The CMS Experiment at the CERN Large Hadron Collider (LHC)

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Fermilab

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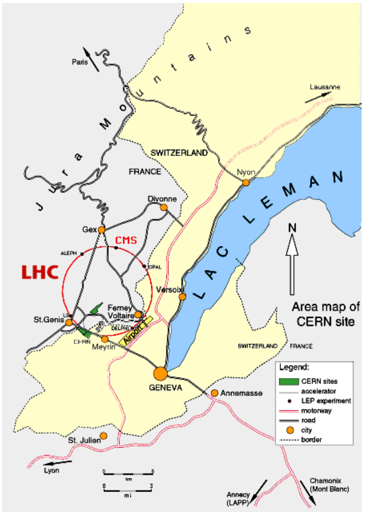
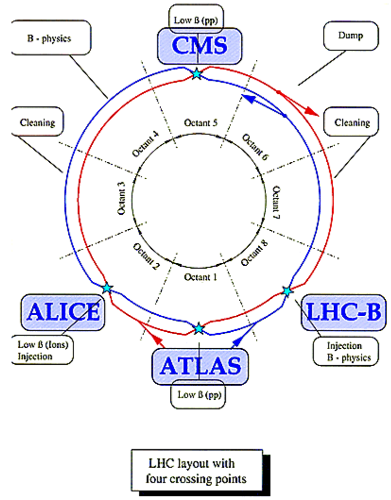
Outline

- Why do we go to the energy frontier?
- What is the CMS collaboration?
- What is the Standard Model? How do we detect the fundamental particles contained in the SM?
- The Higgs boson is the missing object in the SM "periodic table". What is the CMS strategy to discover it?
- What might we find at CMS in addition to the Higgs?
- How is US CMS preparing for the Physics?

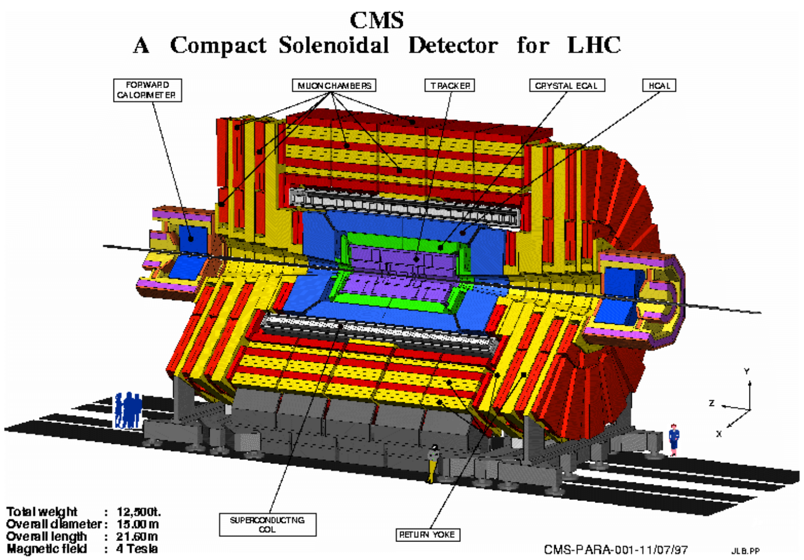
What and Where is CERN, LHC, CMS?



European Center for Nuclear Research (CERN)

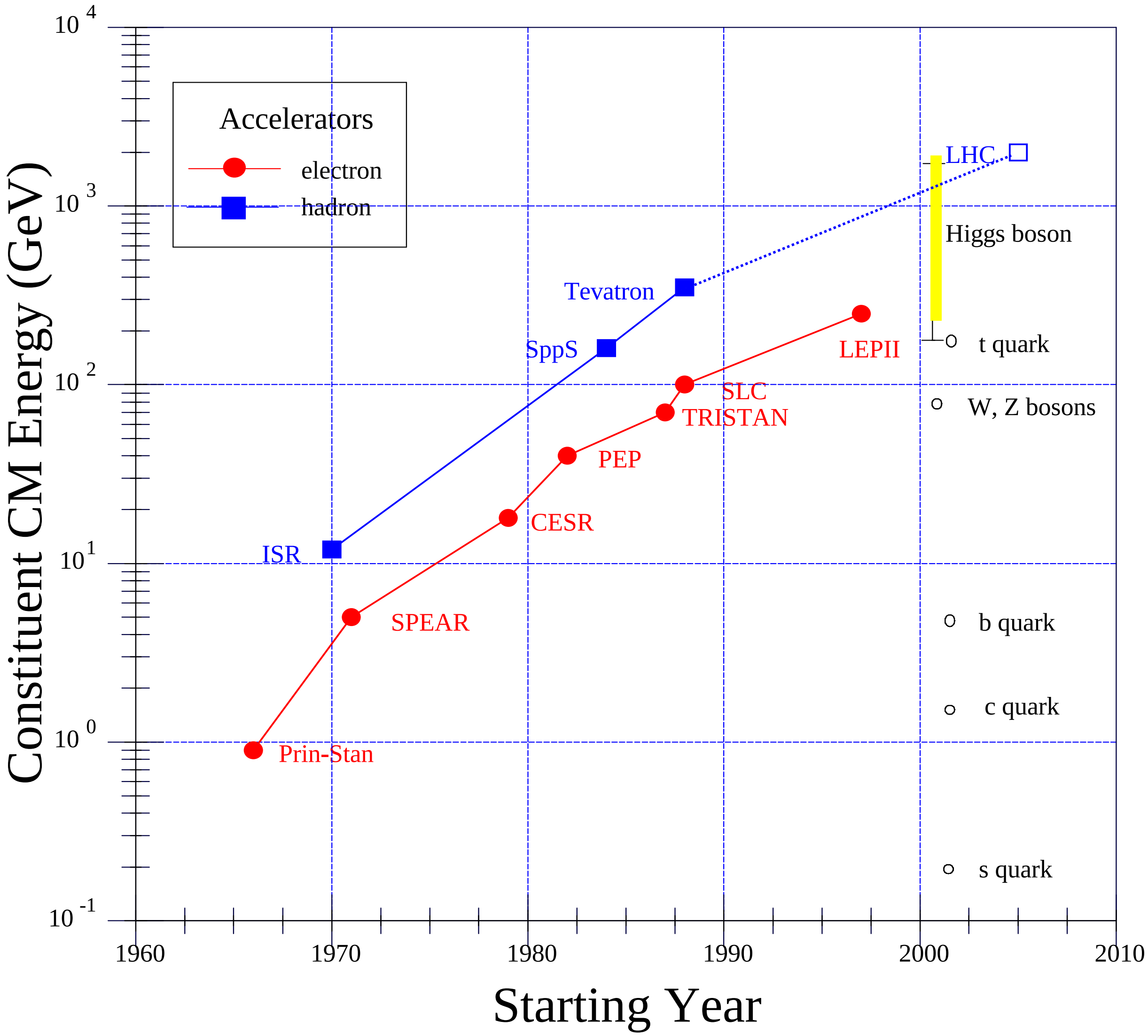


Large Hadron Collider (LHC)



Compact Muon Solenoid (CMS)

Progress in HEP Depends on Advancing the Energy Frontier



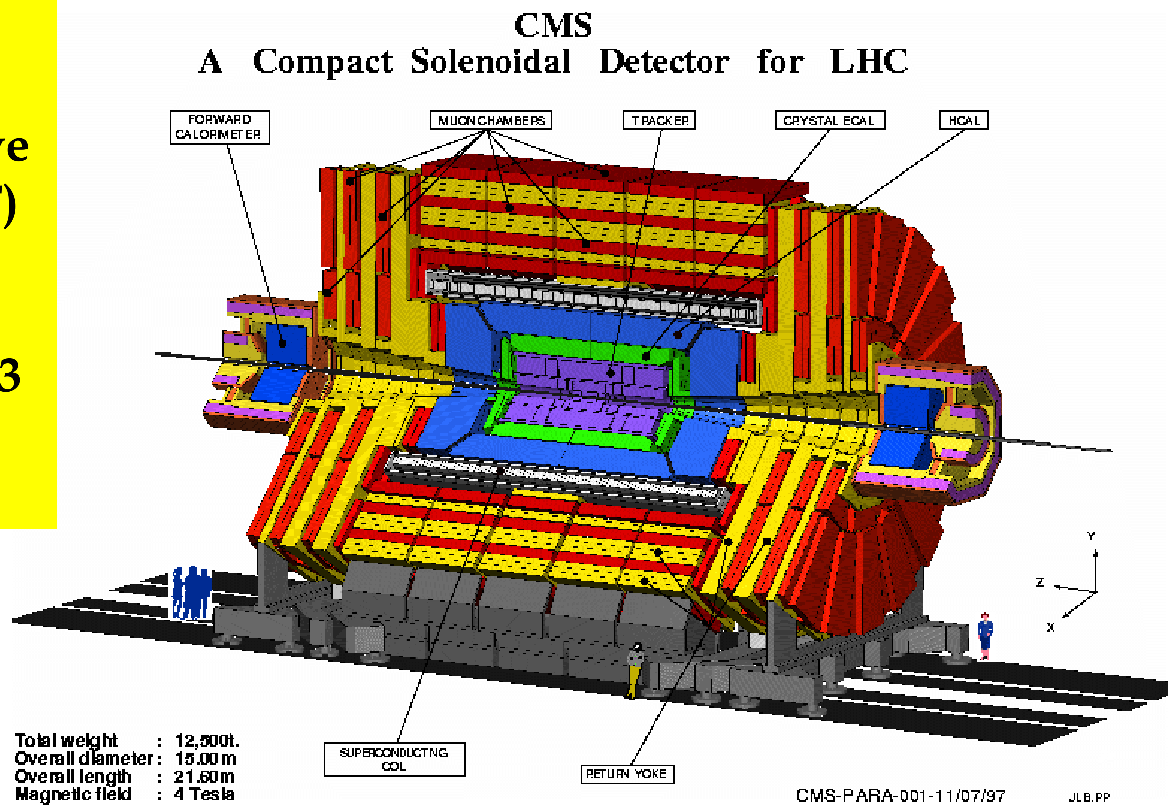
Why?

$E=mc^2$

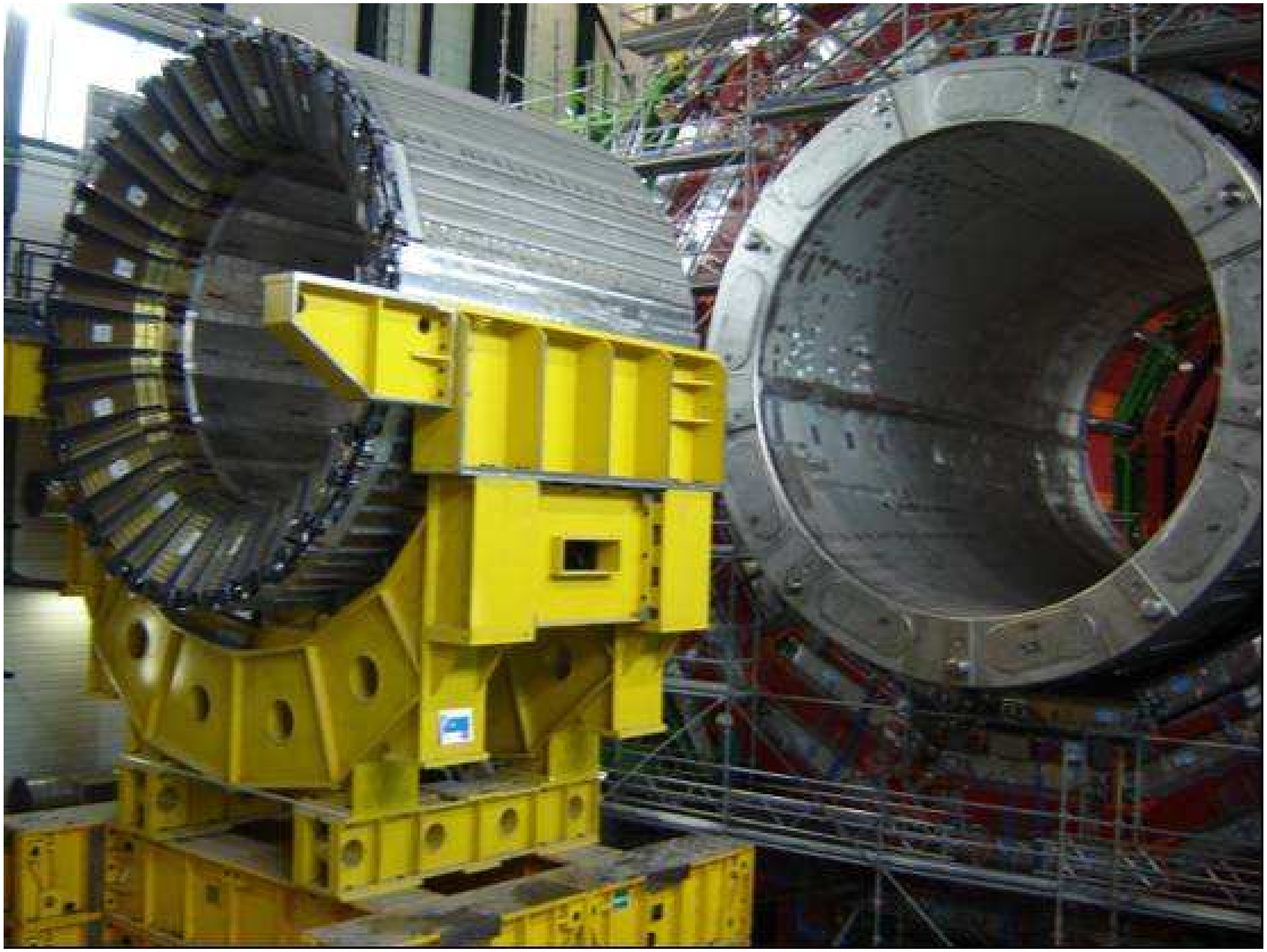
Go back in time to the Big Bang, look at hidden symmetries made manifest at high energies

CMS Detector Subsystems

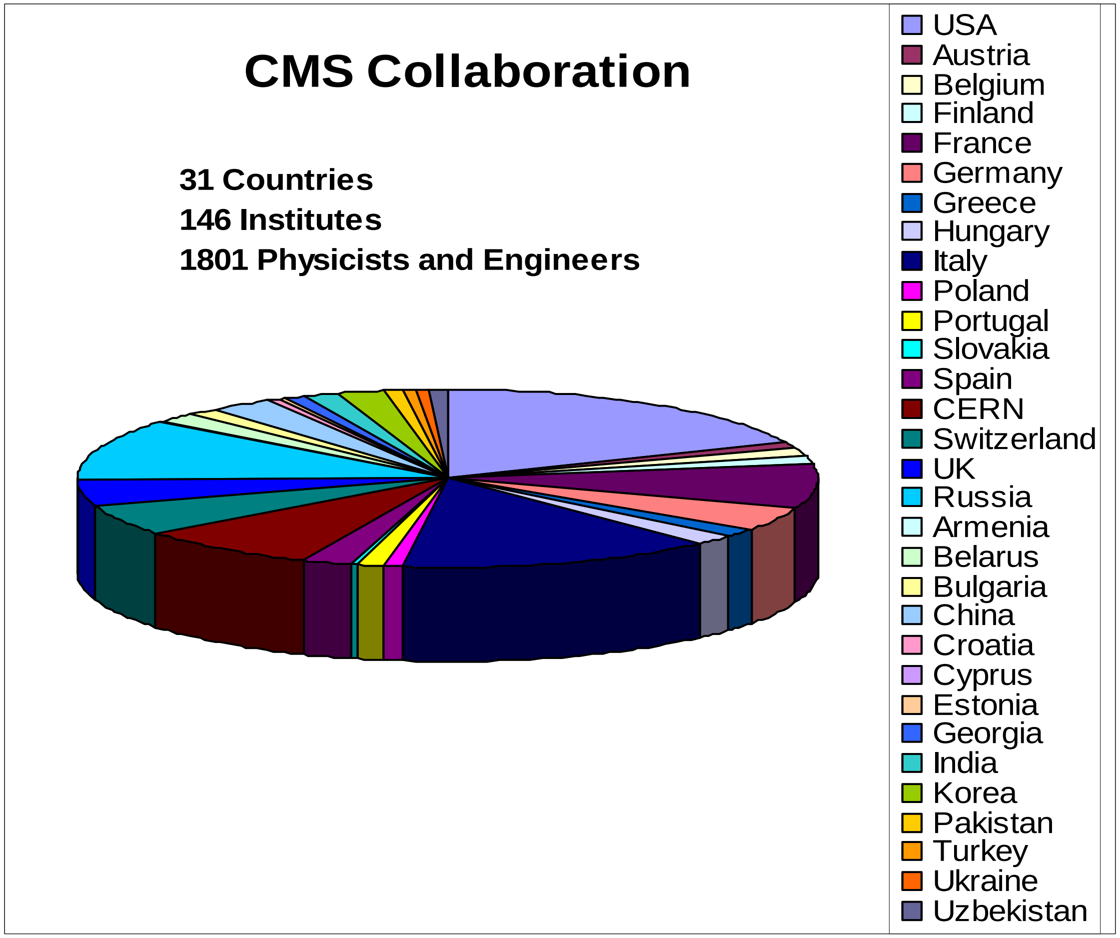
Basic decision was to have a large (4T) magnetic field. Energy of 3 GJ, 1 MW for 1 hr.



CMS Coil is Cryogenic



The CMS Collaboration



The US is the largest national group in CMS – about 1/3.

The US CMS Collaboration

Expected to grow to more than 500 physicists by the start of data taking in late 2007.

