The LHC: The Start of a Revolution in Physics ?

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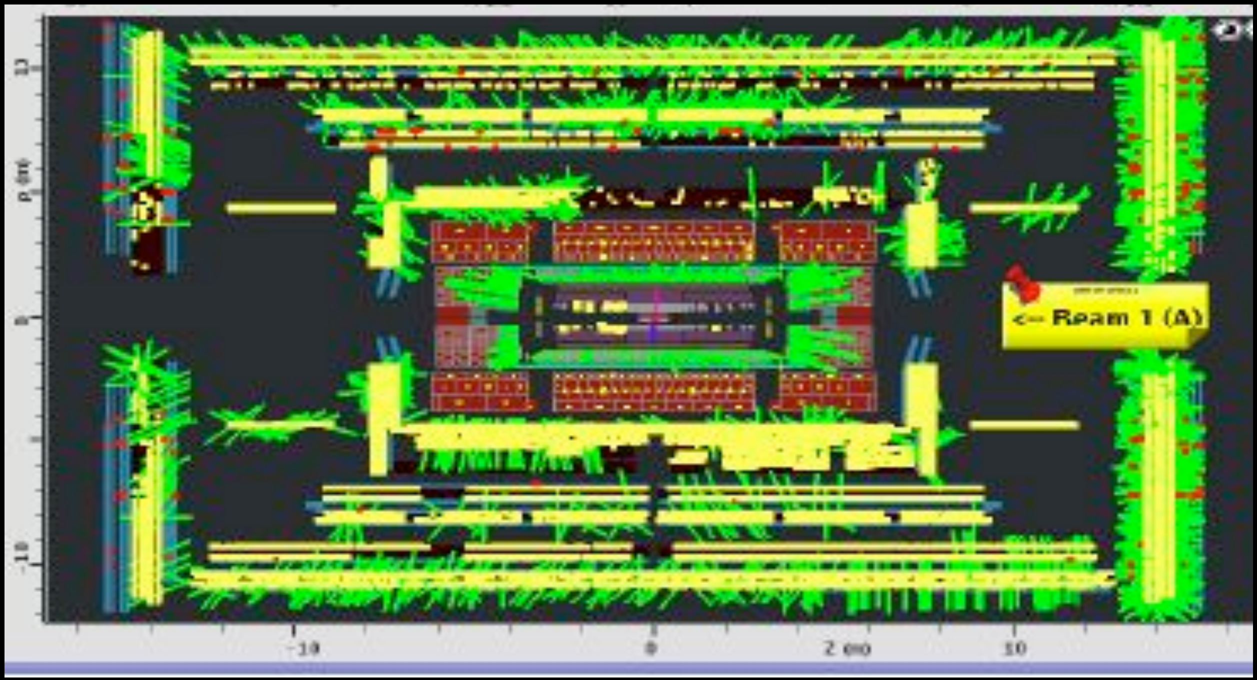


