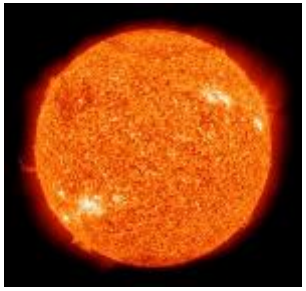
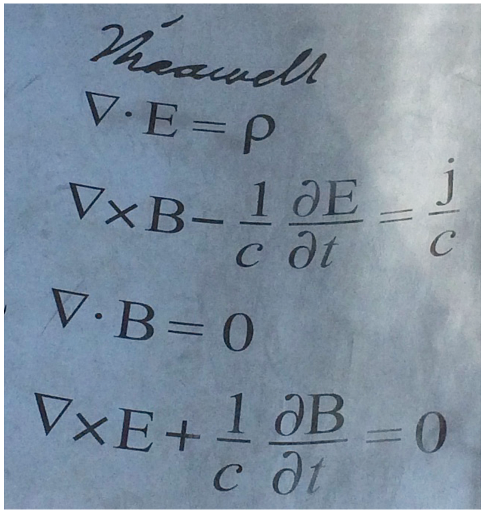
PARTICLE PHYSICS INTRODUCTION

Darin Acosta

The Fundamental Forces of Nature

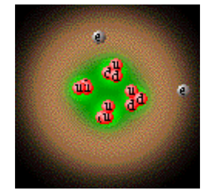


- Gravitation
  - The attractive force between objects with mass
    - Newton's Law of Gravitation $F = G\frac{m_1 m_2}{r^2}$
    - Einstein's General Theory of Relativity $G_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$
- Electromagnetism
  - Electric force between electric charges
    - Coulomb's Law $F = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}$
  - Magnetic force between magnets and electric currents
    - Lorentz force law $\mathbf{F} = q(\mathbf{v} \times B)$
  - Unified in Maxwell's equations



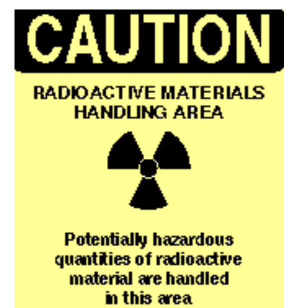
The Fundamental Forces of Nature

- Strong Nuclear Force
  - The force responsible for binding protons and neutrons in atomic nuclei
  - The binding energy is released in nuclear fission and fusion



- Weak Nuclear Force
  - The force responsible for radioactive decay (whereby one particle changes into another type)
  - For example the beta decay of a neutron

$$n \to p + e^- + \bar{\nu}_e$$



Approximate Ranking of Force Strengths

- Strong: 1
- EM: 10^{-2} (0.01)
- Weak: 10^{-6} (0.000001)
- Gravitation: 10^{-40} (0.0000000000000000000000000000000000000001)

Forces, Fields, and Particles

- Forces are conveyed by fields
  - For example the electric field and the magnetic field
  - Allows action at a distance
- But fields are "quantized" into particles in relativistic versions of Quantum Mechanics (atomic physics)
  - Electric field is comprised of photons
- In general the fields corresponding to all forces are propagated by particles

The Particle Zoo

- All stable matter is made of just 3 types of particles:
  - electrons, protons, and neutrons
- But with the advent of particle detectors and accelerators, many other types of particles have been discovered:
  - Muon, 1938, M=106 MeV
  - Pion, 1947, M=135 MeV
  - Kaon, rho, omega, …
  - Delta, Lambda, Sigma, Xi, …

Seeing Particles with a Cloud Chamber

See the listings from the Particle Data Group: http://pdg.lbl.gov

LIGHT UNFLAVORED MESONS (

Mini Reviews

- Form Factors for Radiative Pion and
- Note on Scalar Mesons below 2 GeV
- The $\rho(770)$
- The Pseudoscalar and Pseudovector
- The $\rho(1450)$ and $\rho(1700)$ (rev.)

Particles

$\pi^{\pm}$
π^{0}
η
$f_0(500)$ or σ was $f_0(600)$
$\rho(770)$
$\omega(782)$
$\eta'(958)$
$f_0(980)$
$a_0(980)$
$\phi(1020)$
$h_1(1170)$
$b_1(1235)$
$a_1(1260)$
$f_2(1270)$
$f_1(1285)$
$\eta(1295)$
$\pi(1300)$
$a_2(1320)$
$f_0(1370)$
$h_1(1380)$
$\pi_1(1400)$
$\eta(1405)$
$f_1(1420)$
$\omega(1420)$
$f_2(1430)$
$a_0(1450)$
$\rho(1450)$
$\eta(1475)$

STRANGE MESONS (S =

Mini Reviews

- The Charged Kaon Mass
- Rare Kaon Decays (rev.)
- Dalitz Plot Parameters for K
- $K^{+-}_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors
- CPT Invariance Tests in Neu
- CP Violation in $K^0_S \to 3\pi$
- V_{ud}, V_{us} the Cabibbo Angle,
- CP Violation in K^0_L Decays
- $\Delta S = \Delta Q$ in K^0 Decays
- $K^*(892)$ Masses and Mass

Particles

$K^{\pm}$
K^0
K^0_S
K^0_L
$K^*_0(800)$ or κ
$K^*(892)$
$K_1(1270)$
$K_1(1400)$
$K^*(1410)$
$K^*_0(1430)$
$K^*_2(1430)$
$K(1460)$
$K_2(1580)$
$K(1630)$
$K_1(1650)$
$K^*(1680)$
$K_2(1770)$
$K^*_3(1780)$
$K_2(1820)$
$K(1830)$
$K^*_0(1950)$
$K^*_2(1980)$
$K^*_4(2045)$

CHARMED MESONS

Mini Reviews

- $D^0 - \overline{D}^0$ Mixing (rev.)

Particles

$D^{\pm}$
D^0
$D^*(2007)^0$
$D^*(2010)^{\pm}$
$D^*_0(2400)^0$
$D^*_0(2400)^{\pm}$
$D_1(2420)^0$
$D_1(2420)^{\pm}$
$D_1(2430)^0$
$D^*_2(2460)^0$
$D^*_2(2460)^{\pm}$
$D(2550)^0$
$D^*_J(2600)$ was $D(260$
$D^*(2640)^{\pm}$
$D(2740)^0$
$D(2750)$
$D(3000)^0$

BOTTOM MESONS ($B = \pm 1$)

Mini Reviews

- Production and Decay of b-flavored Hadrons
- A Note on HFAG Activities (rev.)
- Polarization in B Decays (rev.)
- $B^0 - \overline{B}^0$ Mixing (rev.)
- Semileptonic B meson decays and the determination of V_{cb} and V_{ub} (rev.)

Particles

B-particle organization	
$B^{\pm}$	
B^0	
$B^{\pm}/B^0$ ADMIXTURE	
$B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
B^*	
$B_1(5721)^+$	**
$B_1(5721)^0$	***
$B^*_J(5732)$ or B^{**}	
$B^*_2(5747)^+$	**
$B^*_2(5747)^0$	***
$B_J(5840)^+$	**
$B_J(5840)^0$	**
$B_J(5970)^+$	**
$B_J(5970)^0$	**

See the listings from the Particle Data Group: http://pdg.lbl.gov

N BARYONS (S = 0, I

Mini Reviews

- Baryon Decay Paramet
- N and Δ Resonances (

Particles

- p
- n
- $N(1440)\ 1/2^+$
- $N(1520)\ 3/2^-$
- $N(1535)\ 1/2^-$
- $N(1650)\ 1/2^-$
- $N(1675)\ 5/2^-$
- $N(1680)\ 5/2^+$
- $N(1700)\ 3/2^-$
- $N(1710)\ 1/2^+$
- $N(1720)\ 3/2^+$
- $N(1860)\ 5/2^+$
- $N(1875)\ 3/2^-$
- $N(1880)\ 1/2^+$
- $N(1895)\ 1/2^-$
- $N(1900)\ 3/2^+$
- $N(1990)\ 7/2^+$
- $N(2000)\ 5/2^+$
- $N(2040)\ 3/2^+$
- $N(2060)\ 5/2^-$

Δ BARYONS (S = 0

Particles

- $\Delta(1232)\ 3/2^+$
- $\Delta(1600)\ 3/2^+$
- $\Delta(1620)\ 1/2^-$
- $\Delta(1700)\ 3/2^-$
- $\Delta(1750)\ 1/2^+$
- $\Delta(1900)\ 1/2^-$
- $\Delta(1905)\ 5/2^+$
- $\Delta(1910)\ 1/2^+$
- $\Delta(1920)\ 3/2^+$
- $\Delta(1930)\ 5/2^-$
- $\Delta(1940)\ 3/2^-$
- $\Delta(1950)\ 7/2^+$
- $\Delta(2000)\ 5/2^+$
- $\Delta(2150)\ 1/2^-$
- $\Delta(2200)\ 7/2^-$
- $\Delta(2300)\ 9/2^+$
- $\Delta(2350)\ 5/2^-$
- $\Delta(2390)\ 7/2^+$
- $\Delta(2400)\ 9/2^-$
- $\Delta(2420)\ 11/2^+$
- $\Delta(2750)\ 13/2^-$
- $\Delta(2950)\ 15/2^+$
- $\Delta(\sim 3000$ Region)

