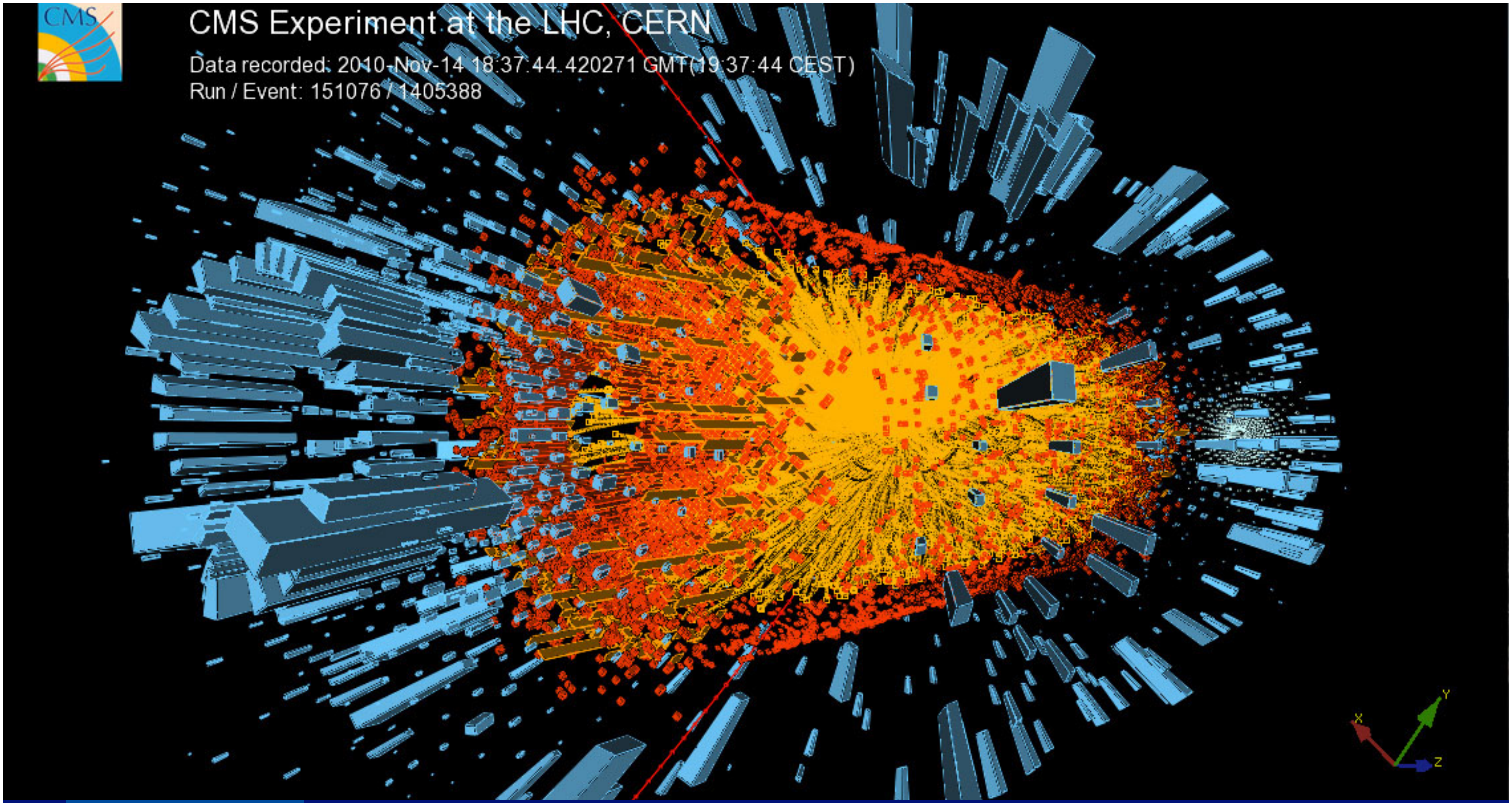


Results from the CMS experiment

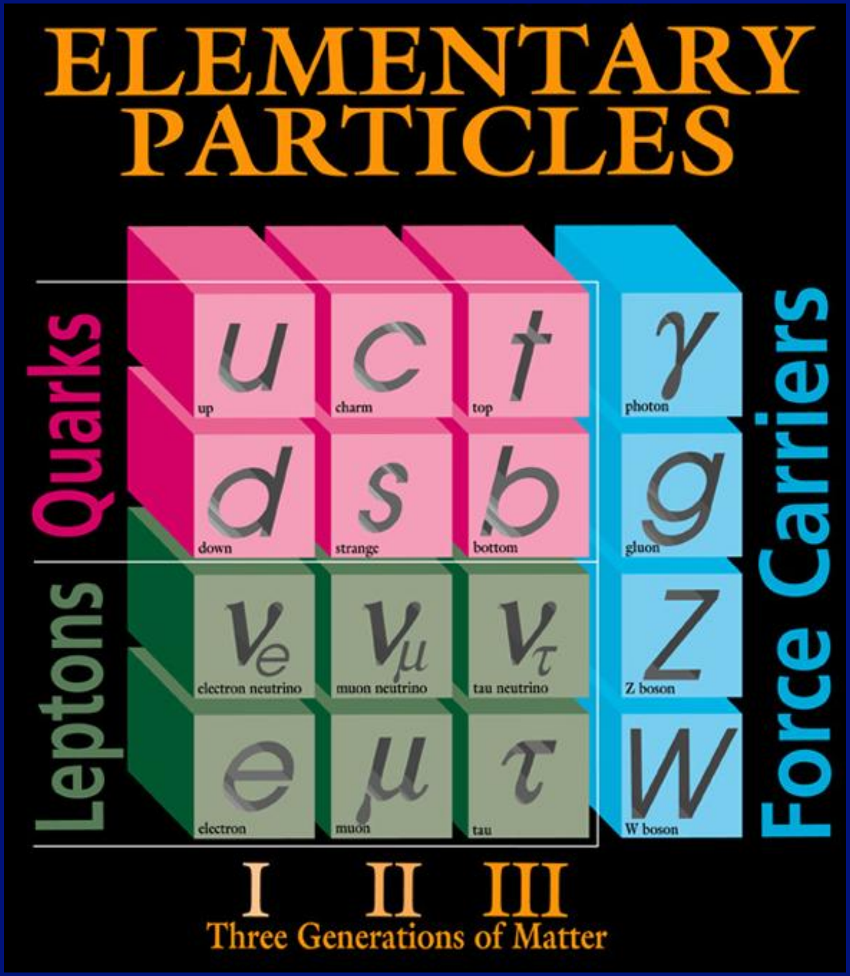
Kevin Stenson
University of Colorado
October 19, 2011

Outline

- Brief description of the Standard Model (SM)
  - How the Higgs mechanism works
- The design of the accelerator and experiments
- Results from Higgs and Supersymmetry searches
- Outlook for 2012 and beyond

What we know (we think)

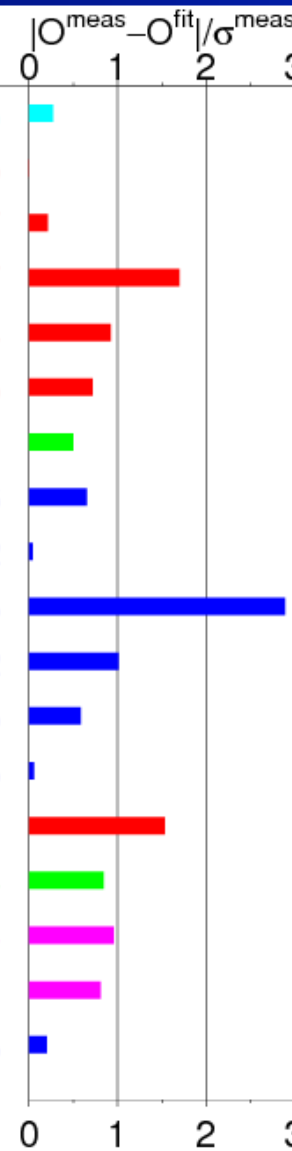
- 3 families of spin ½ quarks & leptons make up matter
- 3 types of interactions with spin 1 force carriers
  - Electromagnetism (QED) carried by massless photons; felt by charged particles
  - Massive (80-90 GeV) W and Z mediate weak force; felt by quarks & leptons
  - Strong force (QCD) carried by massless gluons; felt by quarks



Electroweak theory

- Can combine electromagnetism and weak forces into electroweak theory
- Precision measurements generally find very good agreement between data and theory

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



How to get electroweak theory

- At low energy we see E&M and weak forces
- These are unified at high energy (>1 TeV)
- The weak force contains massive force vector bosons (W^+,W^-,Z^0) but adding mass terms for W & Z to the theory does not work
- Use spontaneous symmetry breaking – the Higgs mechanism
- The Higgs mechanism solves two problems:
  - Mechanism to give W and Z bosons a mass in such a way as to avoid unitarity violation of WW (or ZZ) cross section at high energy
  - Also gives mass to quarks and charged leptons

Spontaneous Symmetry Breaking (SSB)

Solutions which do not respect a symmetry of the Lagrangian

Example 1: Ferromagnetism

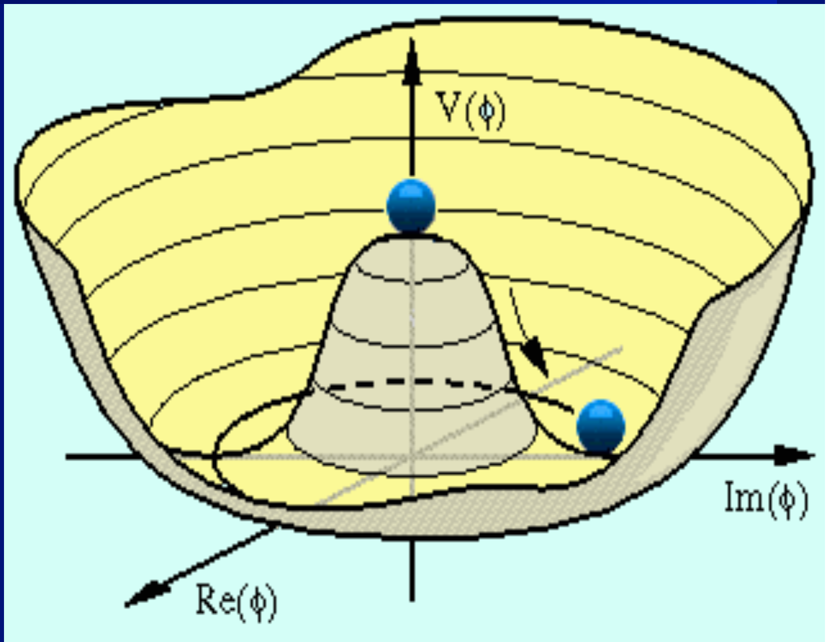
- Above T_C spins are disordered – rotational symmetry
- Below T_C spins align creating spontaneous magnetization along a preferred direction – breaking rotational symmetry

Example 2: A stick?

- An ideal stick has a force compressing its length
- Below a critical force the ideal stick remains intact with cylindrical symmetry
- Above a critical force the stick bows in a particular direction violating the cylindrical symmetry

The Higgs Mechanism

- Complex vacuum scalar field Φ with potential $V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$
- For $\mu^2<0$, minimum at non-zero energy gives vacuum expectation value (v.e.v.): $|\Phi|^2 = -\mu^2/2\lambda$
- This spontaneous symmetry breaking separates electroweak into E&M and weak and gives W and Z mass

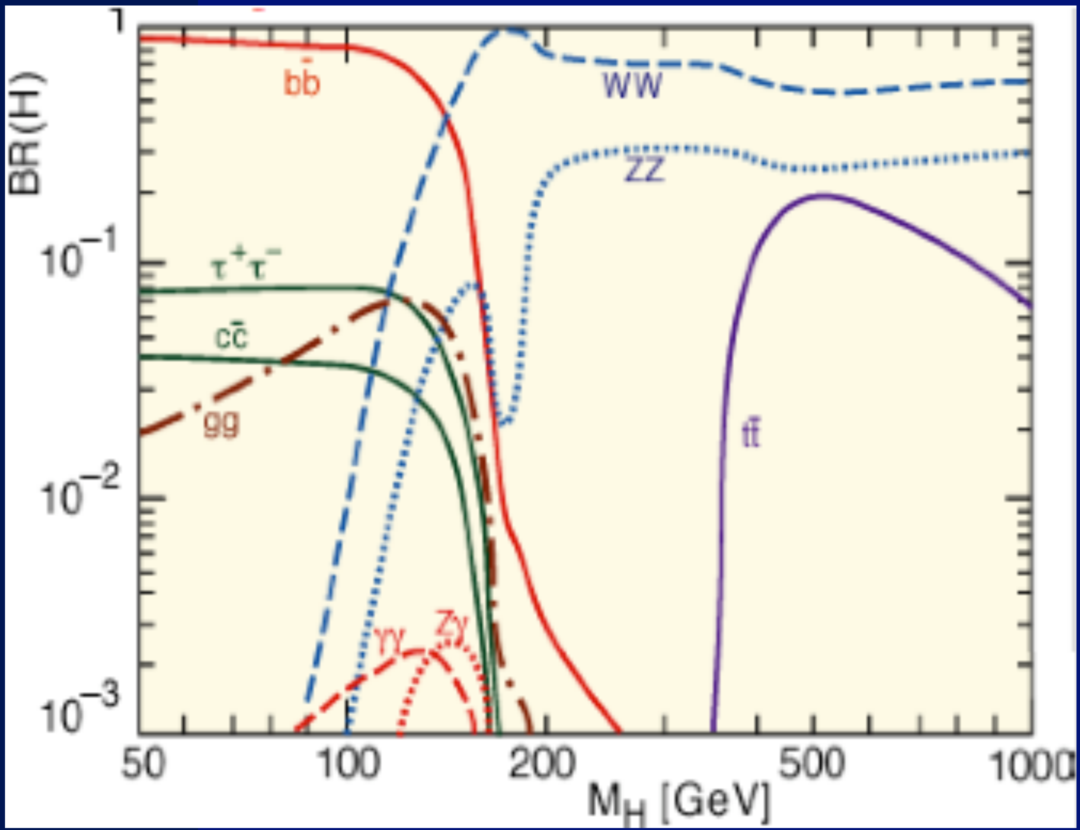


- Higgs field permeates vacuum and the coupling strength to the Higgs determines the elementary particle mass
- The Higgs field also contributes to the vacuum energy density