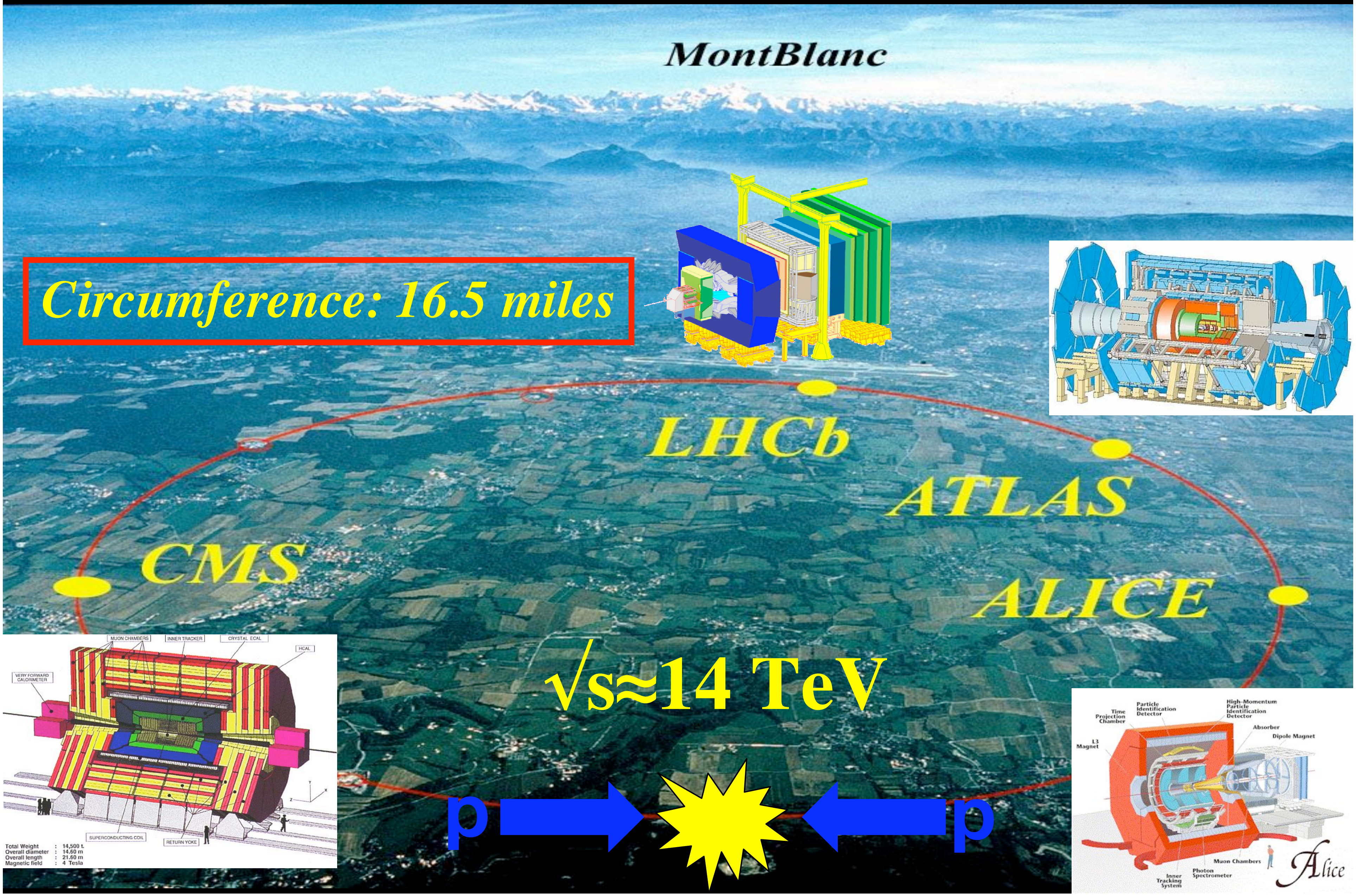
APS California, Carson/CA, October 2008

Outline

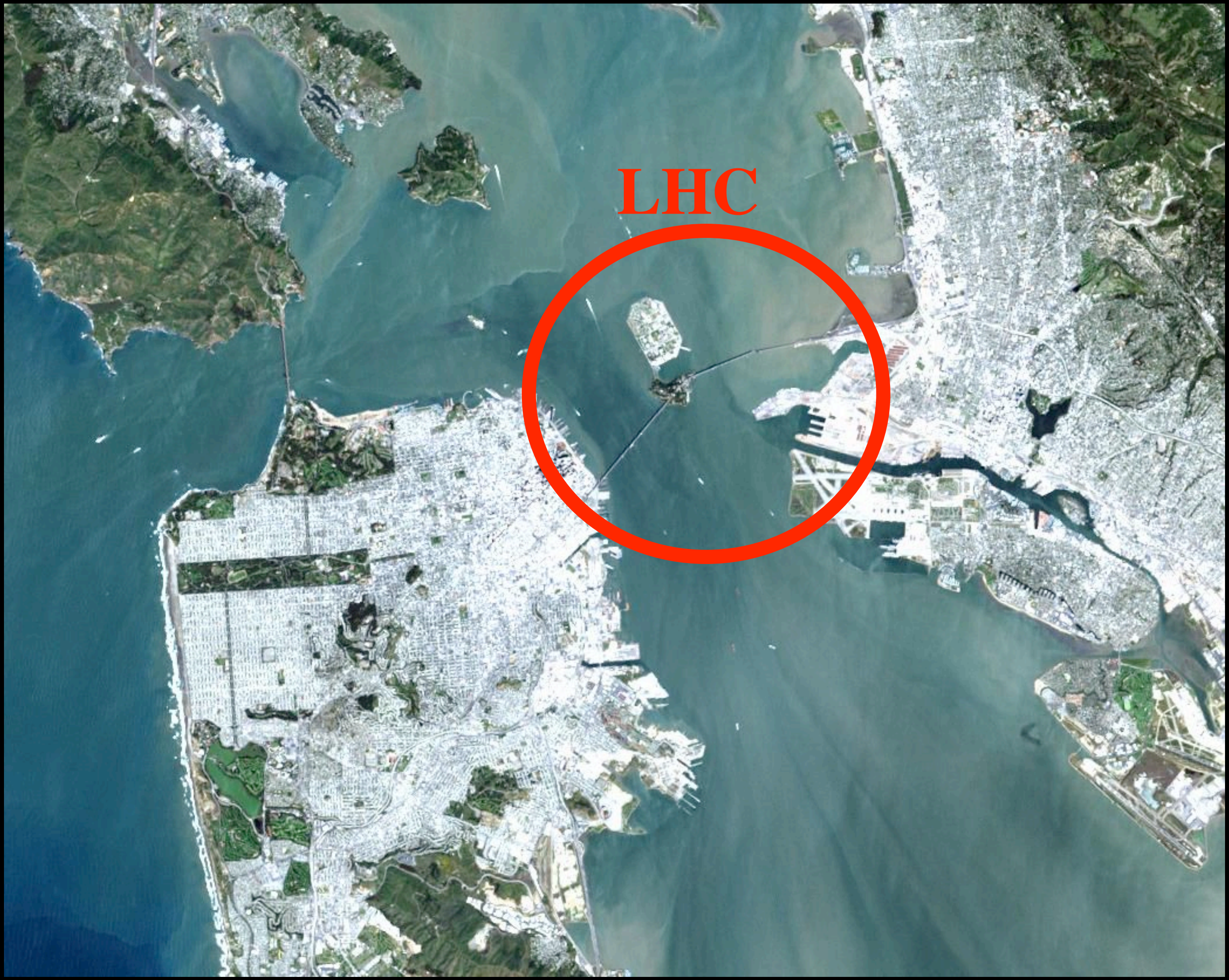
- The Large Hadron Collider
- The Physics Questions
- The Experimental Chellange
- Searches for the Higgs boson and Supersymmetry
- The status of the LHC
- Conclusions

The Large Hadron Collider

The Large Hadron Collider (LHC)

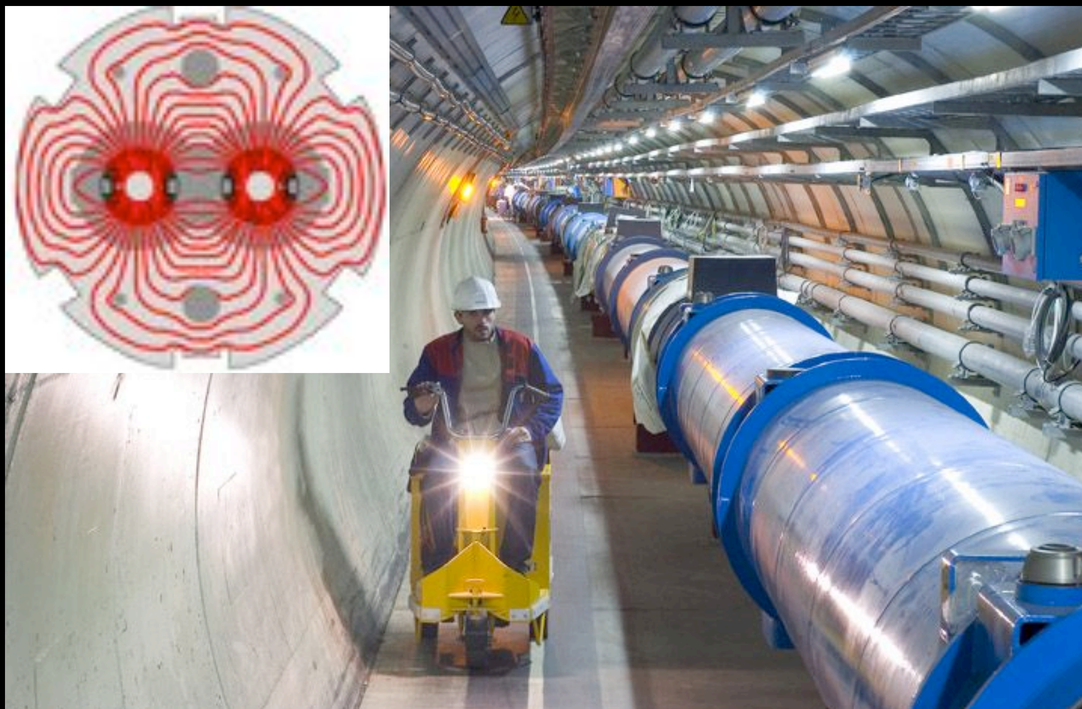


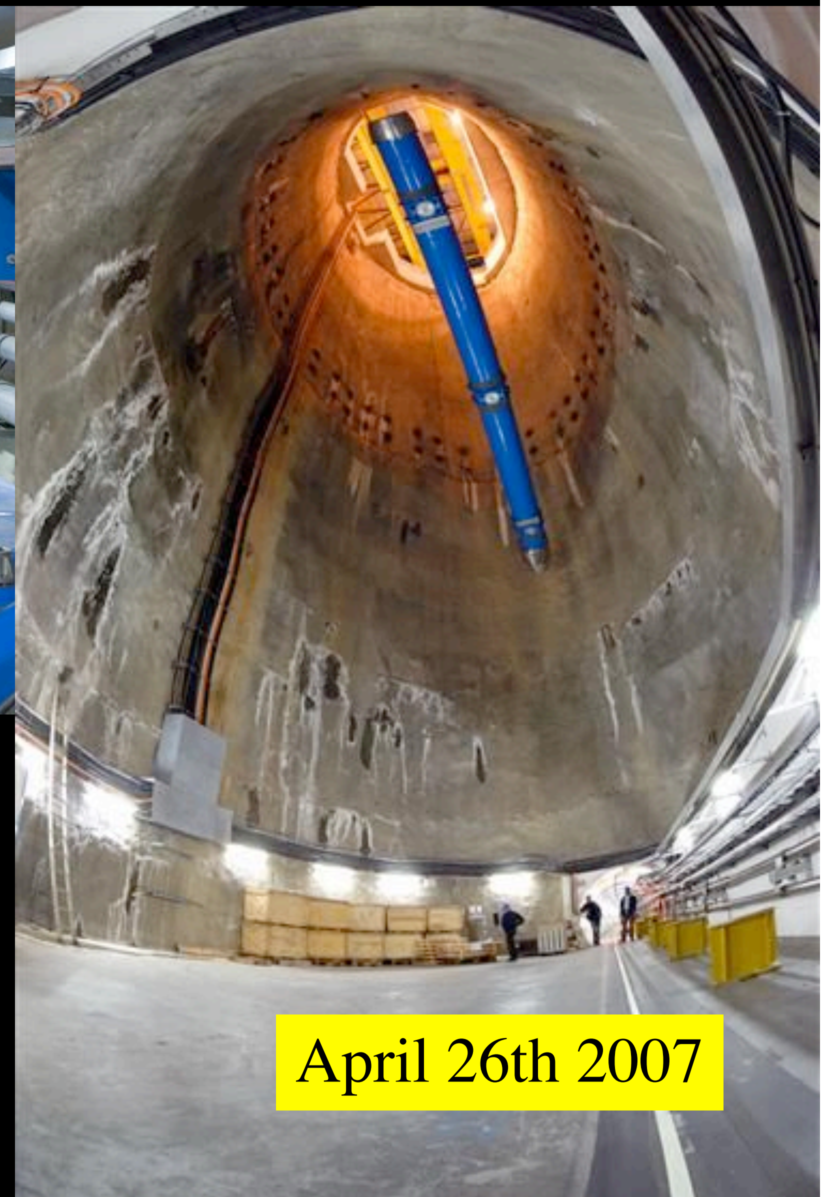
LHC in the Bay



– protons make a full turn 11254 times per second

LHC Accelerator





- 30,000 tons of 8.4T dipole magnets
- Cooled to 1.9K with 90 tons of liquid helium
- Energy of beam = 362 MJ
  - Kinetic energy of 15 ton truck at 500 mph

Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^{\,2}}{A}$$

revolving frequency: f_{rev}=11254/s
#bunches: n_{bunch}=2835
#protons / bunch: $N_p = 10^{11}$
Area of beams: A~40 μm

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

Cross section σ: Given by Nature (calc. by theorists)

Efficiency: optimized by experimentalist

Ability to observe something depends on N_{obs}

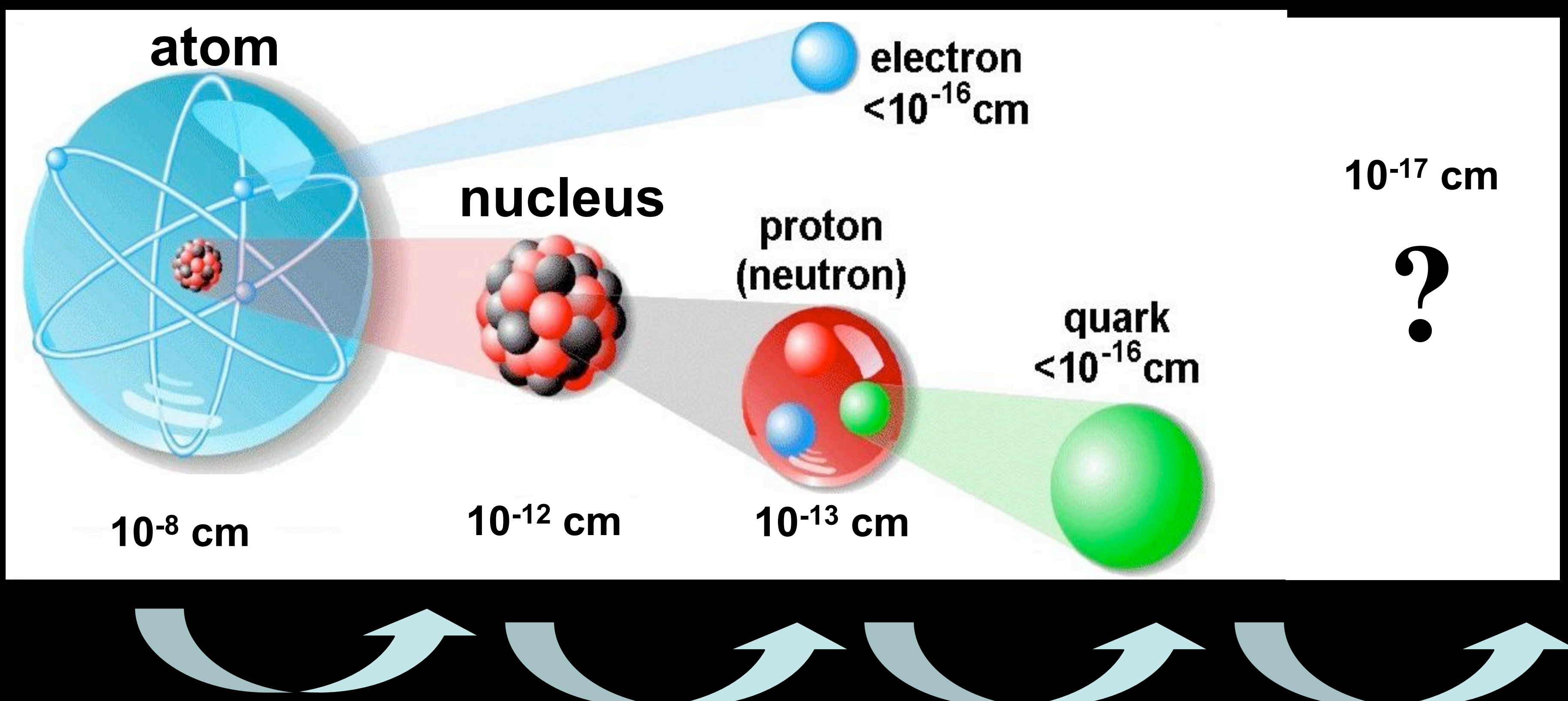
Physics Questions

What Do We Hope to find at LHC?

- Answers to very fundamental and simple questions:
  - **Why do electrons have mass?**
    - Possible answer: The Higgs boson
  - **Why is gravity so weak?**
    - Possible answer: supersymmetric particles
  - **Or ultimately**
    - Are there more symmetries or more Universes?