Λ BARYONS (S =

Mini Reviews

- Baryon Magnetic Mo
- Λ and Σ Resonance
- Λ and Σ Resonance

Particles

- Λ
- $\Lambda(1405)\ 1/2^-$
- $\Lambda(1520)\ 3/2^-$
- $\Lambda(1600)\ 1/2^+$
- $\Lambda(1670)\ 1/2^-$
- $\Lambda(1690)\ 3/2^-$
- $\Lambda(1710)\ 1/2^+$
- $\Lambda(1800)\ 1/2^-$
- $\Lambda(1810)\ 1/2^+$
- $\Lambda(1820)\ 5/2^+$
- $\Lambda(1830)\ 5/2^-$
- $\Lambda(1890)\ 3/2^+$
- $\Lambda(2000)$
- $\Lambda(2020)\ 7/2^+$
- $\Lambda(2050)\ 3/2^-$
- $\Lambda(2100)\ 7/2^-$
- $\Lambda(2110)\ 5/2^+$
- $\Lambda(2325)\ 3/2^-$

Σ BARYONS ($S = -1, I = 1$)

Mini Reviews

- The $\Sigma(1670)$ Region

Particles

Σ^+	****
Σ^0	****
Σ^-	****
$\Sigma(1385)\ 3/2^+$	****
$\Sigma(1480)$ Bumps	*
$\Sigma(1560)$ Bumps	**
$\Sigma(1580)\ 3/2^-$	*
$\Sigma(1620)\ 1/2^-$	*
$\Sigma(1620)$ Production Experiments	
$\Sigma(1660)\ 1/2^+$	***
$\Sigma(1670)\ 3/2^-$	****
$\Sigma(1670)$ Bumps	
$\Sigma(1690)$ Bumps	**
$\Sigma(1730)\ 3/2^+$	*
$\Sigma(1750)\ 1/2^-$	***
$\Sigma(1770)\ 1/2^+$	*
$\Sigma(1775)\ 5/2^-$	****
$\Sigma(1840)\ 3/2^+$	*
$\Sigma(1880)\ 1/2^+$	**
$\Sigma(1900)\ 1/2^-$	*
$\Sigma(1915)\ 5/2^+$	****

Particle Classification

- Hadrons:
  - Particles that interact with the strong nuclear force (carry nuclear charge)
    - Baryons:
      - Fermions (spin = 1/2, 3/2, 5/2, …)
      - Includes the nucleons (p, n) and excitations of them (Δ, Λ, …)
    - Mesons:
      - Bosons (spin = 0, 1, 2, …)
      - π, K, ρ, ω, …
      - Typically lighter than baryons (except when containing heavy quarks)

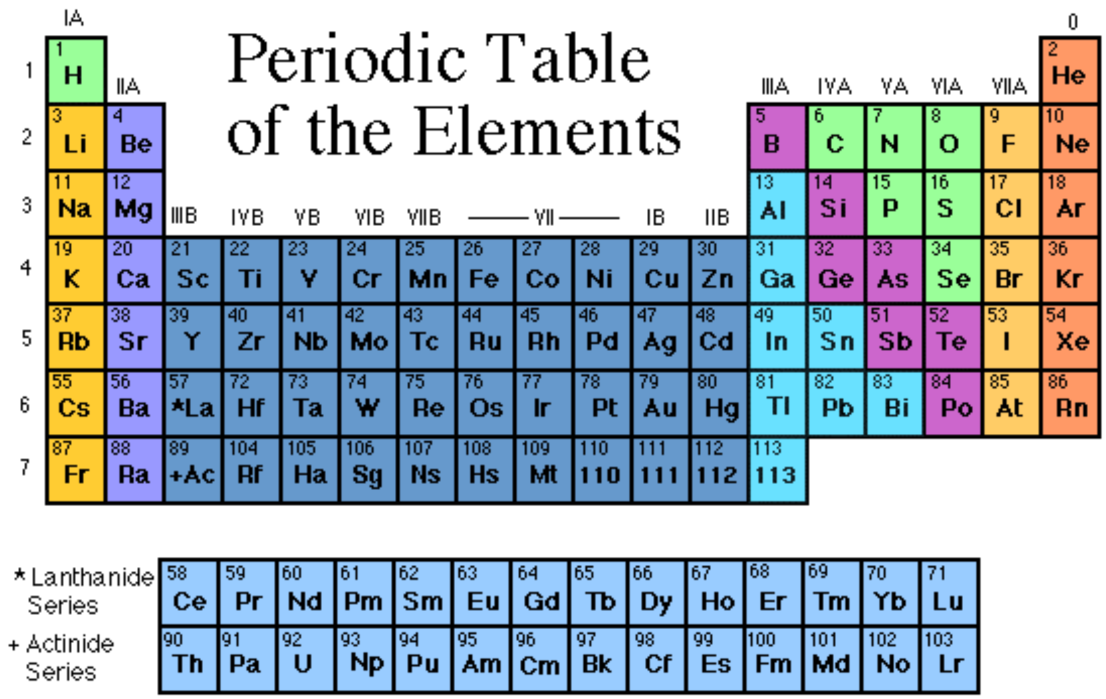
Not fundamental – contain “quarks”

- Leptons:
  - Particles that do not interact with the strong nuclear force (do not bind in nuclei)
    - All spin ½ fermions
      - Charged leptons: $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$
      - Electrically neutral: leptons: ν_e, ν_μ, ν_τ

Fundamental (point-like) as far as we know

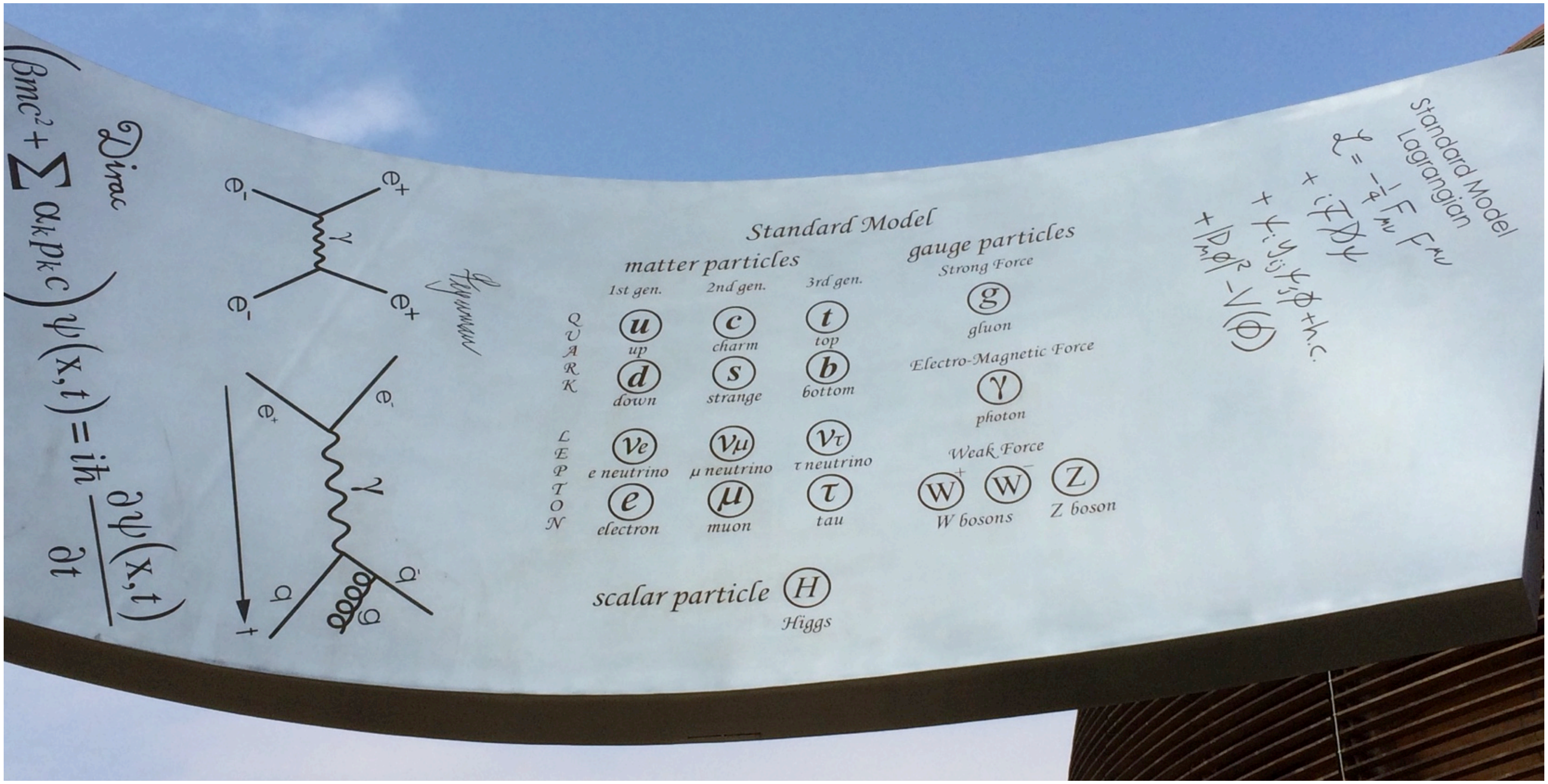
We'll Continue with the Standard Model Description after the "Eightfold-Way" activity…

Do Particle “Multiplets” and the Quark Model remind you of anything?