Standard Model Higgs Decay Modes

Decay rate depends on mass

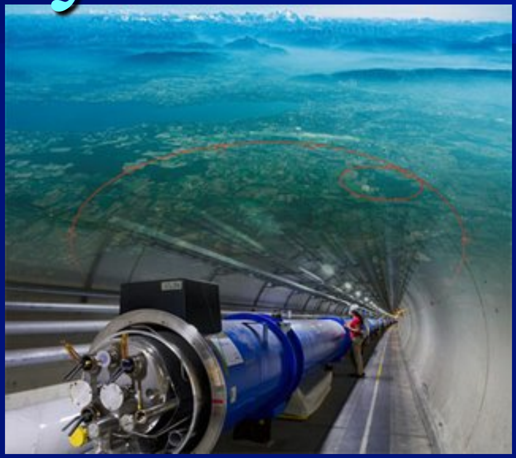
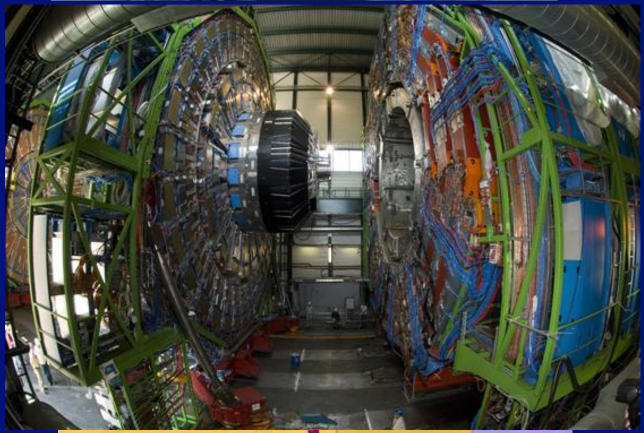
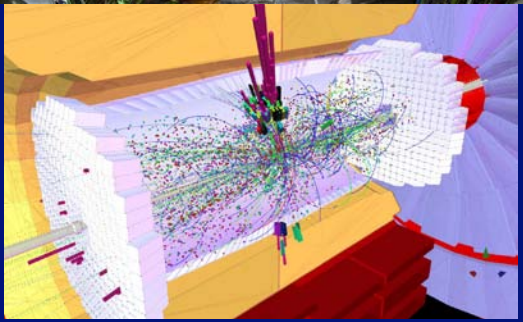
Inclusive $H \to b\bar{b}$ not possible due to QCD background



M_H range (GeV)	Best decay mode
$M_H < 130$	$H \to \gamma\gamma$
$130 < M_H < 200$	$H \to WW$
$200 < M_H < 600$	$H \to ZZ$

How do we find this physics?

- Need a high energy accelerator to produce the interesting particles
- Need detectors to record what happens when the particles decay
- Need to separate the interesting events from the background

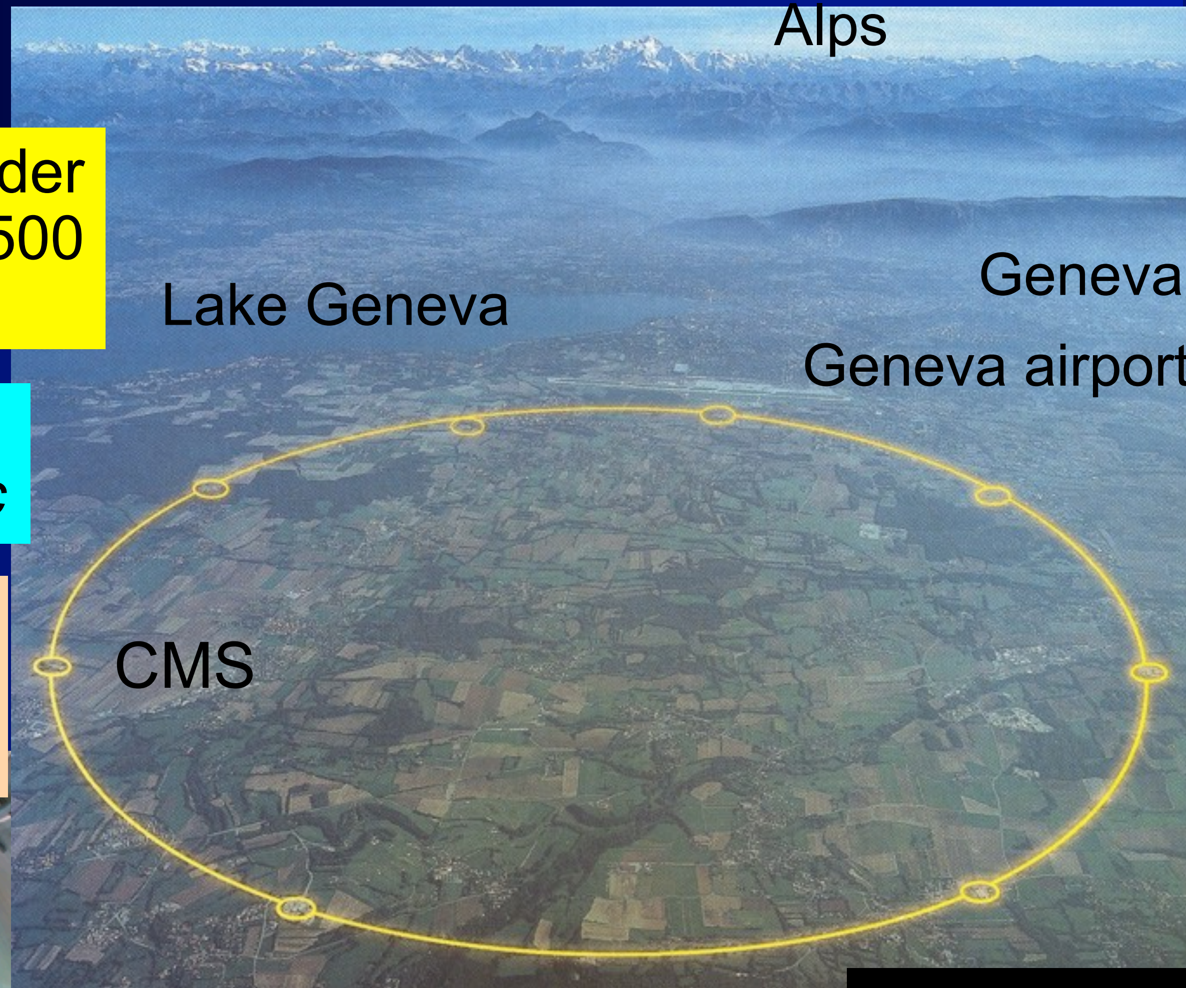




LHC

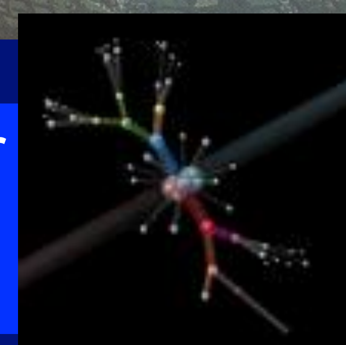
The Large Hadron Collider is 27 km long and 100-500 feet underground.

RF cavities accelerate protons to 0.99999999*c*

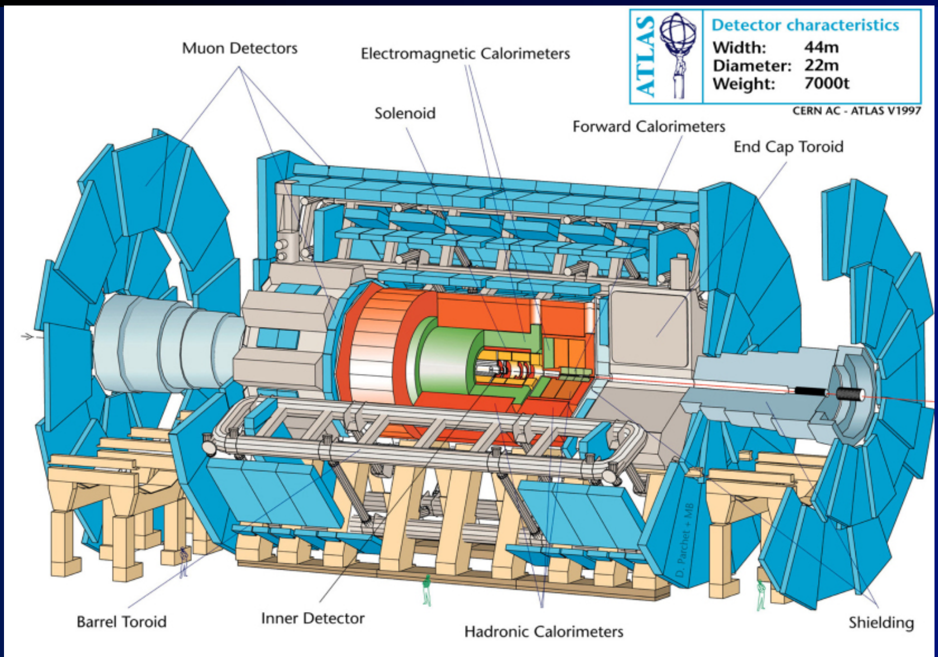
8.3 T superconducting magnets keep the protons going in circles