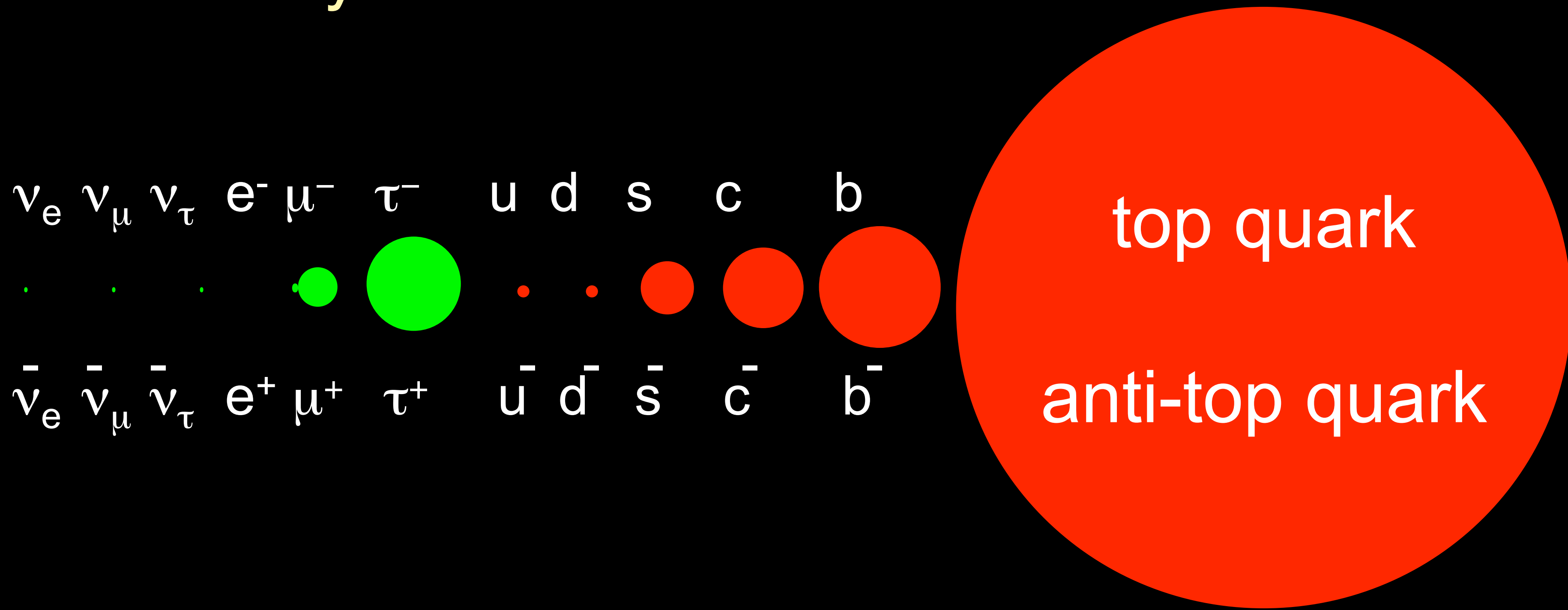
We learned a lot in the last century

~0 ~1910 ~1940 ~1970 LHC



$\frac{1}{10{,}000}$ $\frac{1}{10}$ $\frac{1}{100{,}000}$ $\frac{1}{10}$

Elementary Particles: Matter

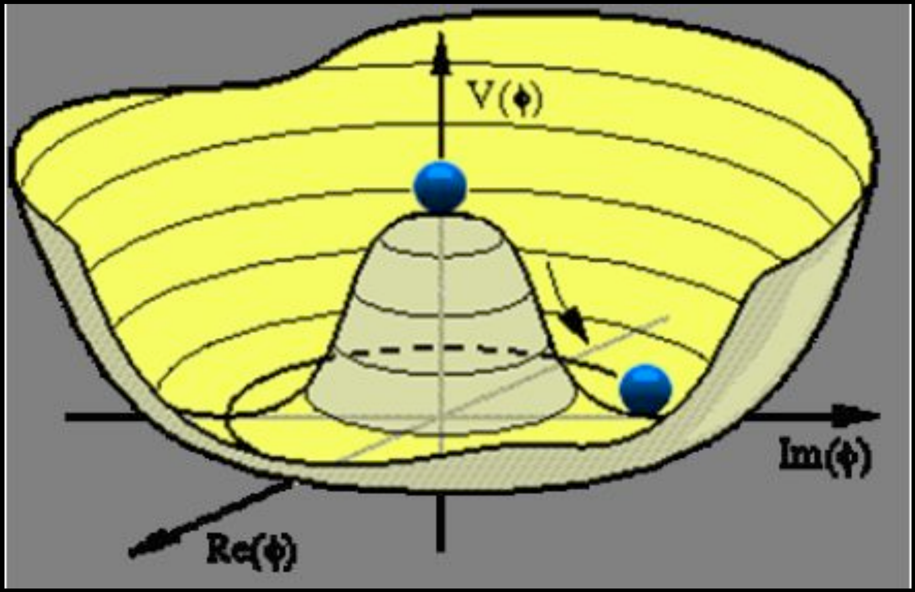


(Mass proportional to area shown but all sizes still < 10^{-19} m)

Why are there so many leptons and quarks?
And, why do they all have different masses?

The Higgs Mechanism

- 1964
  - P. Higgs
  - R. Brout, F. Englert
- New scalar self-interacting field with 4 d.o.f.:



$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2$$

- Ground state: non-zero-value breaks electroweak symmetry generating
  - 3 Goldstone bosons: $W^\pm_L, Z_L$
  - 1 neutral Higgs boson