STANDARD MODEL

The Standard Model



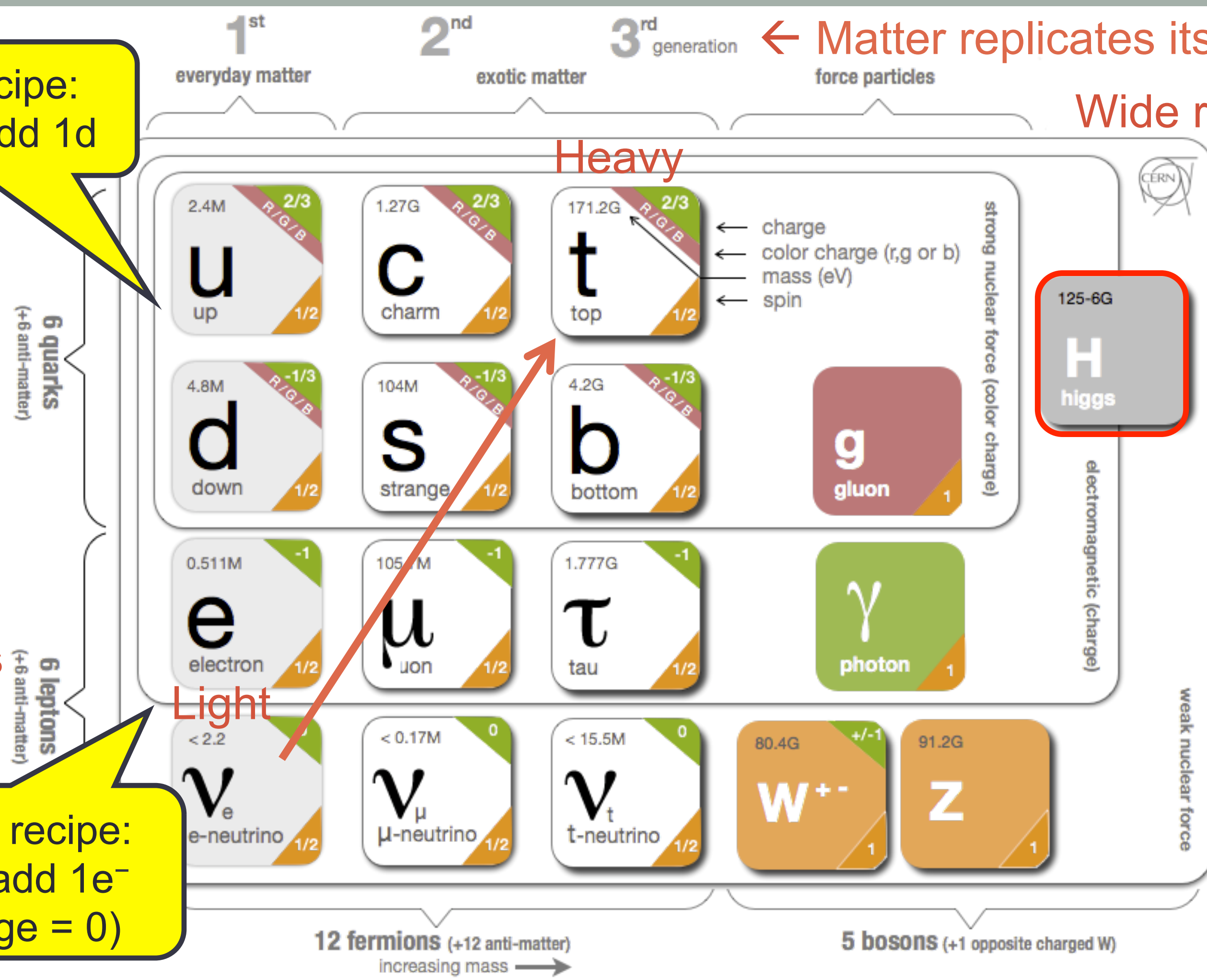
Proton recipe:
Take 2u, add 1d

← Matter replicates itself 3 times

Wide range of masses

Quarks

Leptons



Newly discovered!

Force carrying particles (gauge bosons)

Hydrogen recipe:
Take 1p, add 1e$^-$
(net charge = 0)

The Standard Model of Particle Physics

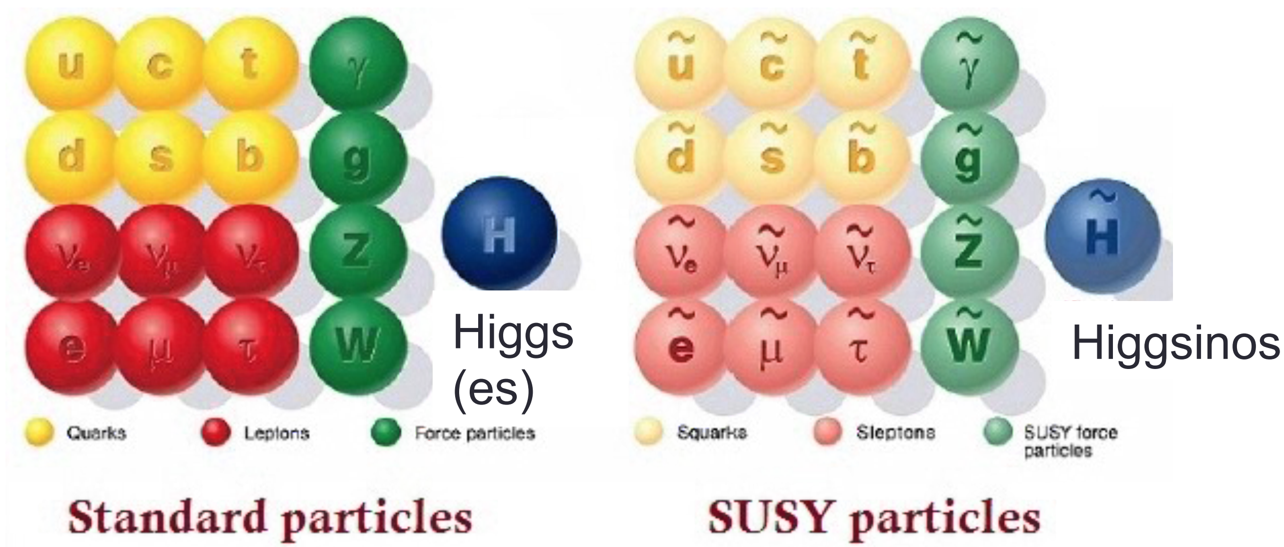
- The (relativistic) quantum field electro-weak theory is described by the SU(2)×U(1) Weinberg-Salam Model (QED+Weak)
  - Responsible for electricity, magnetism, and radioactive decay
- The quantum field theory of the strong force is described by SU(3) Quantum Chromodynamics (QCD)
  - How quarks bind into protons and neutrons, and how nucleons bind in the nucleus
- Collectively, they are referred to as the "Standard Model"
- However, all masses are zero unless we introduce a scalar field
  - Generates mass for the vector bosons (W, Z)
  - Generates mass for the fermions
  - Generates a massive neutral scalar: the Higgs boson

What's Missing?

- The Standard Model can make extremely precise quantitative predictions for measurements
  - For example, the magnetic dipole moment of the muon can be calculated (and agrees with data) to 9 significant digits!
- Nevertheless it has many shortcomings:
  - It does not include gravity
  - It does not unify the strong force with the electroweak (Grand Unification)
  - It has a large number of "free" parameters (particle masses)
  - There is no explanation for the relationships between quarks and leptons (why are atoms neutral?)
    - And why 3 generations?
  - The Higgs mass is "unstable" (requires fine tuning of parameters)
  - No "dark matter" candidate

A Supersymmetric World?

- The leading extension beyond the SM is Supersymmetry, which proposes a symmetry between fermions and bosons



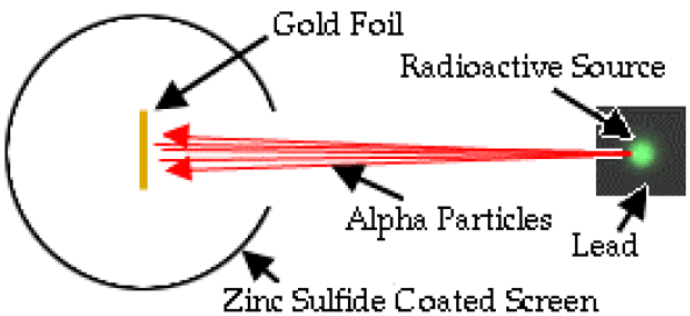
But no evidence yet ☹

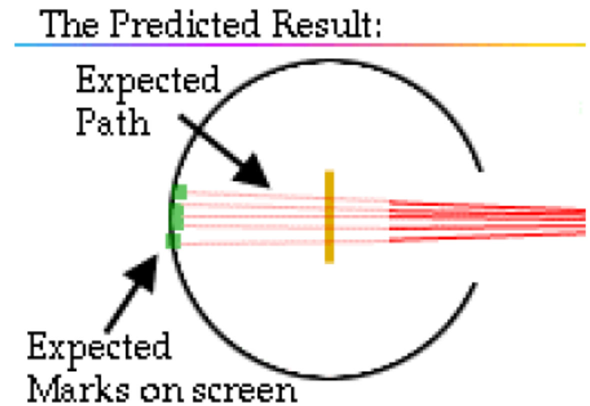
How to go Farther?