The Standard Model of Elementary Particle Physics

- Matter consists of half integral spin fermions. The strongly interacting fermions are called quarks. The fermions with electroweak interactions are called leptons. The uncharged leptons are called neutrinos.
- The forces are carried by integral spin bosons. The strong force is carried by 8 gluons (g), the electromagnetic force by the photon (γ), and the weak interaction by the W^+ Z^o and W^-. The g and γ are massless, while the W and Z have ~ 80, 91 GeV mass.

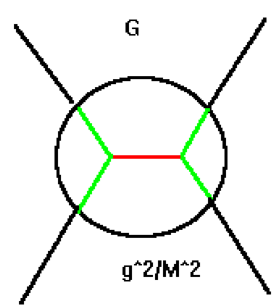
J = 1	g,γ, W^+,Z^o,W^-				Force Carriers
	u d	c s	t b	2/3 -1/3	Quarks
J = 1/2				Q/e=	
	e ν_e	μ ν_μ	τ ν_τ	1 0	Leptons
J= 0		H			

Electro - Weak Unification

- **In the 1980's we found that weak interactions only appear to be weak at low energies.**

$$\Gamma(\pi^o \to \gamma + \gamma)/\Gamma(\pi^+ \to \mu^+ + \nu_\mu) \sim 3x10^8$$

- **At energies above the W and Z mass the electromagnetic and weak coupling constants are ~ equal and the forces are unified.**



$$g_W^2 / M_W^2$$

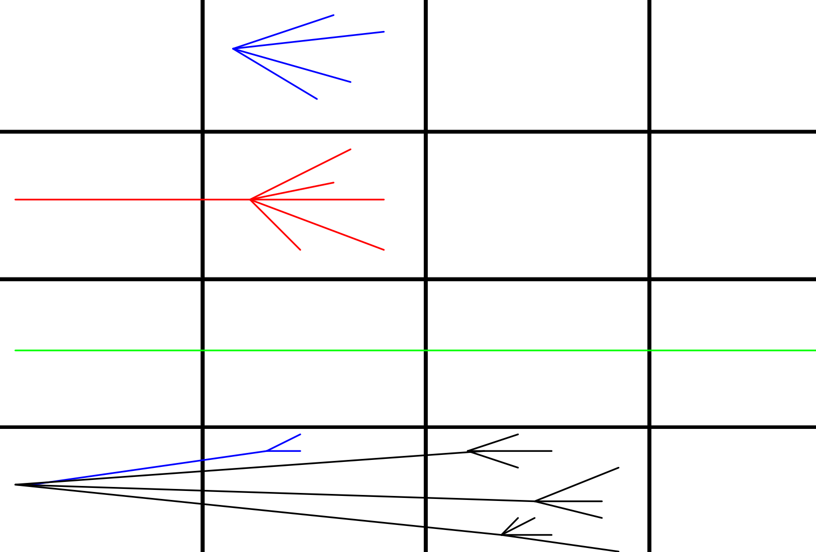
$$1/q^2,\ 1/(q^2+m^2)$$

$$e^2/r,\ \ g_W^2 e^{-r/\lambda}/r$$

$$e = g_W \sin\theta_W$$

Detection of Fundamental Particles

Particle type	Tracking	ECAL	HCAL	Muon
γ				
e				
μ				
Jet				
Et miss				



EM force

(Bremm + pair)

leptons

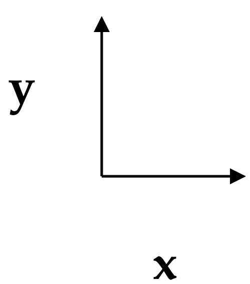
(ionize)

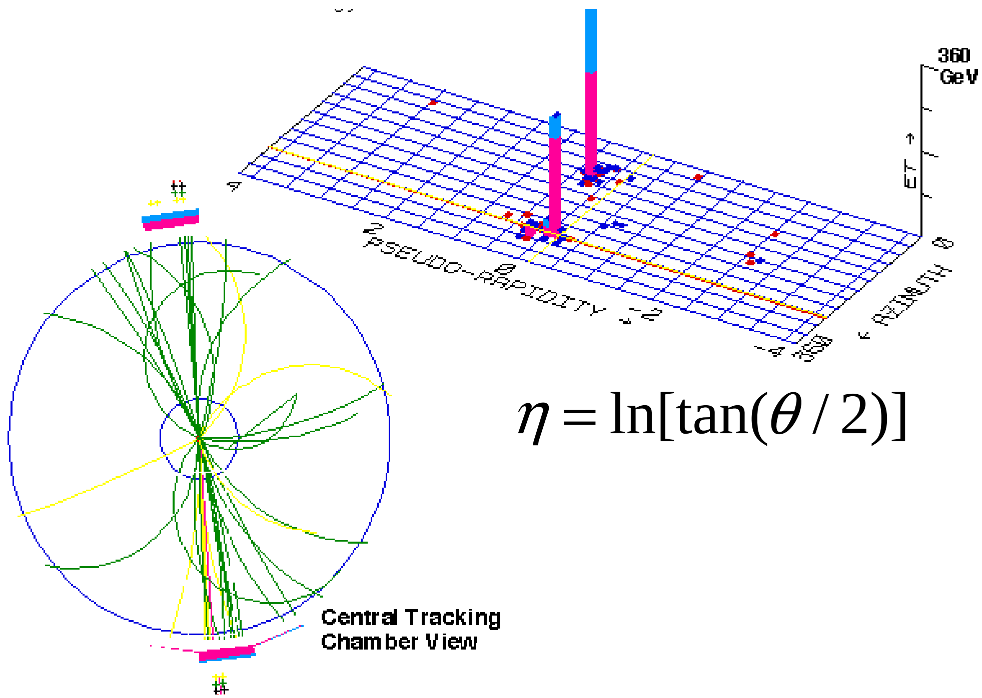
q, g

ν

Dijet Events at the Tevatron

The scattering of quarks inside the proton leads to a "jet" of particles traveling in the direction of, and taking the momentum of, the parent quark. Since there is no initial state P_t, the 2 quarks in the final state are "back to back" in azimuth



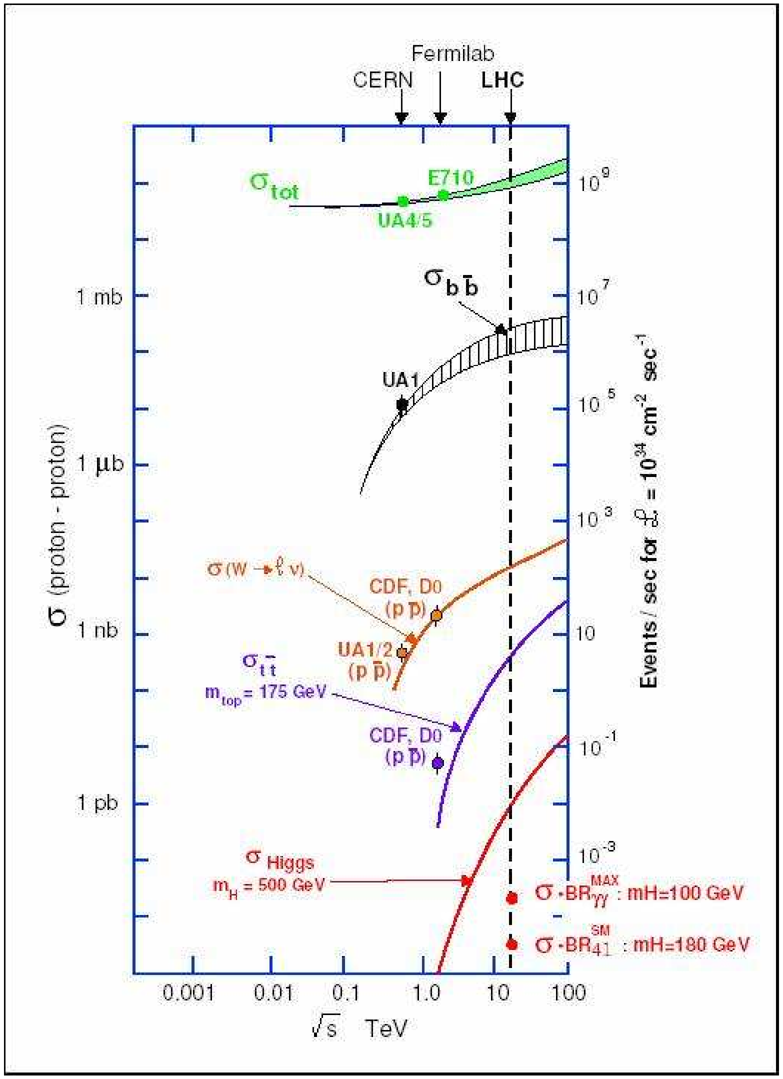


E_T

ϕ

$$\eta = \ln[\tan(\theta / 2)]$$

Higgs Cross Section



CDF and D0 successfully found the top quark, which has a cross section ~ 10^{-10} the total cross section.

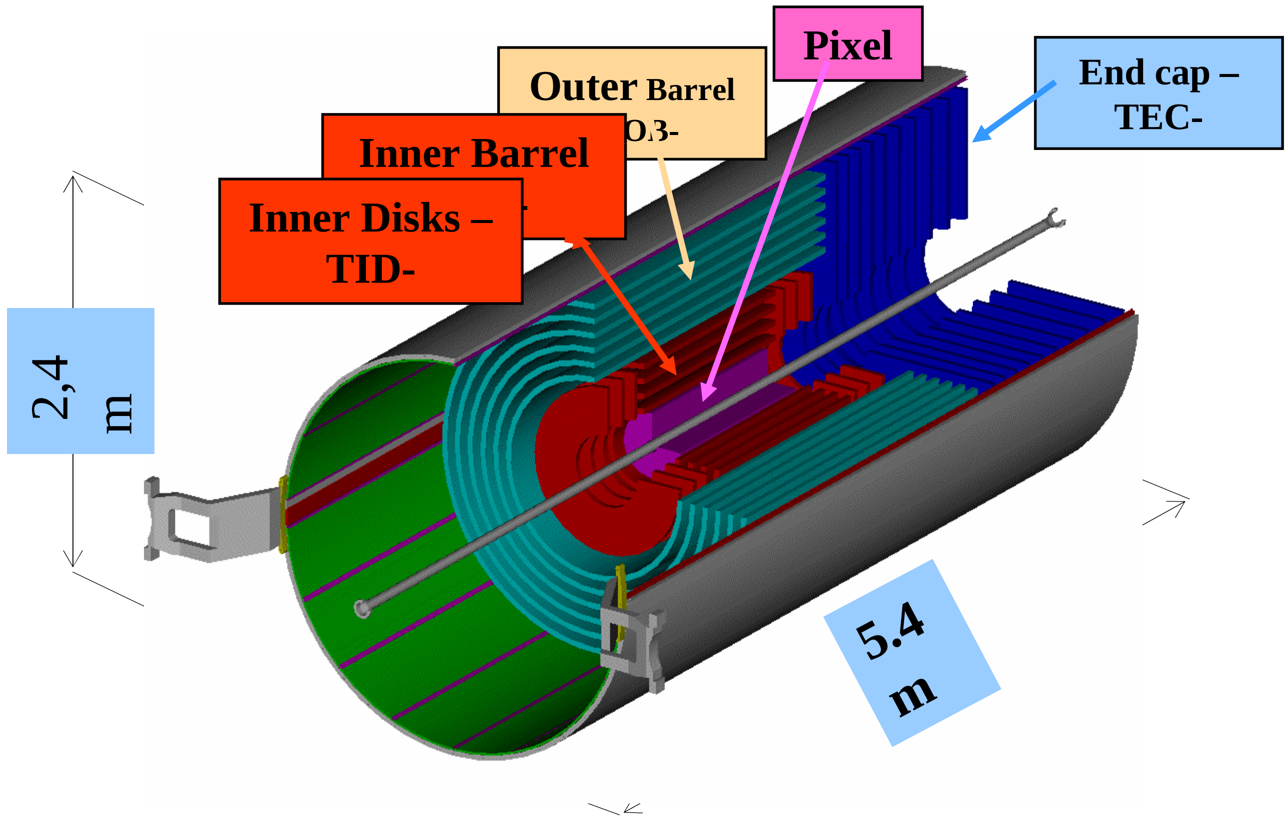
A 500 GeV Higgs has a cross section ratio of ~ 10^{-11}, which requires great rejection power against backgrounds and a high luminosity.

Rate = luminosity * cross section

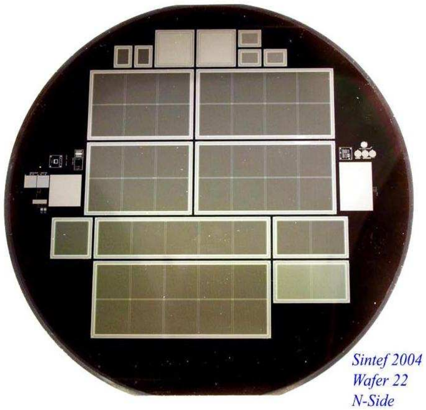
LHC has ~ 100 times the luminosity of the Tevatron and 7 times the energy.

CMS Tracker – All Si

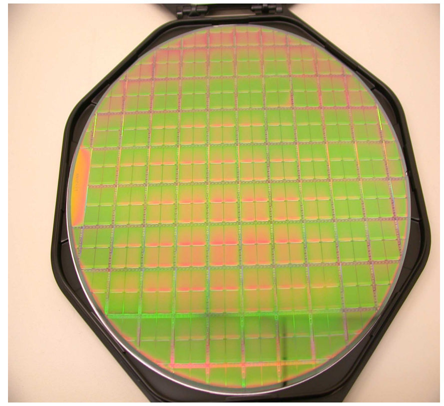
The Higgs is weakly coupled to ordinary matter (couples to mass), as square of u, d quark mass, with no direct coupling to gluons or photons. Thus, high interaction rates are required. The CMS pixel Si system has ~ 70 million elements so as to accommodate the resulting track densities while the tracker has ~ 10 million strips.



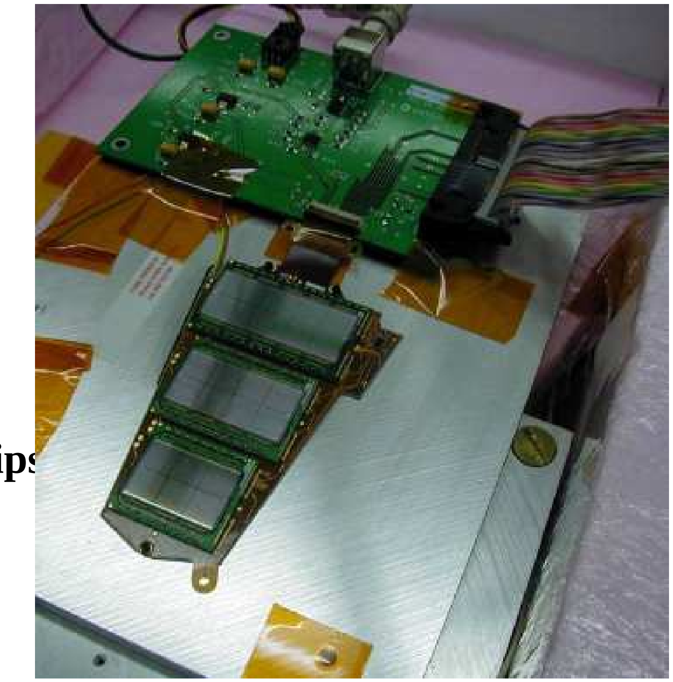
US CMS - FPIX

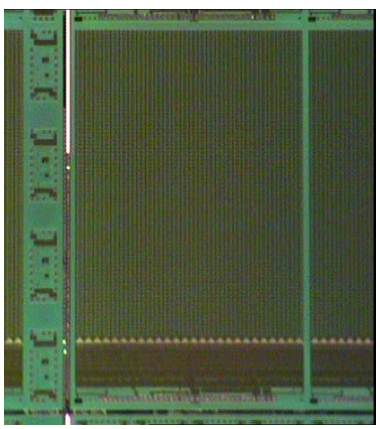


Pixel sensor wafer showing various sizes needed to form "panels"