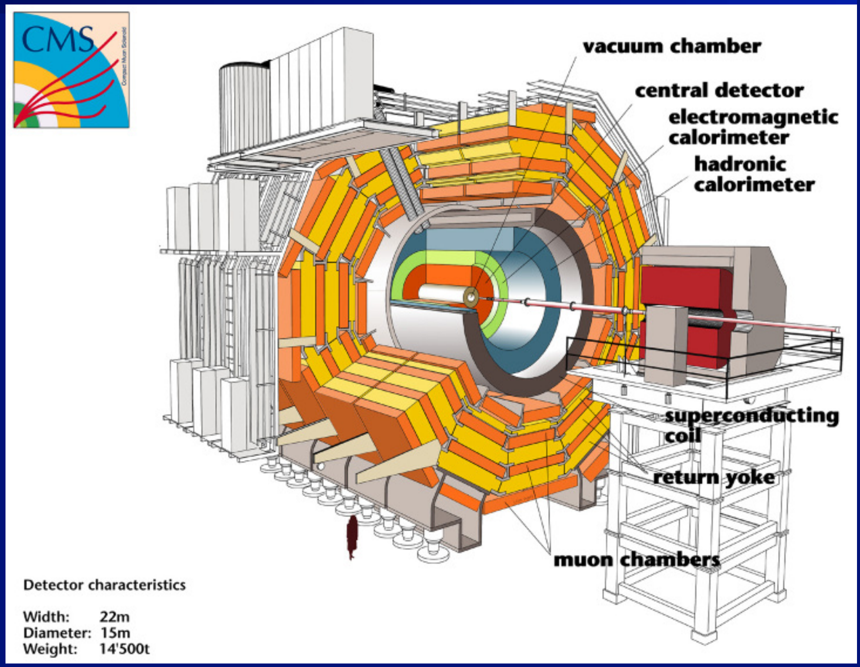


Collisions occur at four places around the ring

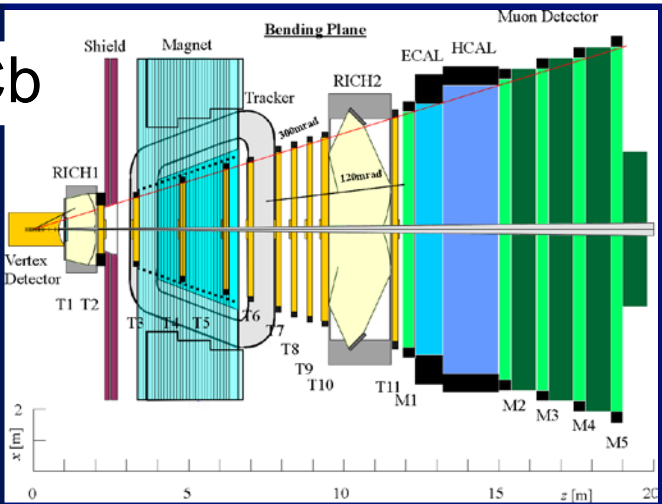


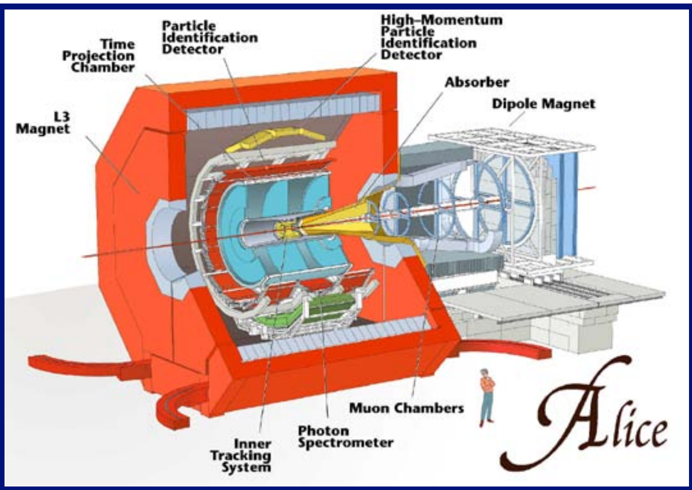
LHC Detectors to record the events





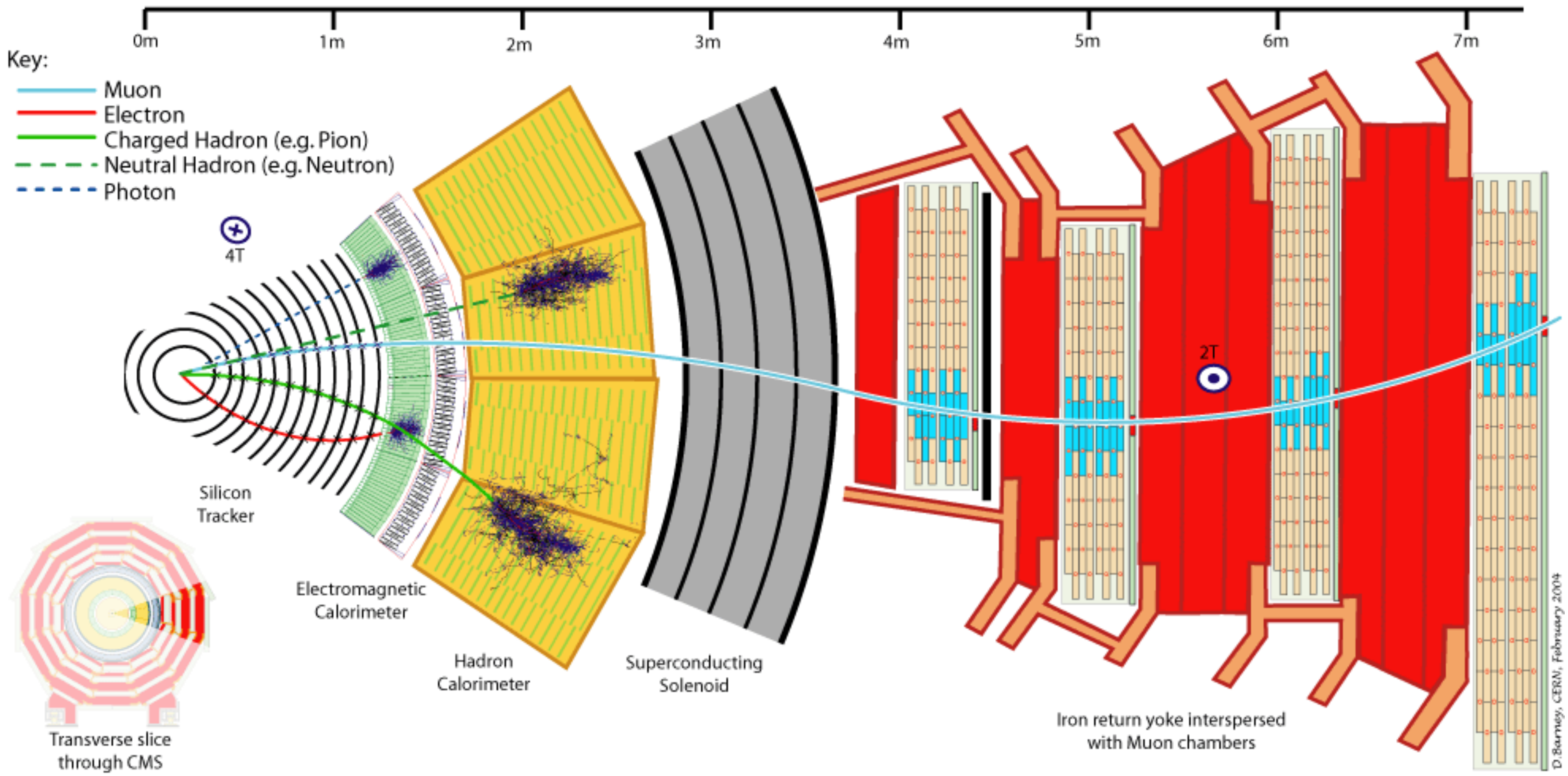
LHCb



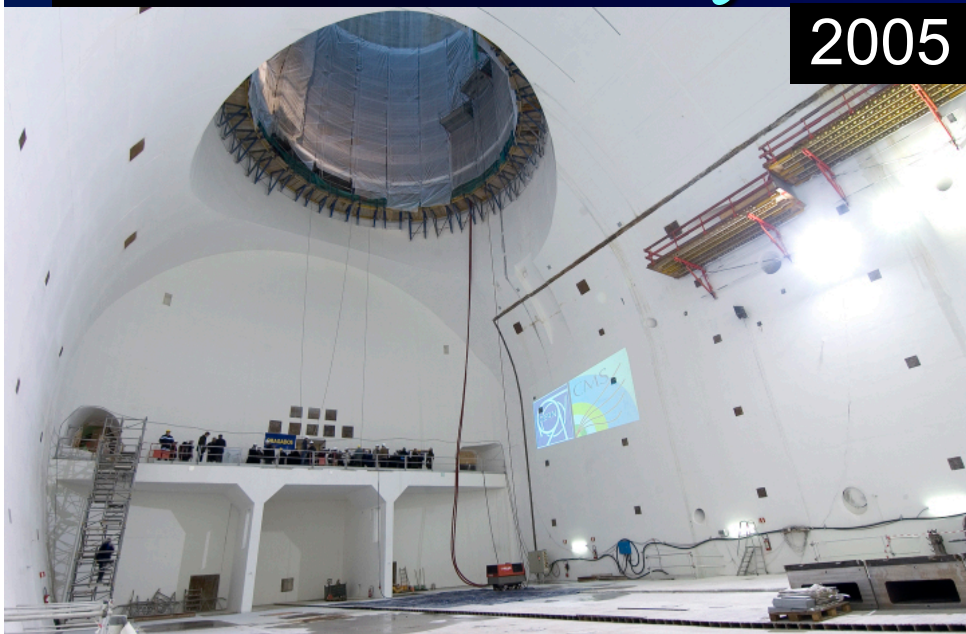


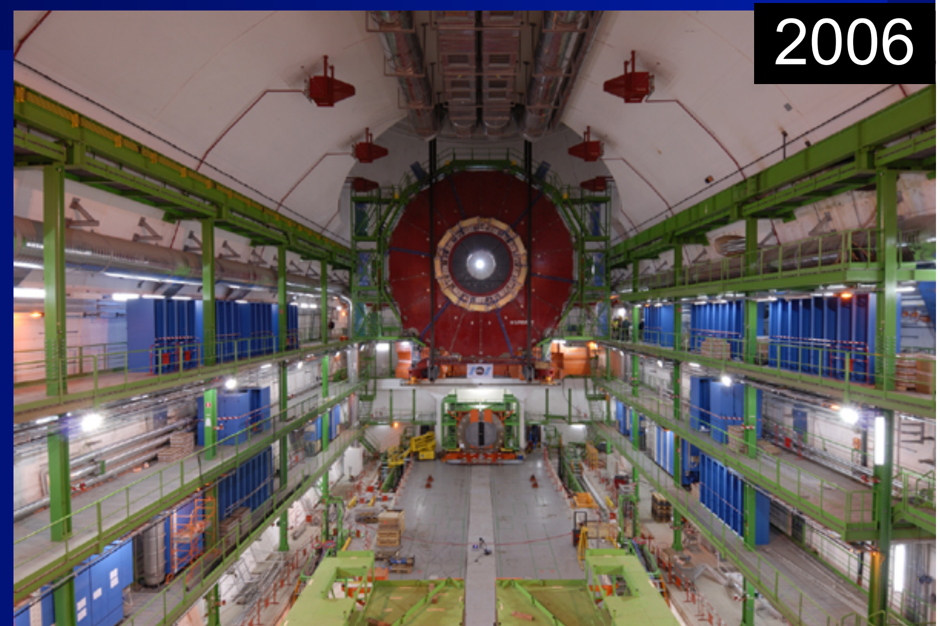
CMS Slice

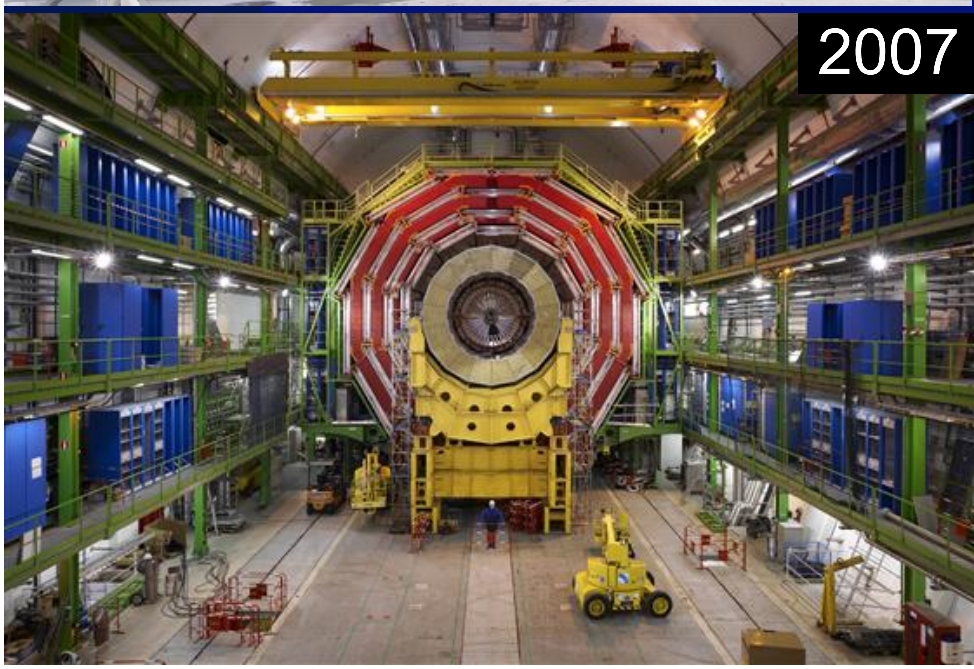
Different particles behave differently as they pass through the detector. This allows us to identify them and measure their energy.

