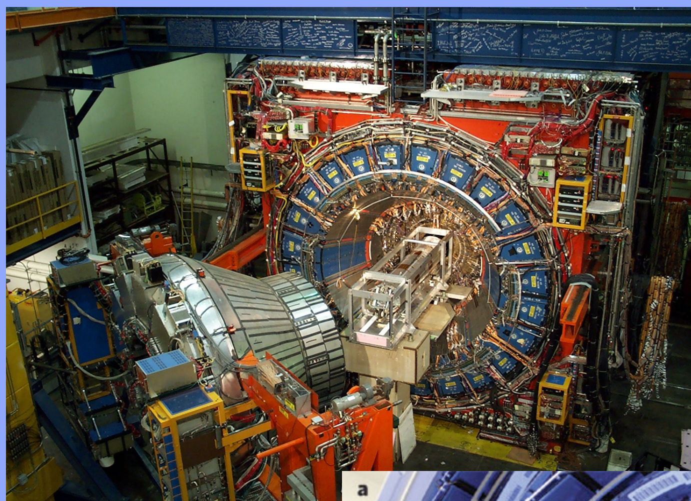
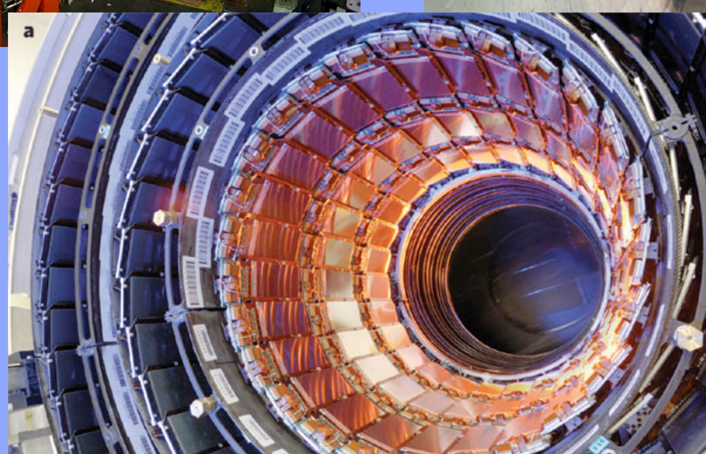
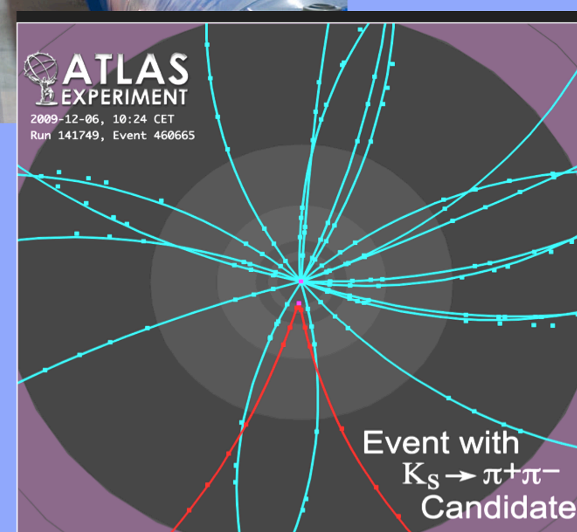
Particle Physics from Tevatron to LHC: what we know and what we hope to discover







Beate Heinemann, UC Berkeley and LBNL

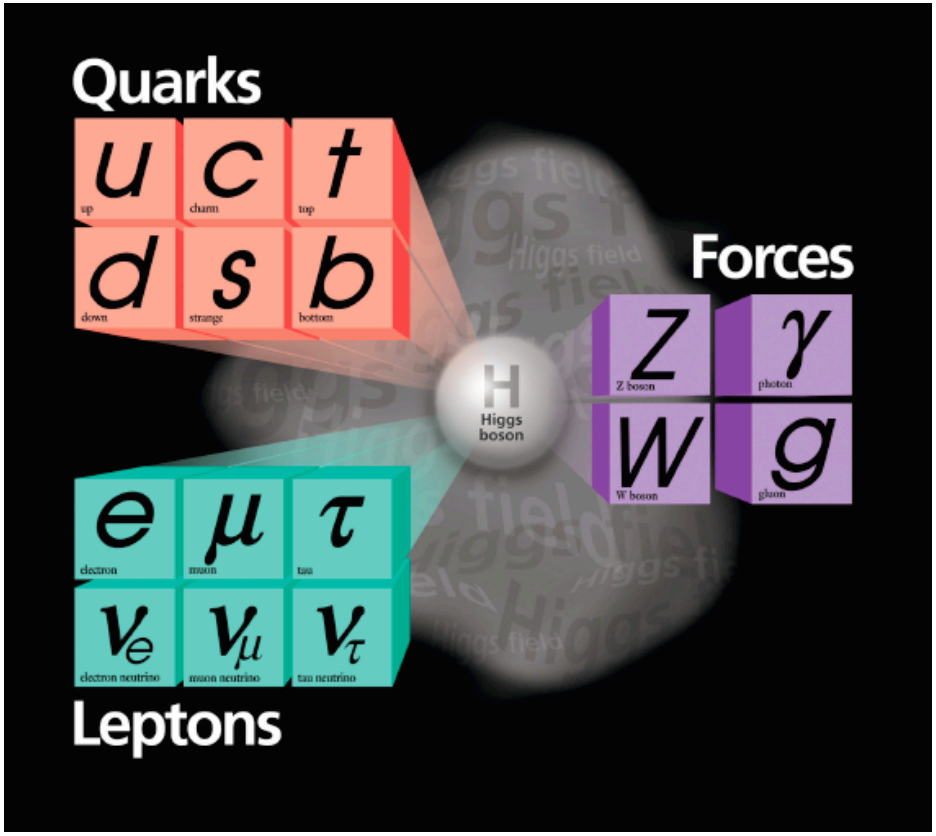
Università di Pisa, February 2010

Outline

- **Introduction**
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current and near future colliders: Tevatron and LHC
  - Hadron-hadron collisions
- **Standard Model Measurements**
  - Tests of QCD
  - Precision measurements in electroweak sector
- **Searches for the Higgs Boson**
  - Standard Model Higgs Boson
  - Higgs Bosons beyond the Standard Model
- **Searches for New Physics**
  - Supersymmetry
  - High Mass Resonances (Extra Dimensions etc.)
- **First Results from the 2009 LHC run**

Outstanding Problems in Particle Physics
and the role of Hadron Colliders

Fundamental Particles and Forces



- **Matter**
  - is made out of fermions
- **Forces**
  - are mediated by bosons
- **Higgs boson**
  - breaks the electroweak symmetry and gives mass to fermions and weak gauge bosons

Amazingly successful in describing precisely data from all collider experiments

The Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi$$
$$+ \psi_i\lambda_{ij}\psi_j h + \text{h.c.}$$
$$+ |D_\mu h|^2 - V(h)$$
$$+ \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j$$

- gauge sector ✓
- flavour sector ✓
- EWSB sector ✓
- ν mass sector

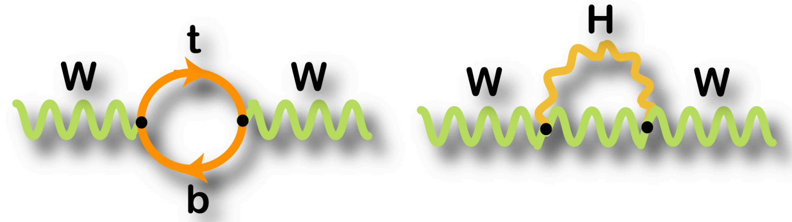
… and beyond?

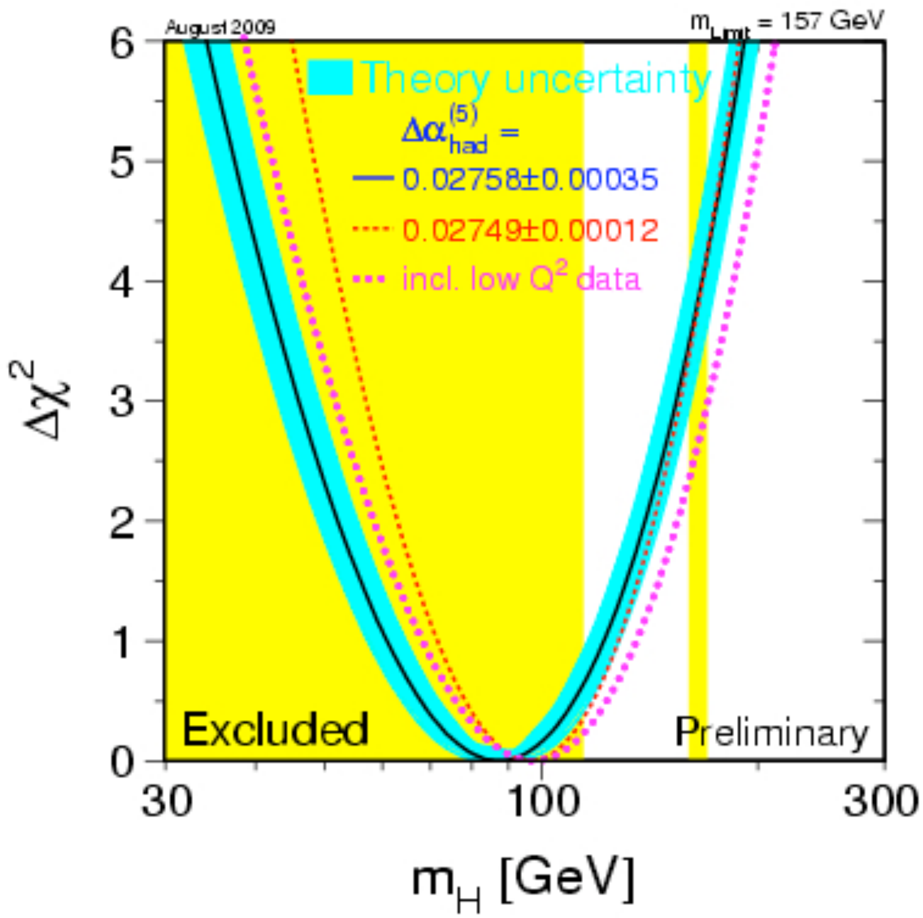
- supersymmetry (many variants)
- extra spacetime dimensions ✓
- compositeness
- strong electroweak symmetry breaking
- …
- something new?!

[W. J. Stirling]

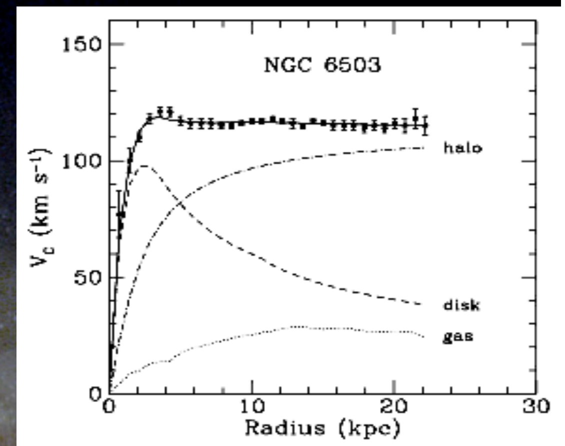
Problem I: Where is the Higgs boson?