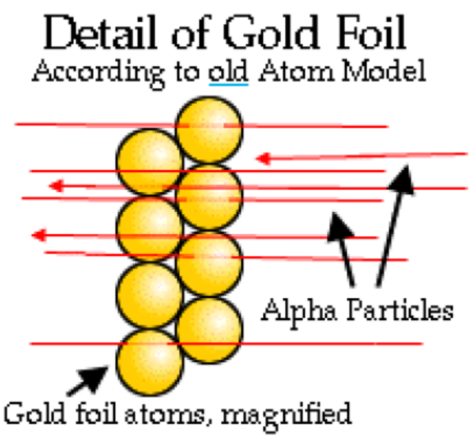
- Precision measurements
  - Many extensions to the Standard Model can make slight changes to production or decays rates of particles
  - “High Intensity” frontier of experiments

- High Energy
  - Directly produce new particles by building higher energy colliders
  - “High Energy” frontier of experiments

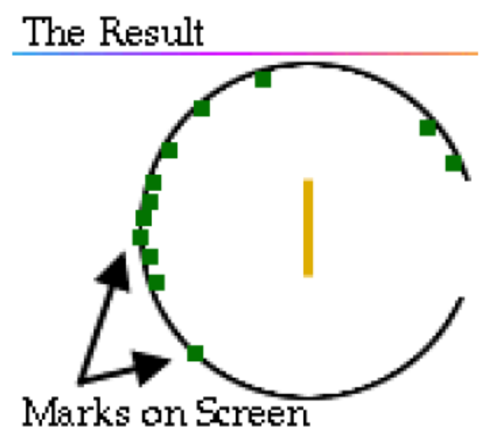
Rutherford Scattering



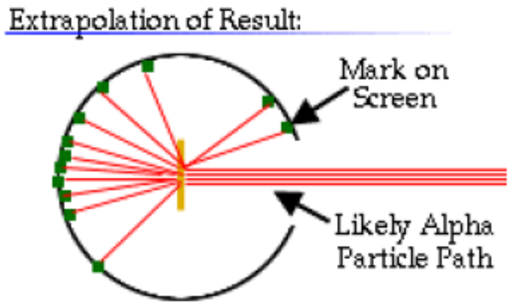


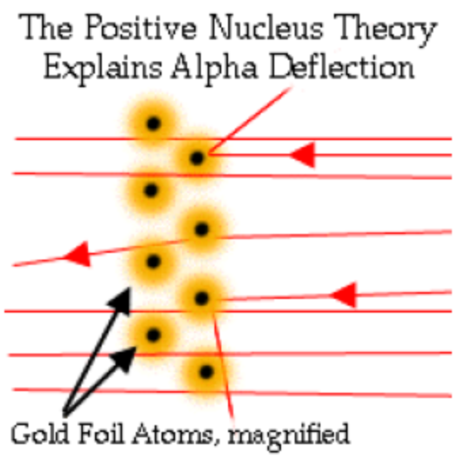


Experiments by Geiger & Marsden in 1909

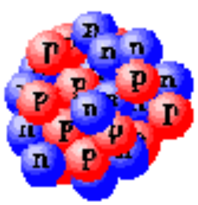


Rutherford Model of the Atom

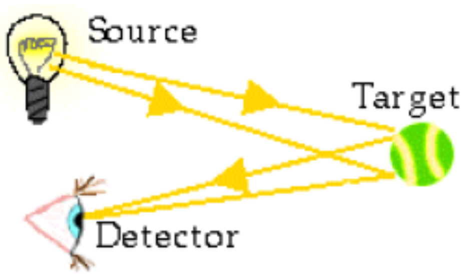




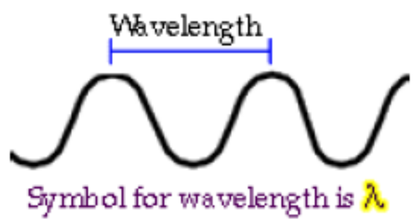
Conclusion: the atom contains a positive nucleus < 10 fm in size (1 fm = 10^{-15} m)



How we “see” particles

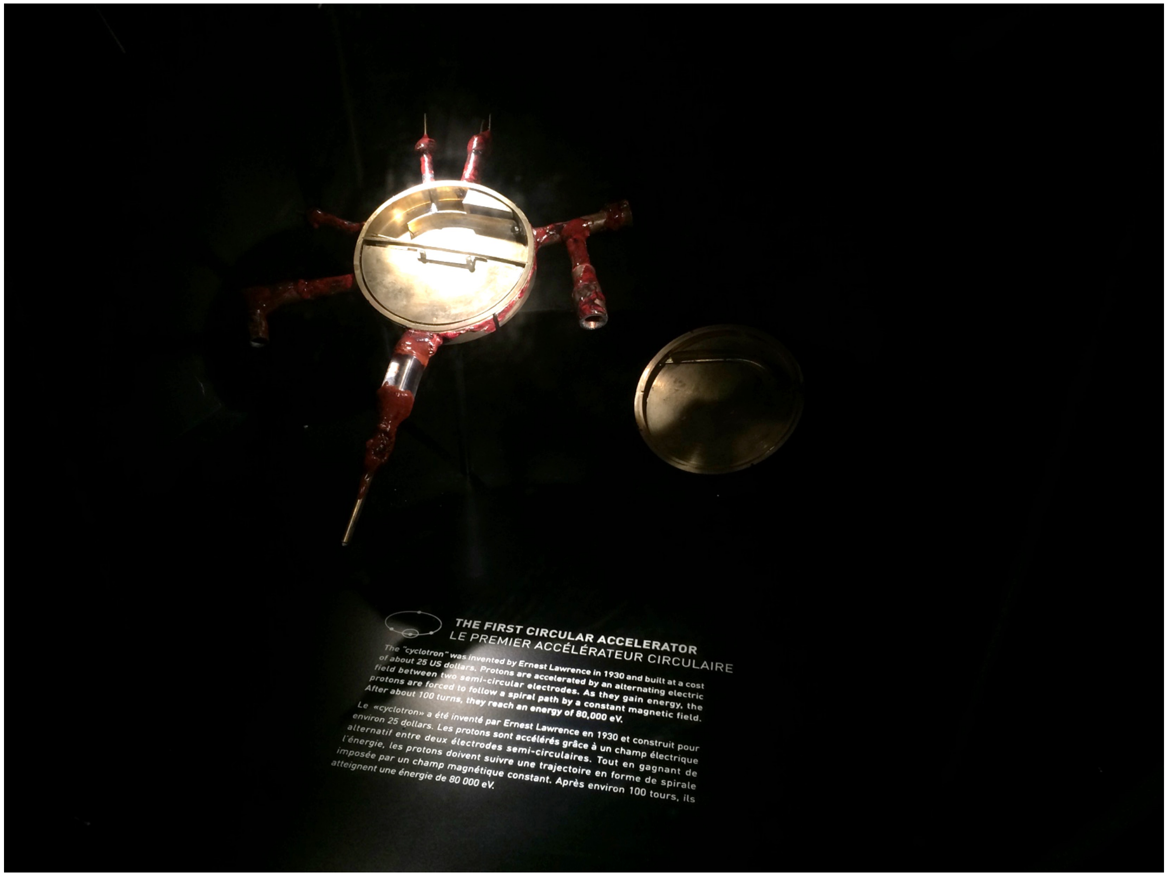


The smaller the wavelength, the smaller the features observed.



- Quantum mechanics tells us that all particles are also waves(!), and thus can be used as probes
- Wavelength is inversely proportional to energy
  - Need high energy to probe quarks, etc.