Wafer of pixel readout chips

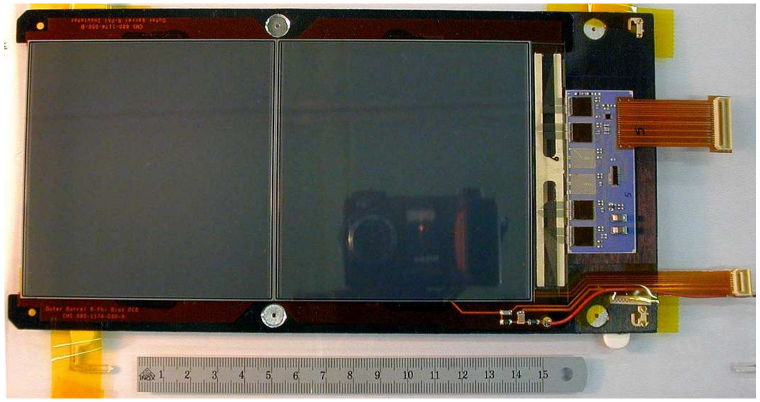


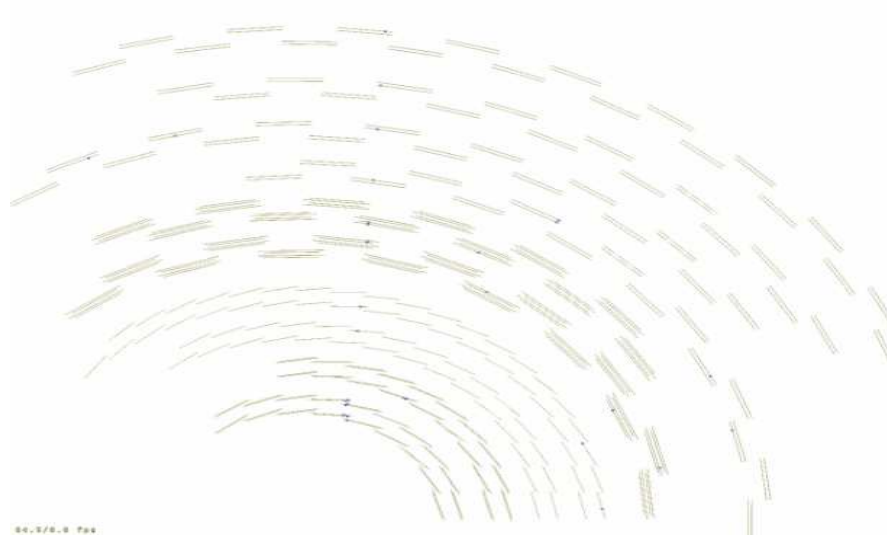


Pixel readout chip: 4160 pixels 100 x 150 μ^2

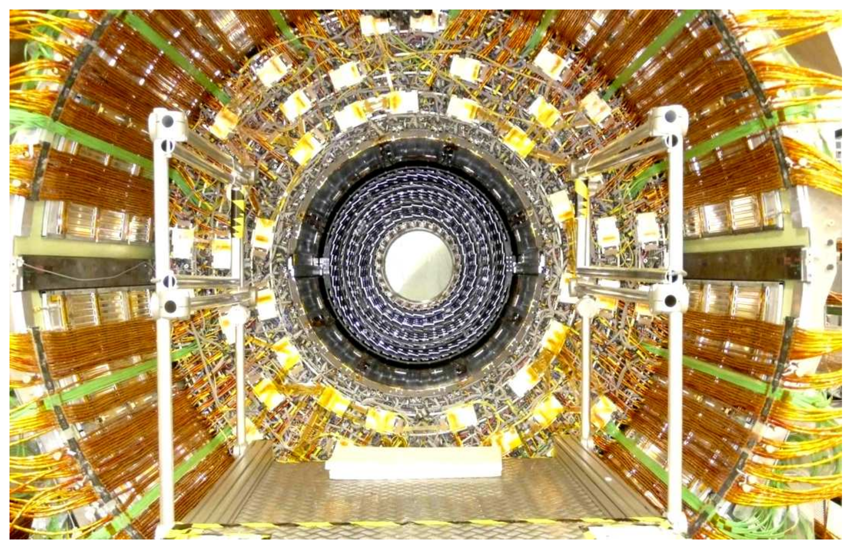
Bump bonded detectors received from vendors

US CMS - TOB

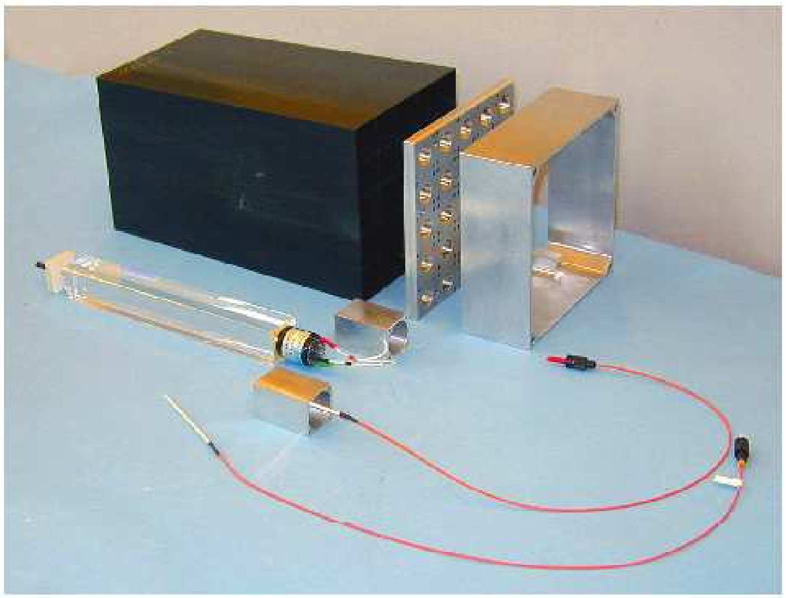


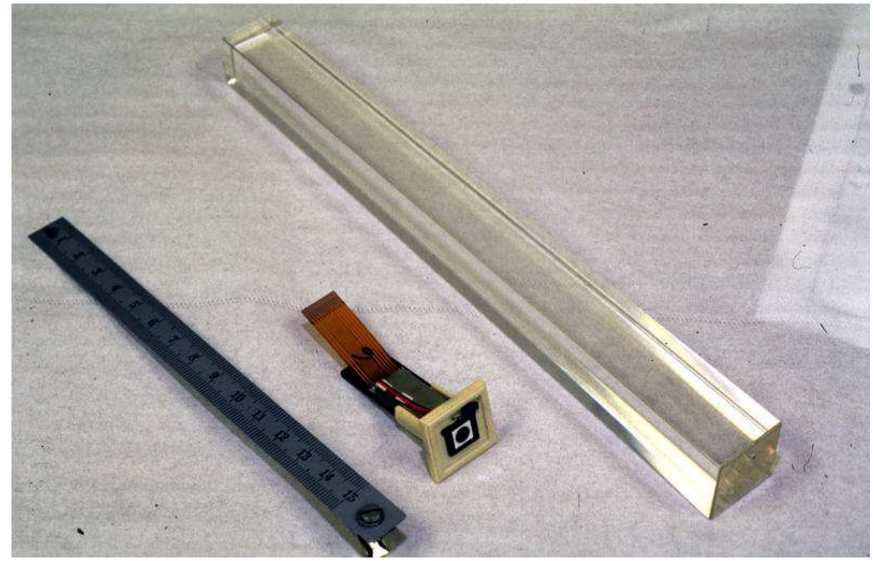


There are about 10 million Si strip detection elements



ECAL - PbWO4 Crystals

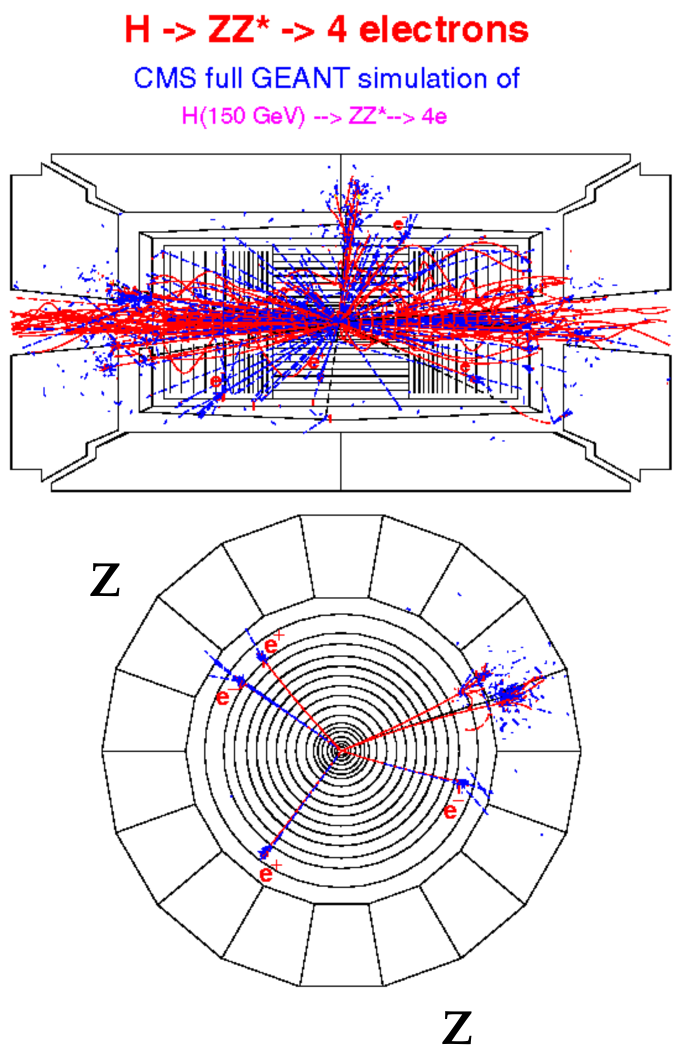




Fully active EM calorimetry. Depth of ~ 20 cm ~ 8″ ➔ compact

Use H --> ZZ --> 4e

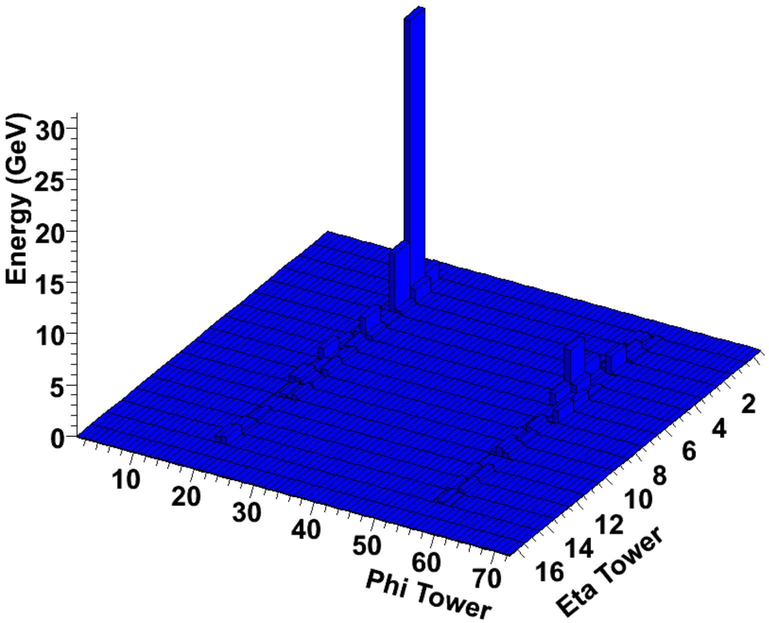
Higgs couples to mass -> most strongly to W and Z. Next strongest is to heavy quarks such as t, b.

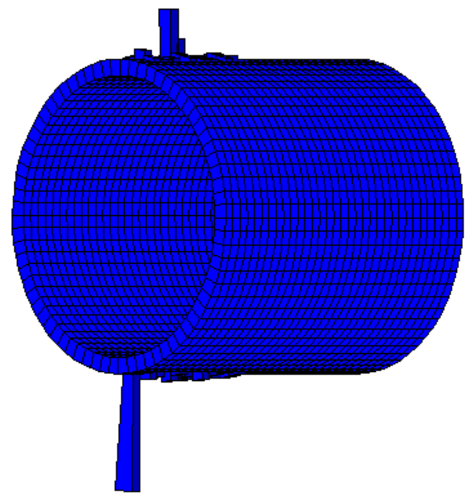


Fully active crystals are the best resolution possible - needed for 2 photon decays of the Higgs and Z+Z-> 4 e decays.

US CMS - HCAL

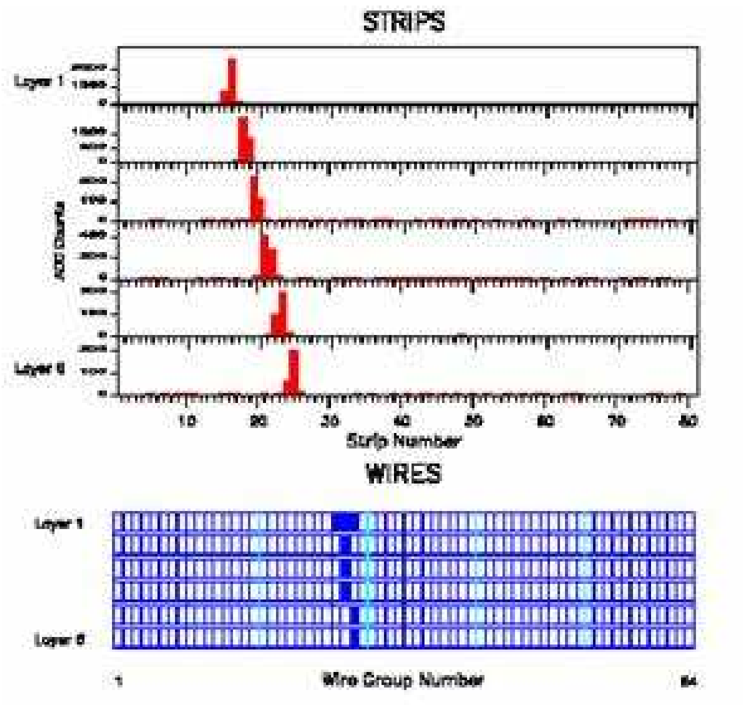
HB – Cosmic Self-Trigger

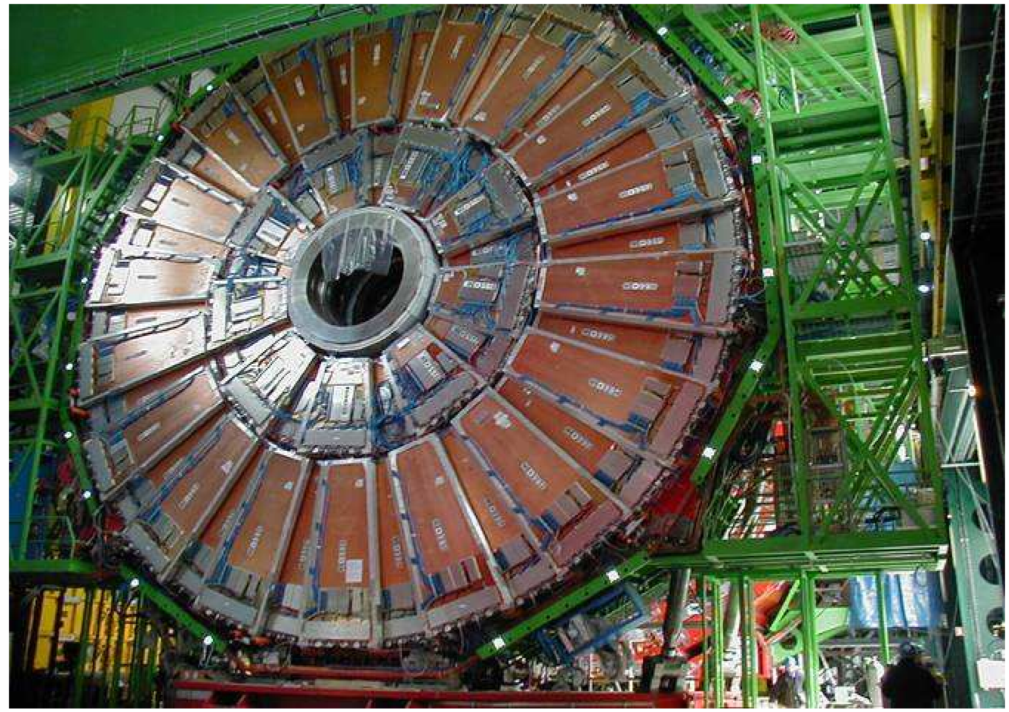




US CMS has celebrated (FY06) completing 97% of the Detector Project. Now exercising the detectors prior to final installation.

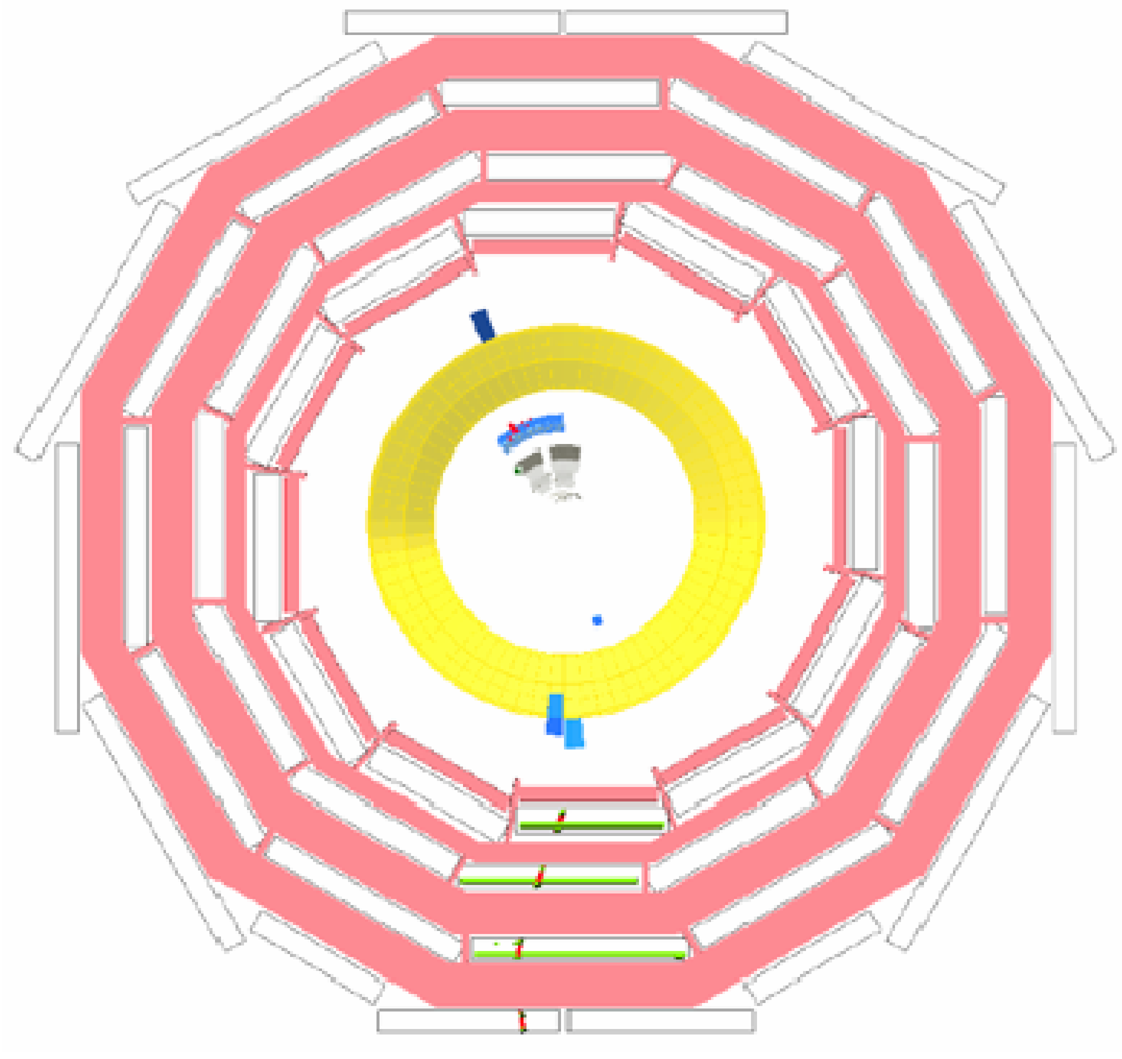
US CMS - Endcap Muon Chambers





We are currently commissioning the US CMS detectors with cosmic rays both above in the Assembly Hall and soon below ground in the Collision Hall.