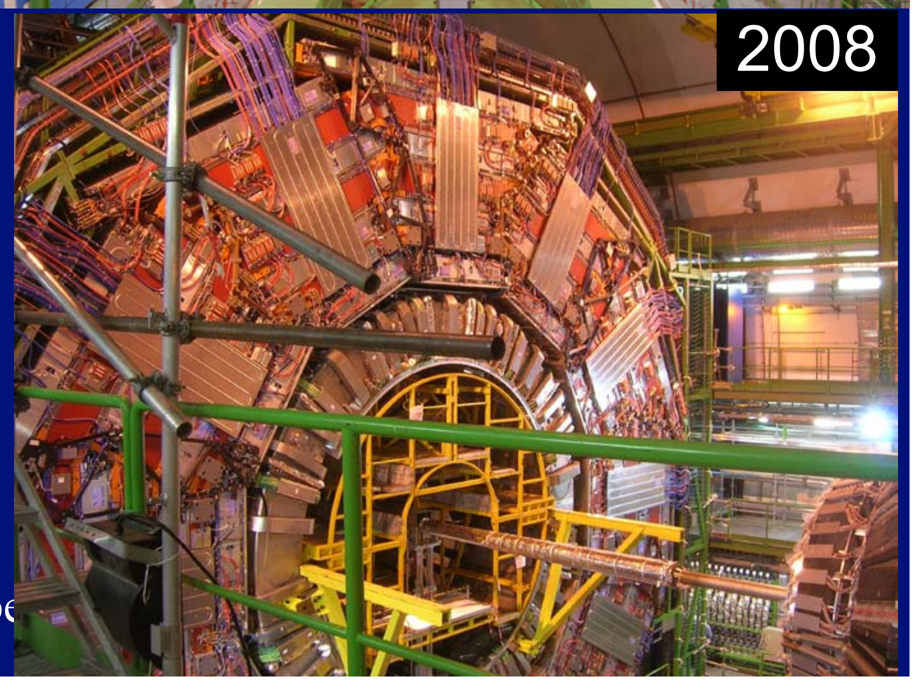


CMS assembly

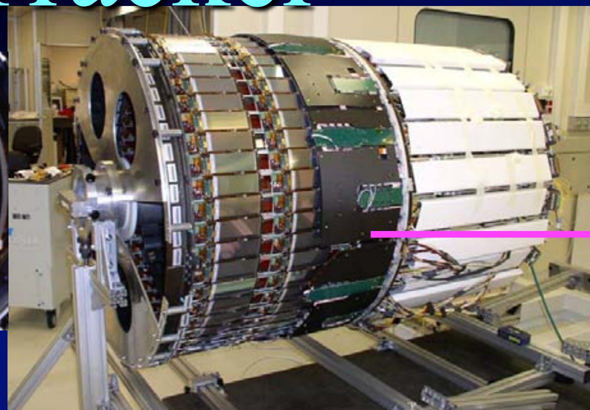




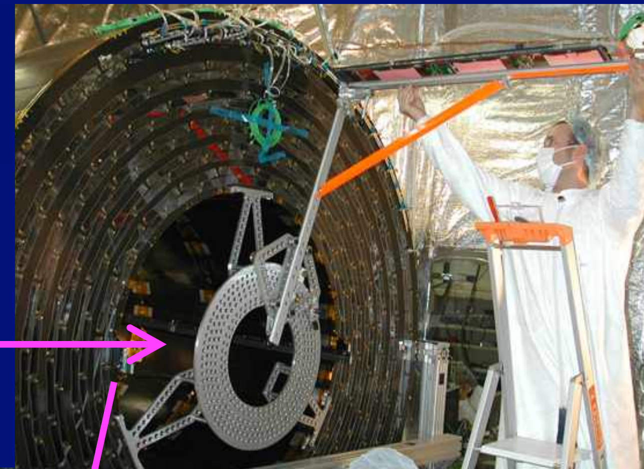




CMS Tracker

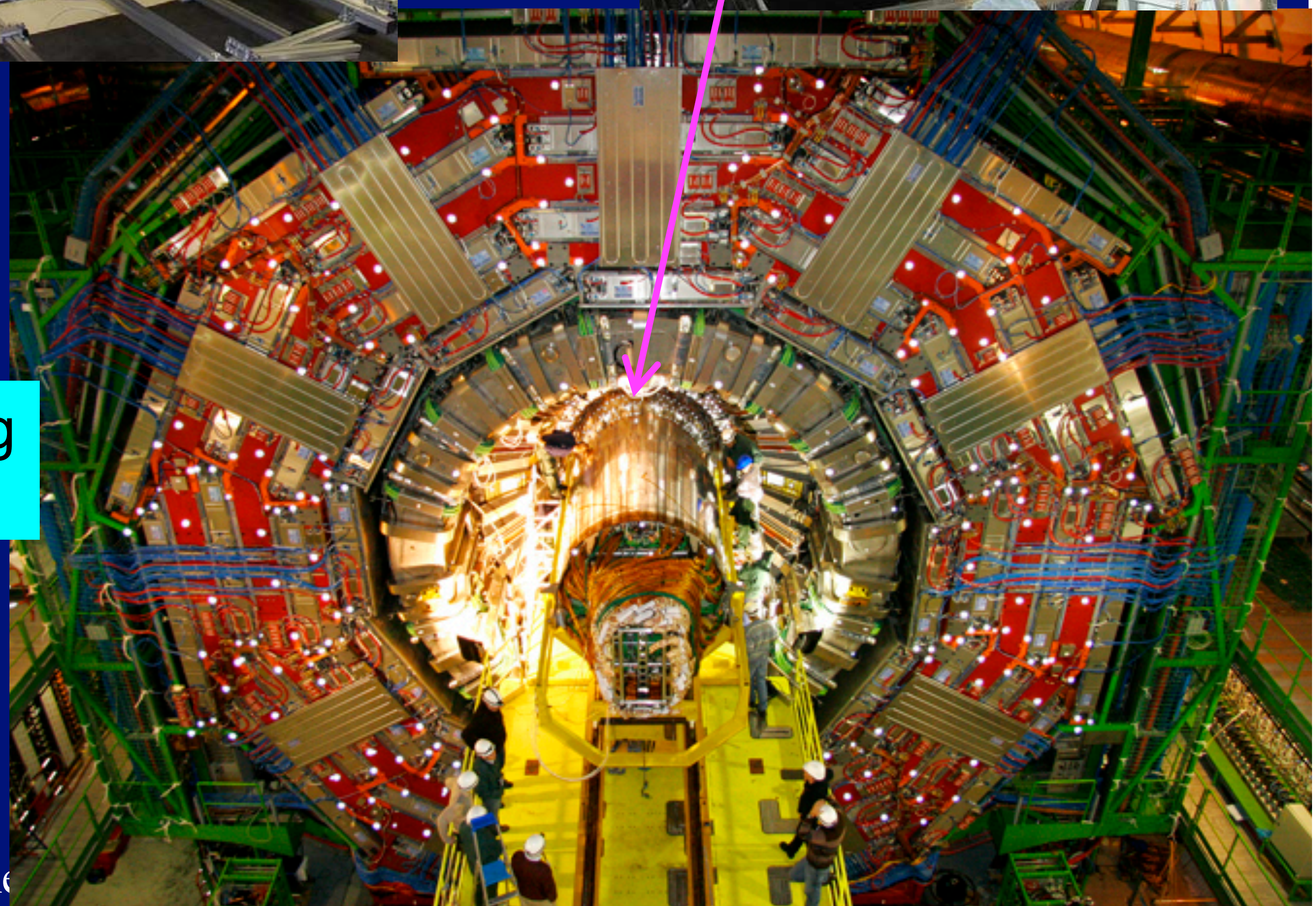


Goes inside



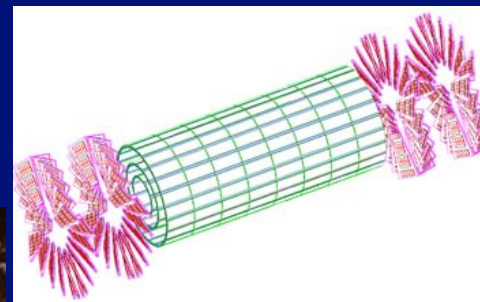
CMS tracker uses 2300 square feet of silicon detectors.

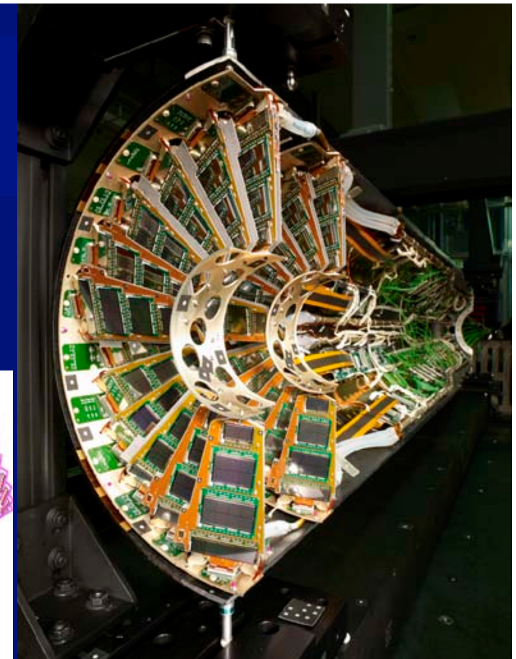
CMS tracker being inserted into CMS



CMS silicon pixel detector

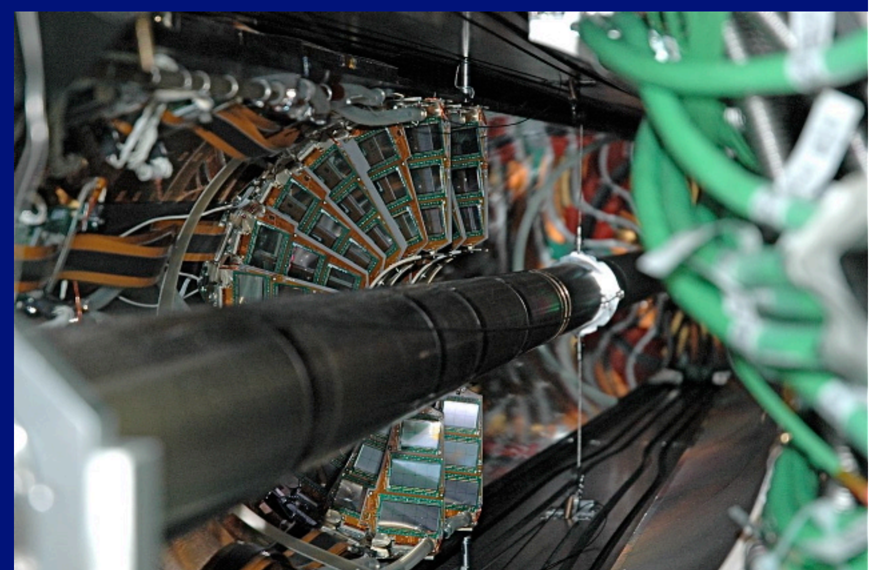
Smallest detector but the most channels. There are 66 million pixels, each 100 μm by 150 μm.





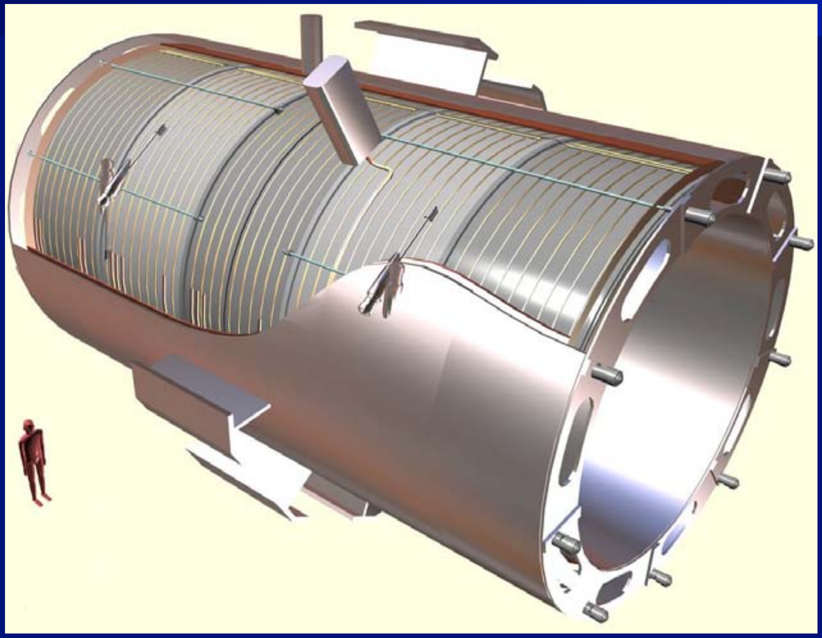
CU postdoc

Inserting the detector



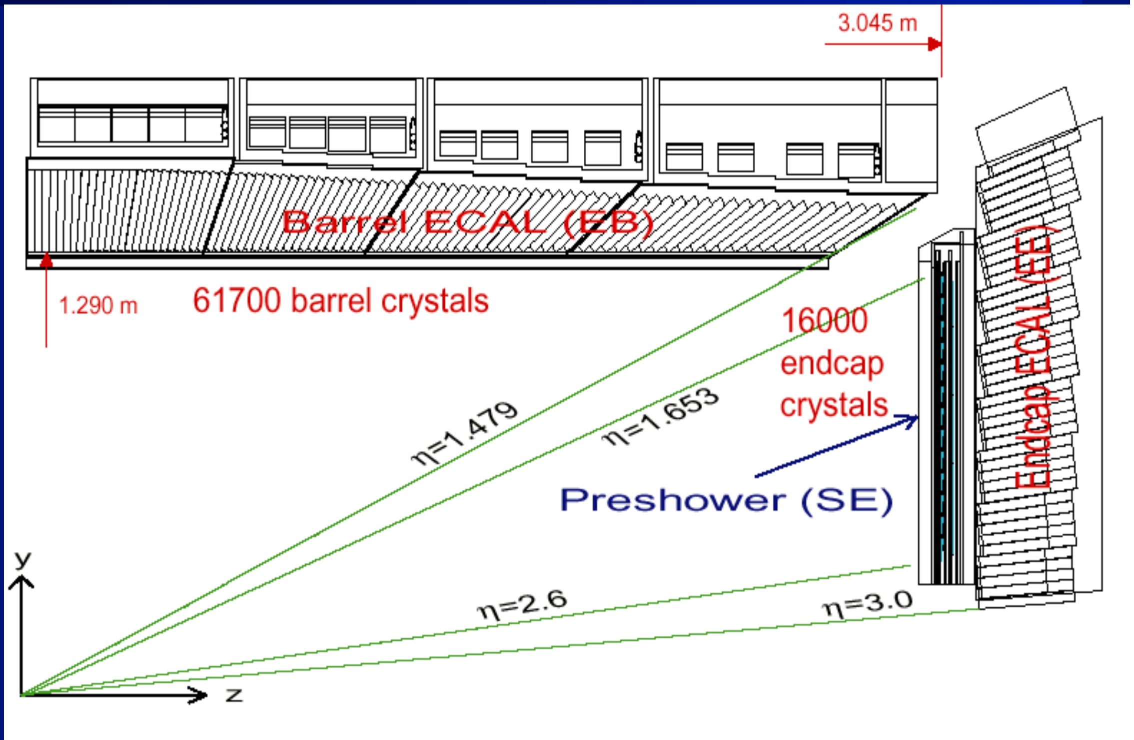
CMS Solenoid

- 4 T magnet at 4 K
- 6 m diameter and 12.5 m long (largest ever built)
- 220 t (including 6 t of NbTi)
- Stores 2.7 GJ — equivalent to 1300 lbs of TNT
- If magnet gets above superconducting temperature, energy is released as heat – need to plan for the worst
- Bends charged particles allowing tracker to measure momentum



CMS ECAL

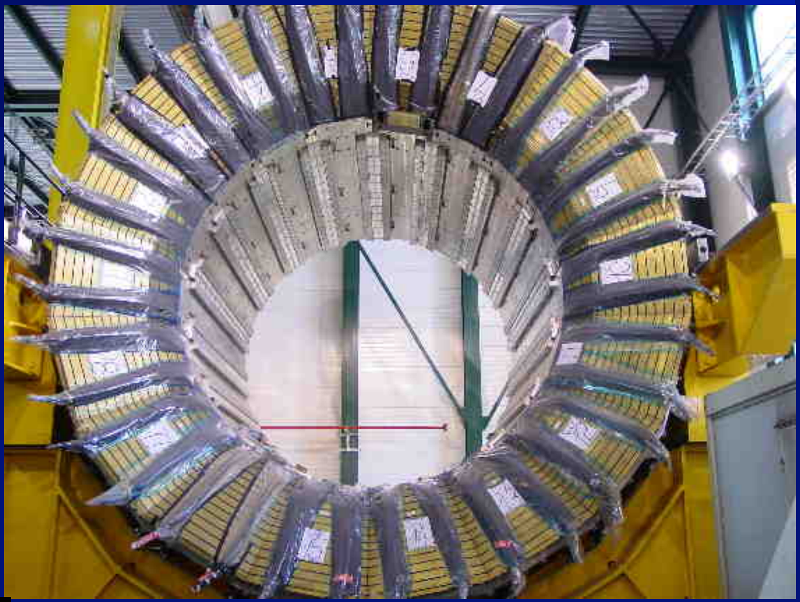
- Photons and electrons shower in high Z material
- Homogenous calorimeter
- Lead tungstate ($PbWO_4$) crystals: 2.3 x 2.3 x 23 cm^3
- Radiation hard, dense, and fast