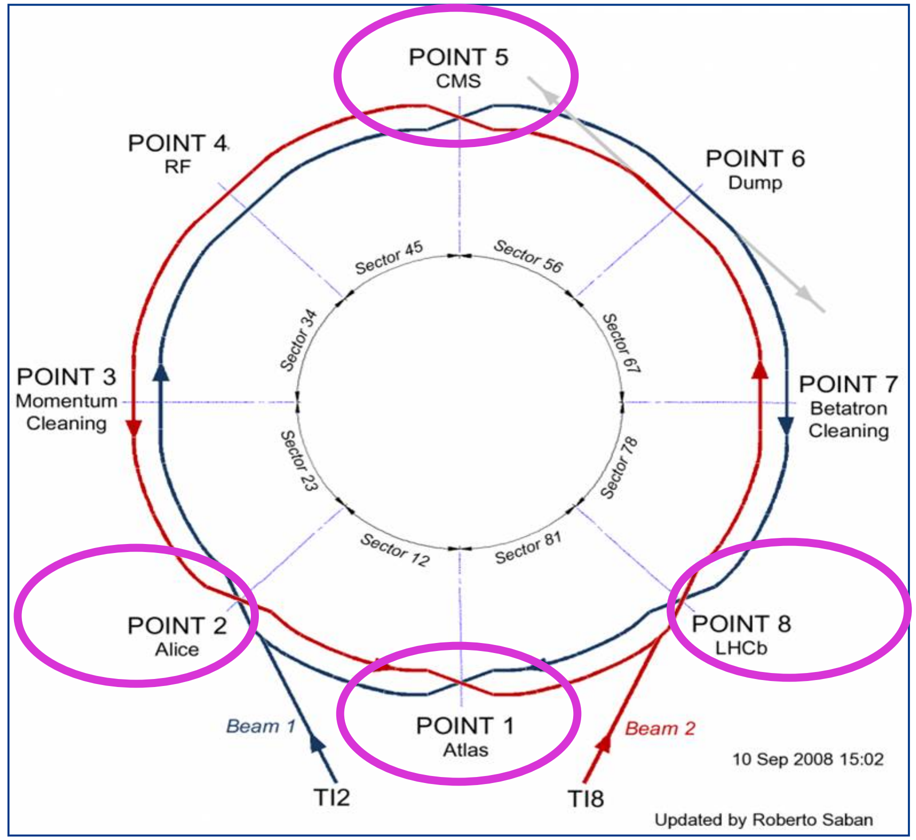
From the very first circular accelerator



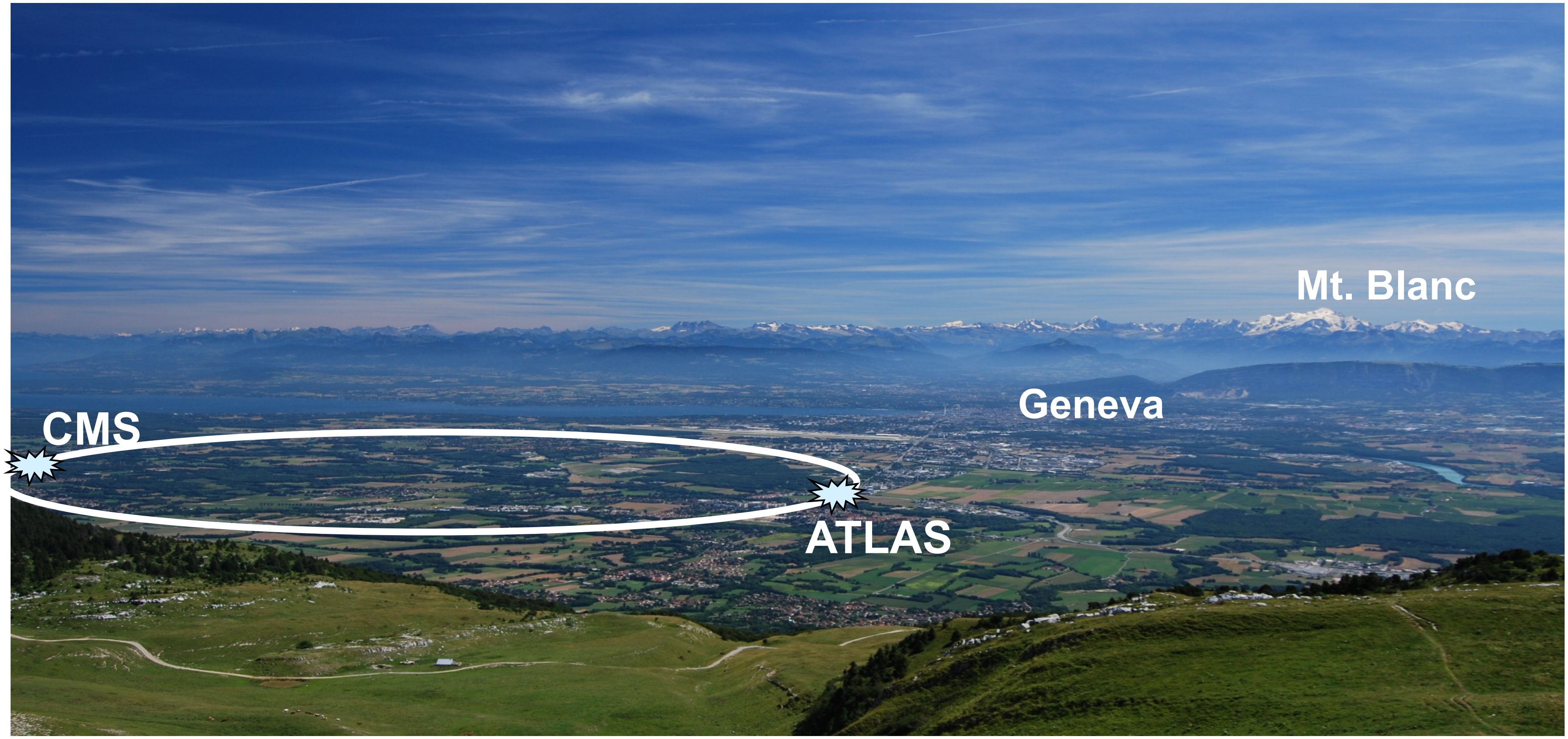
Ernest Lawrence, 1930

To the Large Hadron Collider (LHC)

- Proton and ion collider
- 27 km ring (17mi)
- 6.5 TeV beam energy
- 1232 superconducting 8.4T dipole magnets @ T=1.9°K
  - World's largest cryogenic structure
- 4 major experiments
  - ATLAS, CMS
  - ALICE, LHCb
- First collisions in 2009, then 2010-12, 2015-17