$$\langle\Phi^0\rangle = v/\sqrt{2}, \text{ where } v = 246 \text{ GeV}$$

$$h^0 \equiv \sqrt{2}\,\mathrm{Re}(\Phi^0 - \tfrac{v}{\sqrt{2}})$$

- Mass of h_0 depends on unknown coupling λ

$$m_h = \tfrac{1}{2}\lambda v^2$$

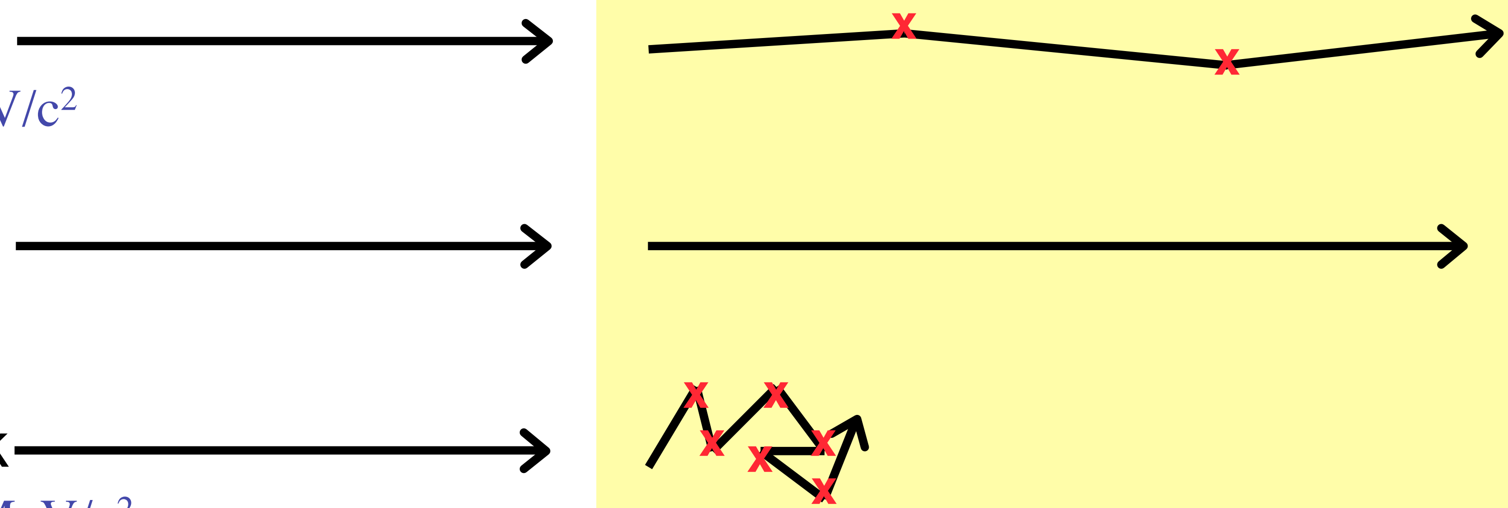
Origin of Mass

Nothing in the universe | Something in the universe

Electron
$m = 0.511\ MeV/c^2$

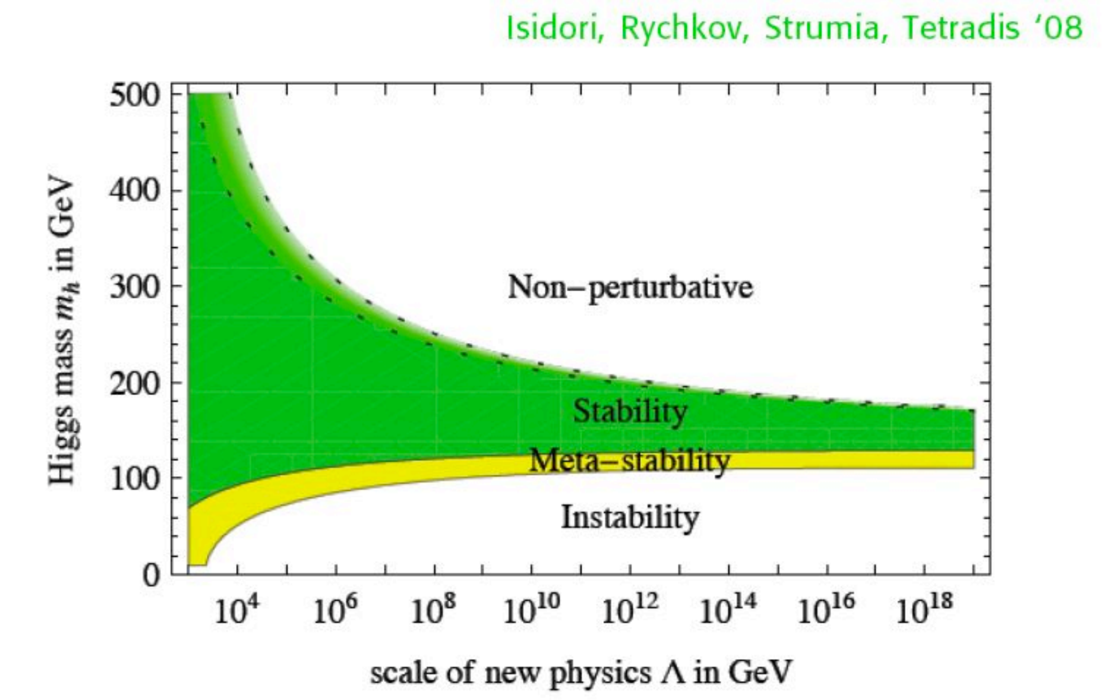
Photon
$m = 0$

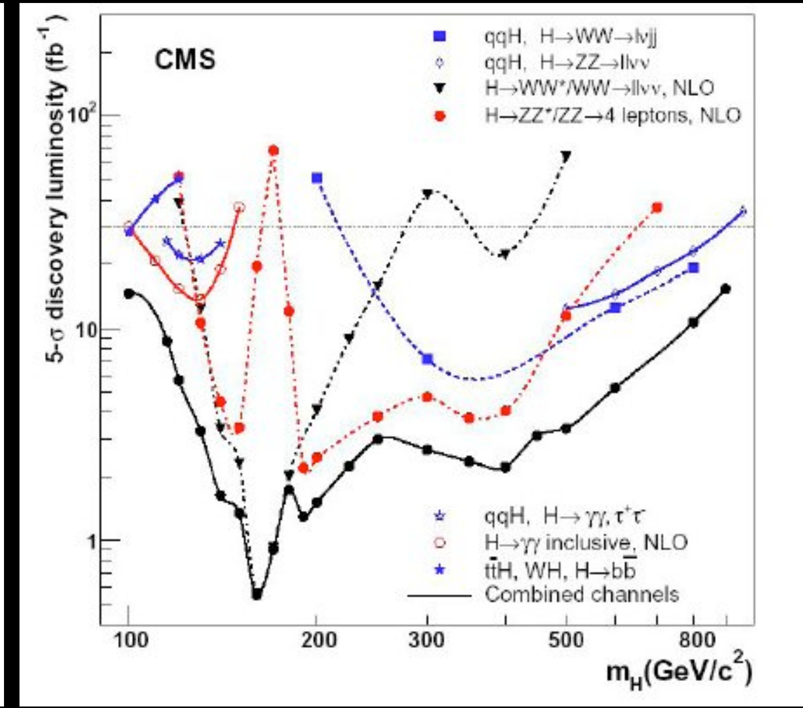
Top Quark
$M \sim 172000\ MeV/c^2$



Higgs Field interact with other particles the stronger the heavier they are

Will the Higgs Boson be found?

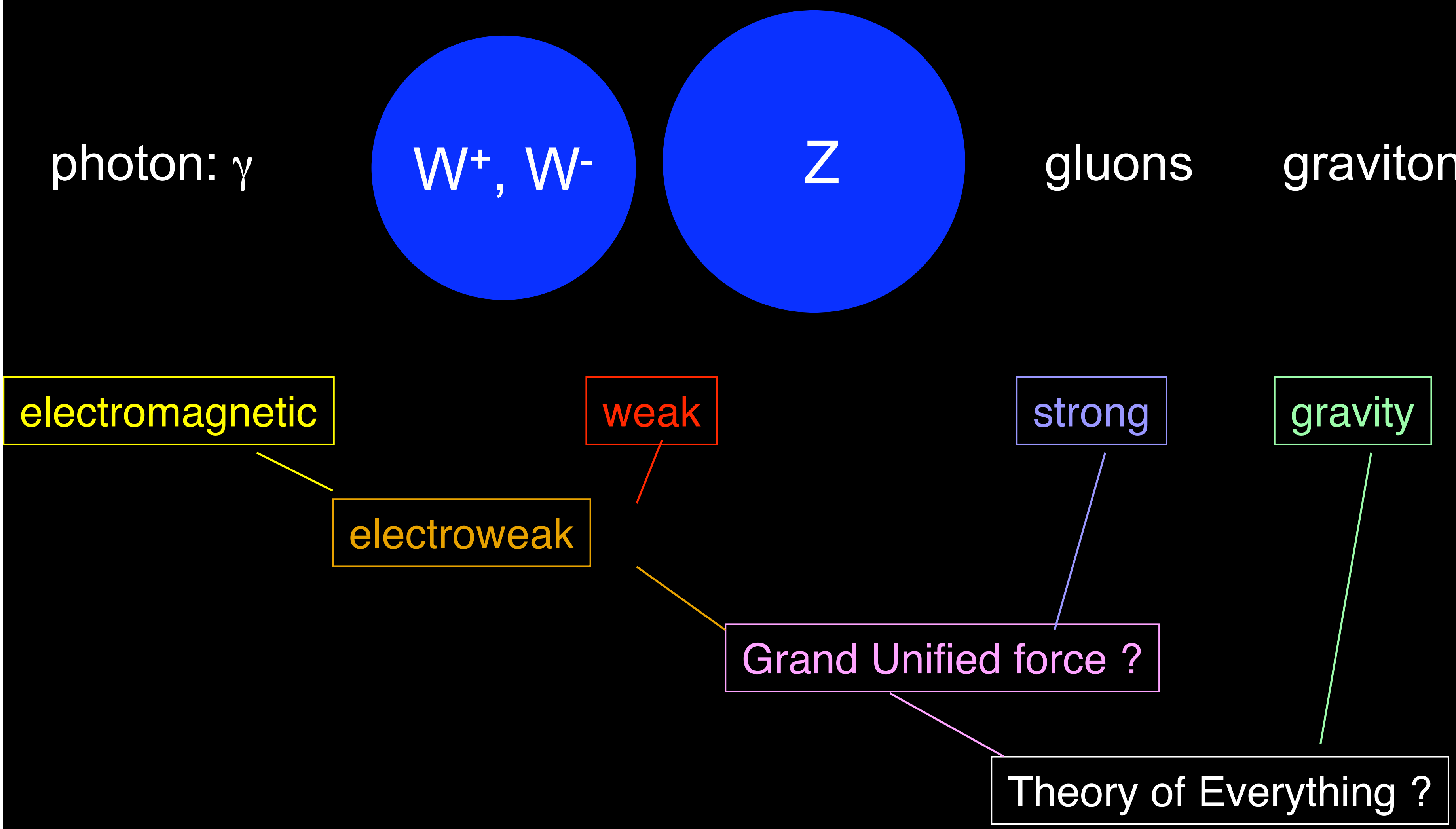




- Theoretically bound to be less than 160-500 GeV
- Experimentally bound to be >114 GeV
- Findable at LHC over full mass range with ~20 fb^{-1}

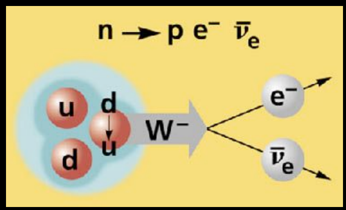
The Higgs boson will be found at LHC if it exists

Elementary Particles: Force Carriers



The "finetuning problem"

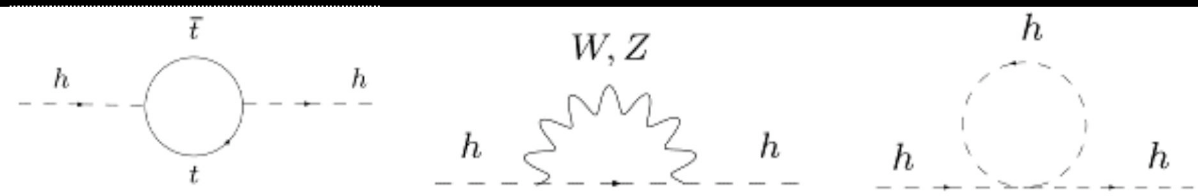
- Why is gravity is so much weaker than the weak force?
  - Newton: G_N=6.67 x 10^{-11} m^3kg/s^2 ~10^{-38} GeV^{-2}
  - Fermi: G_F=1.17 x 10^{-5} GeV^{-2}



- Or why is the W boson mass so small?
  - Weak scale: M_W ~1/M_{weak}=1/$\sqrt{G_F}$ ~10^2 GeV
  - Natural scale: M_{Planck}=1/$\sqrt{G_N}$~10^{19} GeV