- Precision measurements of
  - M_W =80.399 ± 0.023 GeV/c^2
  - M_{top}=173.1 ± 1.2 GeV/c^2
  - Precision measurements on Z pole
- Prediction of higgs boson mass within SM due to loop corrections
  - Most likely value: 87^{+35}_{-26} GeV
- **Direct limits at 95% CL**
  - **LEP: m_h>114.4 GeV**
  - **Tevatron: m_h<163 or m_h>166 GeV**
- **Indirect:**
  - **m_h<157 GeV at 95% CL**





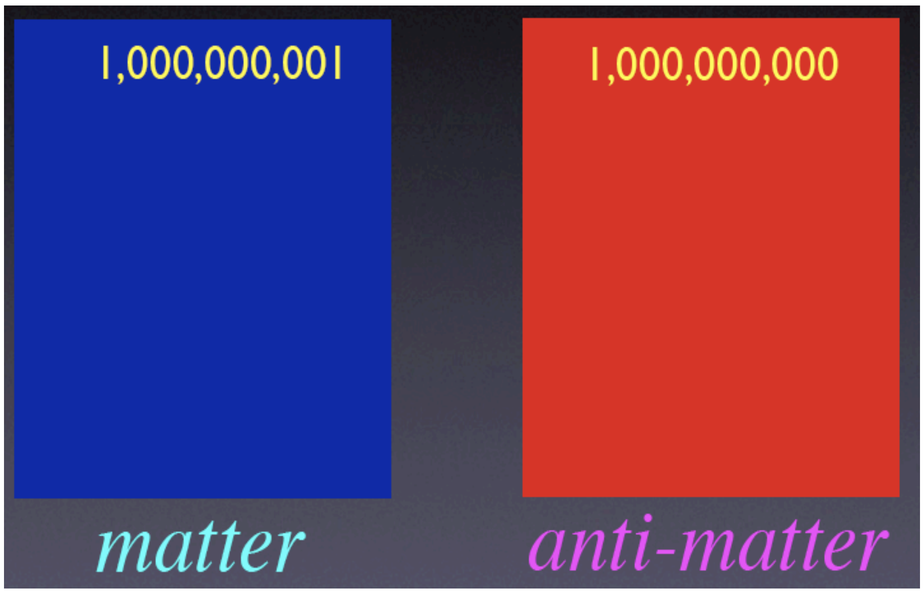
Problem II: What is the Dark Matter?



Standard Model only accounts for 20% of the matter of the Universe

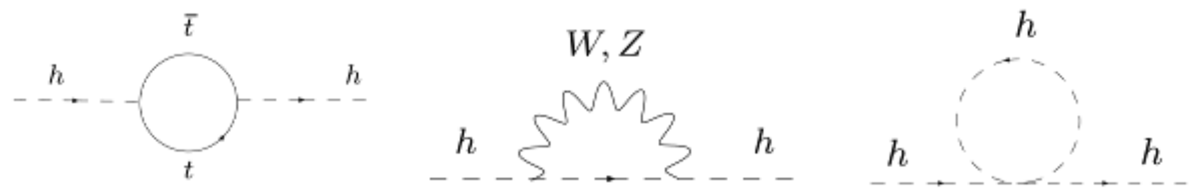
$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

Problem III:
Where did all the Antimatter go?



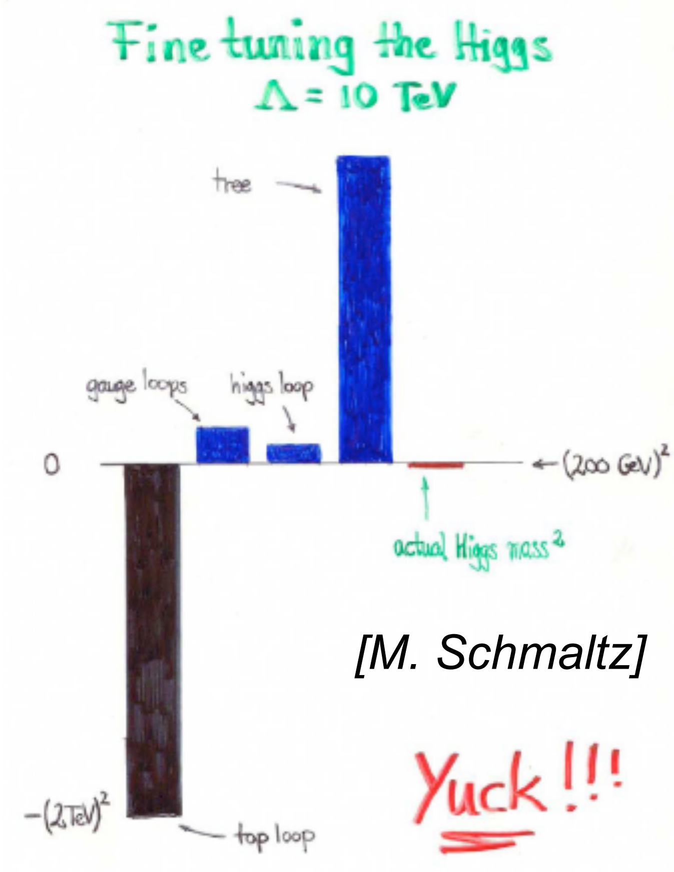
- **Not explained by Standard Model**

Problem IV: Hierarchy Problem



$$m^2_H \approx (200\ \text{GeV})^2 = m^2_H{}^{tree} + \delta\, m^2_H{}^{top} + \delta\, m^2_H{}^{gauge} + \delta\, m^2_H{}^{higgs}$$

- **Why is gravity so weak?**
  - $M_W/M_{Planck} \sim 10^{16}$ or $G_F/G_N \sim 10^{32}$!
  - Free parameter $m^2_H{}^{tree}$ needs to be "finetuned" to cancel huge corrections
- Can be solved by presence of **new particles at M ~1 TeV**
  - Already really bad for M~10 TeV

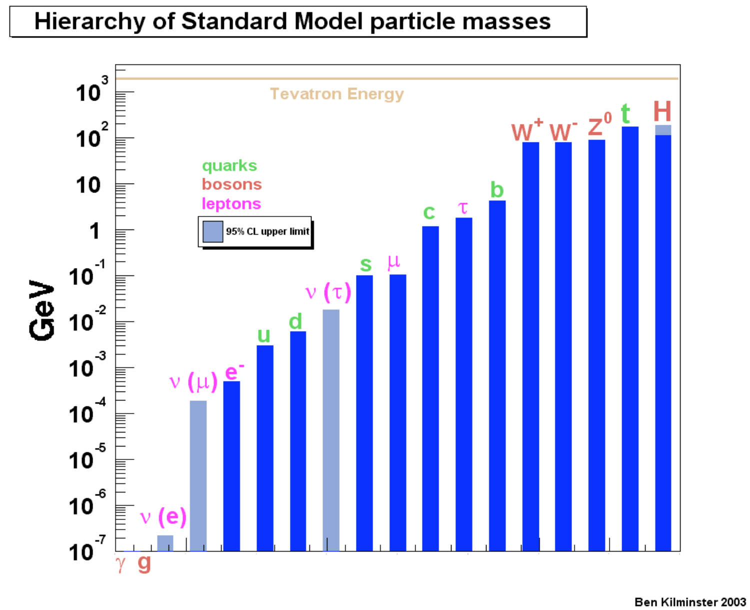


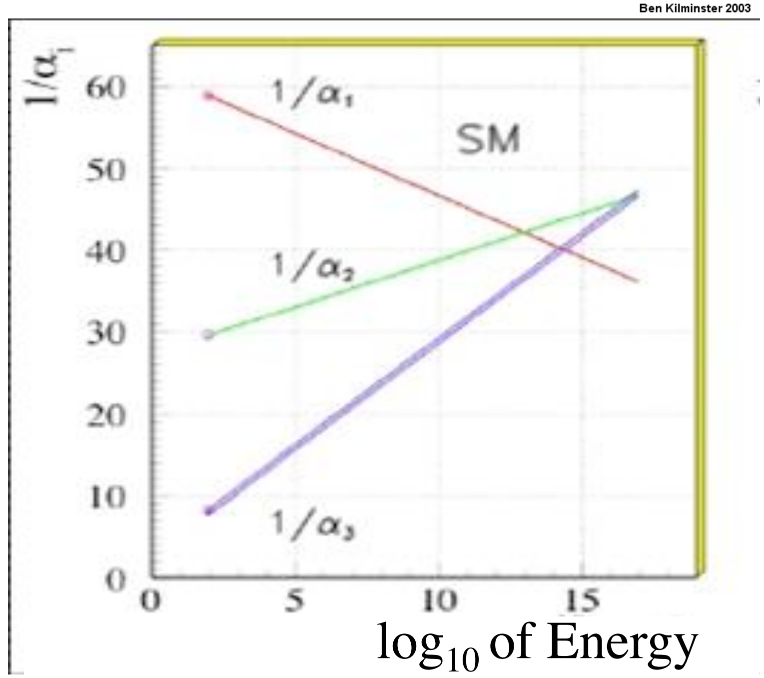
[M. Schmaltz]

(Some) More Problems …

- **Matter:**
  - SM cannot explain **number of fermion generations**
  - or their **large mass hierarchy**
    - m_{top}/m_{up}~100,000
- **Gauge forces:**
  - electroweak and strong **interactions do not unify** in SM
  - SM has no concept of **gravity**
- **What is Dark Energy?**

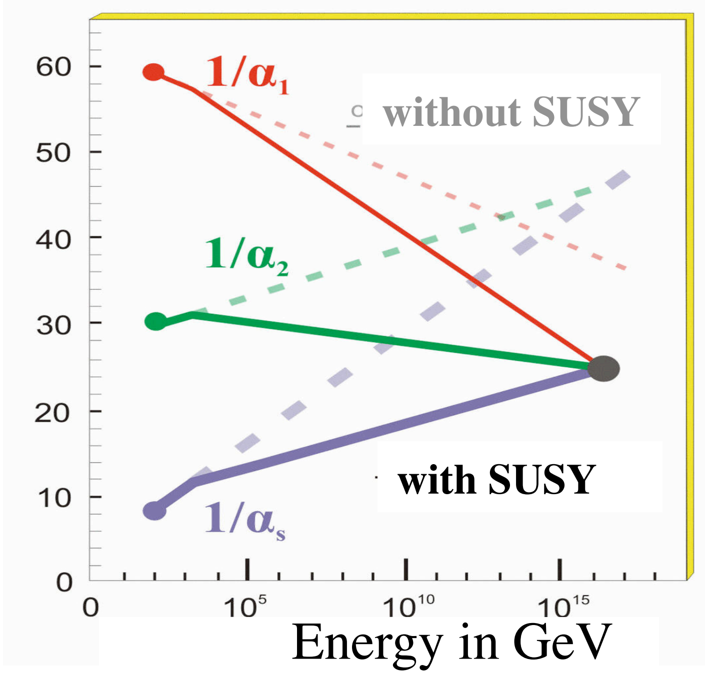
"Supersymmetry" (SUSY) can solve some of these problems

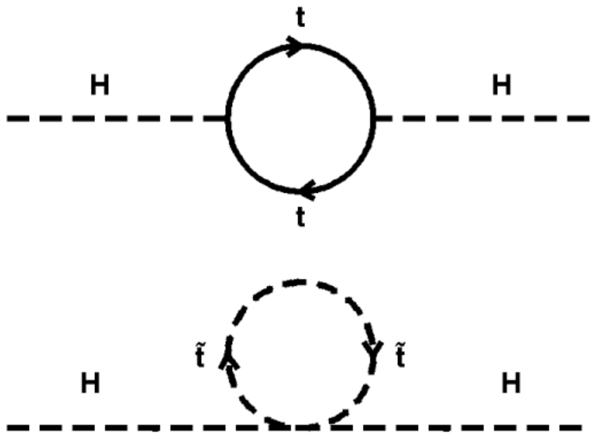




SUSY can solve some problems

- Supersymmetry (SUSY)
  - Each SM particle gets a partner differing in spin by 1/2
- Unifications of forces possible
  - SUSY changes running of couplings
- Dark matter candidate exists:
  - The lightest neutral partner of the gauge bosons
- No (or little) fine-tuning required
  - Radiative corrections to Higgs acquire SUSY corrections
    - Cancellation of fermion and sfermion loops





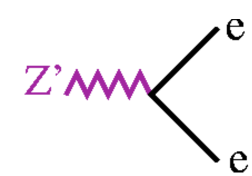
Mass of supersymmetric particles must not be too high (~TeV)

Beyond Supersymmetry

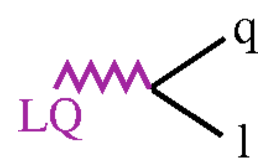
- **Strong theoretical prejudices for SUSY being true**
  - But so far there is a lack of SUSY observation….