Located near Geneva, Switzerland

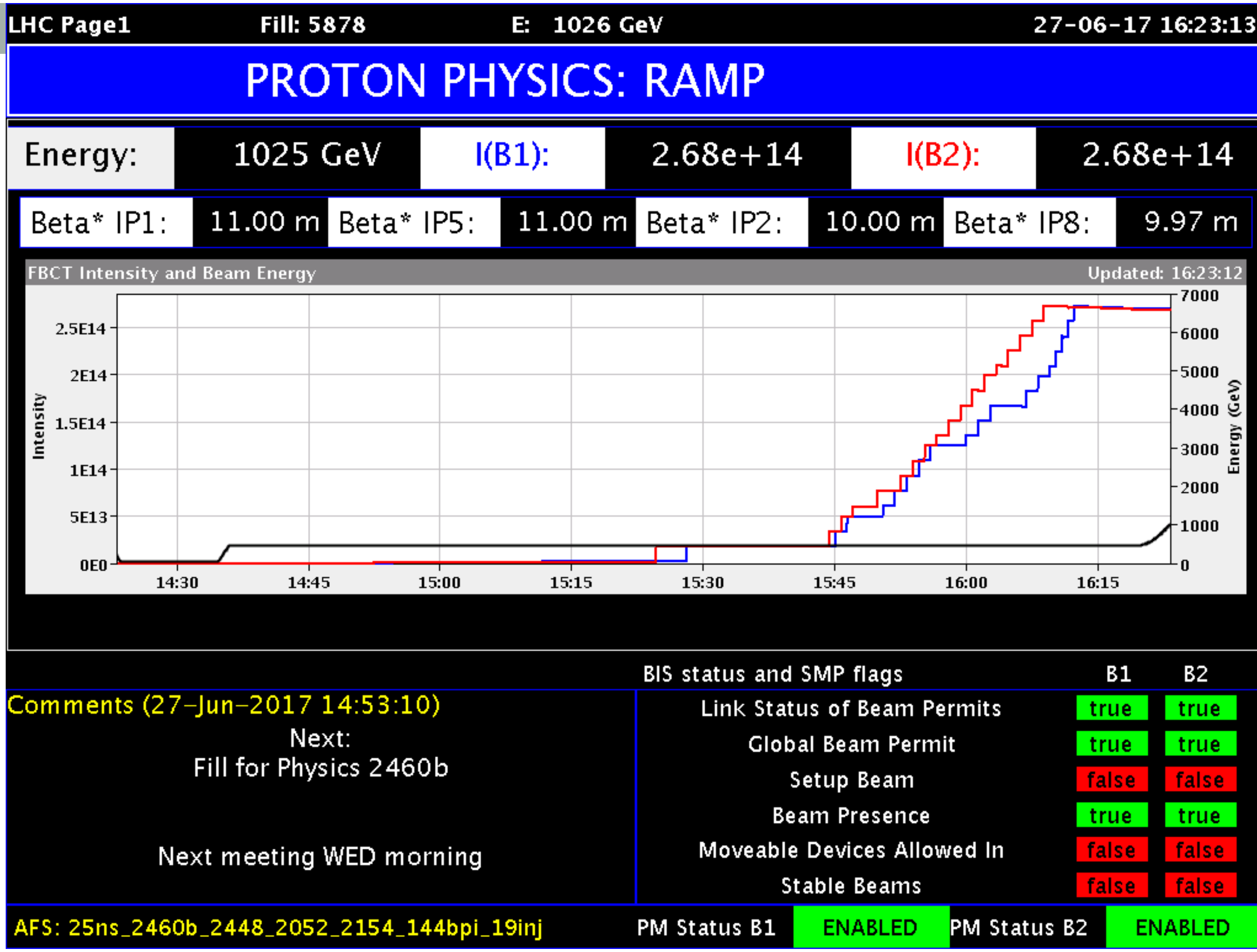


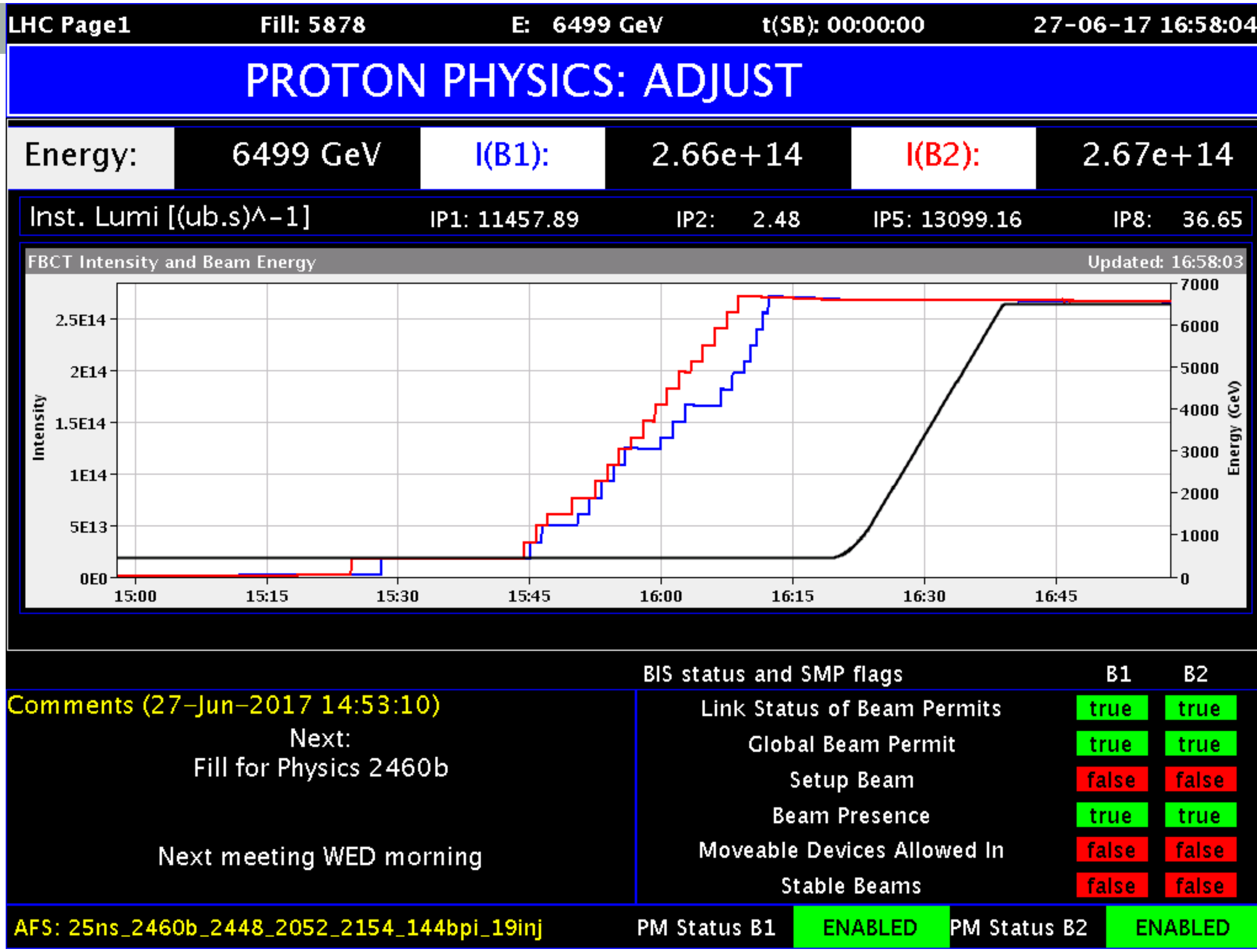
Acceleration scheme

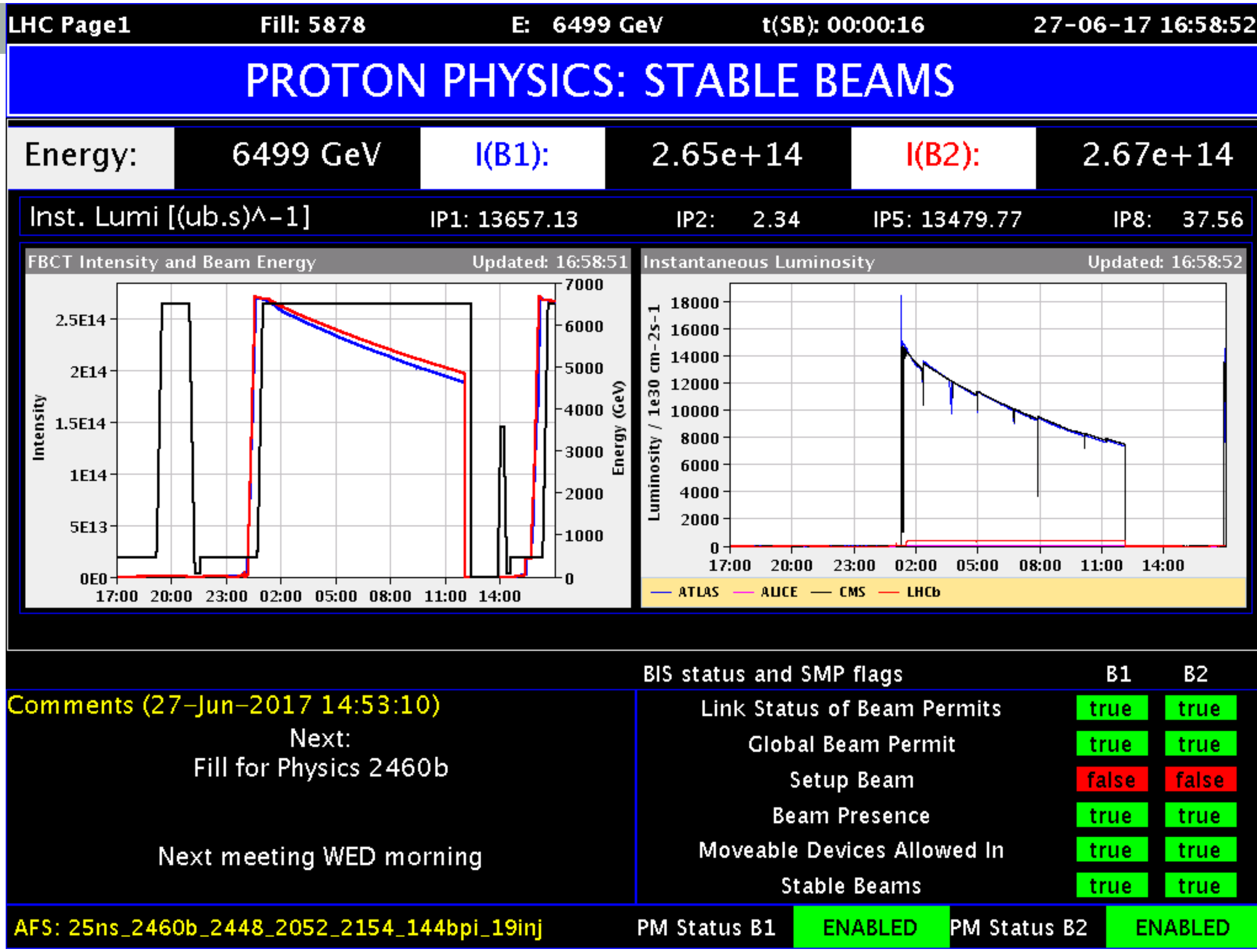
LHC Tunnel and Dipole Magnets

- 15 m (50') long magnets with unique single structure for 2 beams
- Cooled with superfluid helium

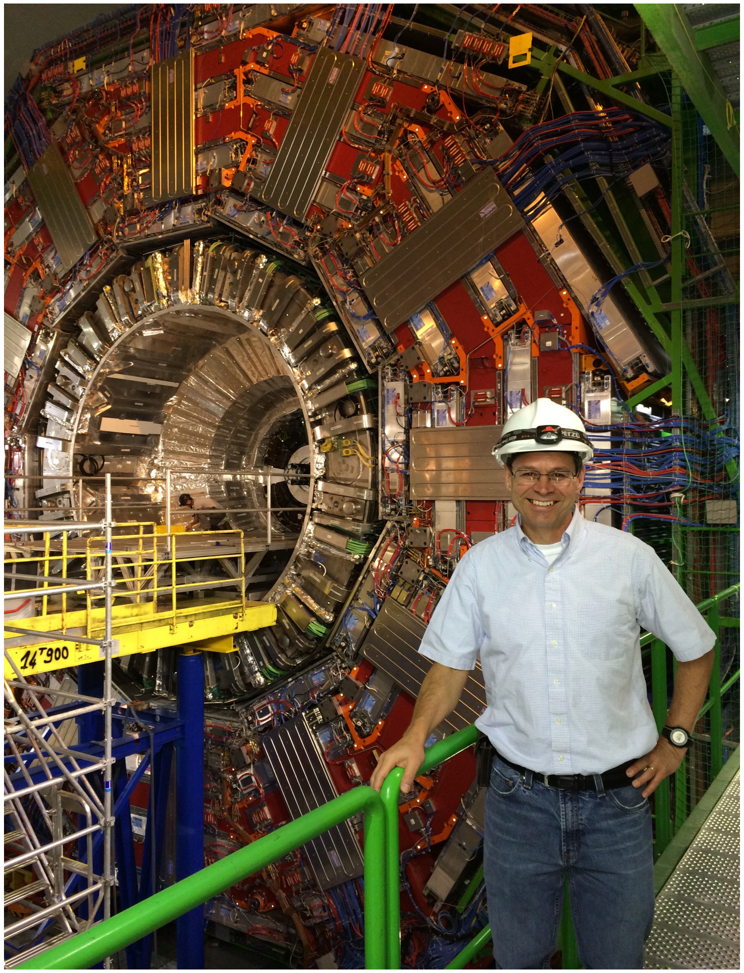
IN OPERATION NOW!