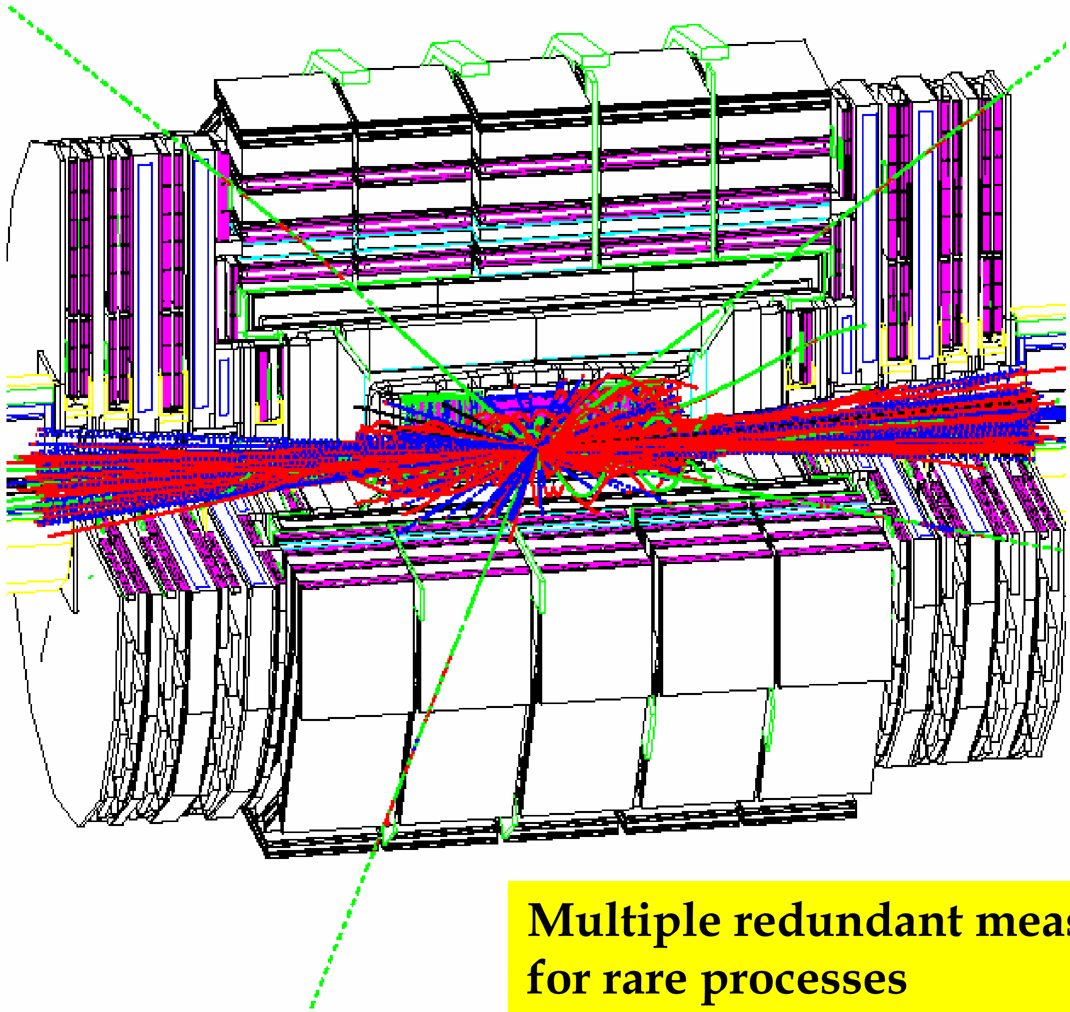
Cosmic Rays – All Together



In late 2006 we put it all together, powered the magnet to full field and ran cosmic rays through the most parts of the CMS detector – tests above ground prior to lowering below ground.

Higgs Decay, H -> ZZ ->4μ

$H(150GeV) \rightarrow Z^0 Z^{0*} \rightarrow 4\mu$ (event 8)



Muons should be the cleanest signal at the LHC:

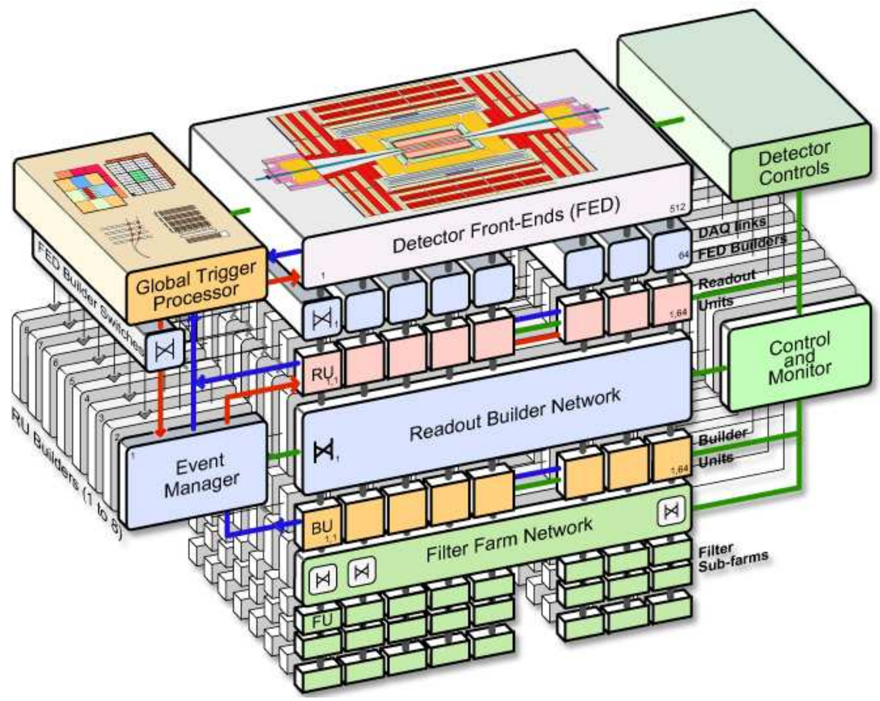
Momentum in tracker * momentum in CSC * match in

(θ, ϕ)

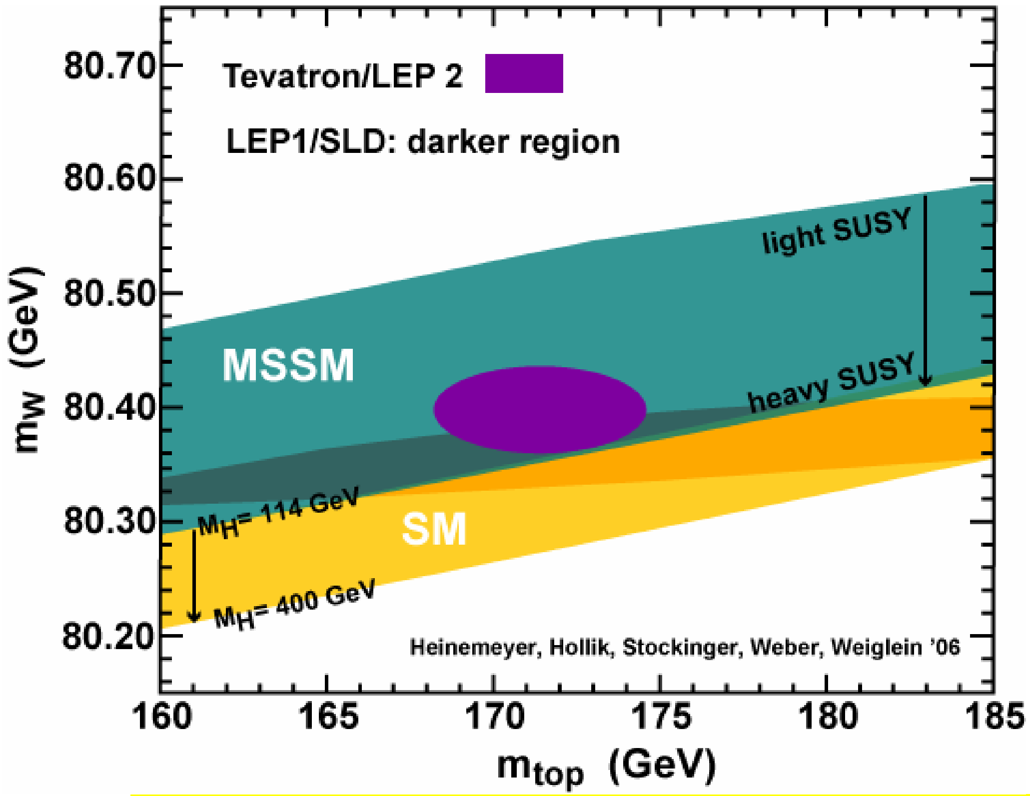
Multiple redundant measurements for rare processes

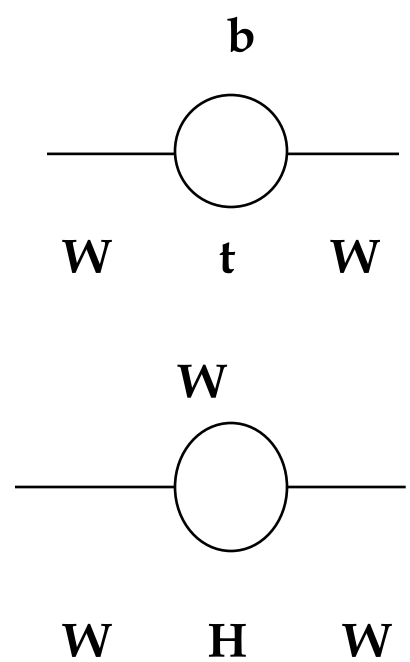
CMS DAQ and Trigger System

The total interaction rate is ~ 1 GHz. Events are selected by a series of "trigger" cuts which reduce the rate to ~ 100 Hz. Find a needle in a haystack – 1 event out of every 10 million interactions that are lost forever.



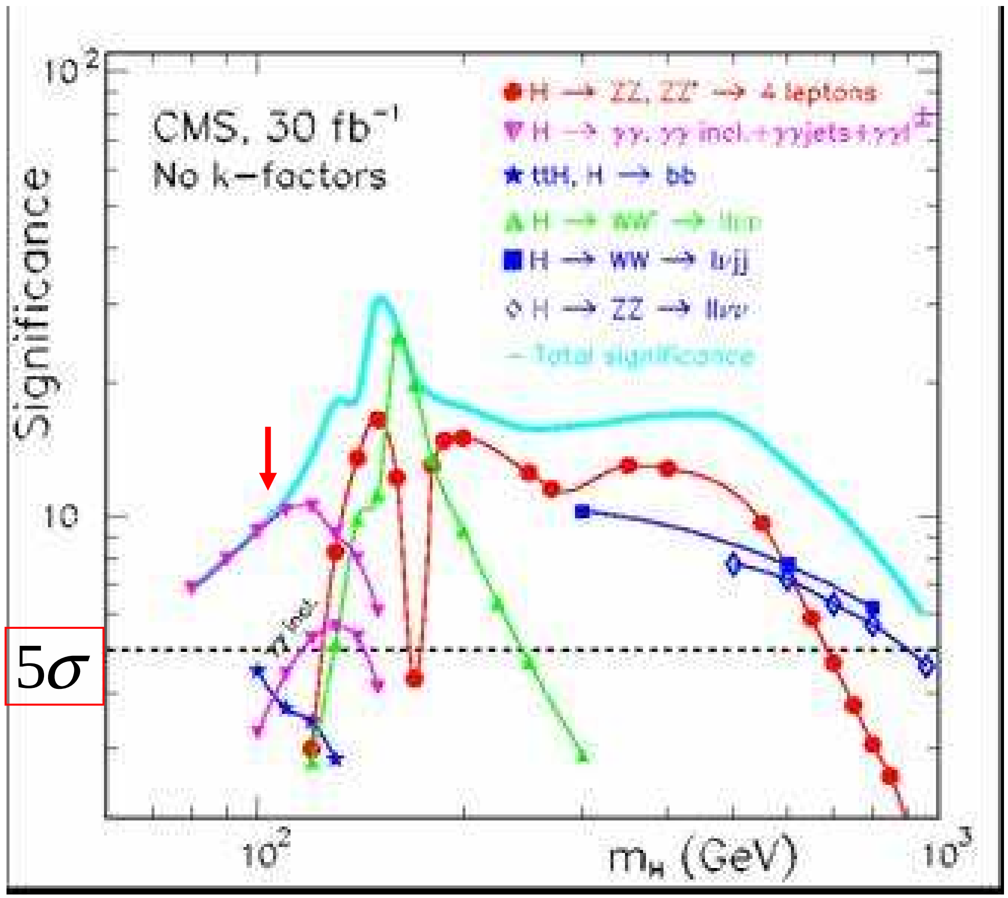
LEP,CDF D0 Data Indicate Light Higgs





Quantum mechanics: traces of higher mass states are seen in radiative corrections due to virtual quantum loops, e.g. Lamb shift in atomic spectrum due to virtual e pairs. Note sign – fermion, boson

Higgs Discovery Limits



1/3 year at design luminosity – CMS designed to find the Higgs.

The main final state is ZZ --> 4l.

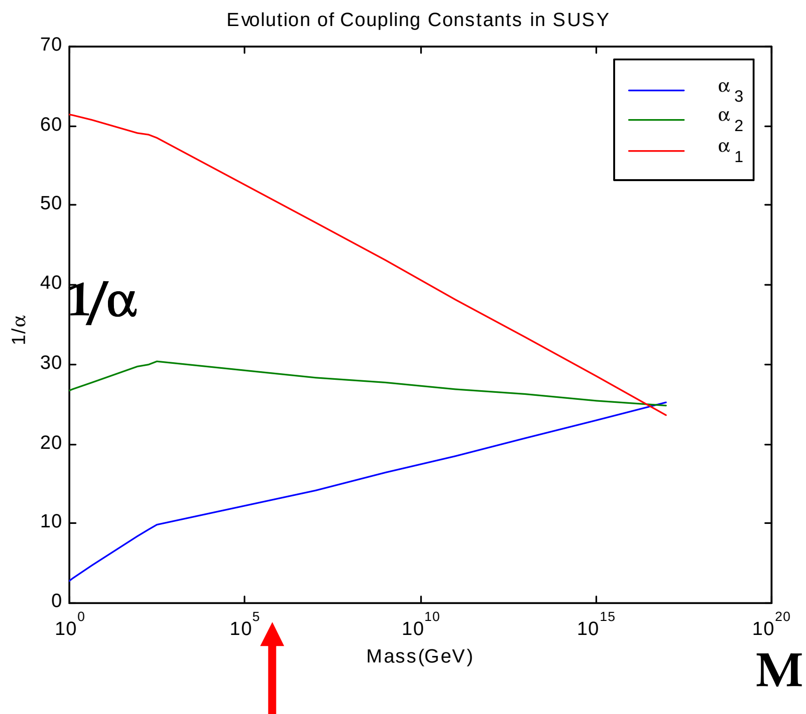
At high masses larger branching ratios are needed.

At lower masses the ZZ*, qqWW* and $\gamma\gamma$ final states are used.

LEP II has set a limit ~ 113 GeV.

CMS will cover the full range from LEPII to 1 TeV.