- **Need to keep an open eye for e.g.:**
  - **Extra spatial dimensions:**

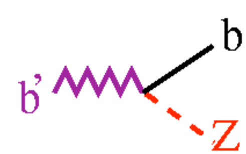
    - Addresses hierarchy problem: make gravity strong at TeV scale
  - **Extra gauge groups: Z', W'**



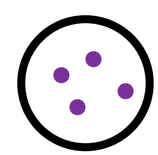
    - Occur naturally in GUT scale theories
  - **Leptoquarks:**



    - Would combine naturally the quark and lepton sector
  - **New/excited fermions**



    - More generations? Compositeness?
  - **Preons:**
    - atom⇒nucleus ⇒ proton/neutron ⇒ quarks ⇒ preons?



  - **… ????**: something nobody has thought of yet

Confusion among Theorists?

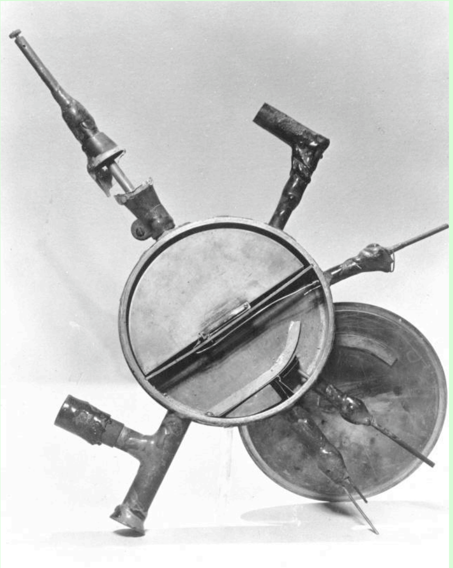
[Hitoshi Murayama]

Need experiments to figure out which (if any) represents Nature

Current Hadron Colliders:
Tevatron and LHC

The Role of Colliders

- **Colliders have been a key tool for discovering most particles we know today, e.g.:**
  - Anti-proton (LBNL, 1955)
  - Quarks (SLAC 1969)
  - W- and Z-boson (CERN, 1983)
  - Top-quark (FNAL, 1994)
  - … plus many more



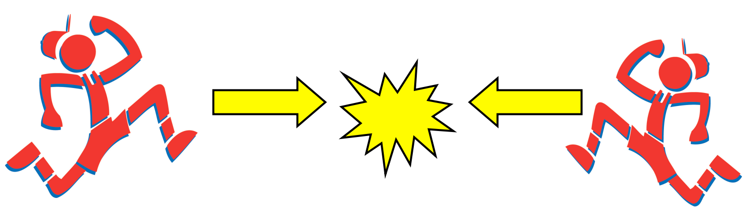
1930, 80 keV, 4.5cm

- **Basic principle follows from E=mc^2**
  - If collider energy ≥ mass of particle the particle can be produced
- **Collider types to date**
  - Hadron colliders (protons and ions)
  - Electron colliders

Why a Hadron Collider?

- Disadvantages:
  - Hadrons are complex objects
    - High multiplicity of other stuff
    - Energy and type of colliding parton (quark, gluon) unknown
      - Kinematics of events not fully constrained
- Advantage:
  - Can access higher energies

Lepton Collider
(collision of two point-like particles)



Hadron collider
(collision of ~50 point-like particles)

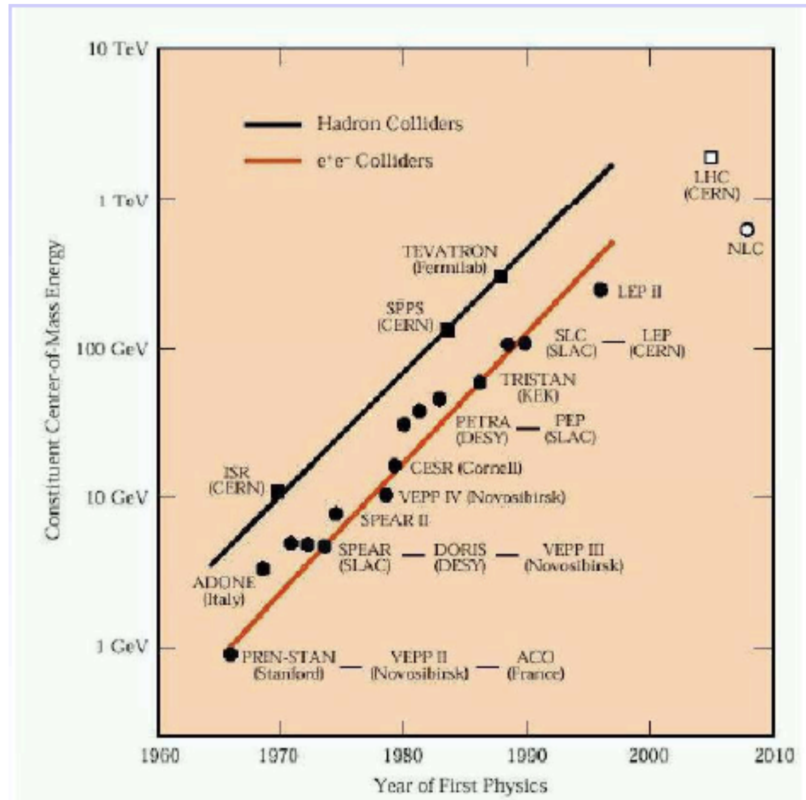
[Karl Jakobs]

e^+e^- vs Hadron Colliders

- Circular colliders:
  - Pro:
    - Reuse their power on each turn
  - Con:
    - Synchrotron radiation reduces energy of particles
      - Problem worsens with m^4
- Linear colliders:
  - Particle sees each component just once
  - Now more cost-effective for electrons than circular collider => proposal of *ILC* (=International Linear Collider)

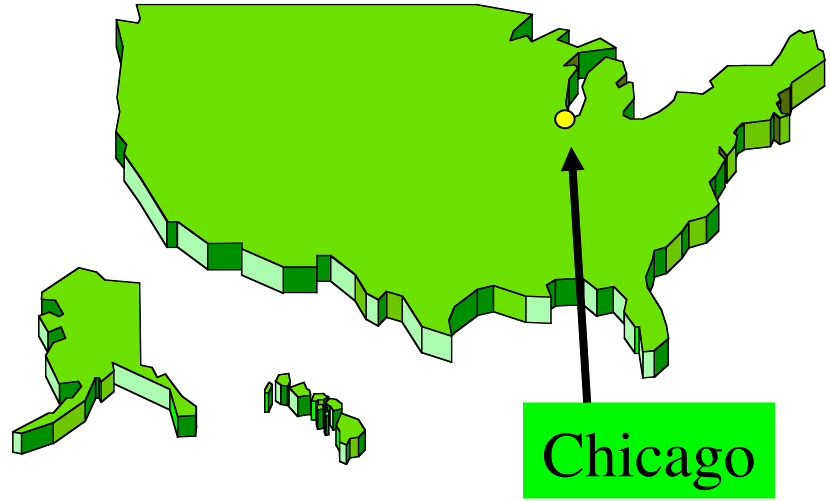
Energy loss per turn: $$-\Delta E \approx \frac{4\,\pi\,e^2}{3\,R}\left(\frac{E}{mc^2}\right)^4$$

Energy loss: e vs p $$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

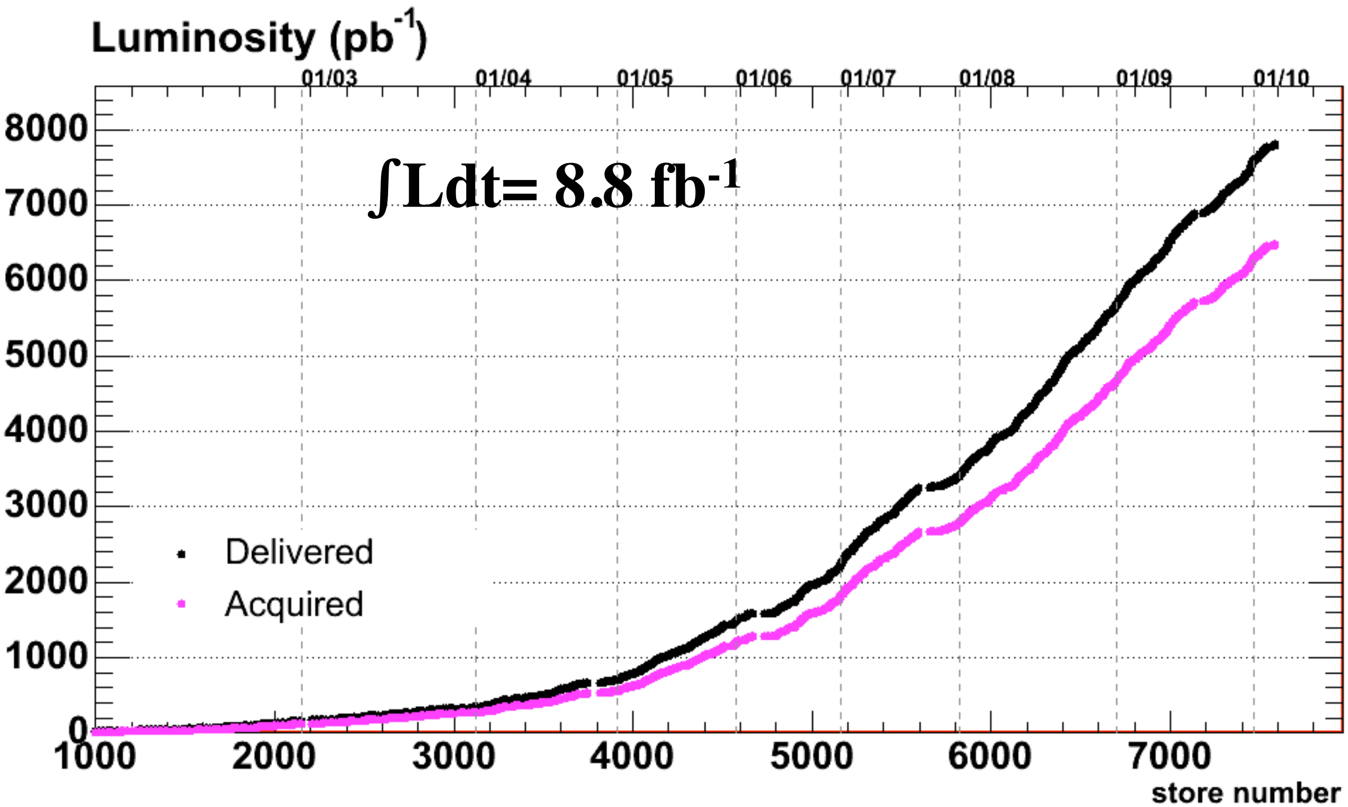


The Tevatron

- $p\bar{p}$ collider:
  - 6.5 km circumference
  - Beam energy: 980 GeV
    - $\sqrt{s}$=1.96 TeV
  - 36 bunches:
    - Time between bunches: Δt=396 ns
- Main challenges:
  - Anti-proton production and storage
  - Irregular failures:
    - Quenches
- CDF and DØ experiments:
  - 700 physicists/experiment