LHC Page1
Fill: 5878
E: 1026 GeV
27-06-17 16:23:13
PROTON PHYSICS: RAMP
Energy: 1025 GeV
I(B1): 2.68e+14
I(B2): 2.68e+14
Beta* IP1: 11.00 m
Beta* IP5: 11.00 m
Beta* IP2: 10.00 m
Beta* IP8: 9.97 m
FBCT Intensity and Beam Energy
Updated: 16:23:12
Intensity
Energy (GeV)
2.5E14
2E14
1.5E14
1E14
5E13
0E0
7000
6000
5000
4000
3000
2000
1000
0
14:30
14:45
15:00
15:15
15:30
15:45
16:00
16:15
BIS status and SMP flags
B1
B2
Comments (27-Jun-2017 14:53:10)
Next:
Fill for Physics 2460b
Next meeting WED morning
Link Status of Beam Permits true true
Global Beam Permit true true
Setup Beam false false
Beam Presence true true
Moveable Devices Allowed In false false
Stable Beams false false
AFS: 25ns_2460b_2448_2052_2154_144bpi_19inj
PM Status B1 ENABLED
PM Status B2 ENABLED


LHC Page1
Fill: 5878
E: 6499 GeV
t(SB): 00:00:00
27-06-17 16:58:04
PROTON PHYSICS: ADJUST
Energy: 6499 GeV
I(B1): 2.66e+14
I(B2): 2.67e+14
Inst. Lumi [(ub.s)^-1]
IP1: 11457.89
IP2: 2.48
IP5: 13099.16
IP8: 36.65
FBCT Intensity and Beam Energy
Updated: 16:58:03
Intensity
Energy (GeV)
2.5E14
2E14
1.5E14
1E14
5E13
0E0
7000
6000
5000
4000
3000
2000
1000
0
15:00
15:15
15:30
15:45
16:00
16:15
16:30
16:45
BIS status and SMP flags
B1
B2
Comments (27-Jun-2017 14:53:10)
Next:
Fill for Physics 2460b
Next meeting WED morning
Link Status of Beam Permits true true
Global Beam Permit true true
Setup Beam false false
Beam Presence true true
Moveable Devices Allowed In false false
Stable Beams false false
AFS: 25ns_2460b_2448_2052_2154_144bpi_19inj
PM Status B1 ENABLED
PM Status B2 ENABLED

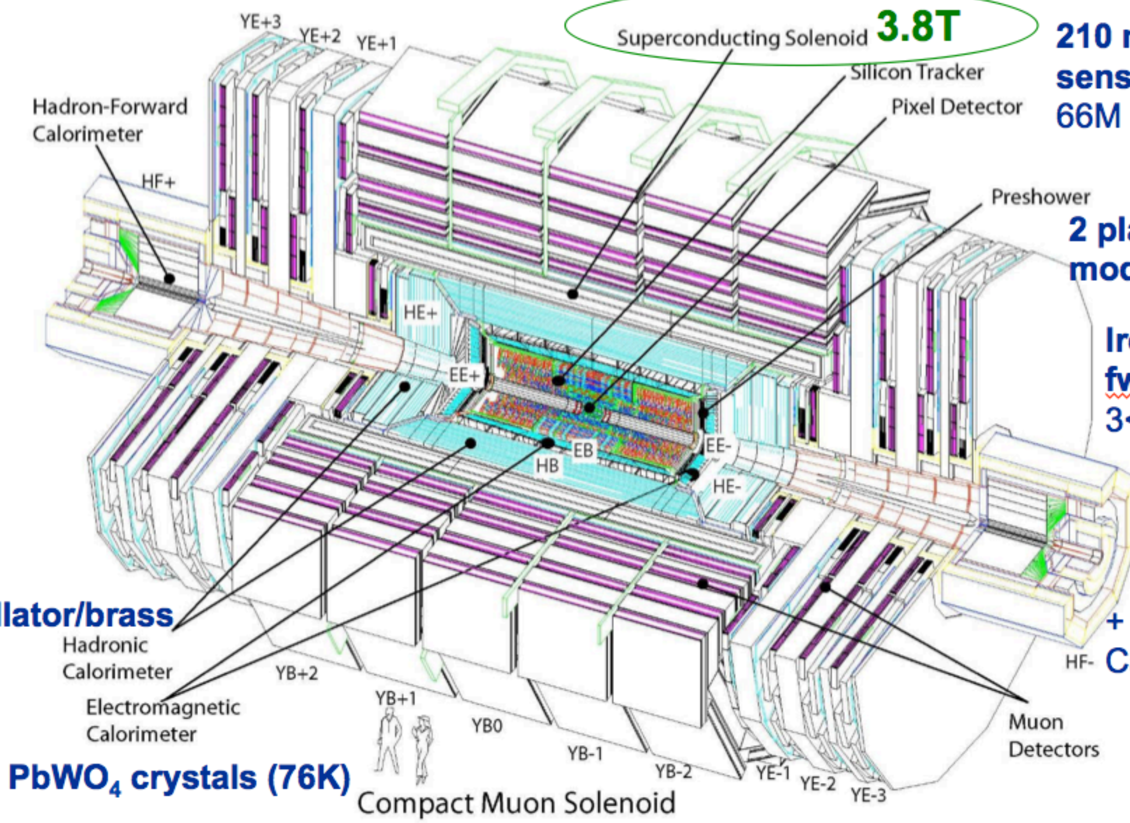

LHC Page1
Fill: 5878
E: 6499 GeV
t(SB): 00:00:16
27-06-17 16:58:52
PROTON PHYSICS: STABLE BEAMS
Energy:
6499 GeV
I(B1):
2.65e+14
I(B2):
2.67e+14
Inst. Lumi [(ub.s)^-1]
IP1: 13657.13
IP2: 2.34
IP5: 13479.77
IP8: 37.56
FBCT Intensity and Beam Energy
Updated: 16:58:51
Intensity
Energy (GeV)
2.5E14
2E14
1.5E14
1E14
5E13
0E0
7000
6000
5000
4000
3000
2000
1000
0
17:00
20:00
23:00
02:00
05:00
08:00
11:00
14:00
Instantaneous Luminosity
Updated: 16:58:52
Luminosity / 1e30 cm-2s-1
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
17:00
20:00
23:00
02:00
05:00
08:00
11:00
14:00
ATLAS
ALICE
CMS
LHCb
BIS status and SMP flags
B1
B2
Comments (27-Jun-2017 14:53:10)
Next:
Fill for Physics 2460b
Next meeting WED morning
Link Status of Beam Permits
true
true
Global Beam Permit
true
true
Setup Beam
false
false
Beam Presence
true
true
Moveable Devices Allowed In
true
true
Stable Beams
true
true
AFS: 25ns_2460b_2448_2052_2154_144bpi_19inj
PM Status B1
ENABLED
PM Status B2
ENABLED

My Experiment: CMS



- At the LHC, the highest energy collider in town
  - Well actually it is in Geneva, Switzerland
  - 13 TeV proton collision energy
- CMS has the world's strongest magnet

The “Compact” Muon Solenoid (CMS)



3.8T

210 m² of silicon sensors: 9.6M (Str) & 66M (Pix) channels

2 planes of silicon modules for ECAL

Iron / Quartz fiber fwd calorimeter,
3<|η|<5;

+ Castor,
5<|η|<6.55

+ Zero Degree Calorimeter

Scintillator/brass

$PbWO_4$ crystals (76K)