⇒"Finetuning" required to make W and Higgs mass small

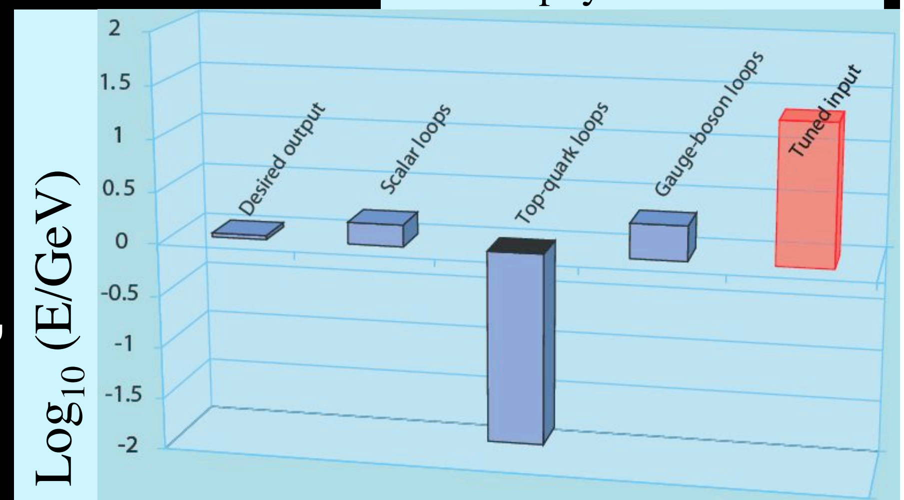
Finetuning Problem

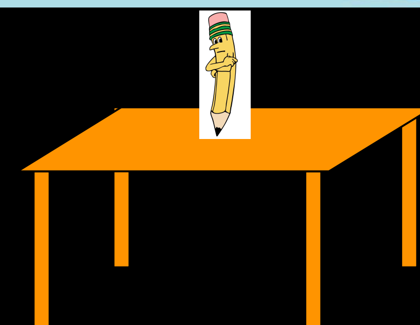


$$m^2_H \approx (200\ \text{GeV})^2 = m^2_H{}^{\text{tree}} + \delta\, m^2_H{}^{\text{top}} + \delta\, m^2_H{}^{\text{gauge}} + \delta\, m^2_H{}^{\text{higgs}}$$

- Free parameter $m^2_H{}^{\text{tree}}$ "finetuned" to cancel huge corrections
- Considered to be "unnatural"
  - Some unknown ad-hoc parameter introduced with superb precision
    - We were very lucky!

$M_{\text{new physics}}$=5 TeV

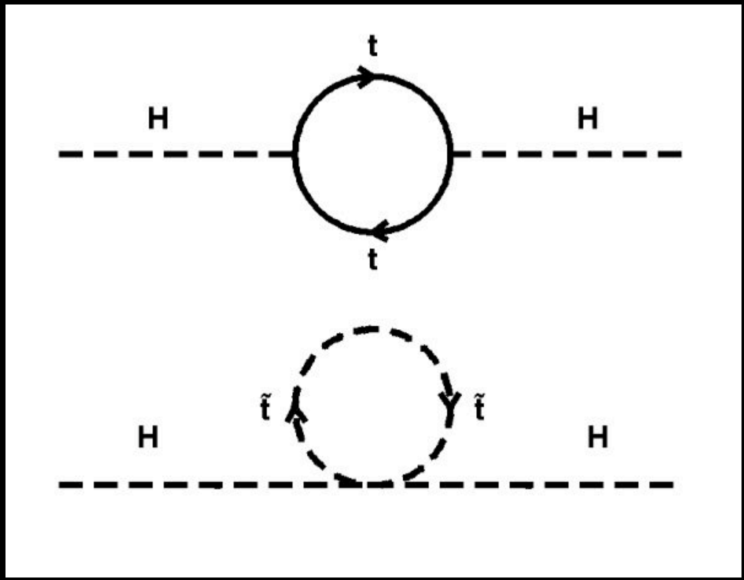


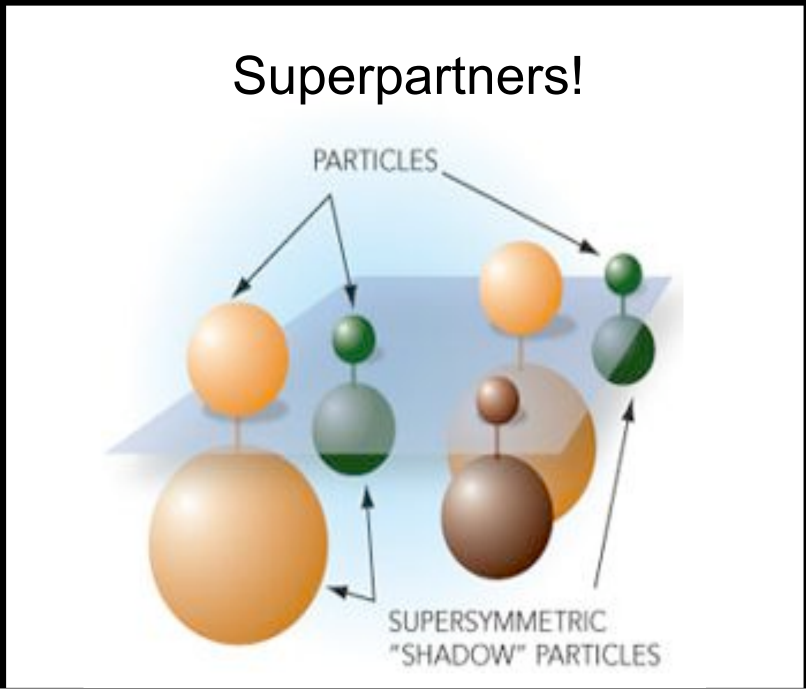


Seems wrong somehow

Solving the finetuning problem

- Add new particles
  - New loops cancel old loops!
    - Size of loops naturally the same
  - No hugely tuned ad-hoc parameter needed
- "Supersymmetric" particles
  - Each standard model particle has a partner, e.g.:
    - Electron => Selectron
    - Quark => Squark
    - Photon => Photino
    - W boson => Wino





Already happened in History!

- May seem "crazy" to have another set of particles introduced to solve aesthetic problem
- Analogy in electromagnetism:
  - Free electron has Coulomb field: $\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$
  - Mass receives corrections due to Coulomb field:
    - $(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\text{Coulomb}}.$
    - With $r_e<10^{-17}$ cm: $0.000511 = (-3.141082 + 3.141593)\ \text{GeV}.$
  - Solution: the positron!

$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}.$$

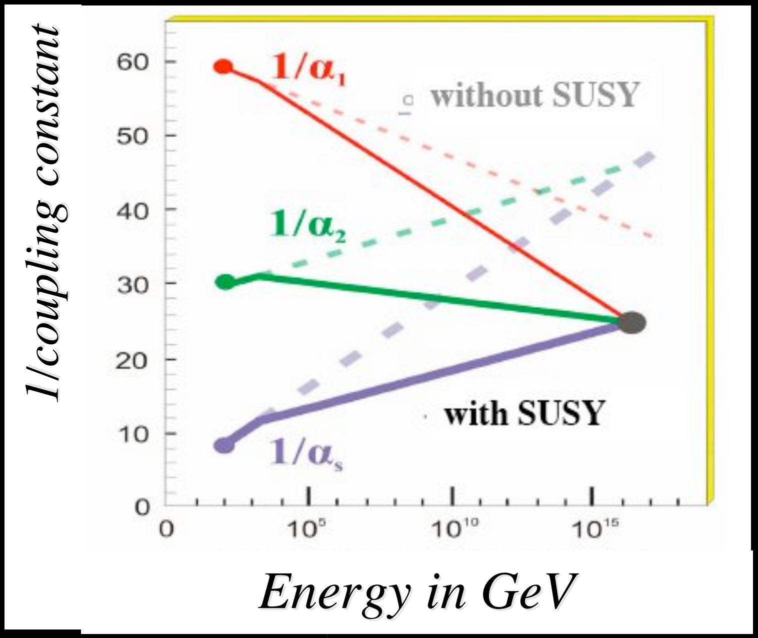
$\ll m_e c^2$

Hitoshi Murayama, UC Berkeley

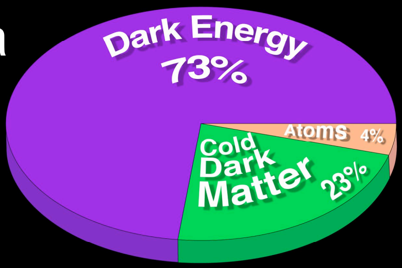
Problem was not as bad as today's but it resulted in new particle species: anti-particles

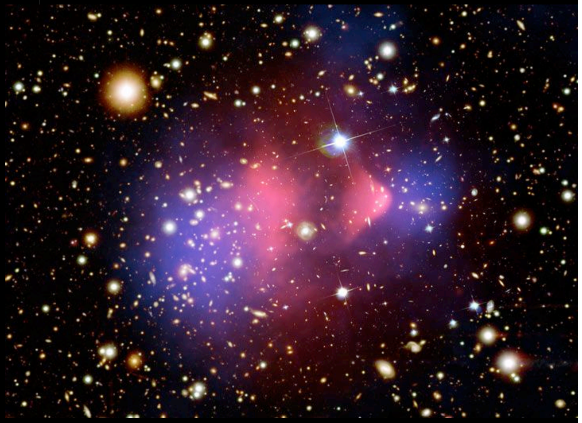
More virtues of Supersymmetry (SUSY)

- Electromagnetic, strong and weak force unify!
  - Miss unification in SM (barely)
  - Unify in SUSY if masses about 1 TeV!