Tevatron Integrated Luminosity



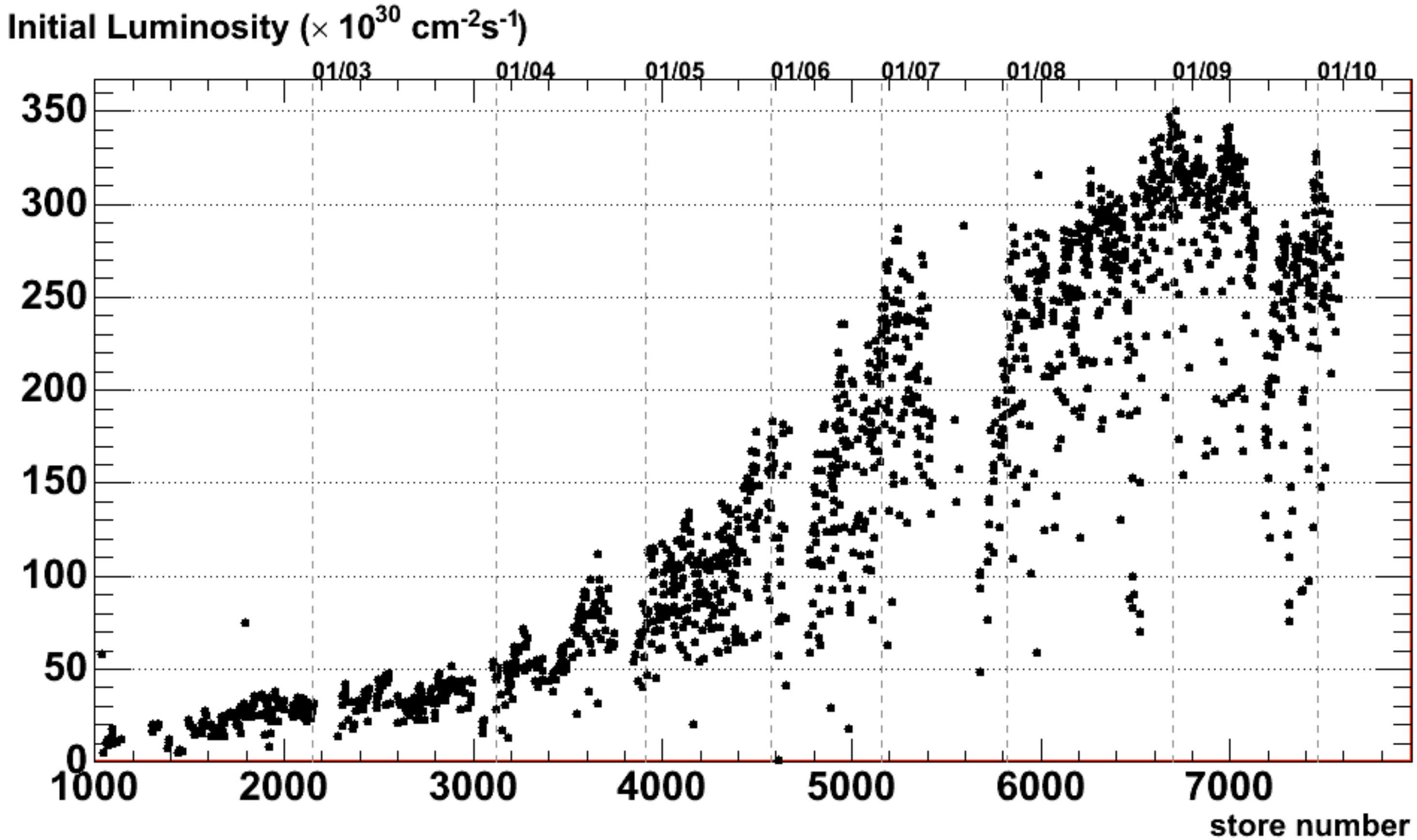
N_{event} = cross section x $\int$Ldt x Efficiency

Given by Nature (calculated by theorists)

accelerator

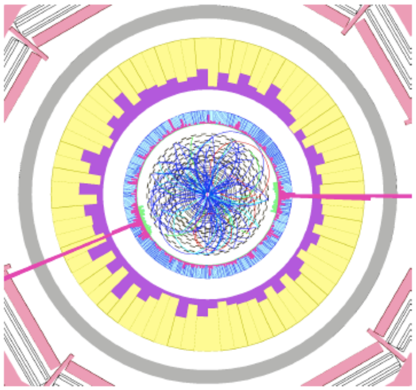
Detector (Experimentalist)

Tevatron Instantaneous Luminosity

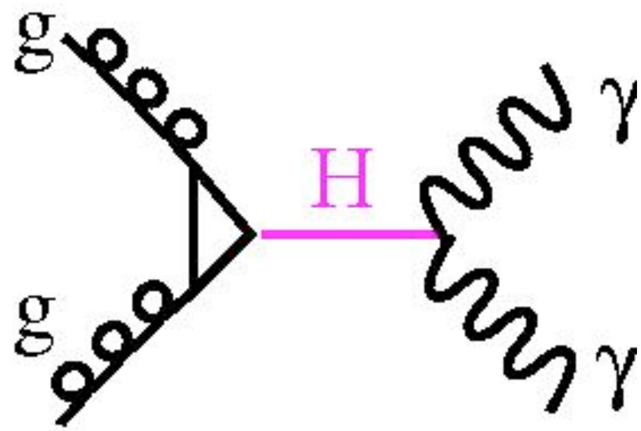


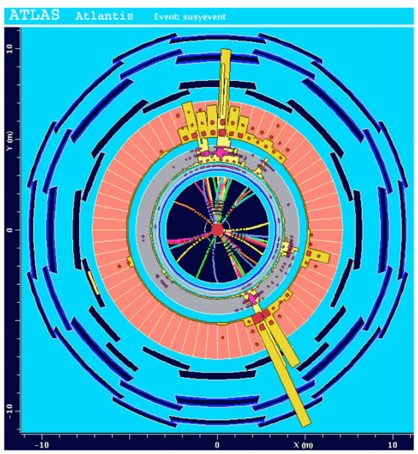
- peak luminosity of 3.5×10^{32} cm^{-2} s^{-1}
- took many years to achieve this!

The Experimental Challenge

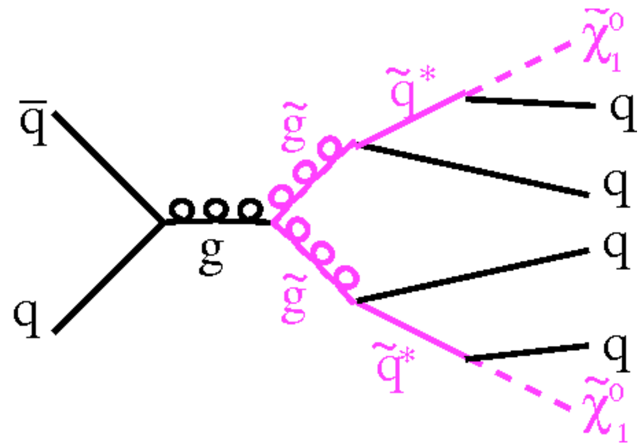


Higgs





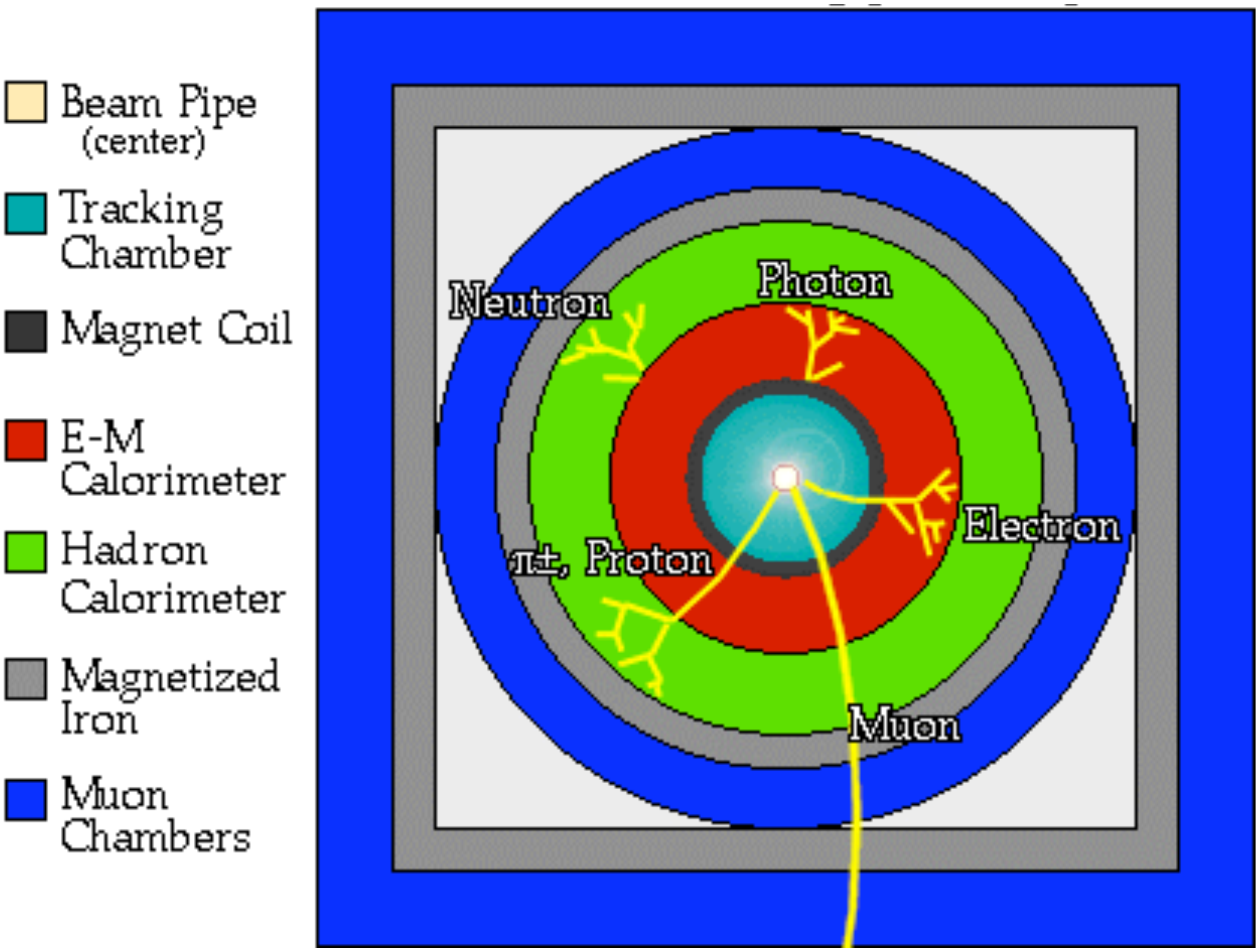
Supersymmetry



- Measured hits in detector
- => use hits to reconstruct particle paths and energies
- => estimate background processes
- => understand the underlying physics

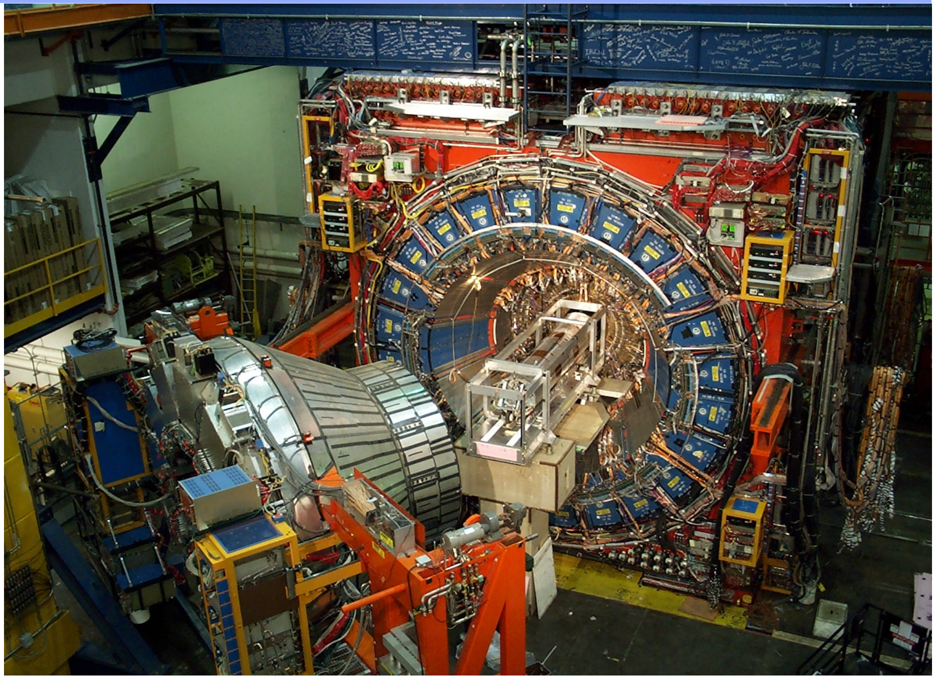
Particle Identification

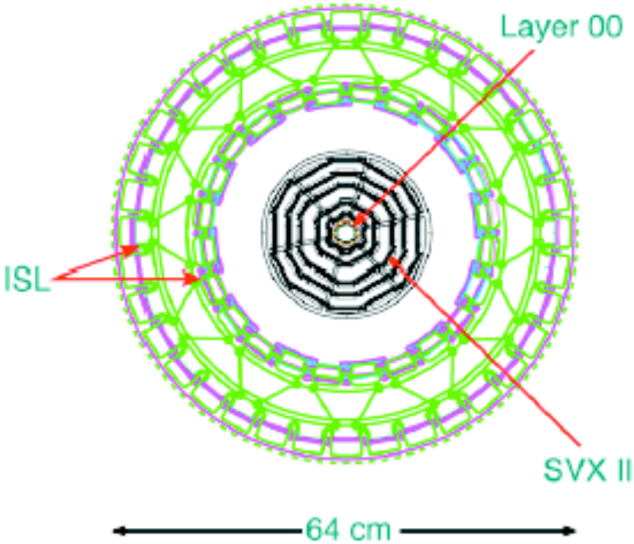
Detector designed to separate electrons, photons, muons, neutral and charged hadrons