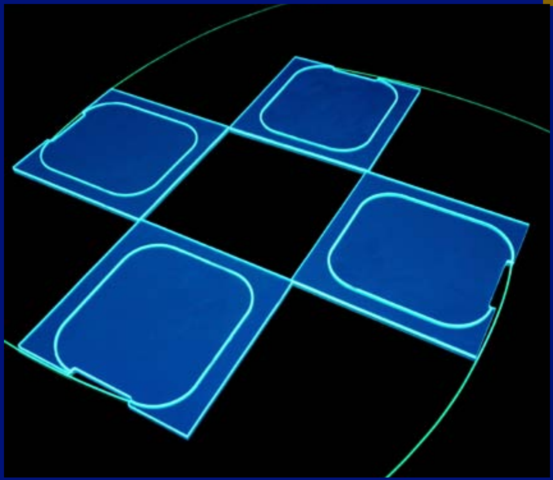


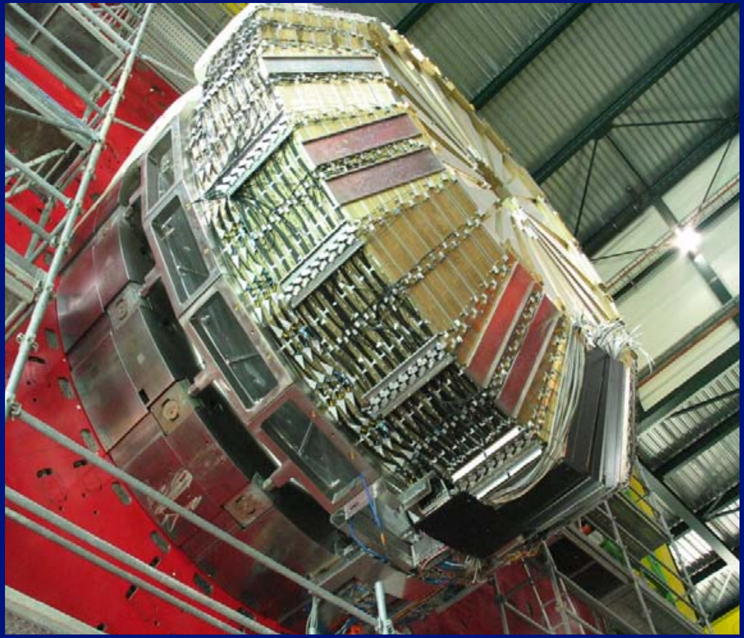
- Low light yield & temperature sensitivity make it difficult
- Magnetic field and radiation require novel electronics APD and VPT

CMS HCAL

- Sampling calorimeter
- Brass absorber from Russian artillery shells (non-magnetic)
- Scintillating tiles with wavelength shifting (WLS) fiber
- WLS fiber is fed into a hybrid photo-diode (HPD) for light yield measurement

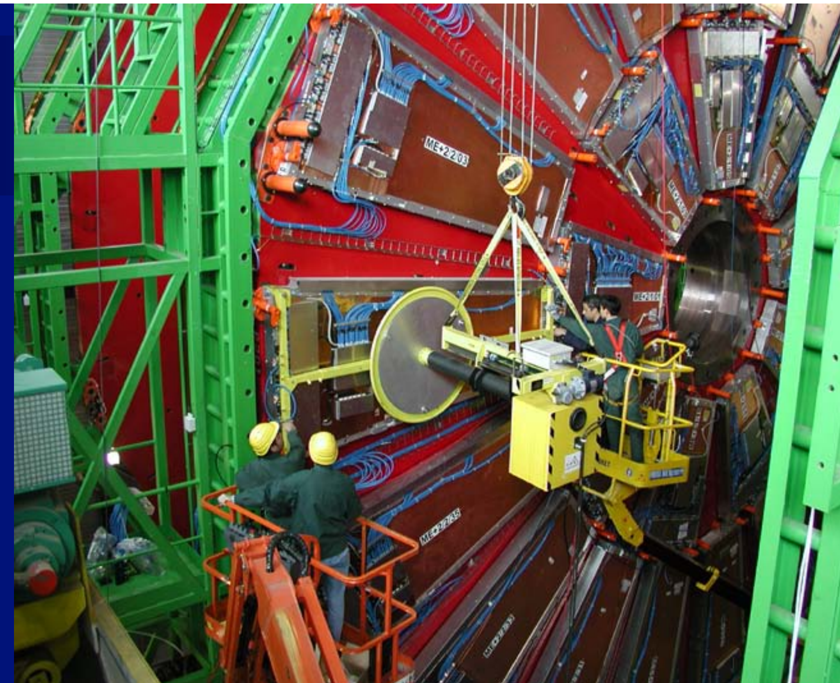


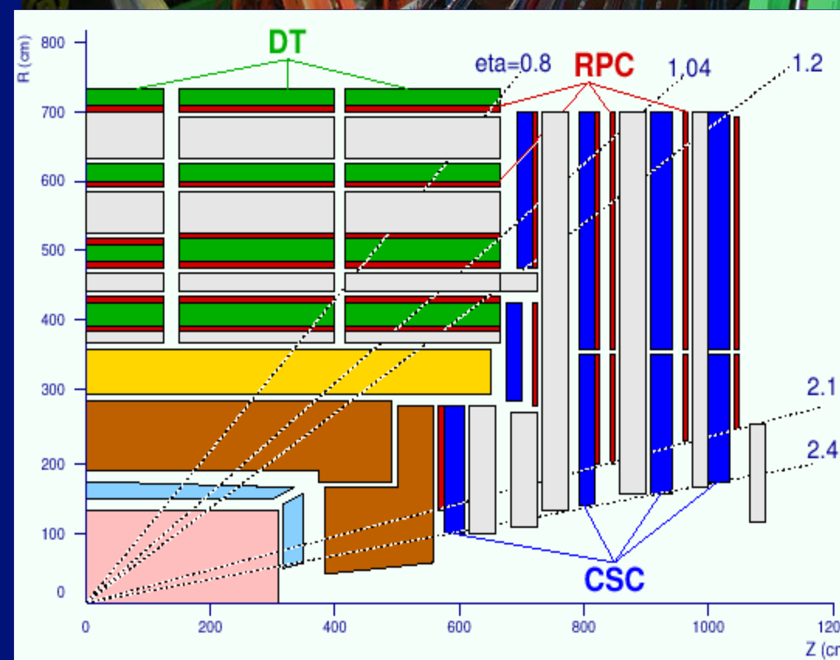




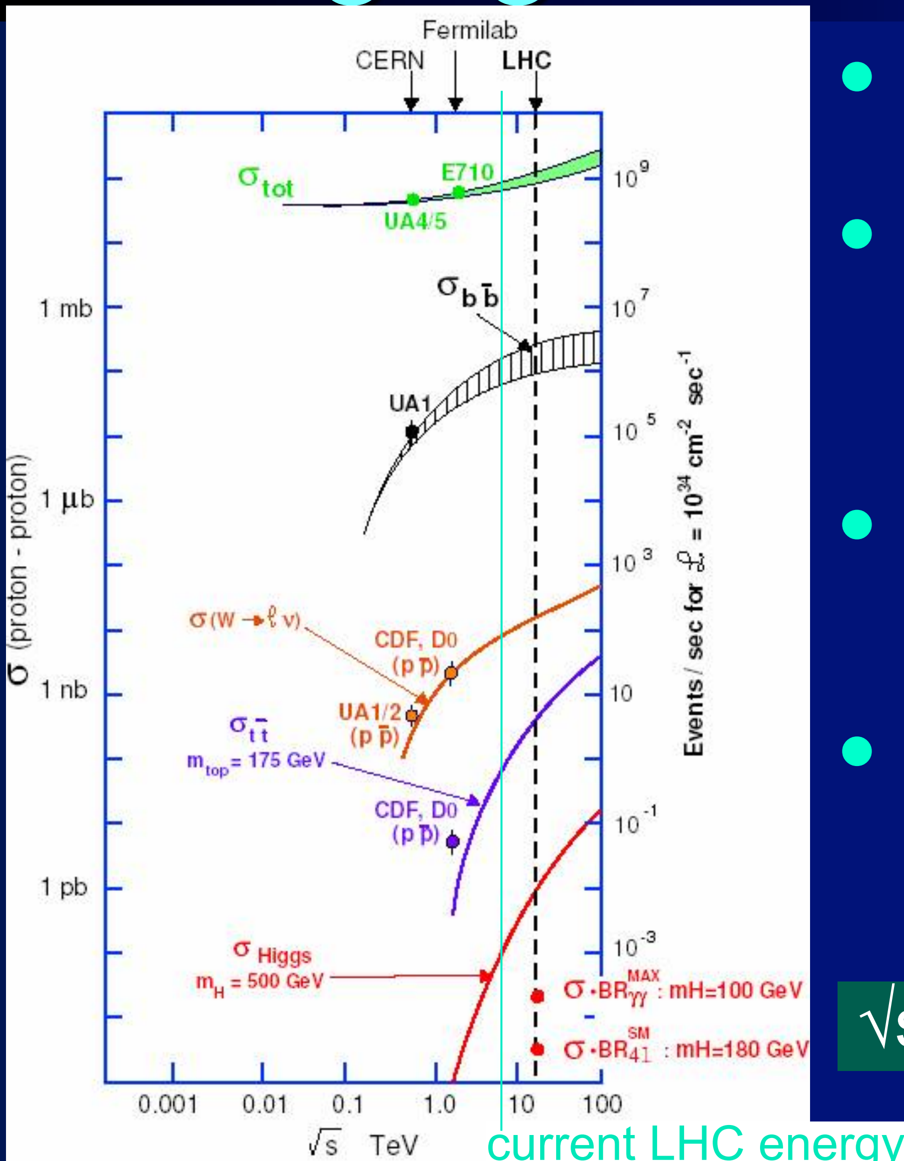
Muon systems

- Muons interact less than other charged particles
- Place detectors after material and what comes through is a muon
- Add B field & tracking to find momentum and link with main tracker
- 12000 t of iron is absorber and solenoid flux return
- Three tracking technologies: Drift Tube, Resistive Plate Chamber, & Cathode Strip Chamber





Picking signal out of background



- Higgs cross section is 10^{-11} of the total cross section
- 99.9% of events are light QCD background: low energy hadrons
  - Reject by requiring high energy or leptons
- $b\bar{b}$ events are another large background that also originate in interesting events
- W, Z, and top are backgrounds *and* signatures for good events

√s is the center-of-mass energy

Triggering and data acquisition

The problem

- Beam crossings generate 1 MB of data from the experiment and occur at 40 MHz = 40 Terabytes/s
- Restricted to ~400 Hz of events = 400 MB/s = 40 TB/day = 4 Petabytes per year
- Need to reject 99.999% of events in quasi real time

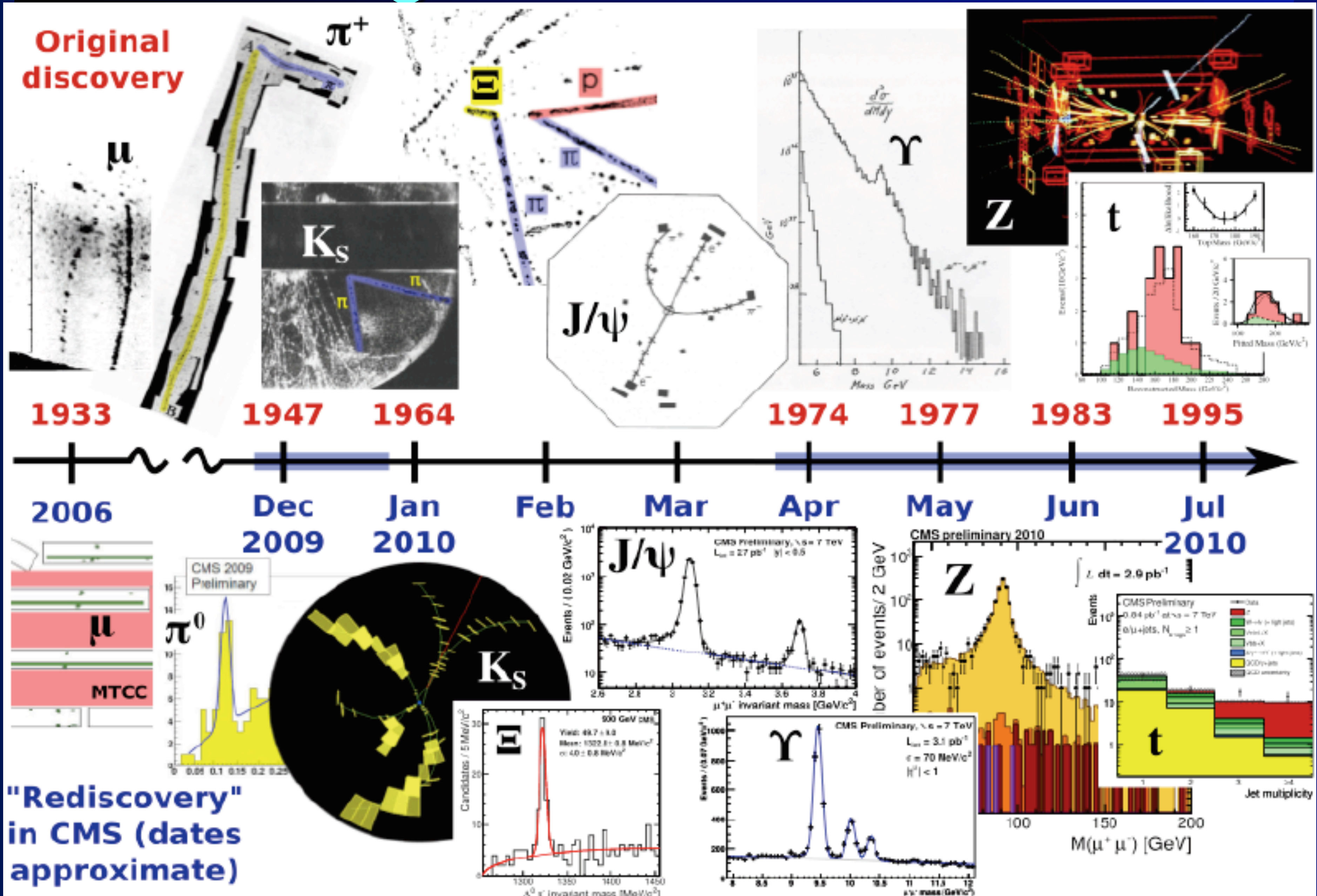
The solution

- Hardware trigger finds jets, electrons, muons, and missing E_T and rejects 99.8% of events in 3 μs
- Surviving events fed into ~1000 CPU farm where events are reconstructed and 400 Hz is kept