- Includes candidate for dark matter with 0.1-1 TeV mass
  - Cosmology data point to such a particle
  - 5 times more than ordinary matter

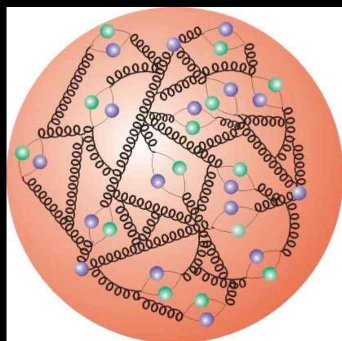




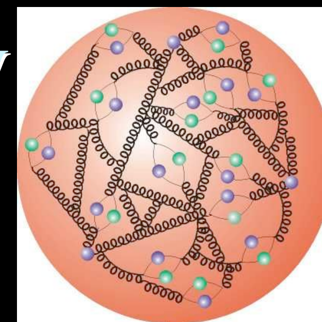
If SUSY particles are the solution to finetuning problem they will be found at the LHC

The Experimental Challenge

Proton-proton collisions

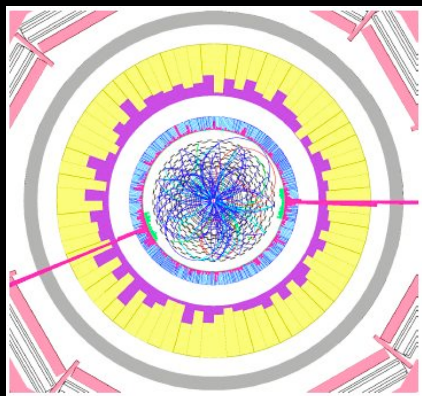


7 TeV → ← 7 TeV

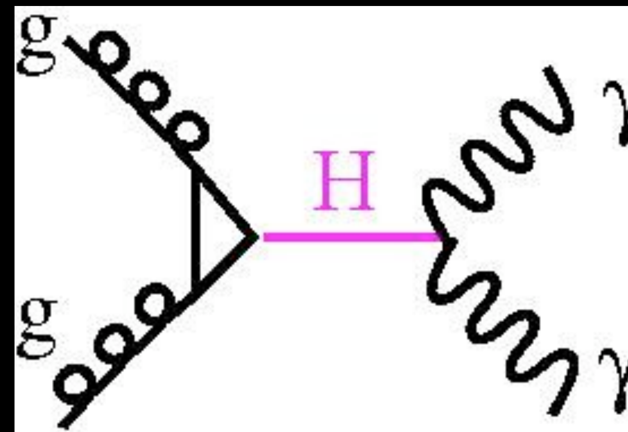


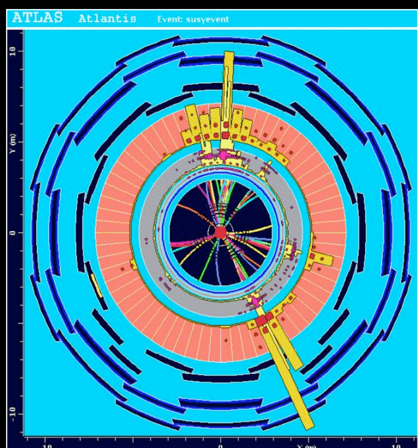
Complex events need to be resolved by high resolution detectors