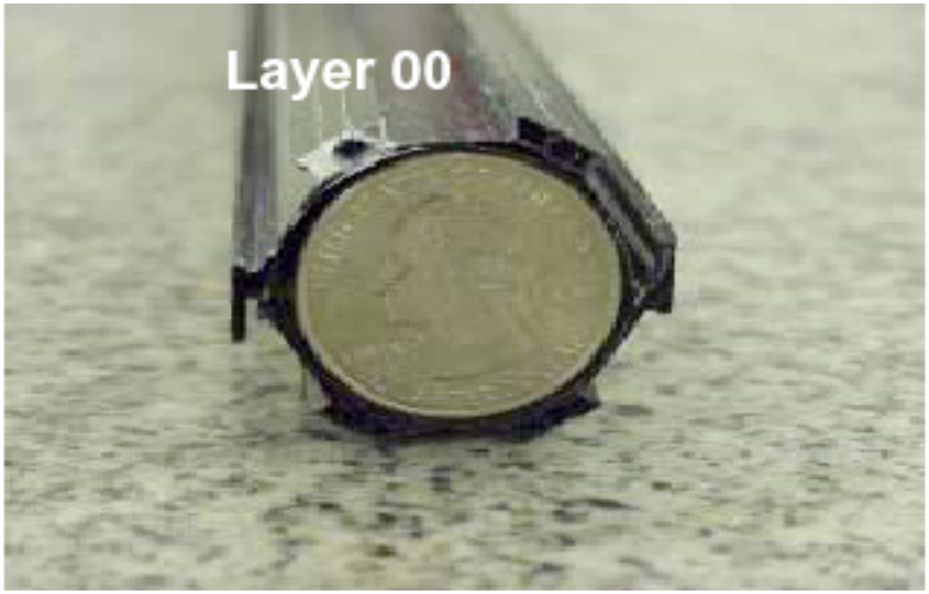
CDF

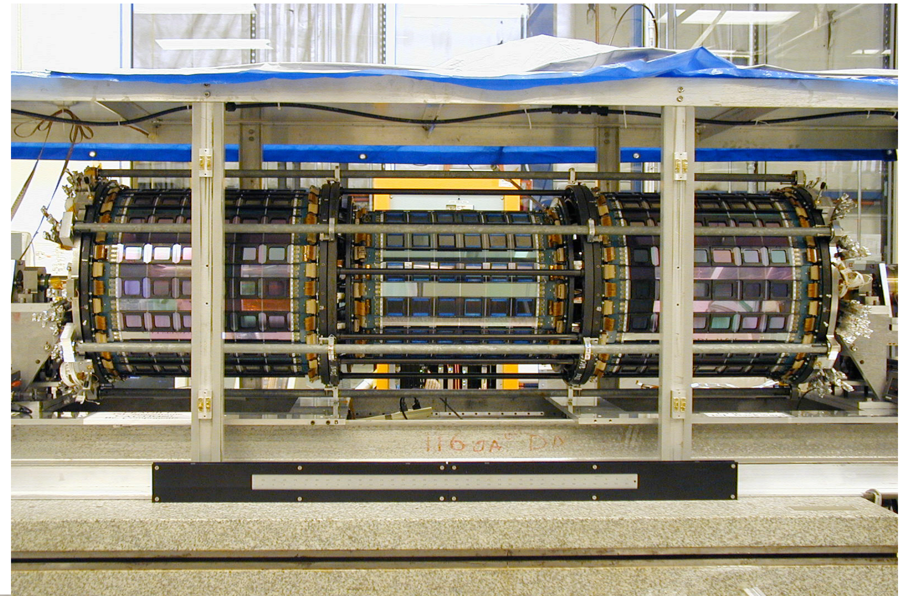
- Core detector operates since 1985:
  - Central Calorimeters
  - Central muon chambers
- Major upgrades for Run II:
  - Drift chamber: COT
  - Silicon: SVX, ISL, L00
    - 8 layers
    - 700k readout channels
    - 6 m^2
    - material:15% X_0
  - Forward calorimeters
  - Forward muon system
    - Improved central too
  - Time-of-flight
  - Preshower detector
  - Timing in EM calorimeter
  - Trigger and DAQ

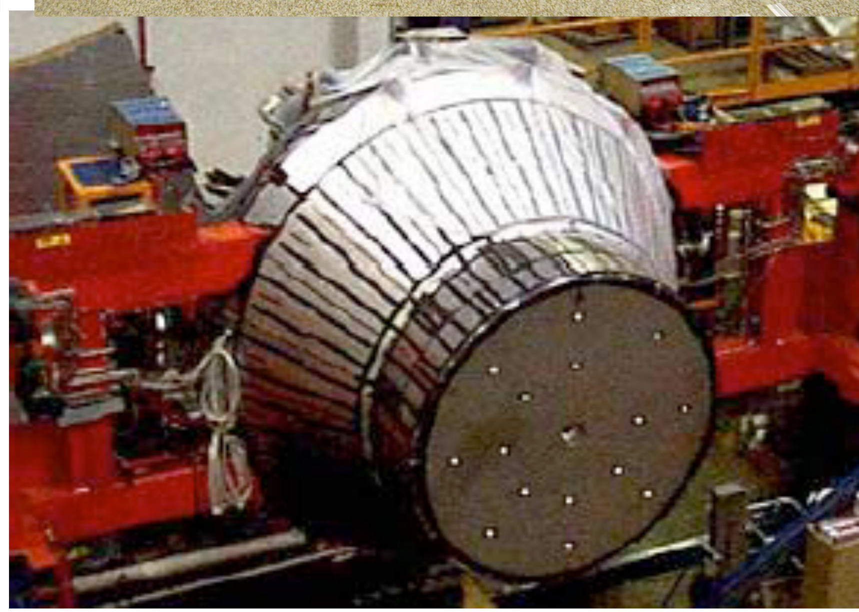




Some CDF Subdetectors



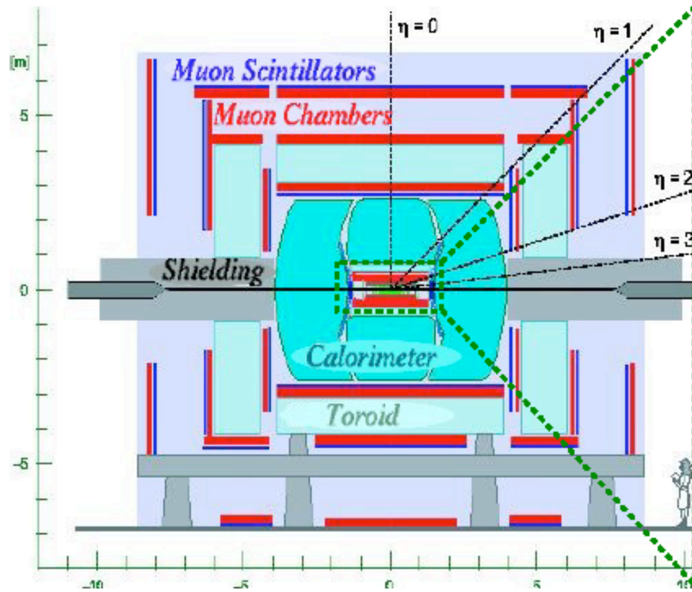


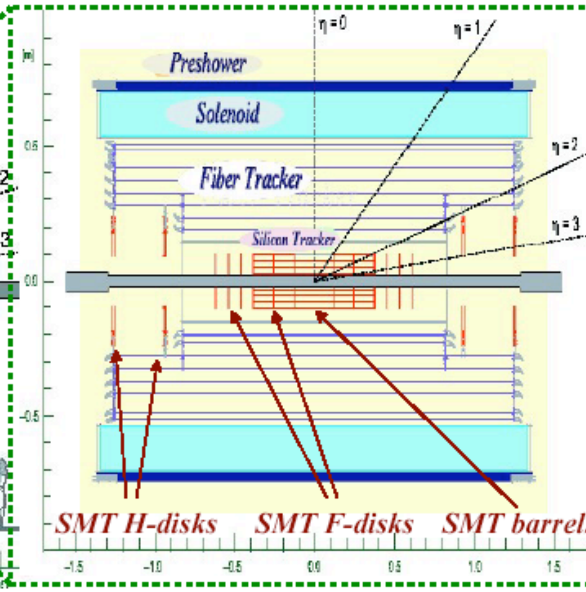


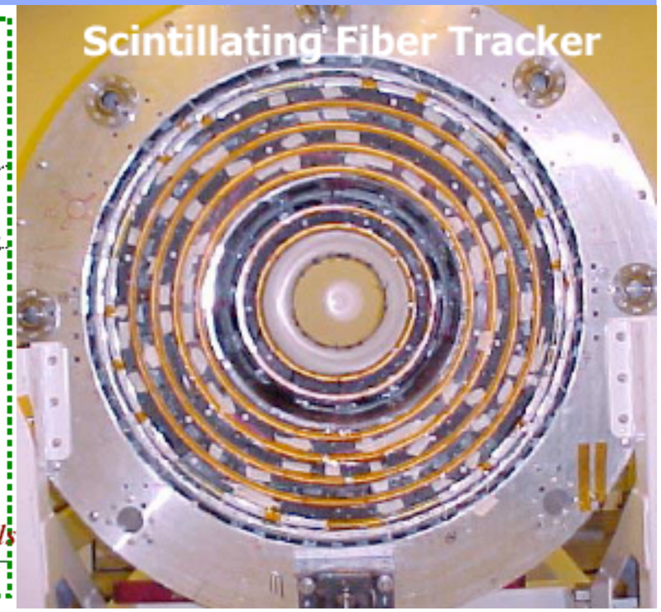
DØ Detector

- Retained from Run I
  - Excellent muon coverage
  - Compact high granularity LAr calorimeter
- New for run 2:
  - 2 Tesla magnet
  - Silicon detector
  - Fiber tracker
  - Trigger and Readout
  - Forward roman pots

DØ Detector


η = 0
η = 1
η = 2
η = 3
[m]
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid

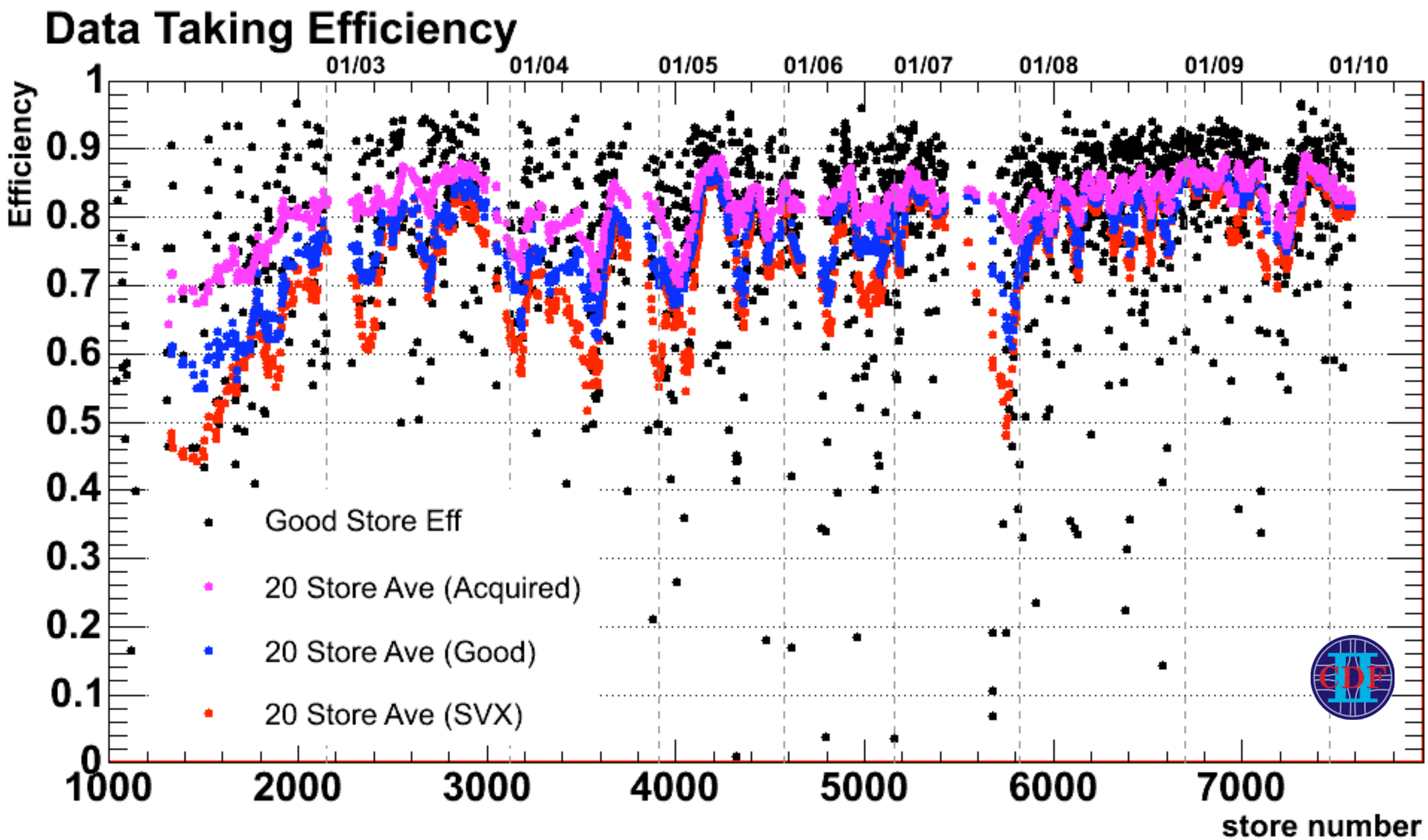

η = 0
η = 1
η = 2
η = 3
Preshower
Solenoid
Fiber Tracker
Silicon Tracker
SMT H-disks
SMT F-disks
SMT barrels


Scintillating Fiber Tracker


Silicon Microstrip Tracker

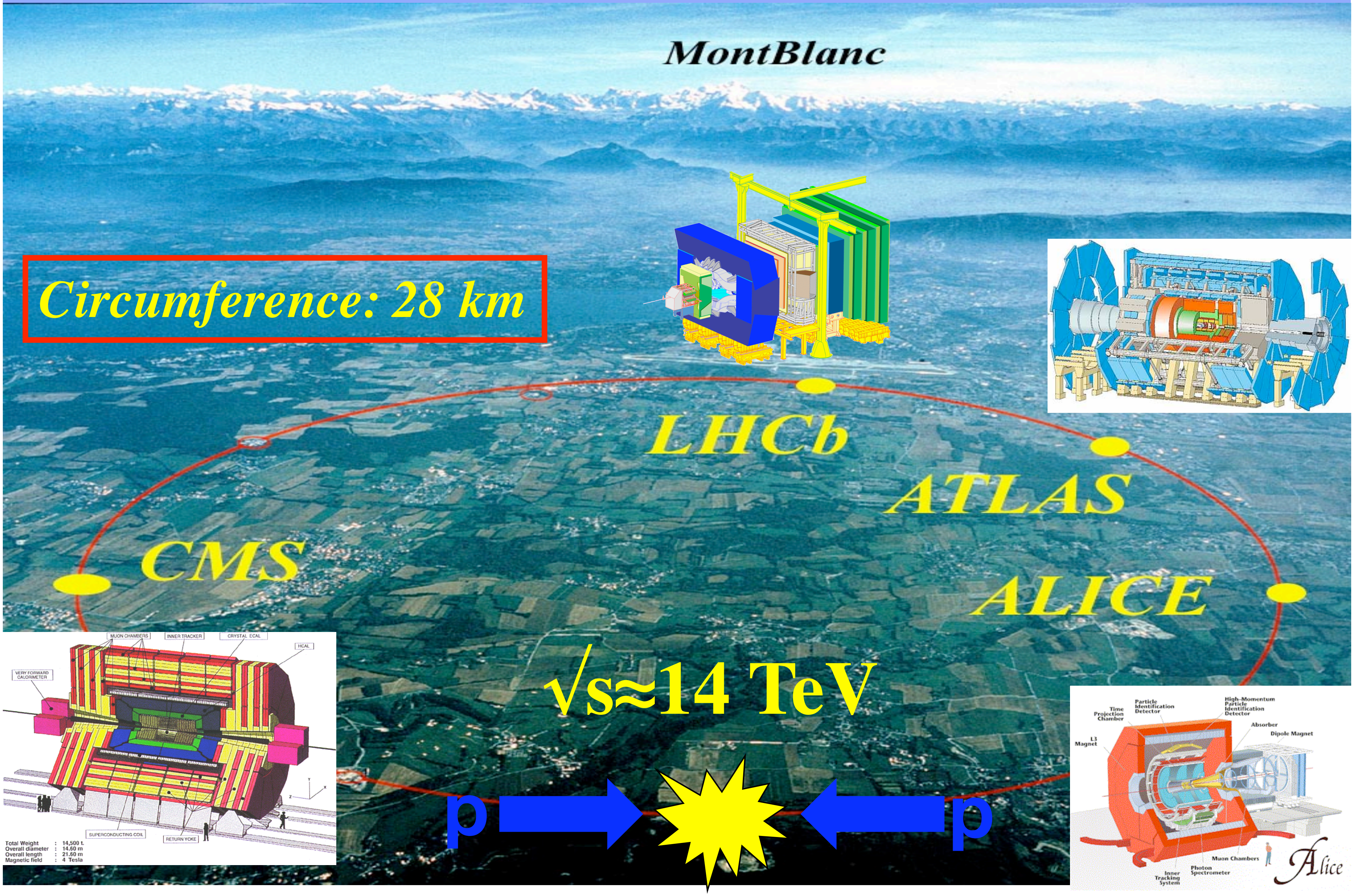

Superconducting
Solenoid

Detector Operation



- Data taking efficiency about 75-85%
  - Depending on which components are needed for analysis

The Large Hadron Collider (LHC)



Design LHC and Tevatron Parameters

	LHC (design)	Tevatron (achieved)
Centre-of-mass energy	**14 TeV**	1.96 TeV
Number of bunches	**2808**	36
Bunch spacing	**25 ns**	396 ns
Energy stored in beam	**360 MJ**	1 MJ
Peak Luminosity	**10^{33}-10^{34} $cm^{-2}s^{-1}$**	3.5 x 10^{32} $cm^{-2}s^{-1}$
Integrated Luminosity / year	**10-100 fb^{-1}**	~2 fb^{-1}

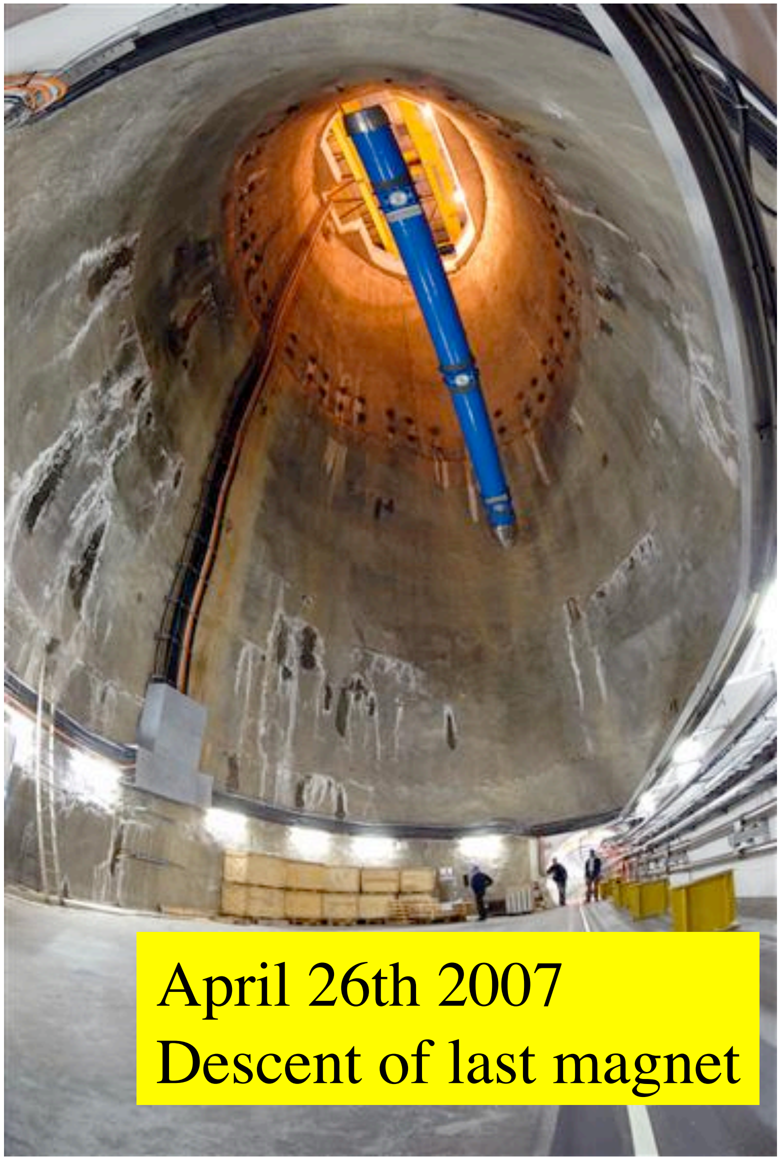
- Factor of ~1000 more powerful than Tevatron
  - 7 times more energy
  - Factor 3-30 times more luminosity
  - Physics cross sections factor 10-1000 larger
- First collisions planned at end of 2009
  - Aims to reach $\sqrt{s}$=7 TeV in 2010

2010/11 LHC vs Tevatron Parameters

	LHC (plan for 2010/11)	Tevatron (achieved)
Centre-of-mass energy	**7 TeV**	1.96 TeV
Number of bunches	**≤ 720**	36
Bunch spacing	**50 ns**	396 ns
Peak Luminosity	**$\sim 10^{32}$ cm^{-2}s^{-1}**	3.5×10^{32} cm^{-2}s^{-1}
Luminosity by end of 2011	**1 fb^{-1}**	~9 fb^{-1}

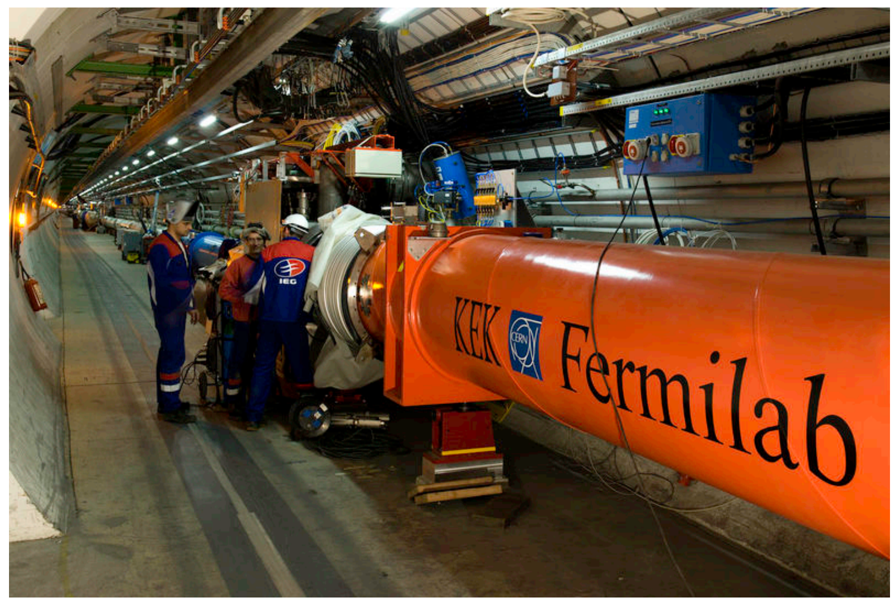
- Power of LHC comparable to 10 years Tevatron
  - 3.5 times more energy
  - 10 times less luminosity
  - Physics cross sections factor 10-1000 larger
    - Will discuss this in detail later