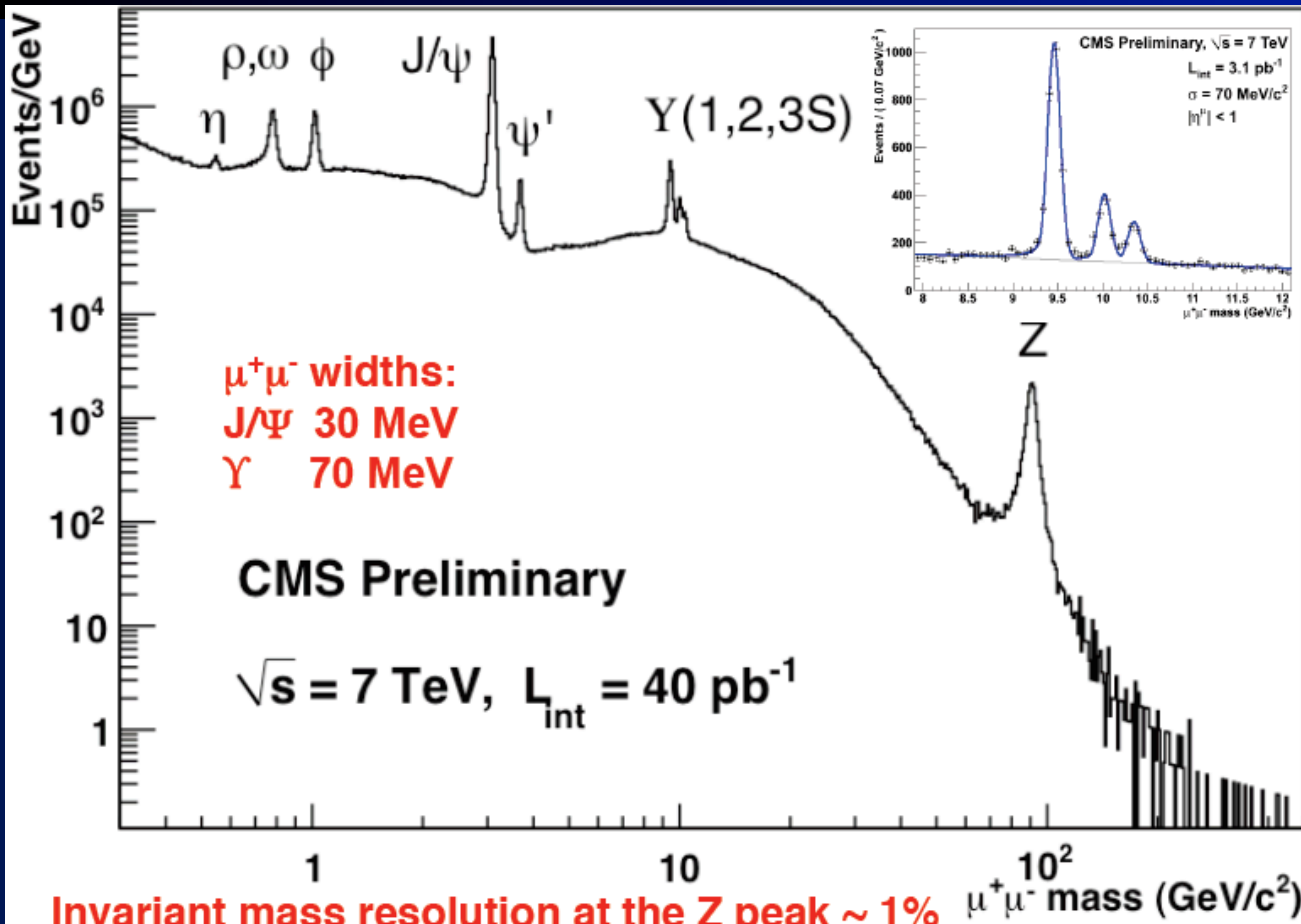
The first LHC physics run

- A short checkout run occurred in December 2009 at center-of-mass energies 0.9 and 2.36 TeV.
- 7 month run at $\sqrt{s}$ = 7 TeV started March 30, 2010.
- CMS was able to use 40 pb^{-1} of integrated luminosity from this run.

Rediscovering the Standard Model at CMS

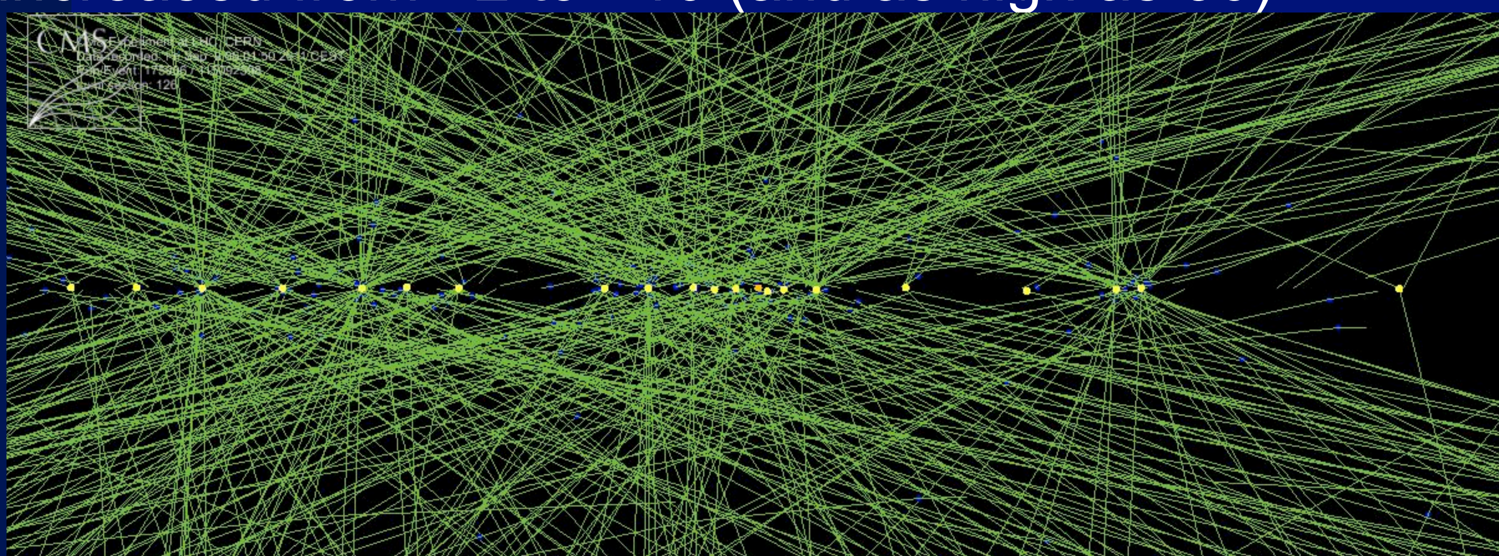


Final states with dimuons



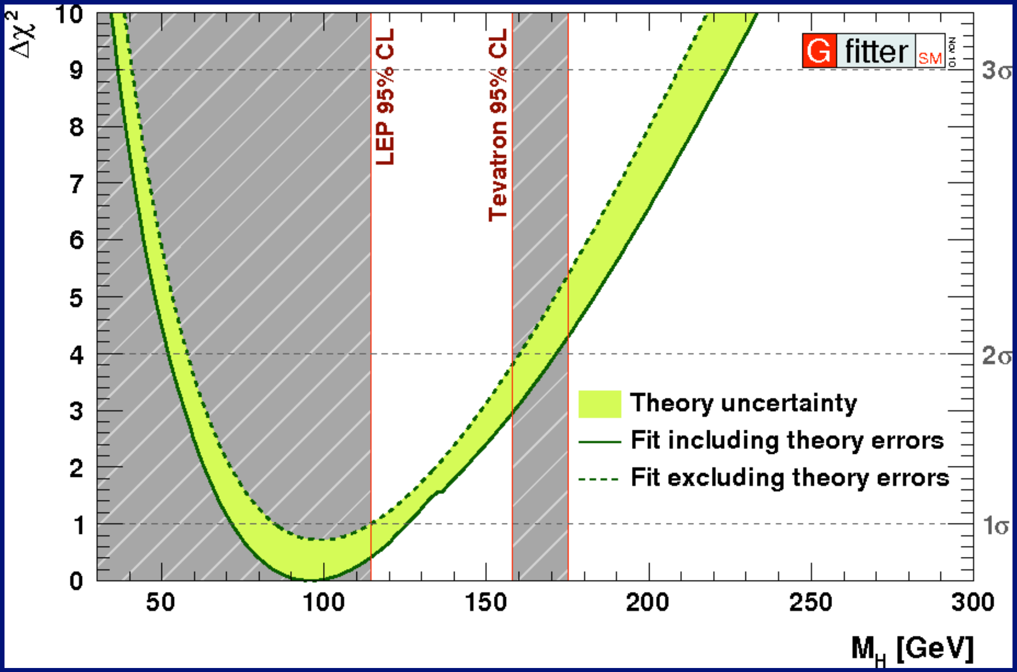
The 2011 LHC physics run (April-October)

- Will record 5 fb^{-1} (>100 times more data than 2010)
- With this flood of data came extra challenges:
  - Triggers needed to be continuously adjusted to cope with the ever increasing rate of interactions.
  - Pileup (multiple interactions per crossing) makes measurements and background rejection much more difficult. Average number of interactions per crossing increased from ~2 to ~10 (and as high as 30).



Higgs status

- The Higgs mass affects other aspects of the Standard Model, allowing indirect measurements.
- Direct searches at 200 GeV e^+e^- collider LEP require mass > 114 GeV.
- Early 2011 results from the Tevatron at Fermilab rule out (@95% CL) a region around 165 GeV.



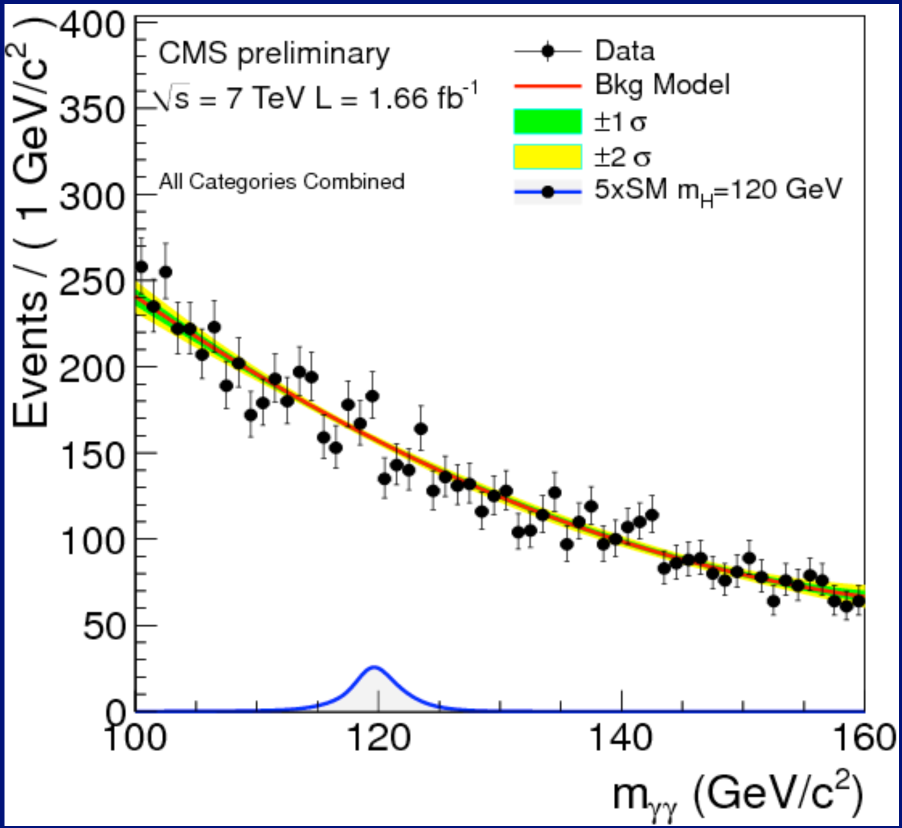
Indirect measurements assume the Standard Model; important to search a broad mass range.