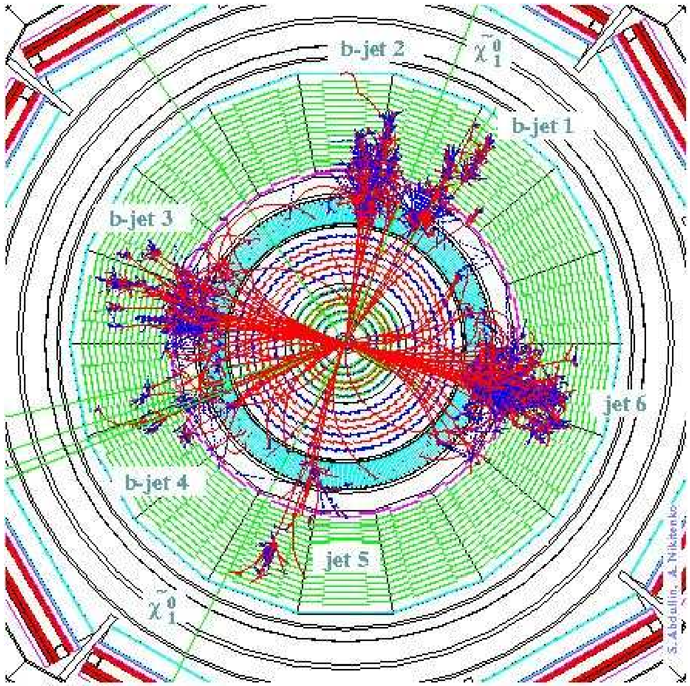
SUSY and Evolution of α

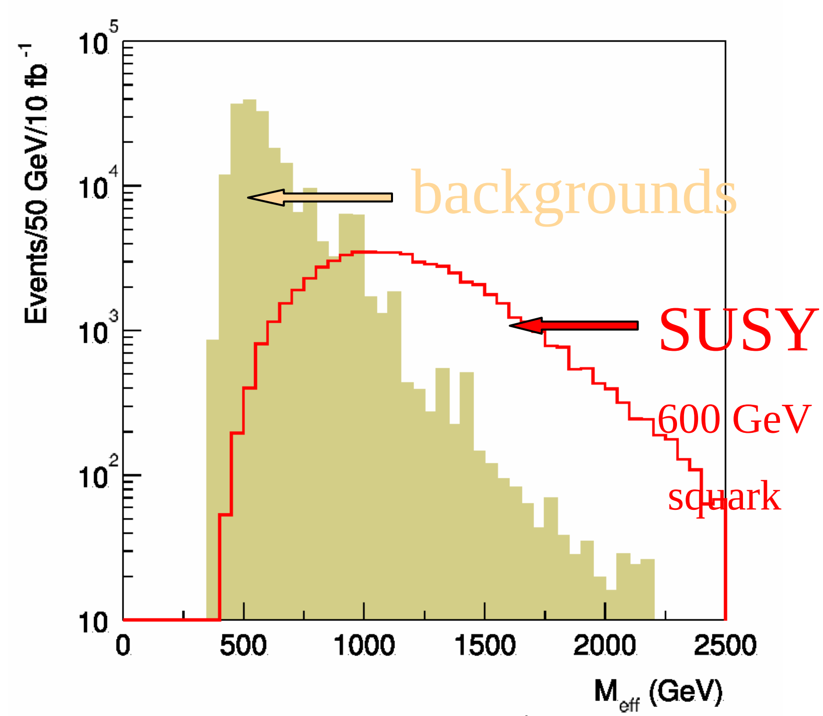


- The coupling constants "run" in quantum field theories due to vacuum fluctuations. For example, in EM the e charge is shielded by virtual γ fluctuations into e+e- pairs on a distance scale set by, $\lambda_e \sim 1/me$. Thus e increases as M increases (logarithmically), α(0) = 1/137, α(MZ) = 1/128.

It is impossible to maintain the big gap between the Higgs mass scale and the GUT mass scale in the presence of quantum radiative corrections (the "hierarchy problem"). One way to restore the gap is to postulate a relationship between fermions and bosons. Each SM particle has a supersymmetric (SUSY) partner with spin 1/2 difference. If the mass of the SUSY partners is ~ 1 TeV, then the GUT unification is good - at 10^{16} GeV. "Close" to M_{Pl} – hint?

SUSY - Discovery

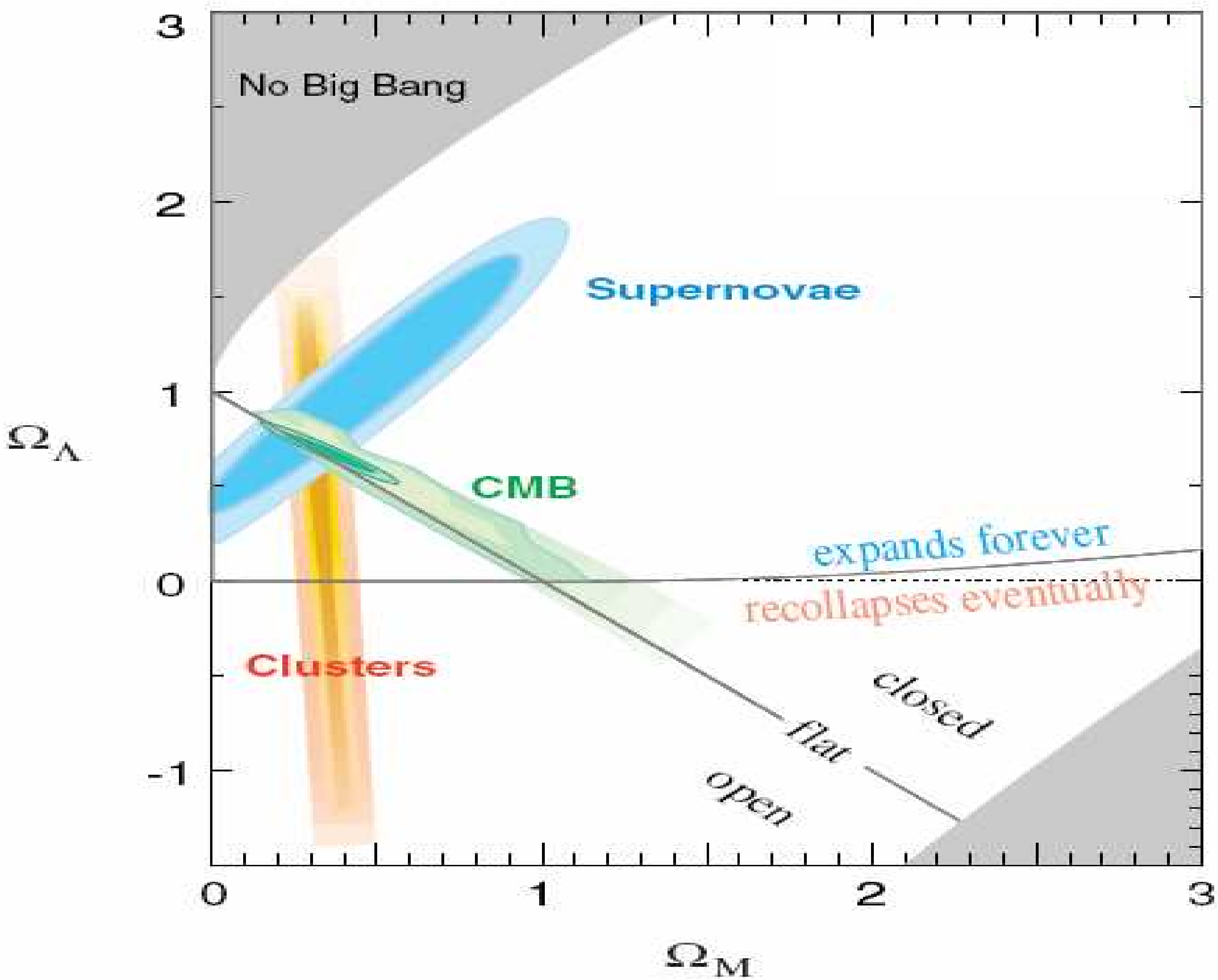




$$M_{eff} = P_T(\nu) + \sum_{1}^{4} P_T(\text{jets})$$

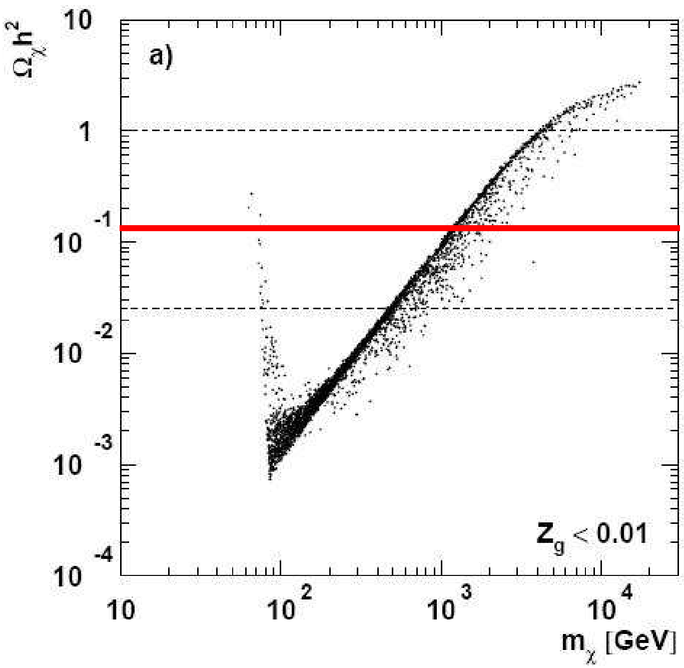
Assuming a conserved SUSY quantum number, the lightest SUSY particle (LSP) is stable. A neutral weakly interacting LSP escapes the detector. Dramatic event signatures (cascade to LSP) and large cross section mean we will discover SUSY quickly, if it exists.

Cosmology and CMS



The universe is flat and composed largely of dark energy (73%) and dark matter (22 %). What are they? We understand only about 5% of the Universe by weight.

Dark Matter and SUSY



SUSY = dark matter?

It may be a big hint that a SUSY LSP with a mass O(TeV) with a weak cross section (neutralino ?) decouples from the Big Bang expansion to give the correct relic density to be "dark matter". The hope is then to produce and detect dark matter at the LHC. The memory of the Big Bang is stored in the vacuum waiting to be reignited at the LHC.

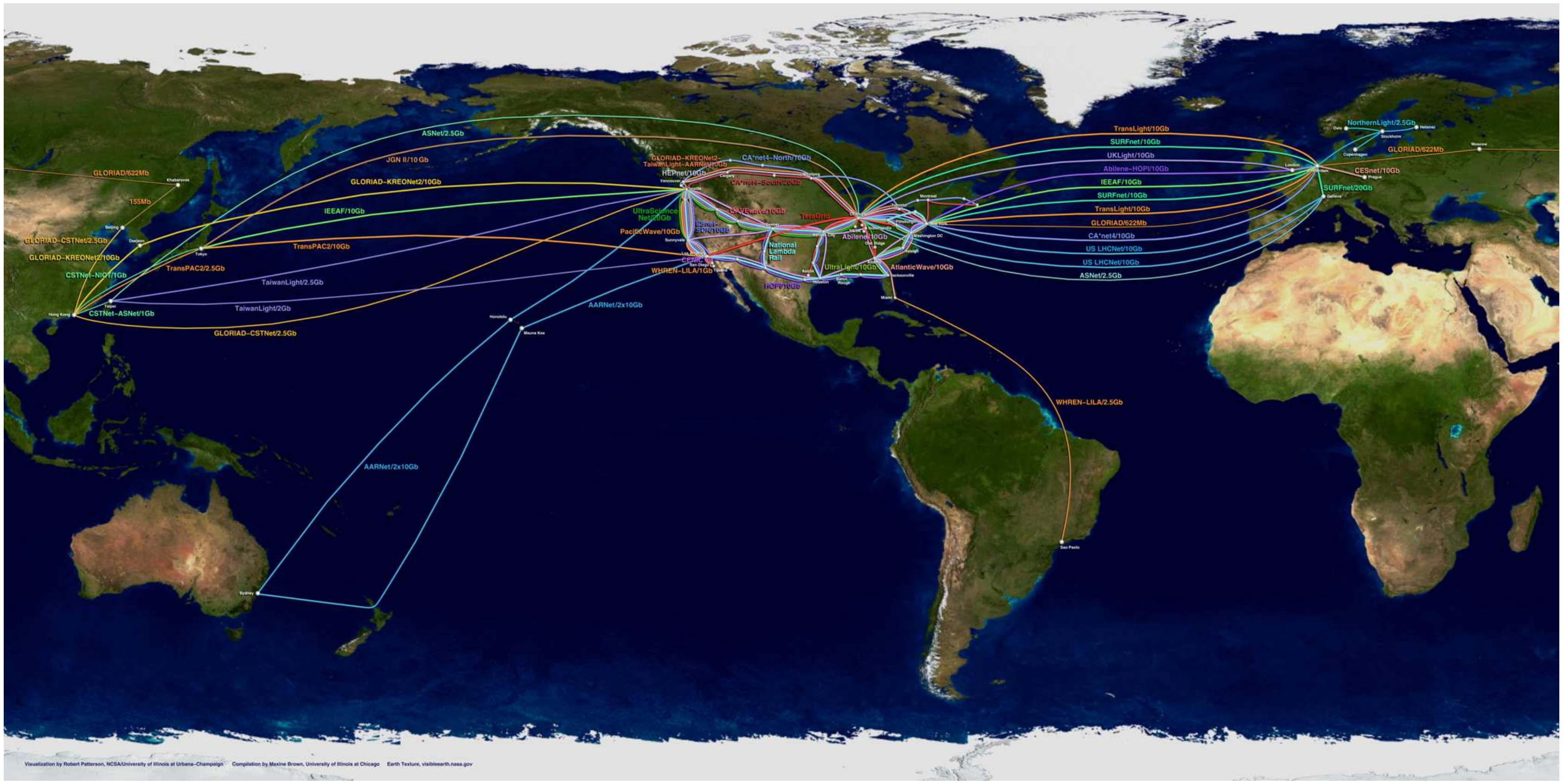
Cosmological Constants

- The dark energy is observed to be ~ 75% of the closure density of the Universe.
- But we have measured the W and Z mass, so we "know" that there is a vacuum Higgs field,

$$<\phi>=246\,GeV, M_W = g_W <\phi>$$ - Landau-Ginzberg

- If so, there is a cosmological mass density ~ $<\phi>^4$ This is ~ 10^{52} larger than the observed dark energy density!
- What is going on? Is the Higgs field gravitationally inert? Try to study the Higgs mass and couplings (especially self couplings).

What do we do with the Data?



A worldwide computing grid is being set up to exploit computing resource around the Earth.

A Hierarchical Computing Model

T0 at CERN, T1 at Fermilab as US CMS national center,

T2 at UCSD, Caltech, UFlorida, Wisconsin, MIT, Nebraska and Purdue as regional US CMS centers. (+ Brazil + China)

A National LHC Physics Center

The LHC Physics Center

LPC-at-Work

LPC Pictures

USCMS

iCMS site

cms eye cam

Remote Operations Center

The LHC Physics Center (LPC) at FNAL was created so the USCMS community can provide the maximum possible service to the CMS experiment. Our goal is to ensure that those physicists who must reside inside the United States can still contribute optimally to the many tasks required for the CMS experiment to produce physics and be full members of the CMS team. The components of the LPC are:

- a "brick and mortar" location for CMS physicists to find experts on all aspects of data analysis, particle ID, software, and event processing within the US, working during hours convenient for U.S.-based physicists
- a center of physics excellence within the US for LHC physics
- a place for workshops/conferences/gatherings on LHC physics
- a place for the training of graduate and postgraduate scientists.
- a center for the development of software and physics analysis in the US
- a "remote operations center" that CMS physicists can use to participate in data taking and quality control for the CMS experiment in the U.S.
- a tool to help provide a graceful transition between the Tevatron and LHC experiments for those physicists participating in both, maximizing the manpower available to each during the transition time.

The center is run by Avi Yagil (FNAL) and Sarah Eno (UMD) and is located on the 11th floor of the FNAL hi-rise. **For more information, choose one of the links on the side.**

Time left until Nov. 1, 2007: 274 days 13h 14m 06s

Remote Operations of US CMS

The LHC is a discovery machine so we must be ready on "day one". Practice data transfer and data quality monitoring and remote data analysis.

What will we find at the LHC?

- There is a single fundamental Higgs scalar field. This appears to be incomplete and unsatisfying.

- Another layer of the “cosmic onion” is uncovered. Quarks and/or leptons are composites of some new point like entity. This is historically plausible – atoms → nuclei → nucleons → quarks.