Cathode Strip Chambers, Drift Tubes, Resistive Plates

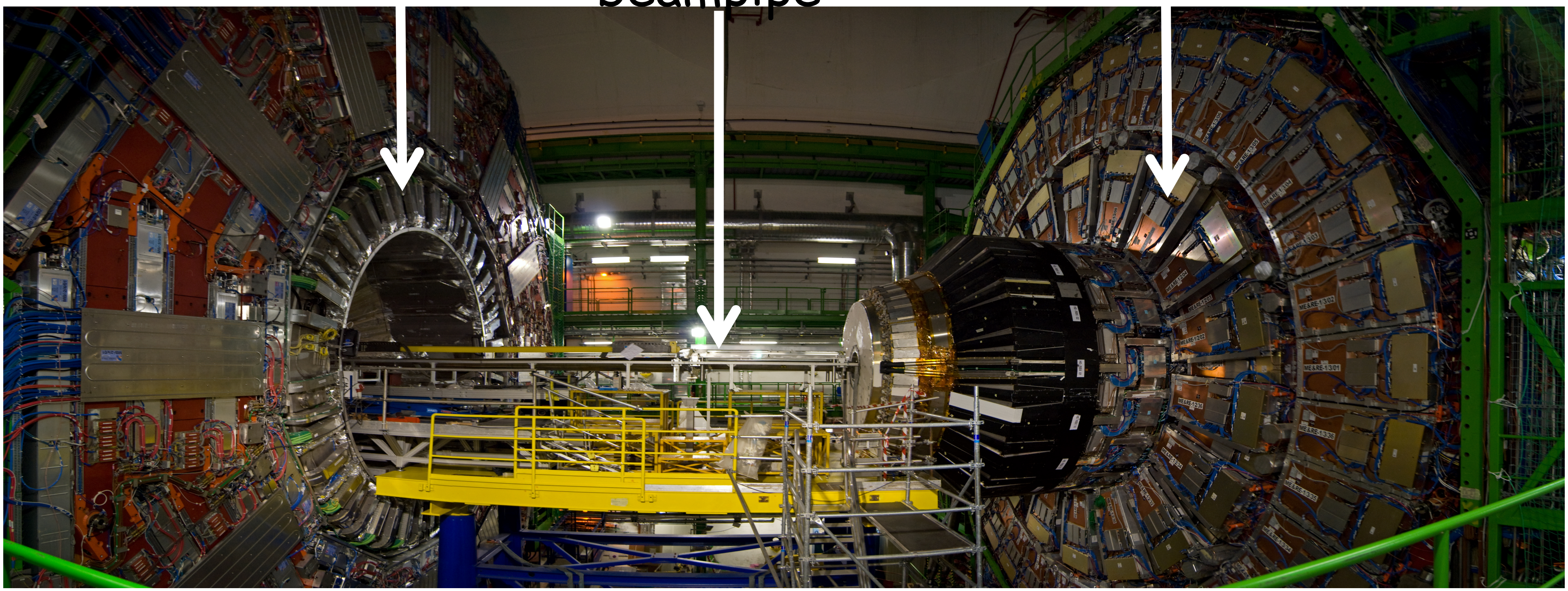
+ Trigger and data acquisition systems

CMS Experiment Opened

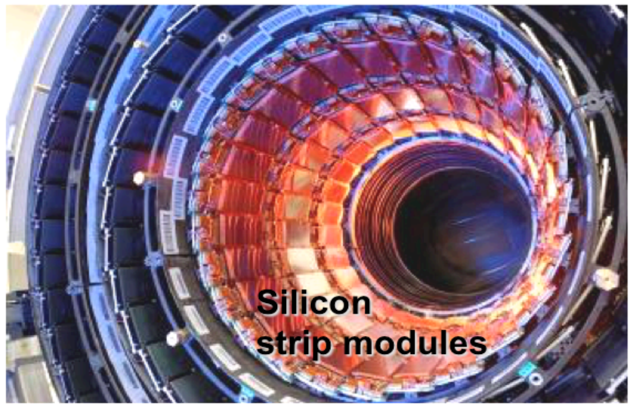
3.8T solenoid (2.7 GJ!)

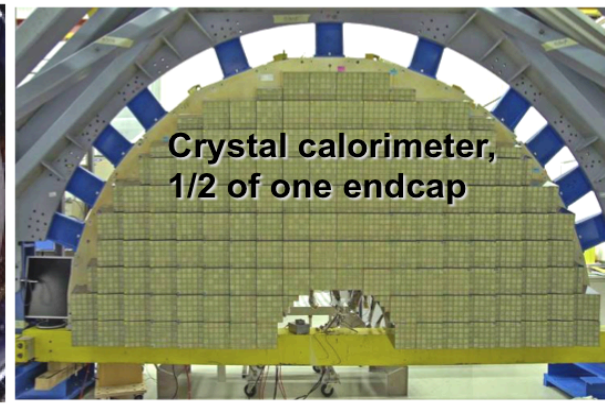
beampipe

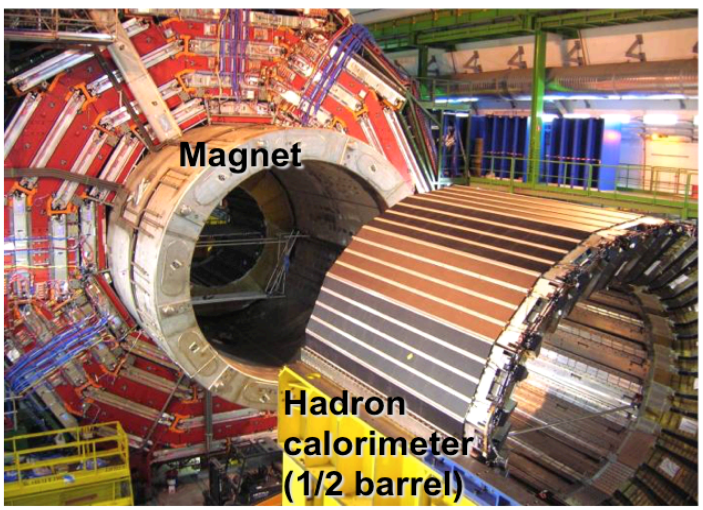
Muon detectors

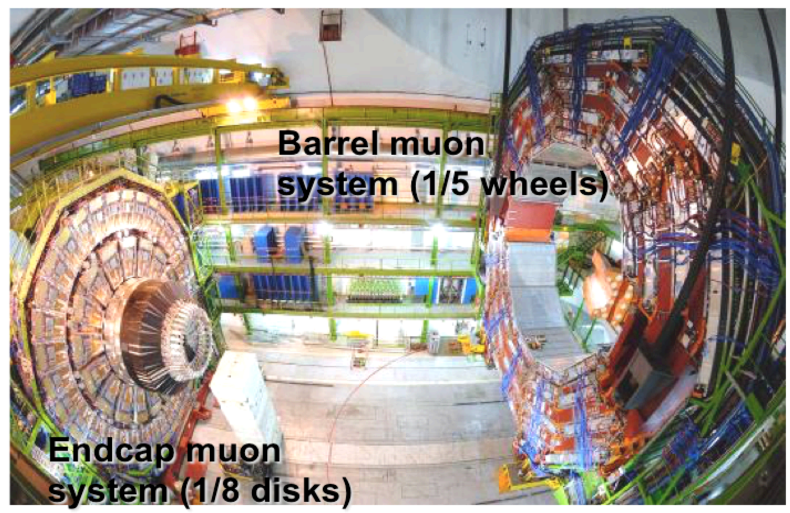


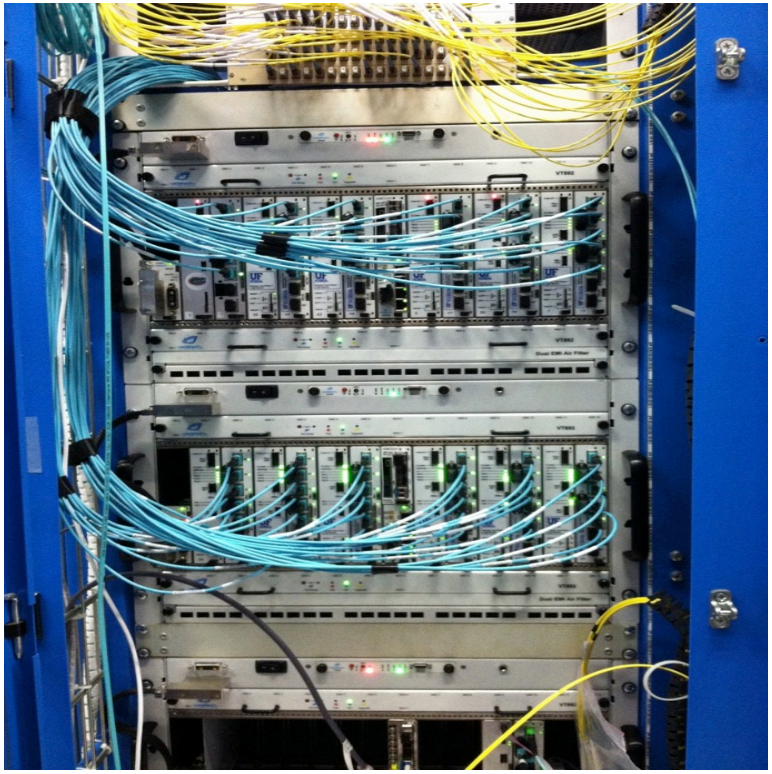
CMS Detector Systems











The Trigger System – the first step in collecting data:
Select interesting collisions and throw away 99.998% of rest!