CMS searches for the Higgs

- CMS currently has Higgs searches in 8 modes:

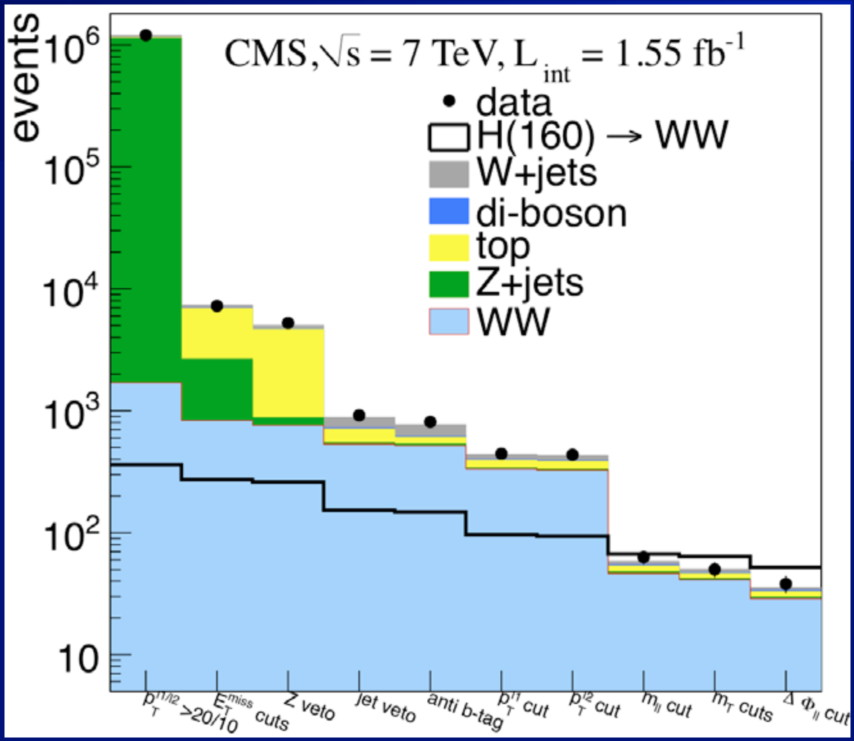
$$H \to b\bar{b},\ H \to \tau\tau,\ H \to \gamma\gamma,\ H \to WW,\ H \to ZZ \text{ (4 modes)}$$

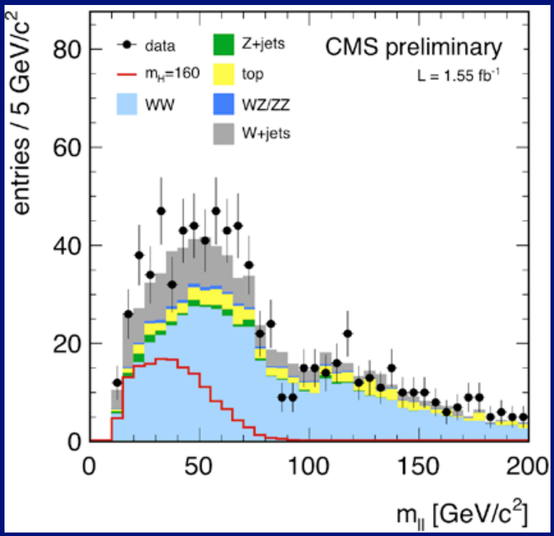
- No time to cover all searches; one of the easiest conceptual searches is the Higgs to two photons.
- Select events with two isolated, high p_T photons
- Look for excess above background
- The sensitivity of the analysis depends critically on the photon resolution (width of the Gaussian signal)

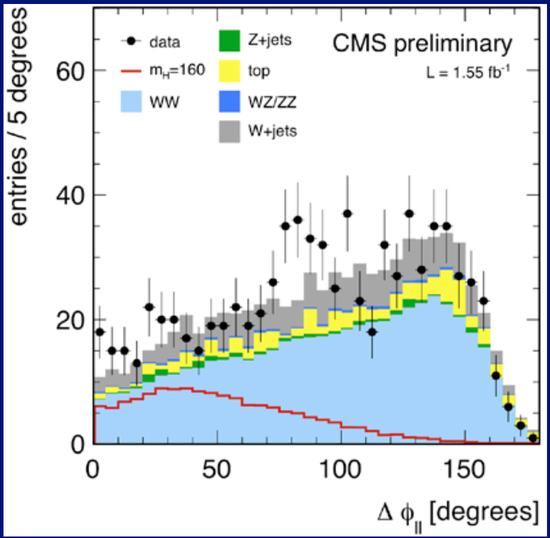


H→WW search

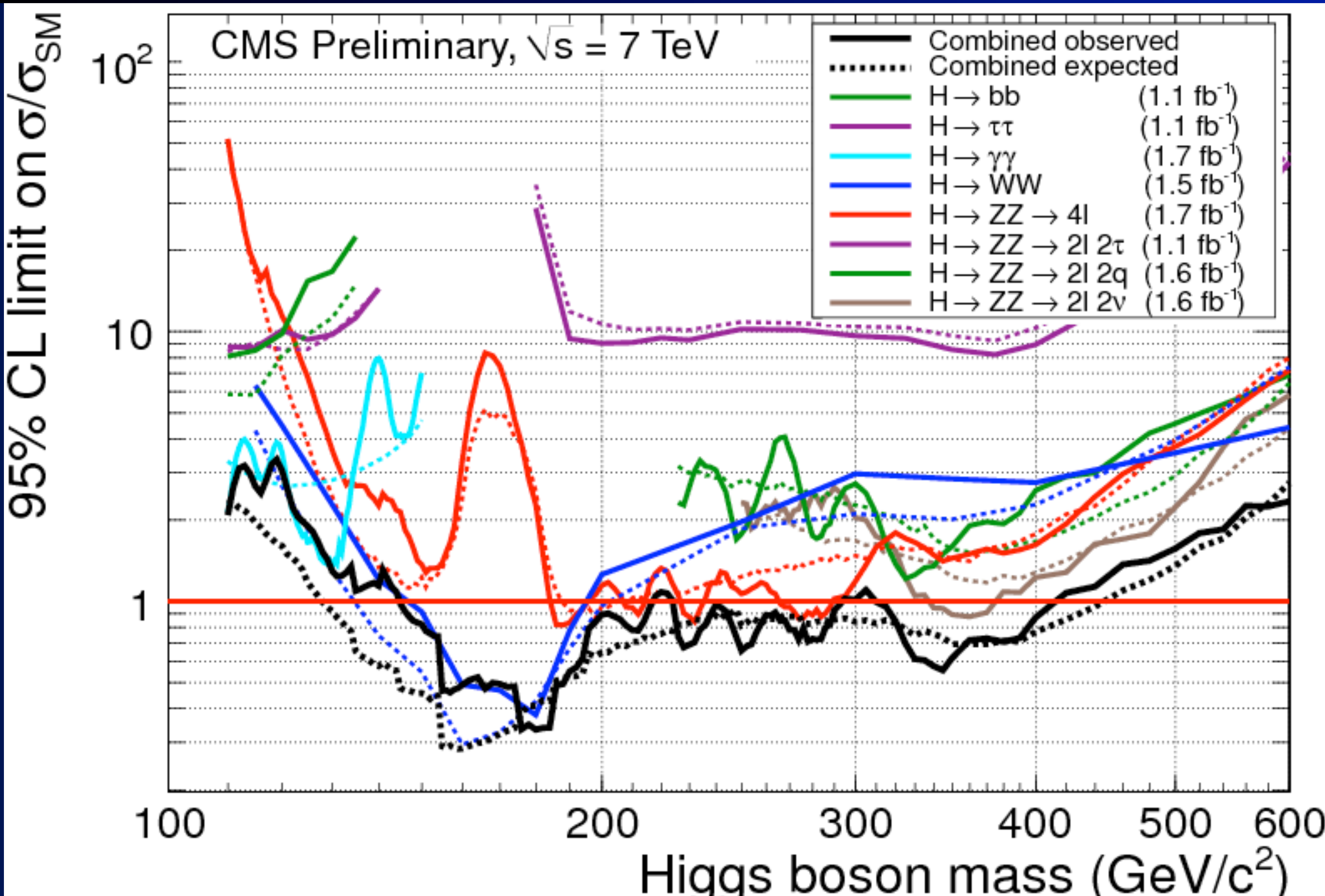
- Each W decays to lepton + neutrino. Neutrino escapes the detector (missing p_T) making it impossible to obtain a mass peak.
- Use a bunch of variables to enhance signal to background
- Obtain background from data-driven methods.
- Last three cuts set differently at each Higgs mass point.
- Measure deviation of data from expected background.



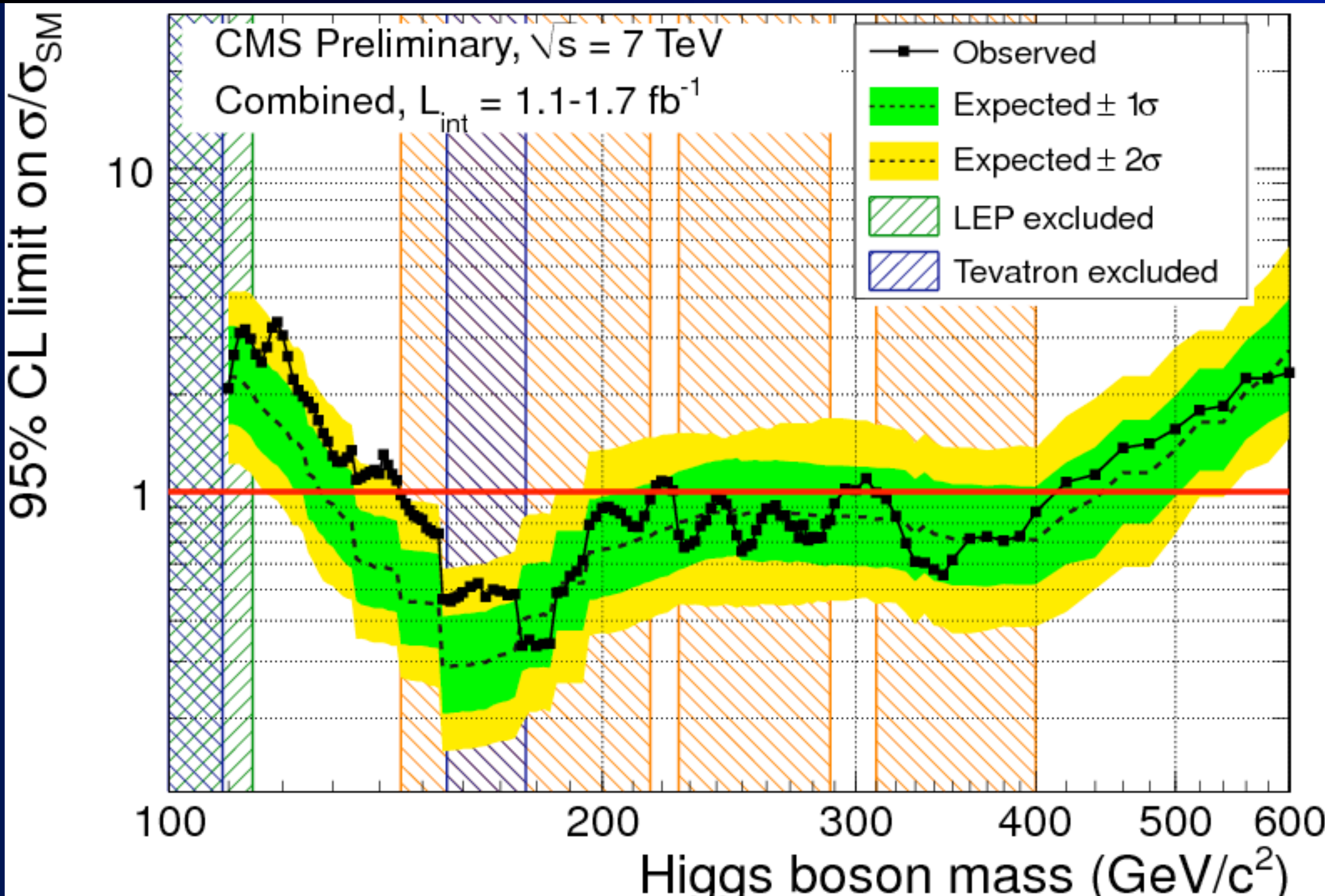




Combined Higgs upper limits

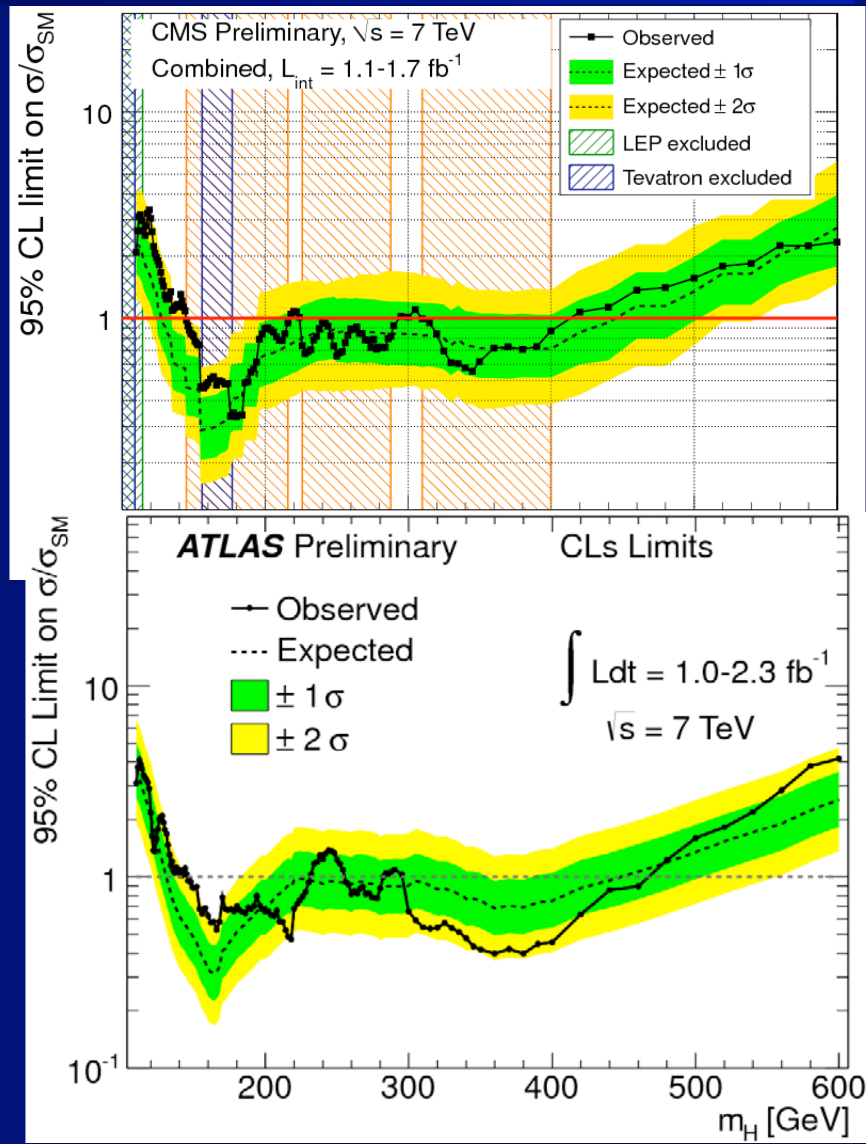


Combined Higgs upper limits



ATLAS and CMS Higgs upper limits

- ATLAS and CMS results are quite similar.
- Although there is a region between 290-300 GeV, basically everything between 144 and 460 GeV is excluded.
- A proper combination will be presented at HCP2011 on November 14.
- Results from entire 2011 data set should be done by the end of the year and could rule out entire mass range.
- Probably need 2012 data to make a discovery.