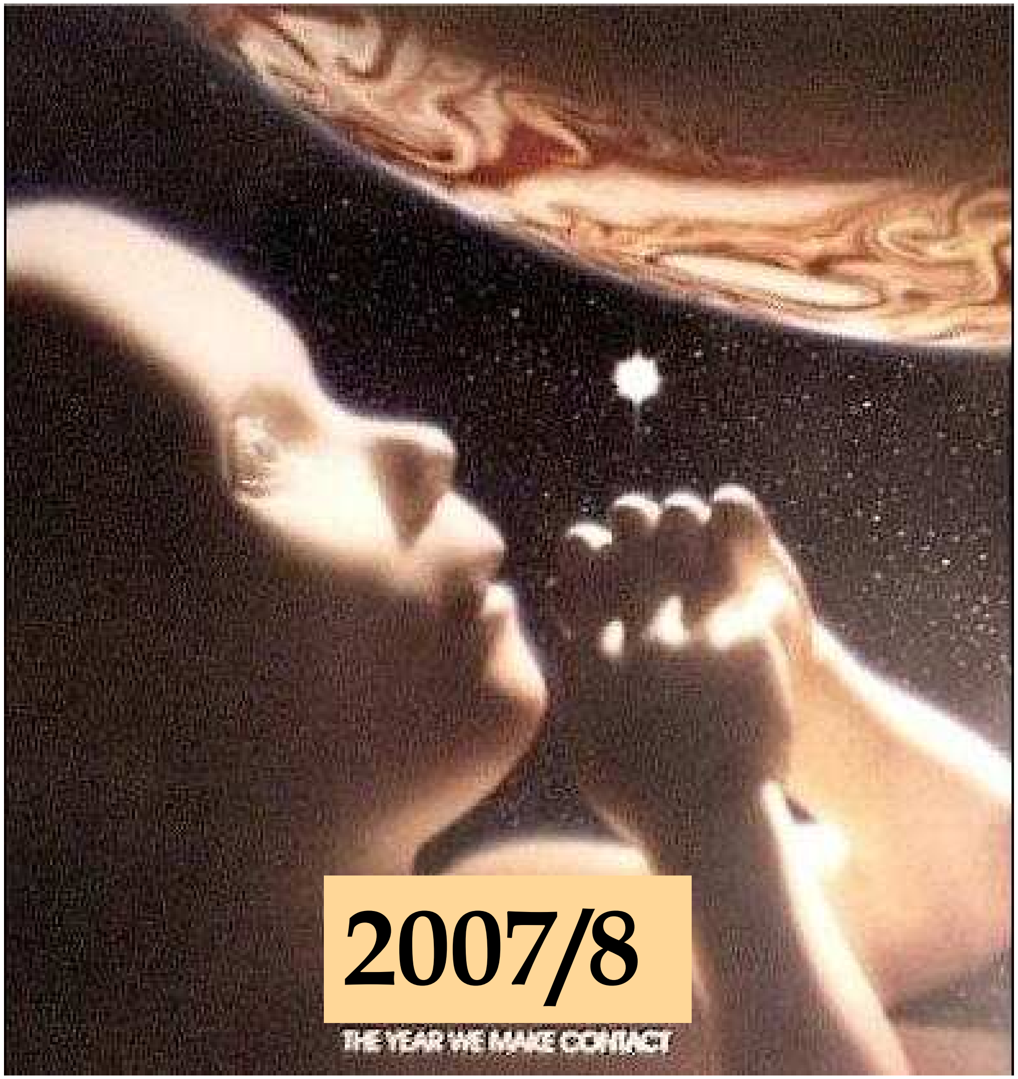
- There is a deep connection between Lorentz generators and spin generators. Each known SM particle has a “super partner” differing by ½ unit in spin. An extended set of Higgs particles exists and a whole new “SUSY” spectroscopy exists for us to explore.

- The weak interactions become strong. Resonances appear in WW and WZ scattering as in $\pi + \pi \rightarrow \rho$. A new force manifests itself, leading to a new spectroscopy.

- There are extra dimensions at the ~ 1 TeV mass scale, so there is no hierarchy problem. Gravity is weak because it exists in the complete space-time geometry, while SM forces are only in 4 - d.

- “There are more things in heaven and earth than are dreamt of”

One Year to First Beam

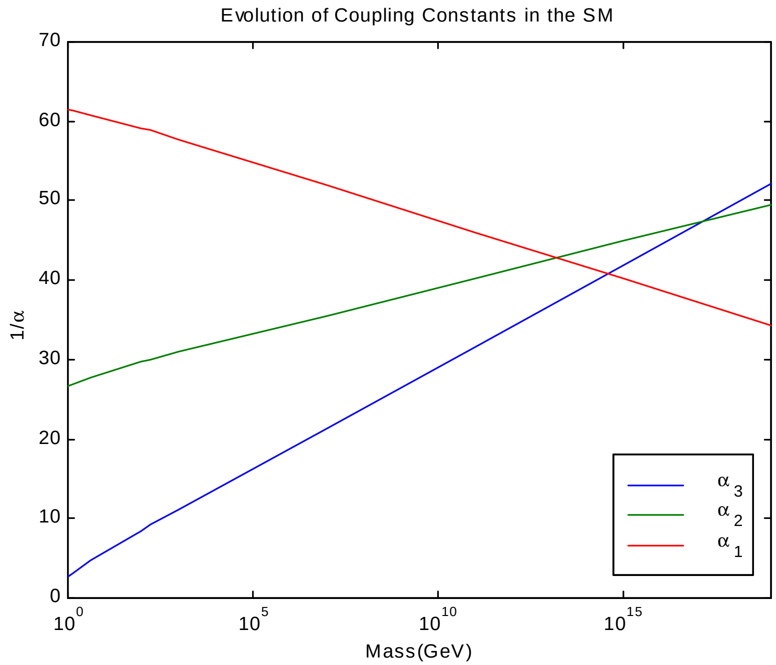


A Few Unresolved Fundamental Questions in HEP

- How do the Z and W acquire mass and not the photon?
- What is M_H and how do we measure it?
- Why are the known mass scales so different? $\Lambda_{QCD} \sim 0.2$ GeV << EW $\langle\phi\rangle \sim 246$ GeV << $M_{GUT} \sim 10^{16}$ GeV << $M_{PL} \sim 10^{19}$ GeV
- Why is charge quantized?
- Why is matter (protons) ~ stable?
- Why is the Universe made of matter?
- What is "dark matter" made of? Dark energy?
- Why is the cosmological constant small?
- How does gravity fit in with the strong, electromagnetic and weak forces? Are there extra dimensions in the Universe, as yet unobserved?

Grand Unified Theories

- Perhaps the strong and electroweak forces are related. In that case leptons and quarks would make transitions and p would be unstable. The unification mass scale of a GUT must be large enough so that the decay rate for p is < the rate limit set by experiment.
- The coupling constants "run" in quantum field theories due to vacuum fluctuations. For example, in EM the e charge is shielded by virtual γ fluctuations into e^+e^- pairs on a distance scale set by, $\bar{\lambda}_e \sim 1/m_e$. Thus α increases as M increases (logarithmically), $\alpha(0) = 1/137$, $\alpha(M_Z) = 1/128$.



Assume no new Physics. "Run" the coupling "constants" to a high mass. Observe approximate unification of the forces.

Why is Matter (protons) ~ Stable?

- There is no gauge motivated conservation law making protons stable.
- Indeed, SU(5) relates quarks and leptons and possesses "leptoquarks" with masses ~ the GUT mass scale.
- Thus we expect protons (uud) to decay via uu --> $e^+ + \bar{d}$, ud --> $\bar{d}\nu$. Thus p --> $e^+ \pi^o$ or $\nu\pi^+$
- Looking at the GUT extrapolation, we find $1/\alpha$ ~ 40 at a GUT mass of ~ 10^{14} GeV.
- One dimensional grounds, the proton lifetime should be, $\Gamma_p = 1/\tau_p \sim \alpha_{GUT}^2 (M_p/M_{GUT})^4 M_p$ or $\tau_p \sim 4 \times 10^{31}$ yr (propagator).
- The current experimental limit is 10^{32} yr. The limit is in disagreement with a careful estimate of the p decay lifetime in simple SU(5) GUT models. Thus we need to look a bit harder at the grand unification scheme.

Why is Charge Quantized?

- There appears to be approximate unification of the couplings at a mass scale $M_{GUT} \sim 10^{14}$ GeV.
- Then we combine quarks and leptons into GUT multiplets - the simplest possibility being SU(5).

$[d_R\ d_B\ d_G\ e\ \nu] = 3(-1/3\ ) + 1 + 0 = 0$

- Since the sum of the projections of a group generator in a group multiplet is = 0 (e.g. the angular momentum sum of m), then charge must be quantized in units of the electron charge.

$$\sum_{-\ell}^{\ell} m_\ell = 0$$

- In addition, we see that quarks must have 1/3 fractional charge because there are 3 colors of quarks - SU(3).

GUT Predicts θ_W

- **A GUT has a single gauge coupling constant. Thus, α and α_W must be related. The SU(5) prediction is that $\sin(\theta_W) = e/g = \sqrt{3/8}$. Before we had to rely on measurements – no prediction.**

- **This prediction applies at M_{GUT}**

- **Running back down to the Z mass, the prediction becomes; $\sqrt{3/8[1 - 109\,\alpha/18\pi(\ln(M_{GUT}/M_Z))]^{1/2}}$**

- **This prediction is in ~ agreement with the measurement of θ_W, but not exactly (SUSY).**

Why is the Universe Made of Matter?

- The present state of the Universe is very matter-antimatter asymmetric.
- The necessary conditions for such an asymmetry are that CP is violated, that Baryon number is not conserved, and that the Universe went through a phase out of thermal equilibrium.
- The existence of 3 generations allows for CP violation and it has been observed in decays of K and B mesons.
- The GUT has, of necessity, baryon non-conserving reactions due to lepto-quarks.
- Thus the possibility to explain the asymmetry exists in GUTs, although agreement with the data, $N_B/N_\gamma \sim 10^{-9}$, and calculation may not be plausible.

"Particle Physics" in the 20th Century

- The e^- was discovered by Thompson ~ 1900. The nucleus was discovered by Rutherford in ~ 1920. The e^+, the first antiparticle, was found in ~ 1930. The μ , indicating a second "generation", was discovered in ~ 1936.

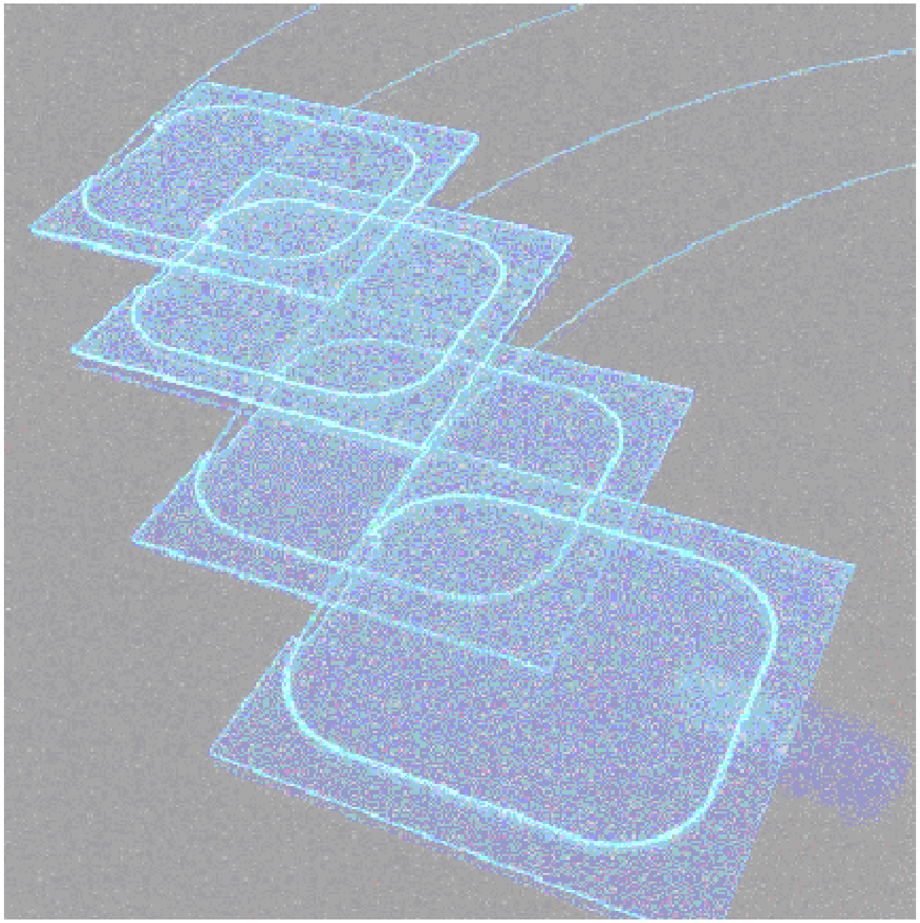
- There was an explosion of baryons and mesons discovered in the 1950s and 1960s. They were classified in a "periodic table" using the SU(3) symmetry group, whose physical realization was point like, strongly interacting, fractionally charged "quarks". Direct evidence for quarks and gluons came in the early 1970s.

- The exposition of the 3 generations of quarks and leptons is only just, 1996, completed with the top quark discovery and the observation of the neutrino associated with the tau lepton in 2002 at Fermilab. In the mid 1980s the unification of the weak and electromagnetic force was confirmed by the W and Z discoveries at CERN.

- The LHC, starting in 2007, will be THE tool to explore the origin of the breaking of the electroweak symmetry (Higgs field?) and the origin of mass itself. The Higgs boson is postulated to be responsible for the mass of all the known elementary particles.

The Hadron Calorimeter

HCAL detects jets from quarks and gluons. Neutrinos are inferred from missing Et.

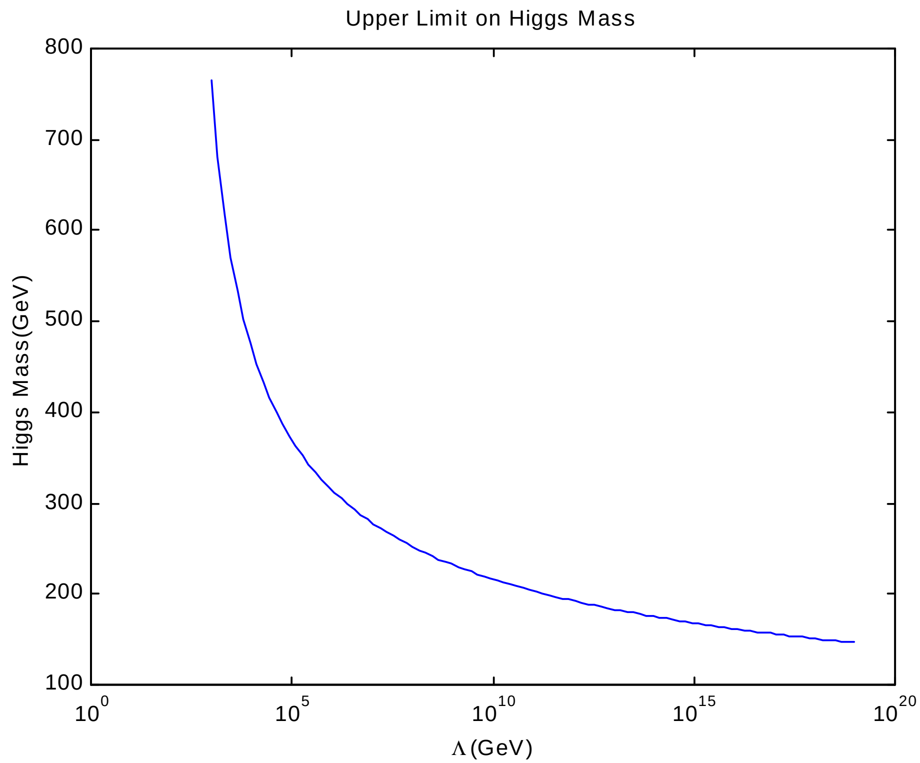


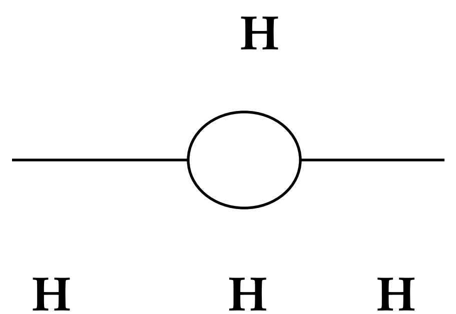
Scintillator + WLS gives "hermetic" readout for neutrinos.

Cool the light, blue -> green and thus shrink area ratio by a factor

$$e^{\hbar\Delta\omega/kT}$$

Higgs Mass - Upper Limit



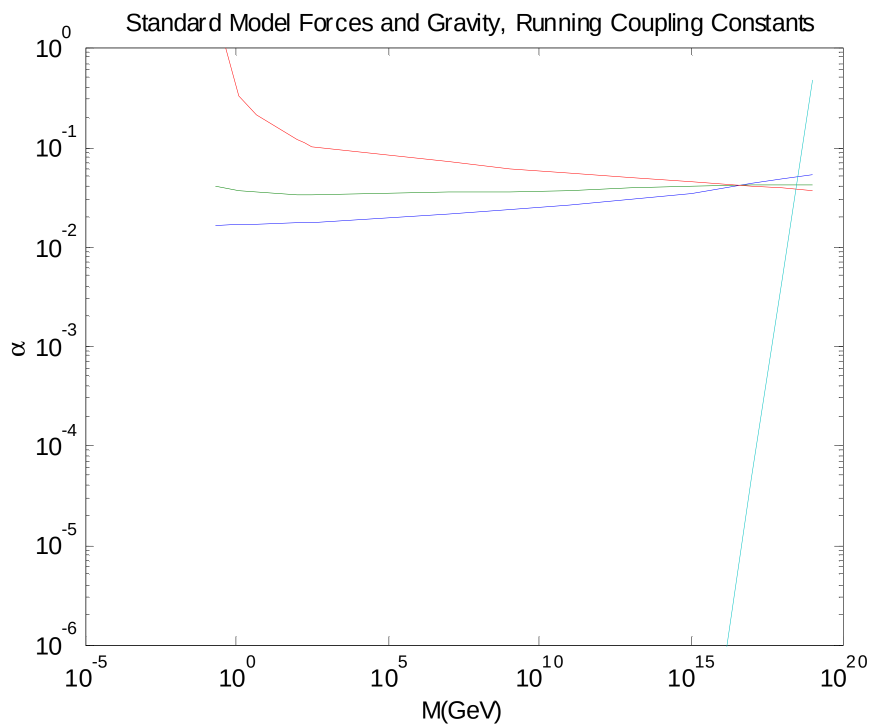


In quantum field theories the constants are altered in higher order processes (e.g. loops). Asking that the Higgs interactions be well behaved up to a high mass scale (no new Physics) implies a low mass Higgs. Is a high scale plausible?

(GUTs ?)