LHC Construction

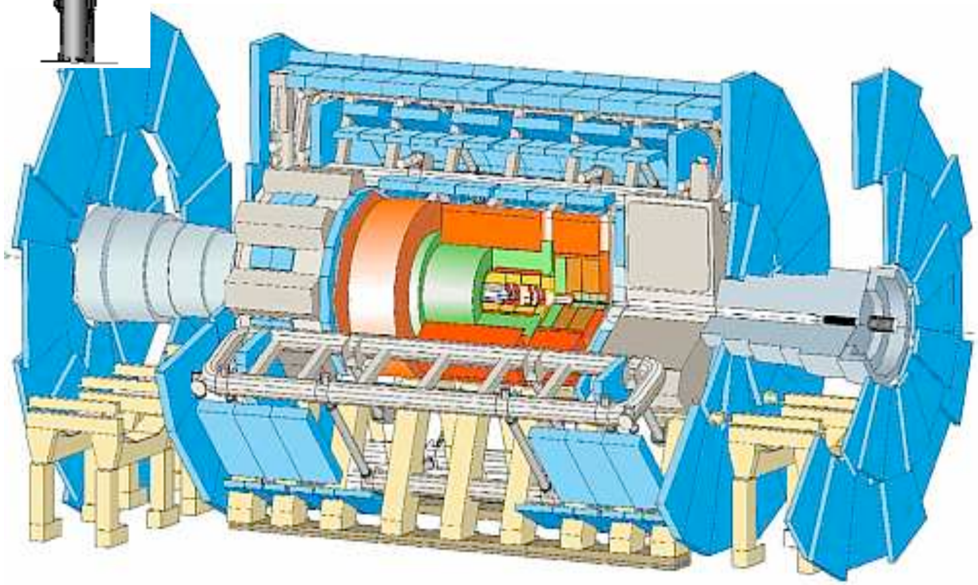


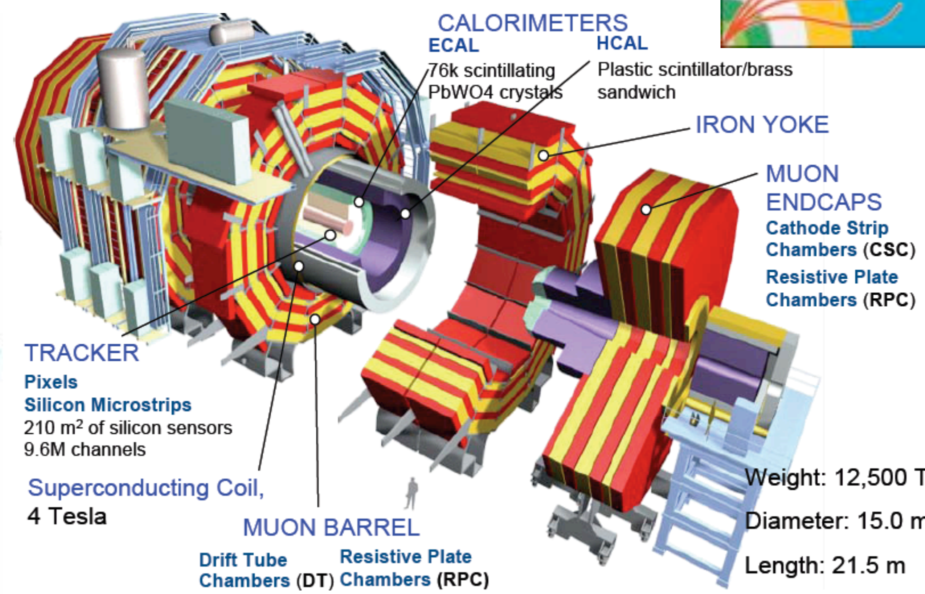
April 26th 2007
Descent of last magnet

Cryostating	425 FTE.years
Cold tests	640 FTE.years



ATLAS and CMS Detectors

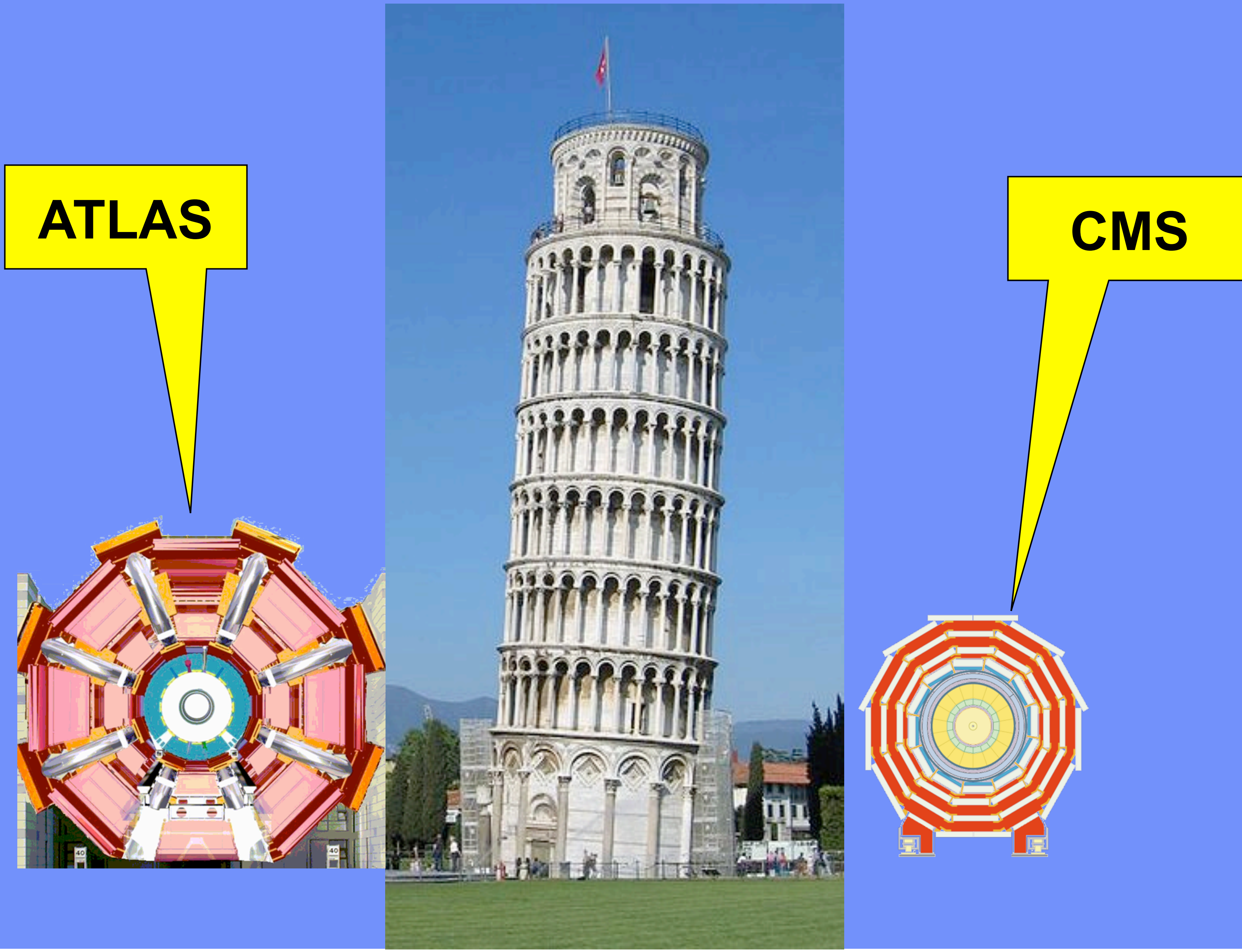




	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

~2000 Scientists per experiment
+ many engineers and technicians

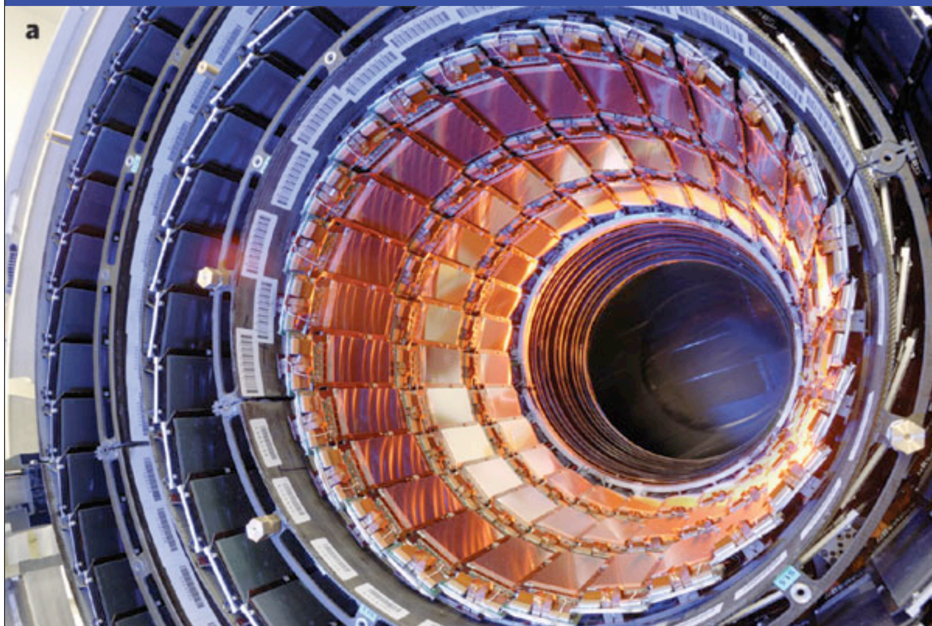
ATLAS and CMS in Pisa

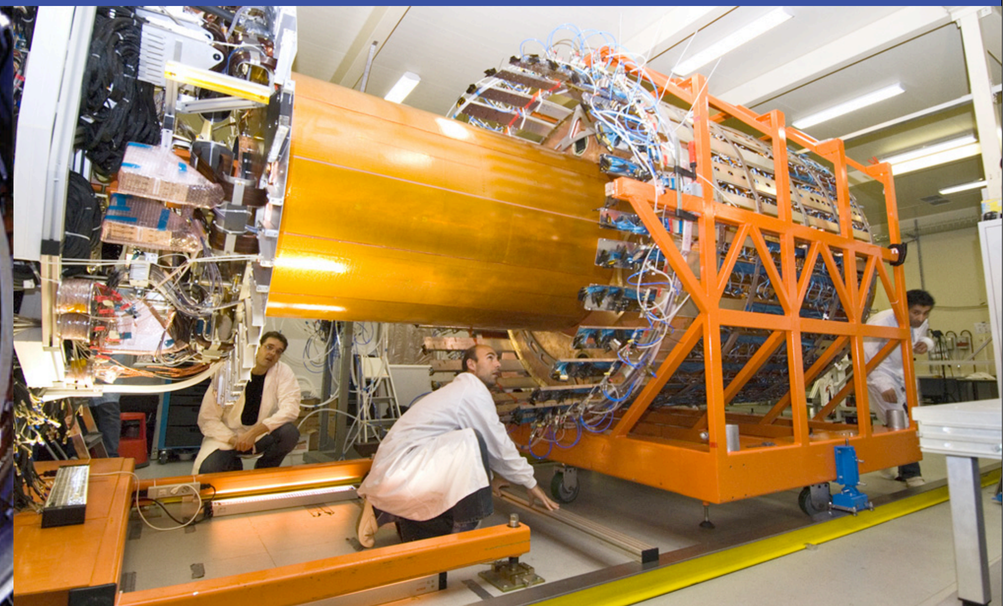


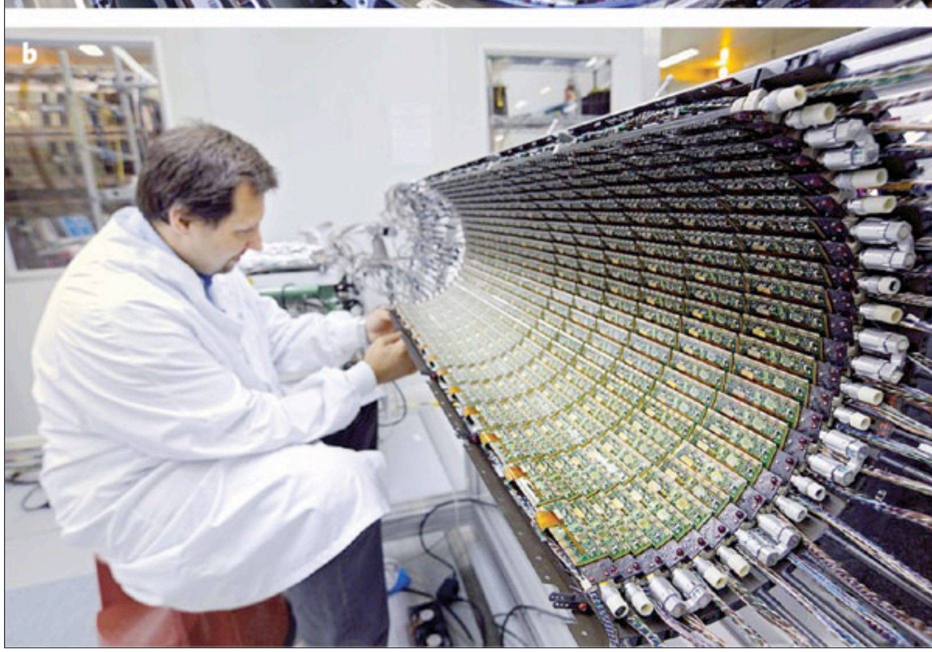
Detector Mass in Perspective

CMS is 30% heavier than the Eiffel tower

Silicon Tracking Detectors

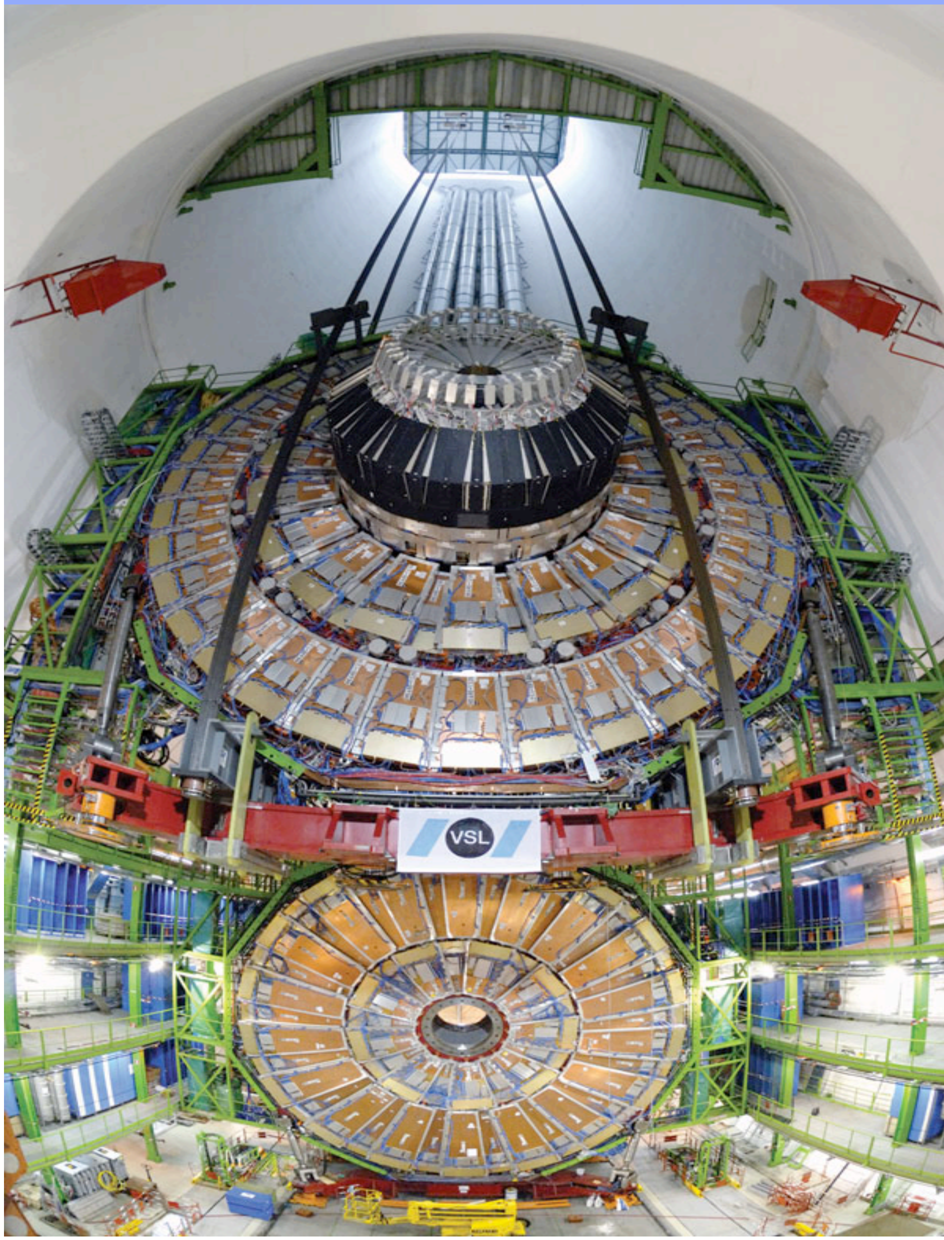


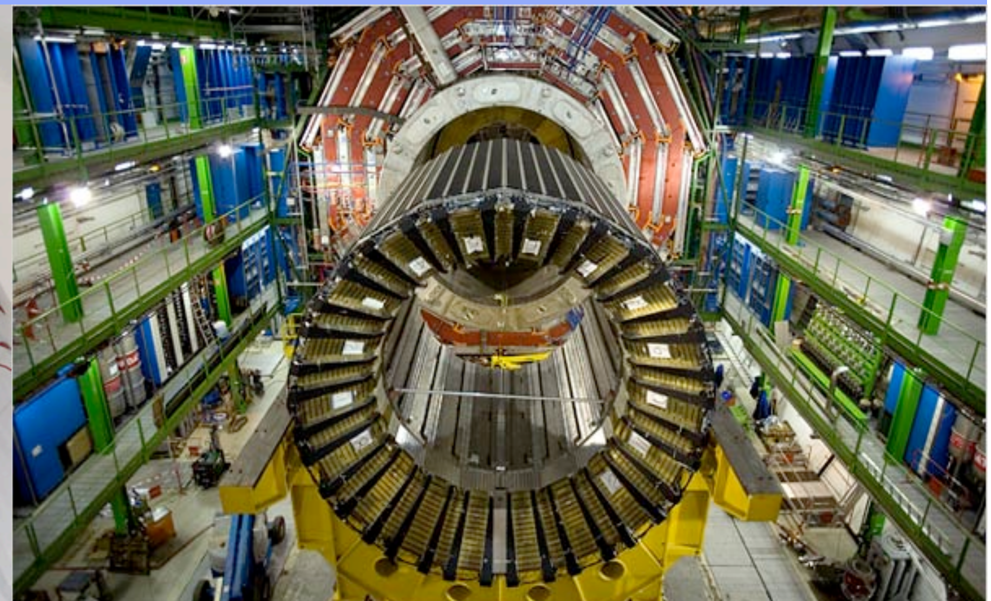


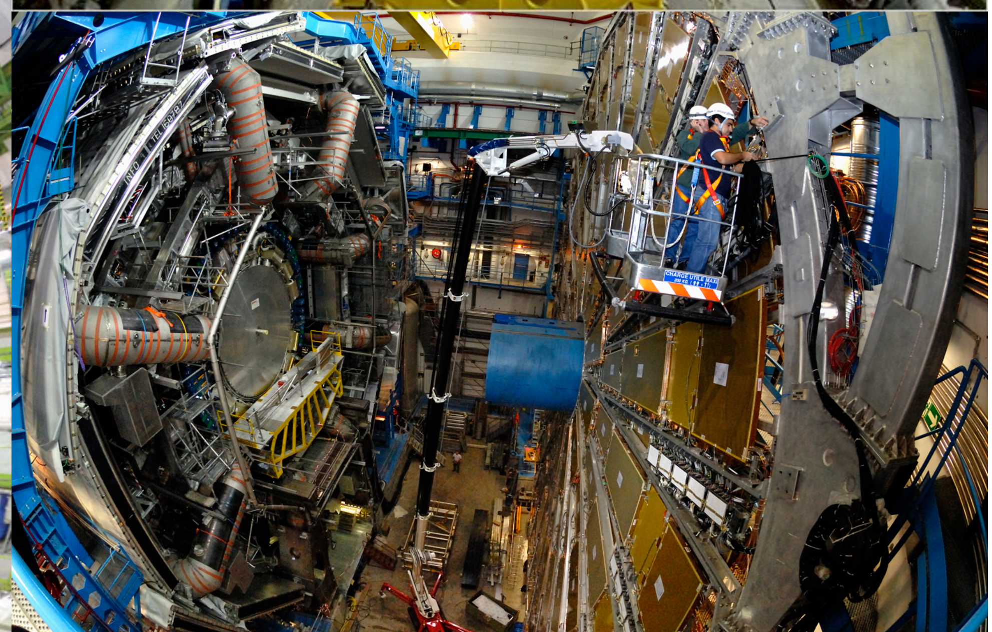


- Silicon strip and pixel detectors
  - Pixels used for first time at hadron colliders
  - Huge!
    - area of CMS silicon ~200 m^2
    - Like a football field!

Muon Systems and Calorimeters

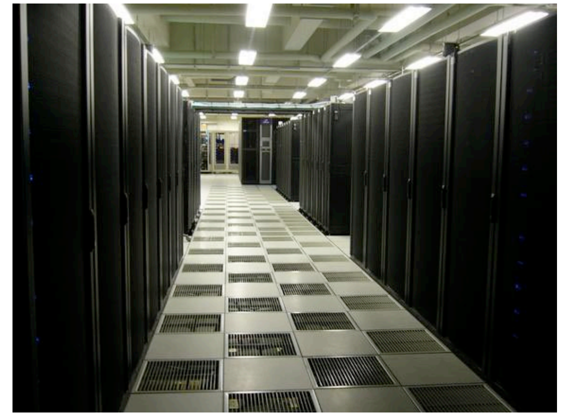




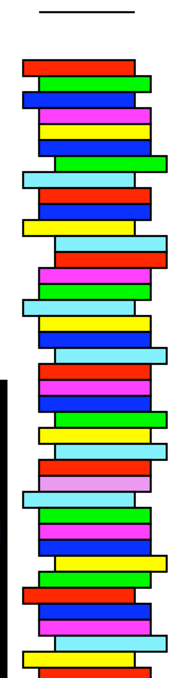


Enormous Data Volumes

- **Pushing the computing limits!**
  - 1 second of LHC data: 1,000 GigaBytes
    - **10,000 sets of the Encyclopedia Britannica**
  - 1 year of of LHC data: 10,000,000 GB
    - **25 km tower of CD's (~2 x earth diameter)**
  - 10 years of LHC data: 100,000,000 GB
    - **All the words spoken by humankind since its appearance on earth**



- **Solution: the "Grid"**
  - Global distribution of CPU power
    - More than 100 CPU farms worldwide share computing power



Conclusion of 1st Lecture

- Hadron Colliders
  - can address many of the problems with the Standard Model
    - Higgs boson
    - Physics beyond the Standard Model (e.g. Supersymmetry)
  - access higher energies than lepton colliders
    - Thus higher mass particles
  - are experimentally challenging
    - Many uninteresting background processes
    - The collisions themselves are complex
- Current colliders:
  - Tevatron is running since 2001
    - Planned to run at least until Fall 2010
  - LHC started last year as the world's highest energy collider
    - Highest energy: 2.36 TeV
    - 2010/2011 run: about 3.5 times higher energy than Tevatron