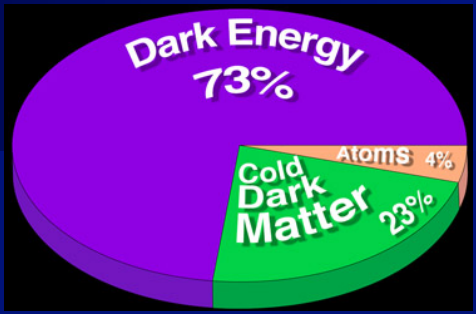


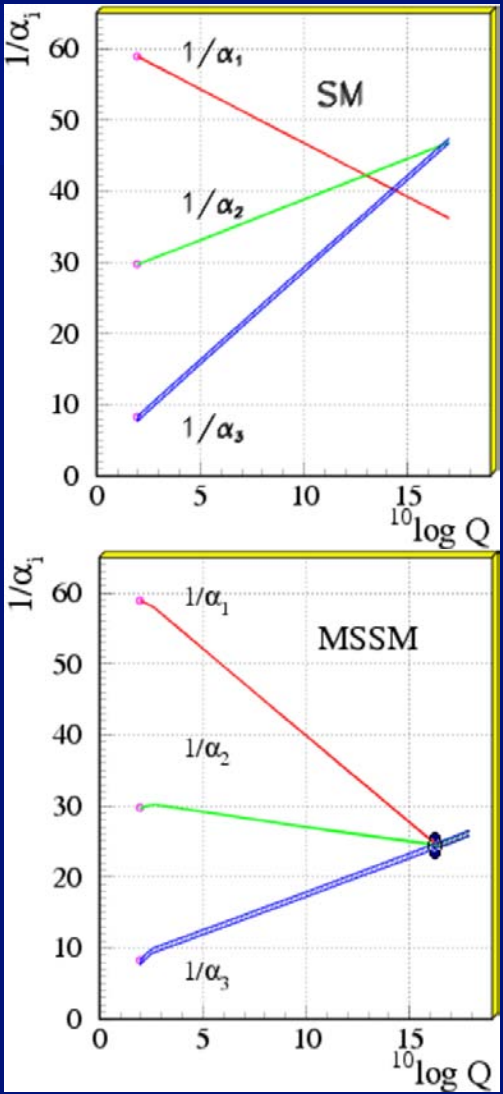
Searches for new physics

The other high priority for CMS is discovering physics beyond the Standard Model. This could be:

- Supersymmetry (SUSY)
- Extra dimensions – warped, large, or compactified
- Fourth generation of quarks
- New resonances such as W′ and Z′
- Microscopic black holes
- New interactions (such as technicolor)
- Whatever else the theorists come up with…

Supersymmetry





- Several nice features:
  - Solves the hierarchy problem (can explain why the Higgs mass is ~100 GeV instead of 10^{15+} GeV)
  - Can provide a dark matter candidate
  - Is more GUT friendly
- Every elementary particle has a supersymmetric partner with cool names like squark, gluino, wino (none of which have been observed).
- >100 free parameters in SUSY. Often consider a constrained version: (C)MSSM (aka MSUGRA) with only 5 parameters including the universal scalar and fermion masses: m_0 & $m_{½}$

Searching for supersymmetry

A few rules for most SUSY searches:

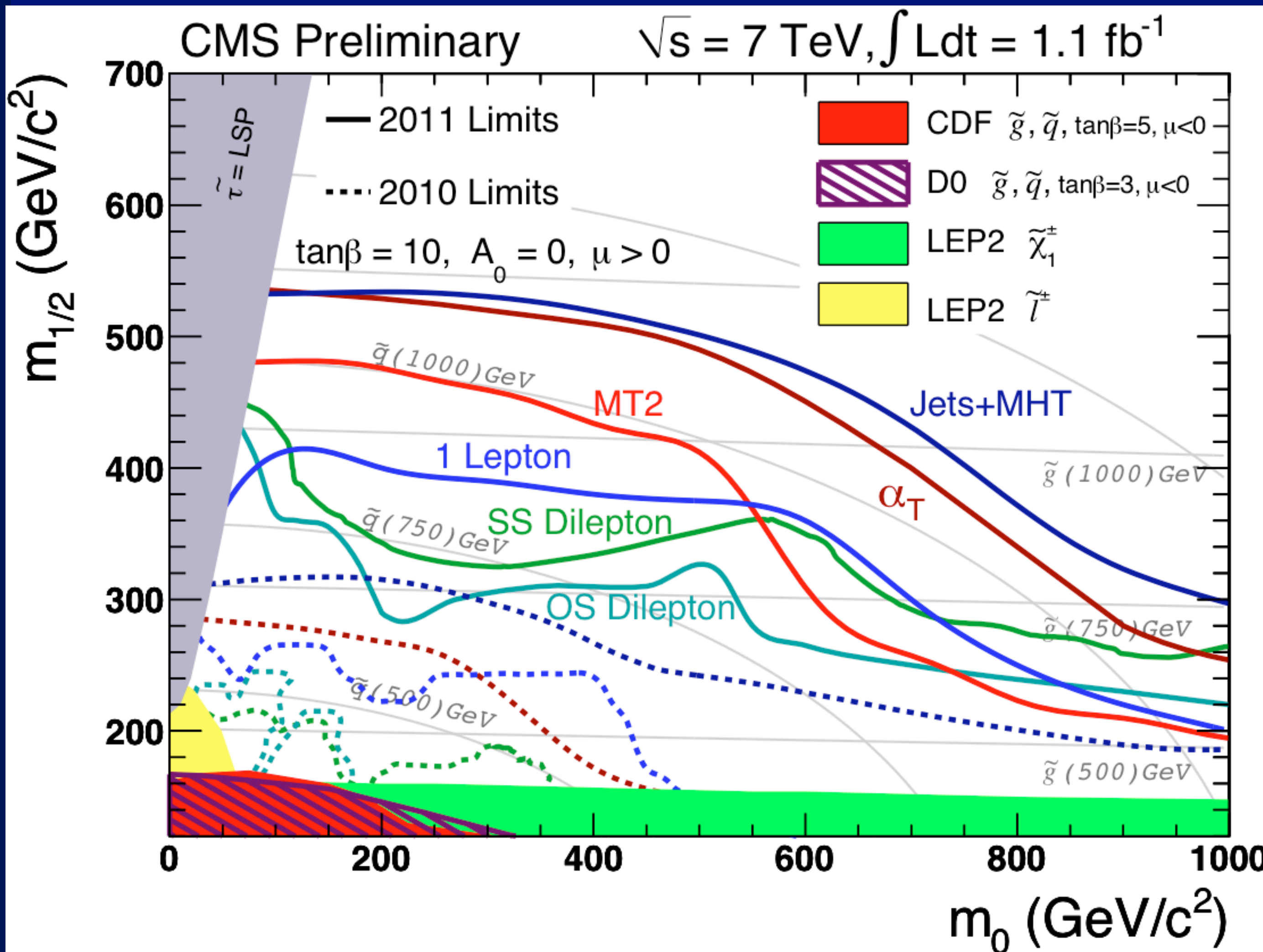
- squarks and gluinos are predominantly produced because they couple to the strong force
- SUSY particles produced in pairs (R-parity conservation)
- Decay cascades end with lightest supersymmetric particle (LSP) which escapes detection.
  - Cascades produce jets & leptons (electrons, muons, taus)
  - The escape of LSP’s results in missing energy (MET).

These rules suggest search strategies:

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

New exclusions for CMSSM

Large areas of CMSSM space is excluded by CMS

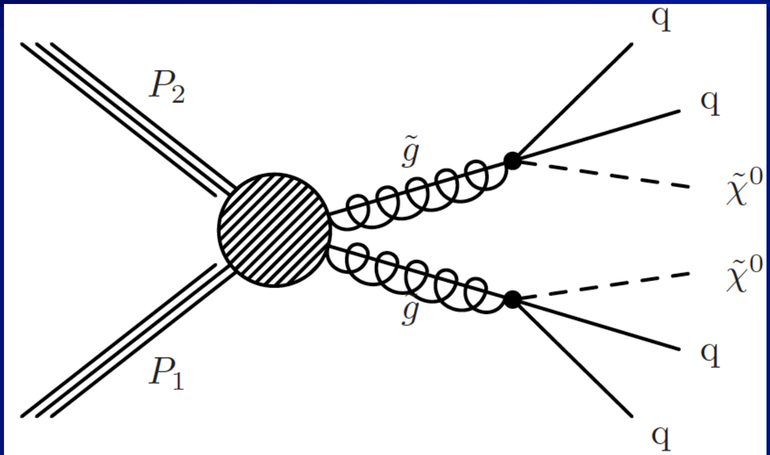


Prospects for SUSY

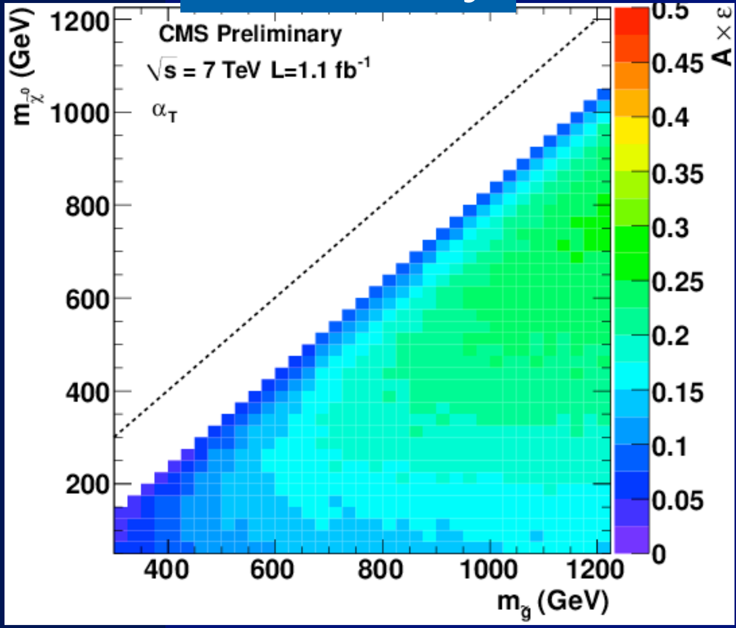
- Excluding regions of CMSSM is a convenient way to present results but the results do not directly translate to other SUSY models.
- Progressing toward presenting experimental results in a more universal fashion so theorists can check their theories against the experimental results.
- Basically set limits on cross sections for particular signatures.
- Theorist collaboration has produced *baseline topology sets (simplified models)* which are intended to generically cover the signature space of well-motivated theories: www.lhcnewphysics.org/

Search in all-hadronic events with α_T

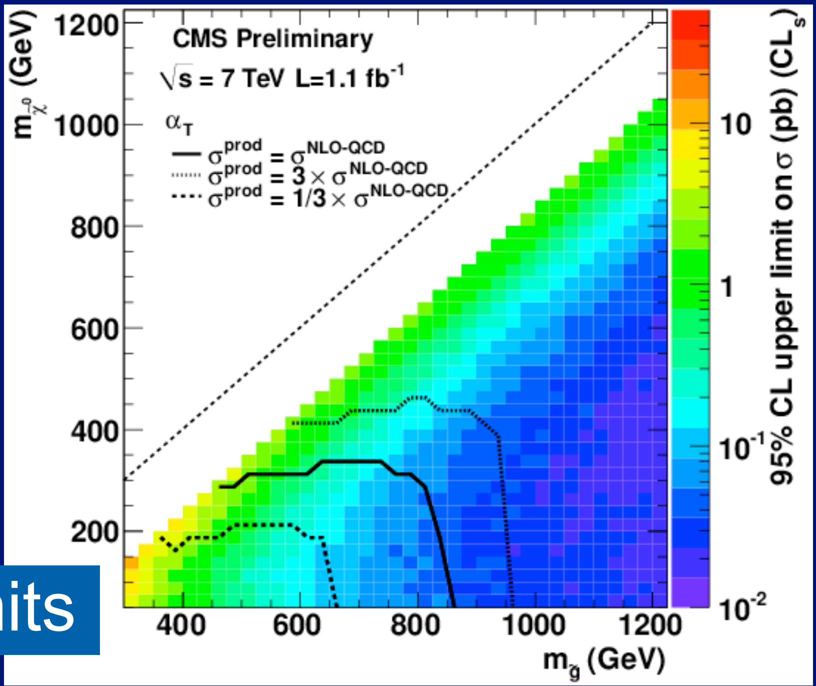
Produce 2 gluinos which decay to LSP neutralinos (which escape) plus 4 quark jets. Jets+MET signature.



Efficiency



Limits



Summary

- We are learning more about the Standard Model with measurements of light hadrons, strange particles, B hadrons, top quarks, and gauge bosons (none of which I had time to show).
- While the Higgs has not been found, we have not yet excluded the most likely region (114 to 140 GeV).
- No sign yet of supersymmetry but it could still be present at a higher mass scale than we have reached, with different signatures than we have checked, etc.
- No sign yet of physics beyond the Standard Model like extra dimensions, black holes, fourth generation quarks, or high mass resonances.

Outlook

- Current results are from <2 fb^{-1} of data.
- CMS will have 5 fb^{-1} of data by the end of October with Higgs search results by year's end.
- Next year should provide 10 fb^{-1} which should give a definitive statement on the Standard Model Higgs.
- It is difficult to rule out new physics theories; we are still in discovery mode.
- LHC and detector improvements in 2013 and 2014.
- In 2015 we will start taking data at 13 TeV (currently 7 TeV) which will greatly expand the search for new physics at higher mass scales.

More photos to end on…