Gravity and SM Forces

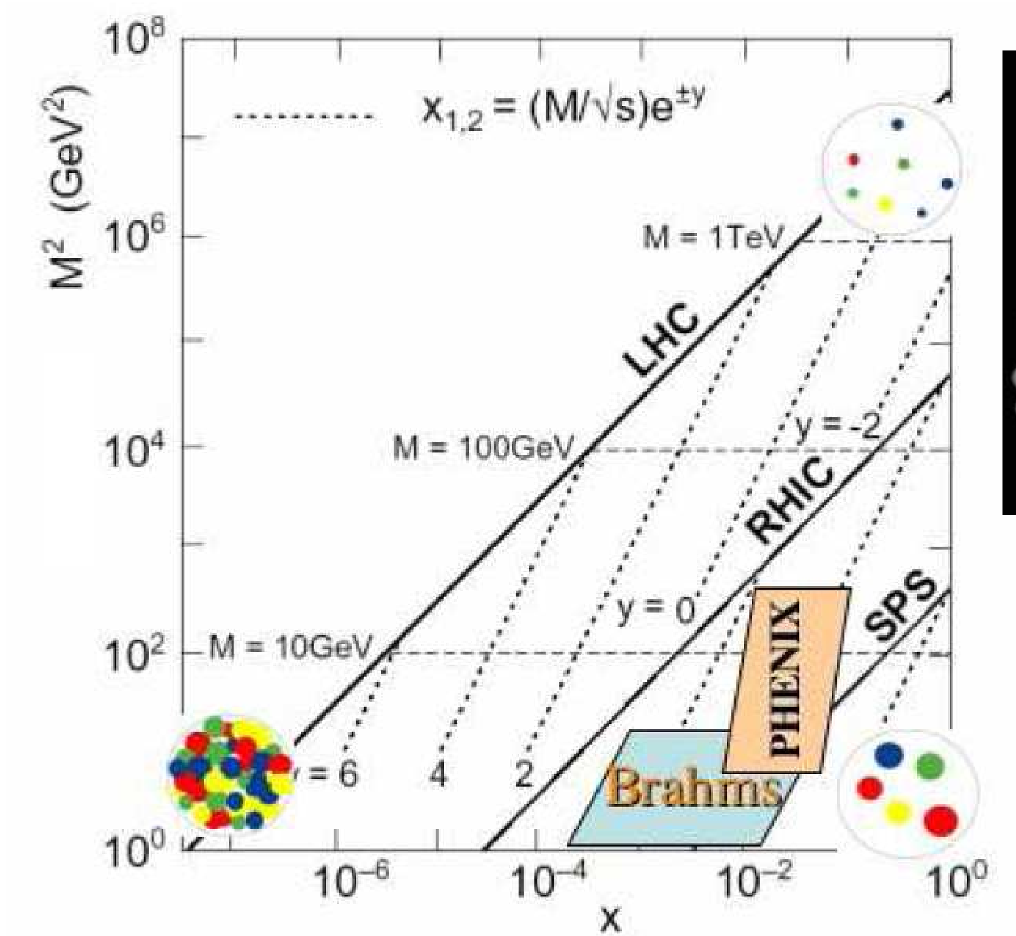
α

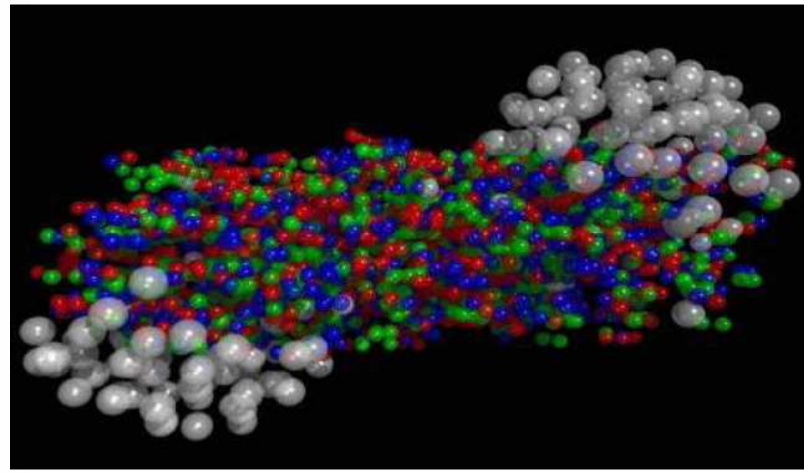


A completely naïve classical extrapolation of gravity comes close to the GUT mass scale. Is that a hint? Note that $\alpha_G \sim M^2$

We expect fundamental issues with quantum gravity as it defines the geometry of space-time. It appears that point particles are not possible, but rather strings existing in many dimensions, with those > 4 curled up or "compactified" to dimensions ~ 1/M. Gravity is very, very weak – a small magnet can overcome the whole Earth and pick up a nail. Is that because gravity spreads out thinly into additional dimensions?

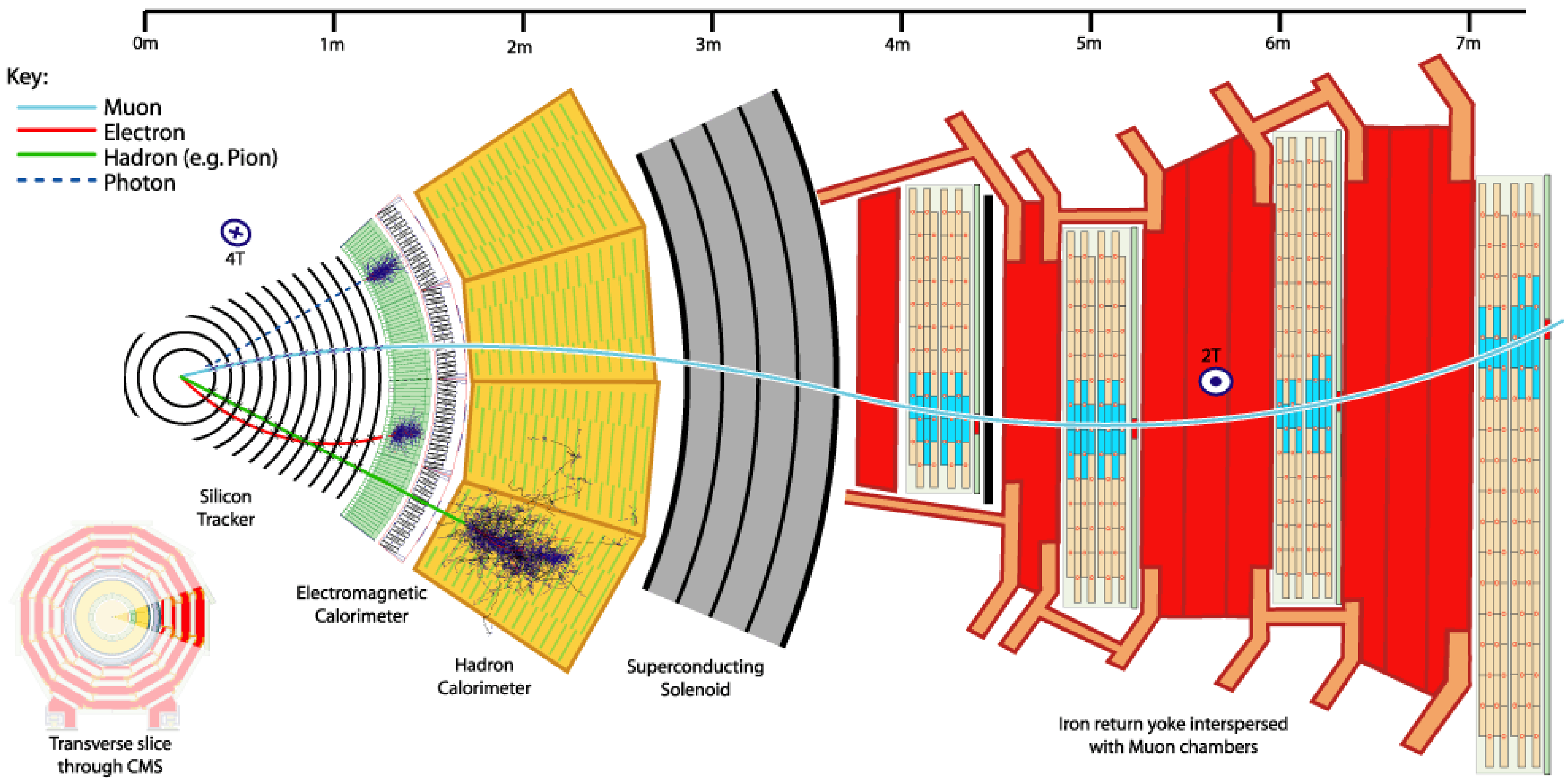
Is there a quark-gluon plasma?





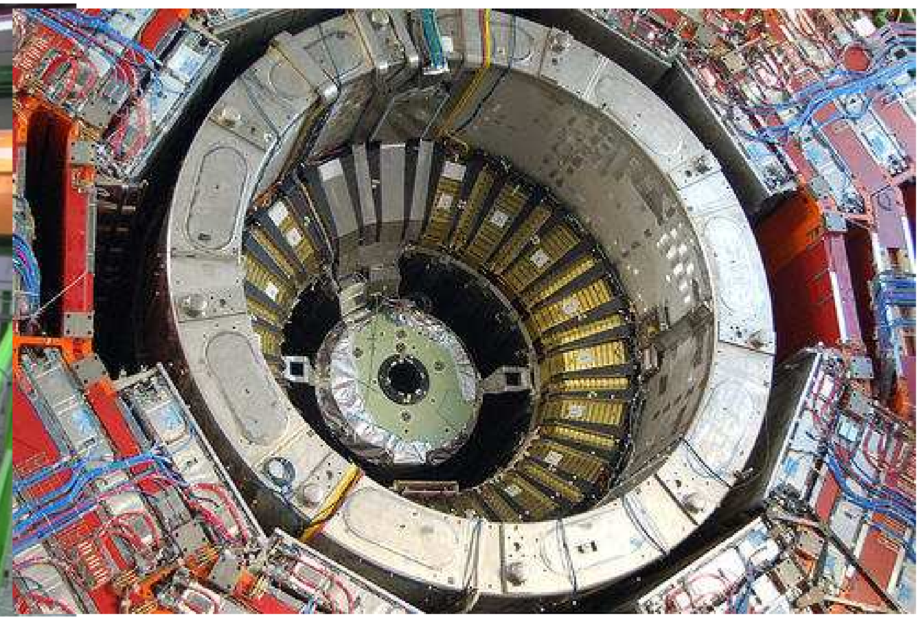
The LHC and CMS offer a ~ 35 fold increase in C.M. energy for heavy ion collisions w.r.t. RHIC. Will that allow the formation of a true plasma?

Particle ID

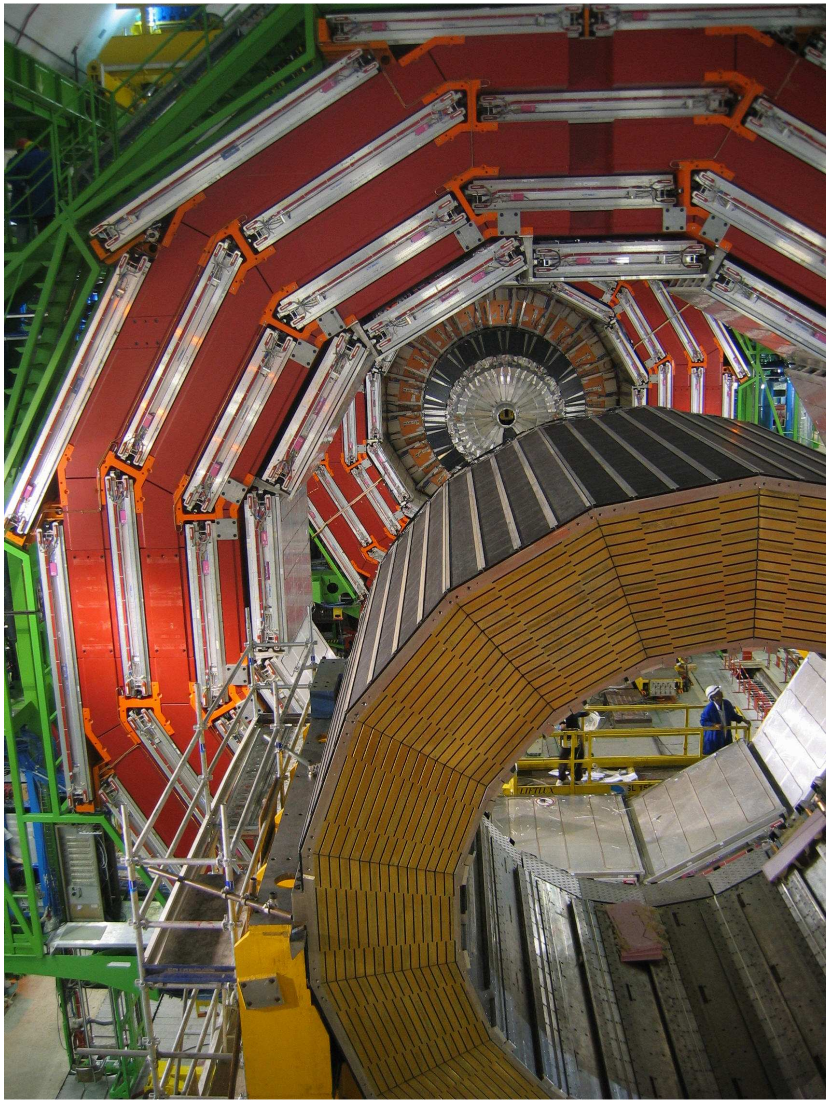


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Hadron (e.g. Pion)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS

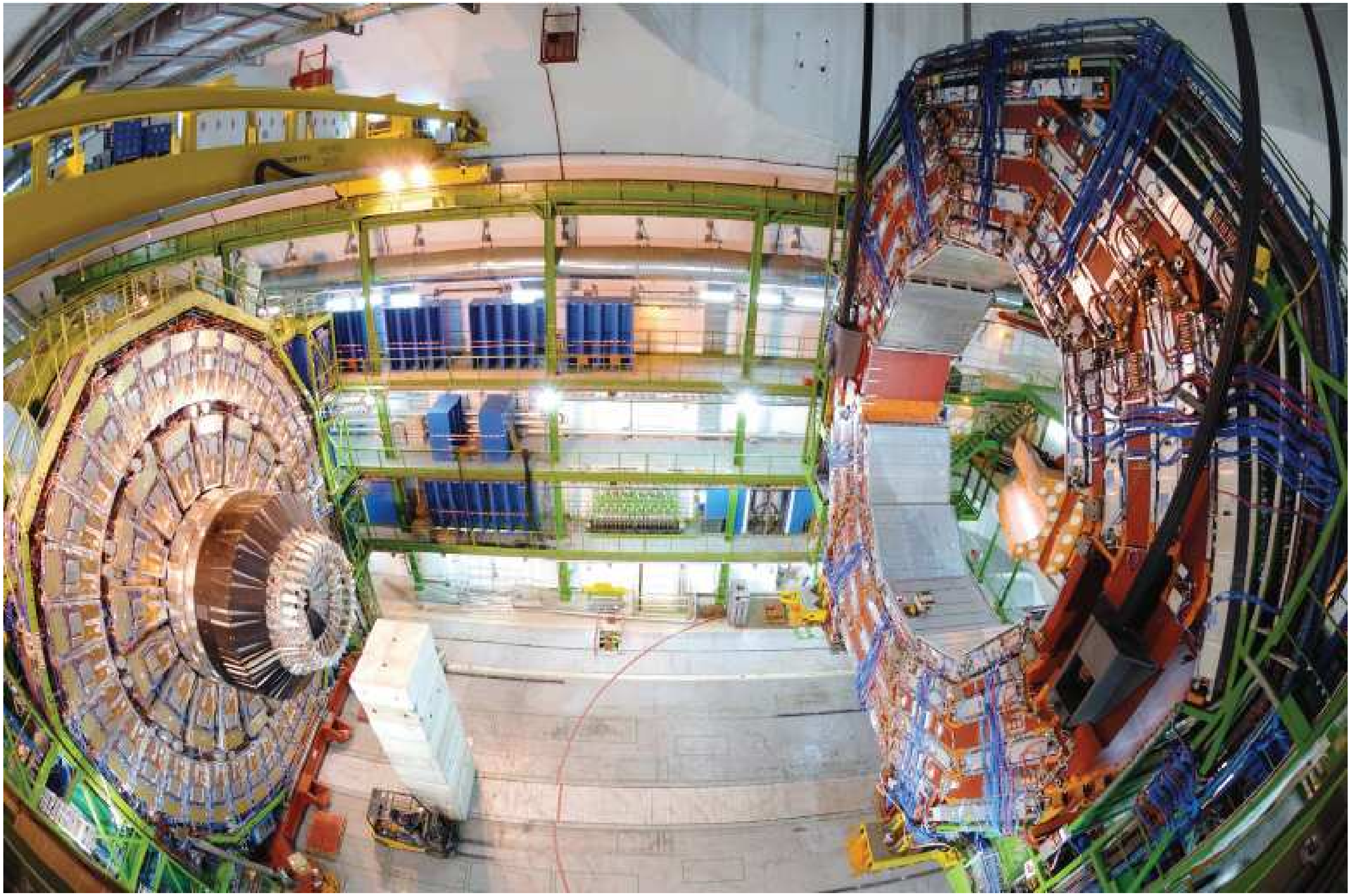
CY06 – HF Rig, MTCC



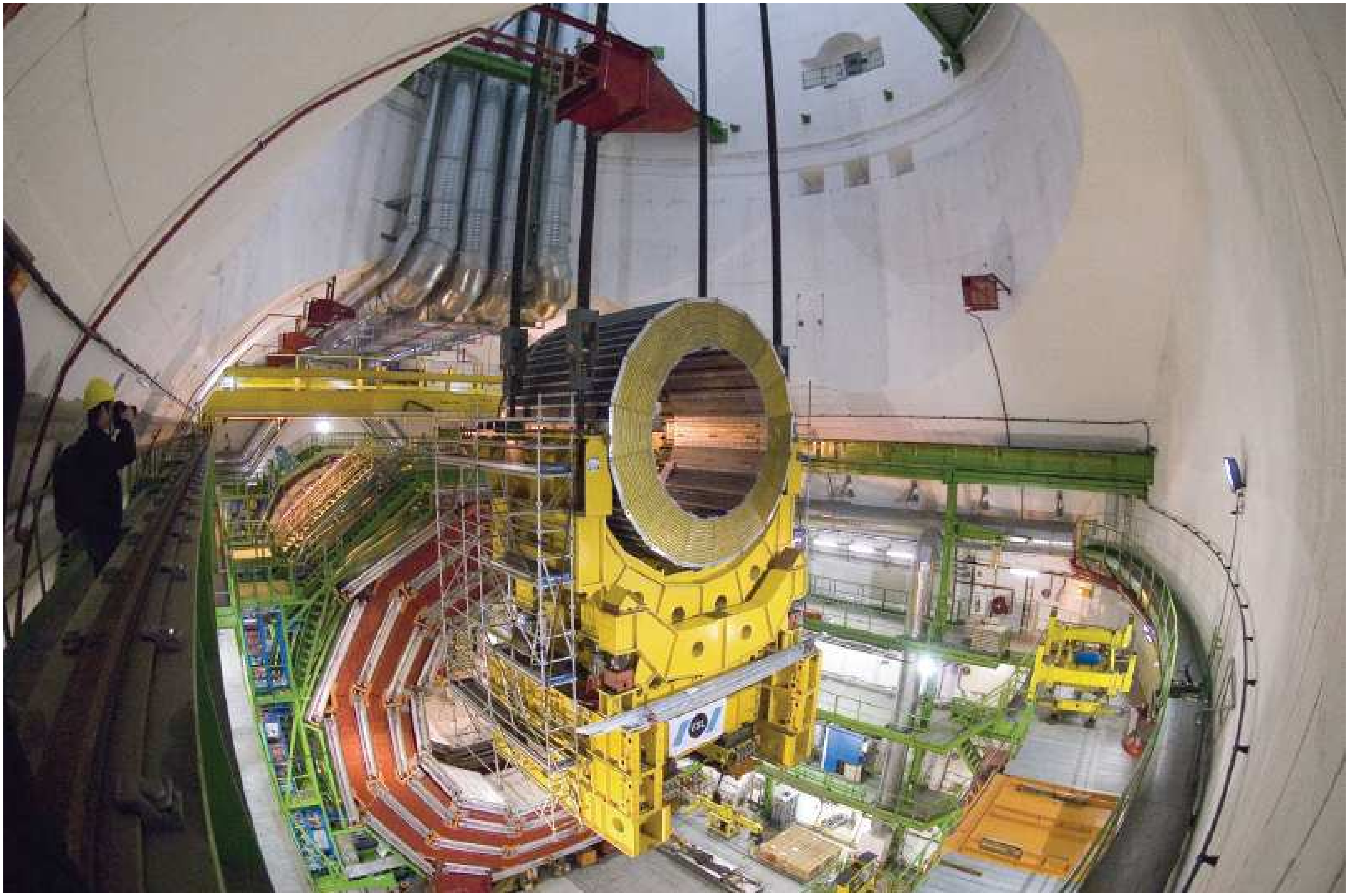
UX – The "-z" Side



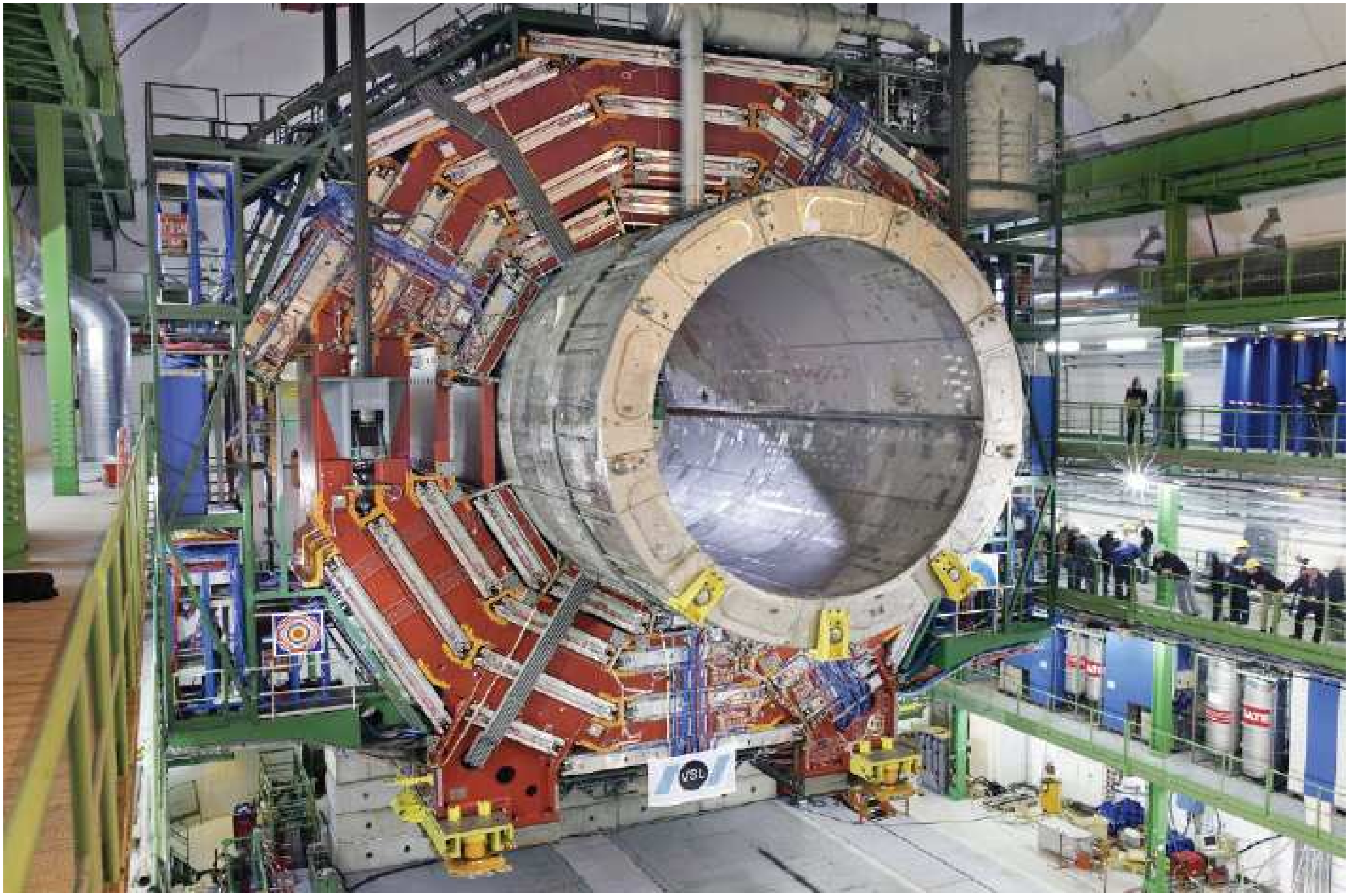
Rigging into UX



HB – Feb, 2007



YB0 – Feb 28, 2007

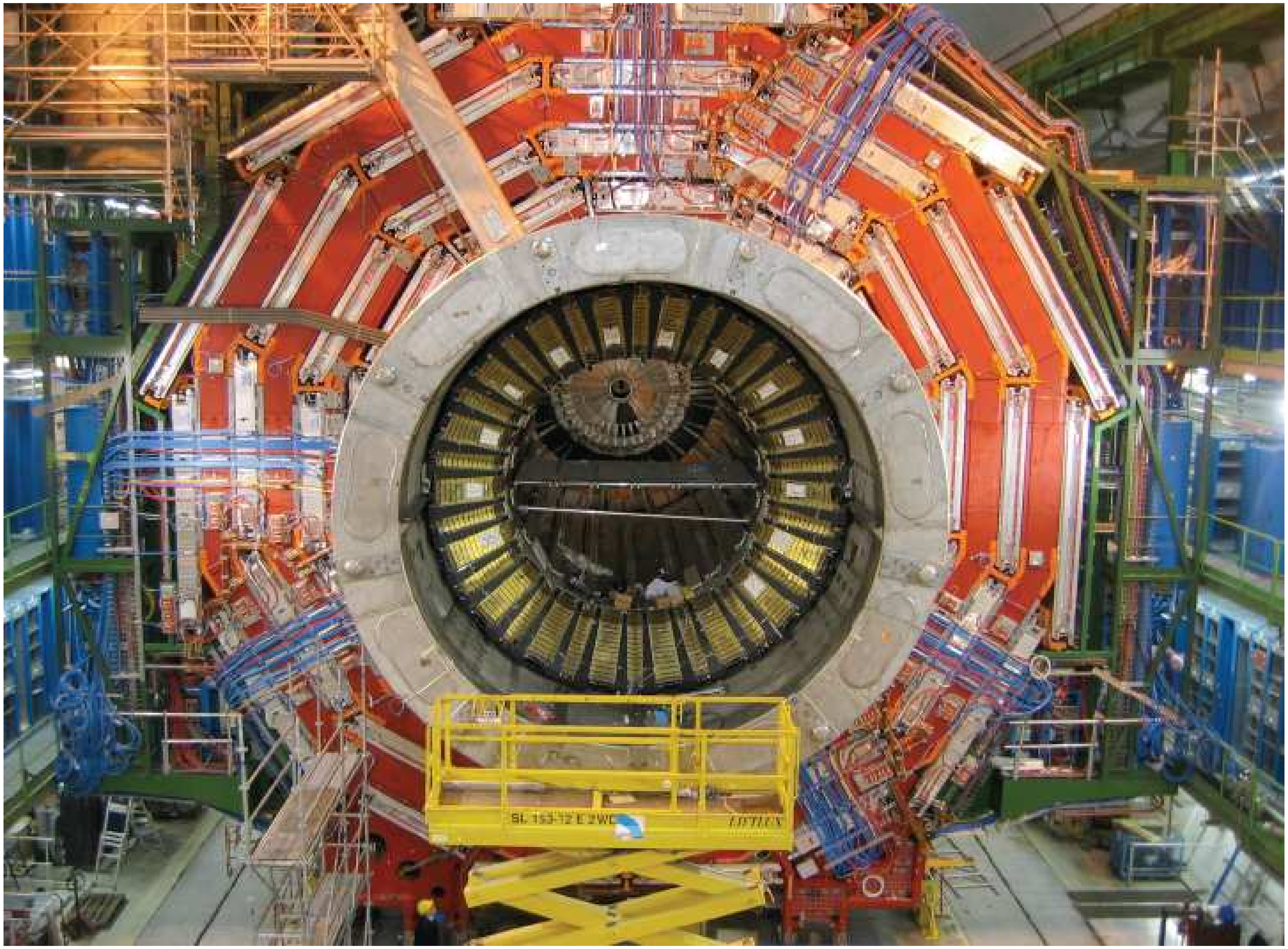


Webcam "Movies"

http://cmsinfo.cern.ch/outreach/cmseye/yb0_lowering.htm

http://cmsinfo.cern.ch/outreach/cmseye/ye1_lowering.htm

UX – April 9, 2007



Remote Operations

Standard Candles

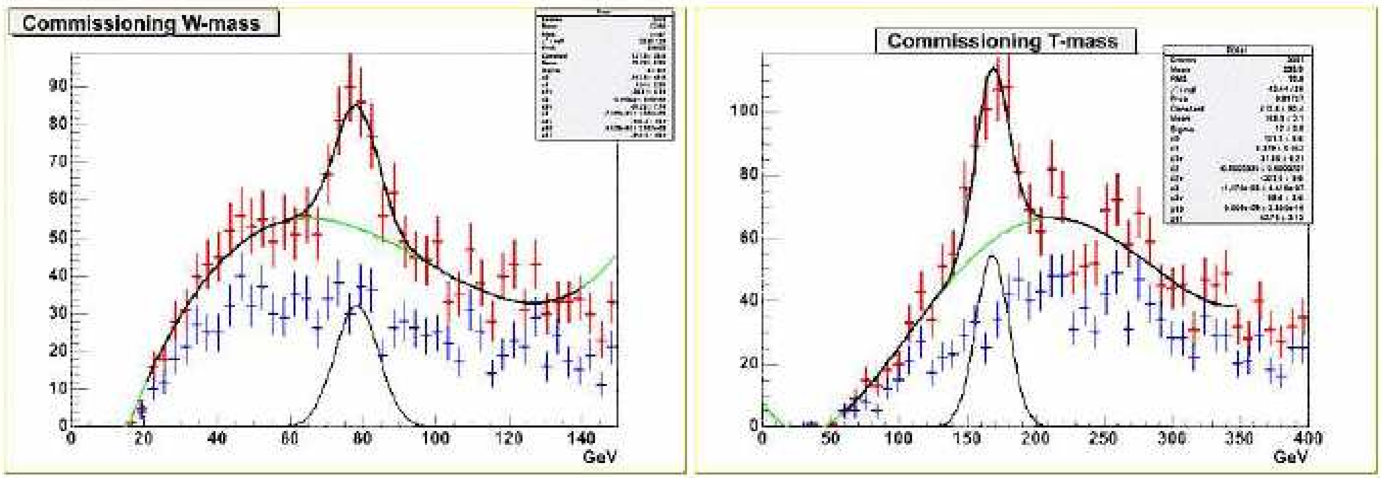
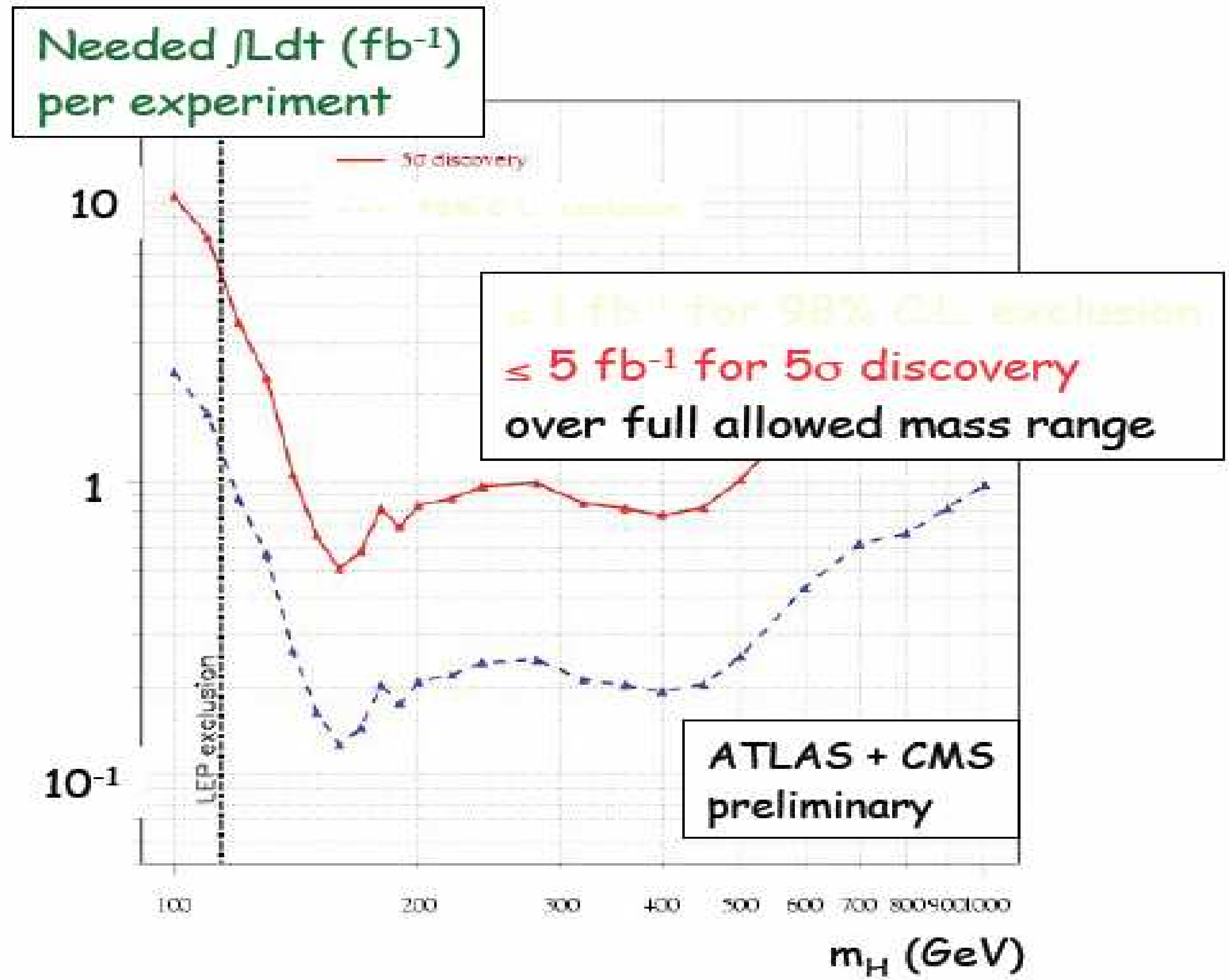


Figure 11: *Reconstructed W and top masses, without b-jet tagging, for 30 pb^{-1} of data. The background corresponds to W+4 jet events.*

Dijet, lepton (W) and dilepton (Z) and tau (Z decay) and top pairs (jets+MET+lepton + b tags) will commission CMS for Physics with a few pb^{-1}.

Early Physics Reach



Getting to the Terascale