The Experimental Challenge

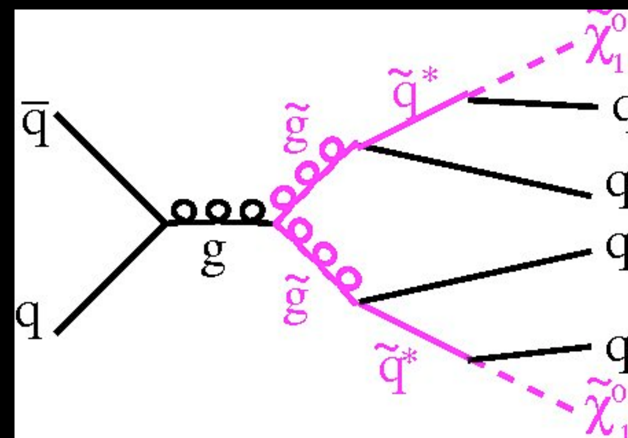


Higgs





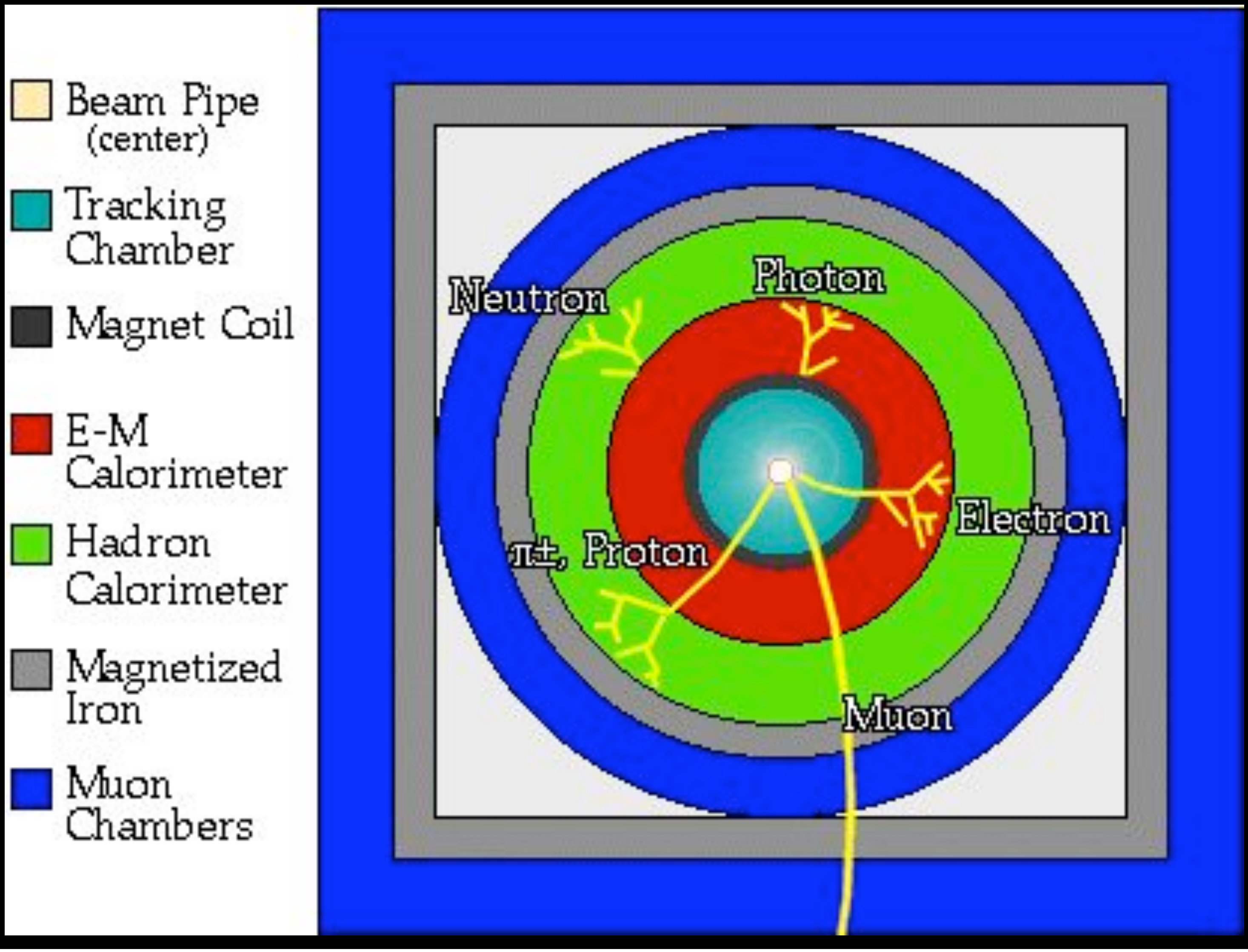
Supersymmetry



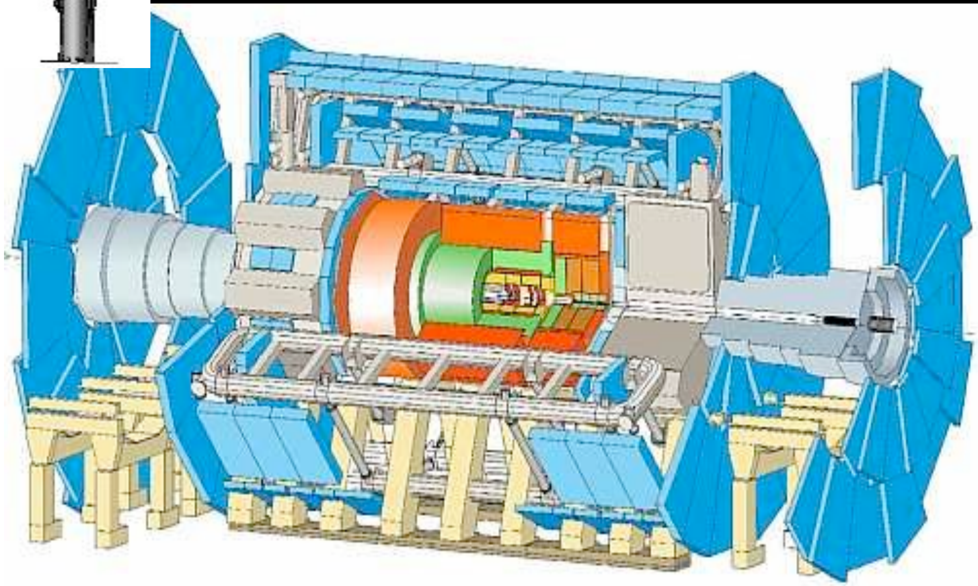
- Measured hits in detector
- => use hits to reconstruct particle paths and energies
- => estimate background processes
- => understand the underlying physics

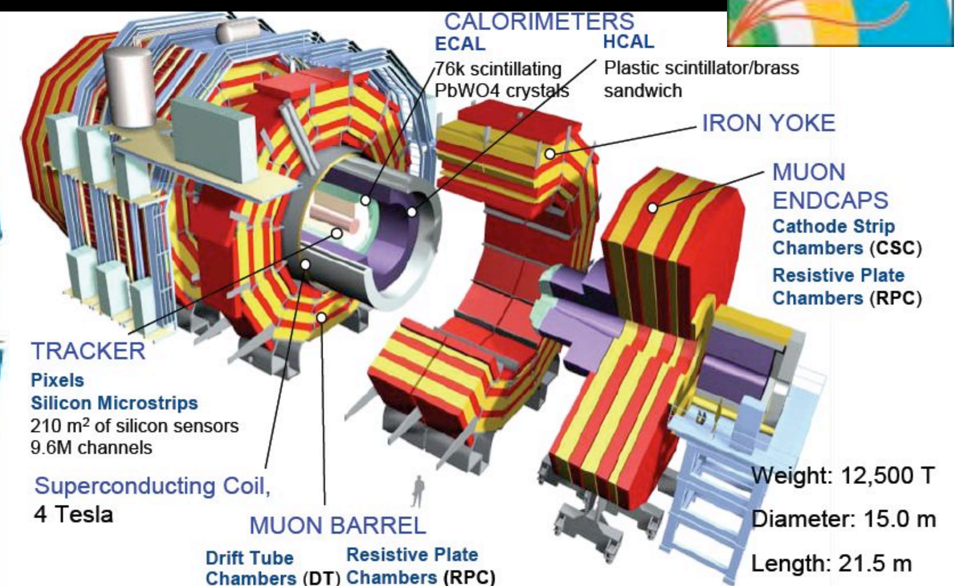
Particle Identification

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



ATLAS and CMS Detectors





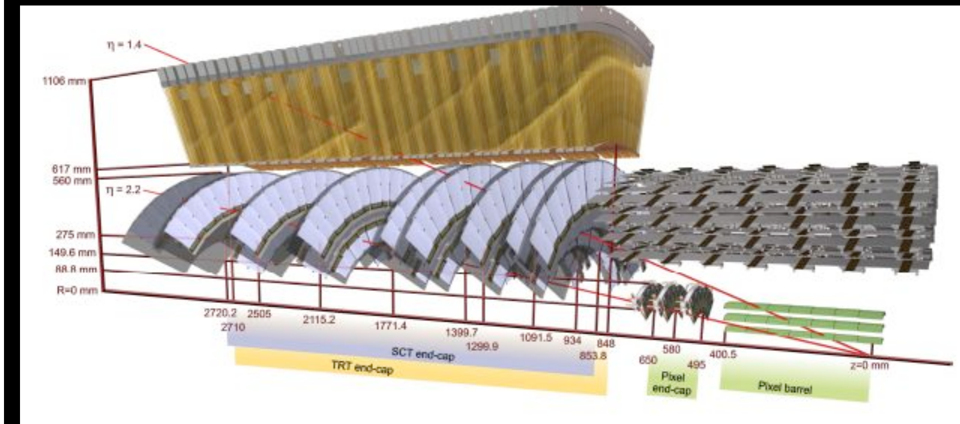
	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

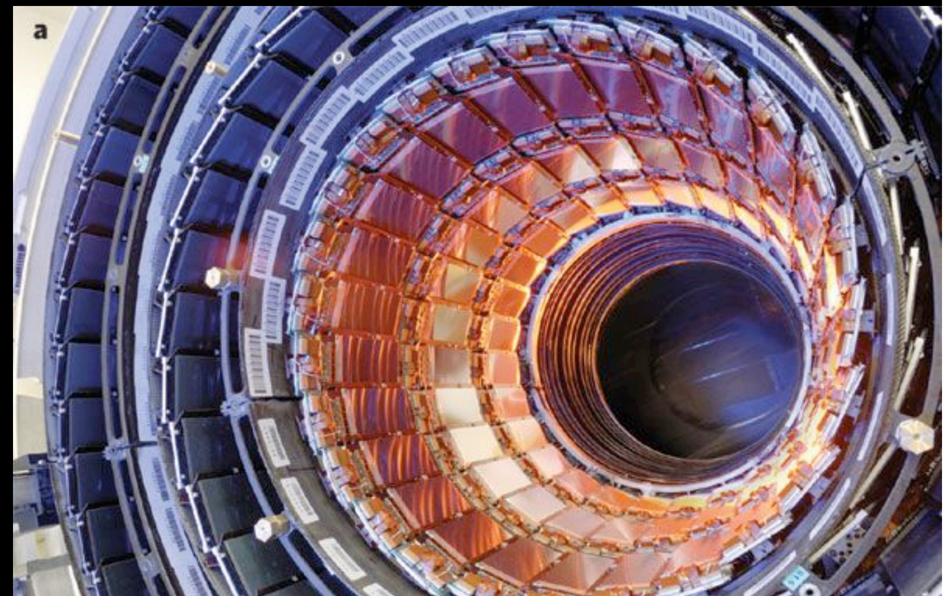
ATLAS and CMS in Berlin

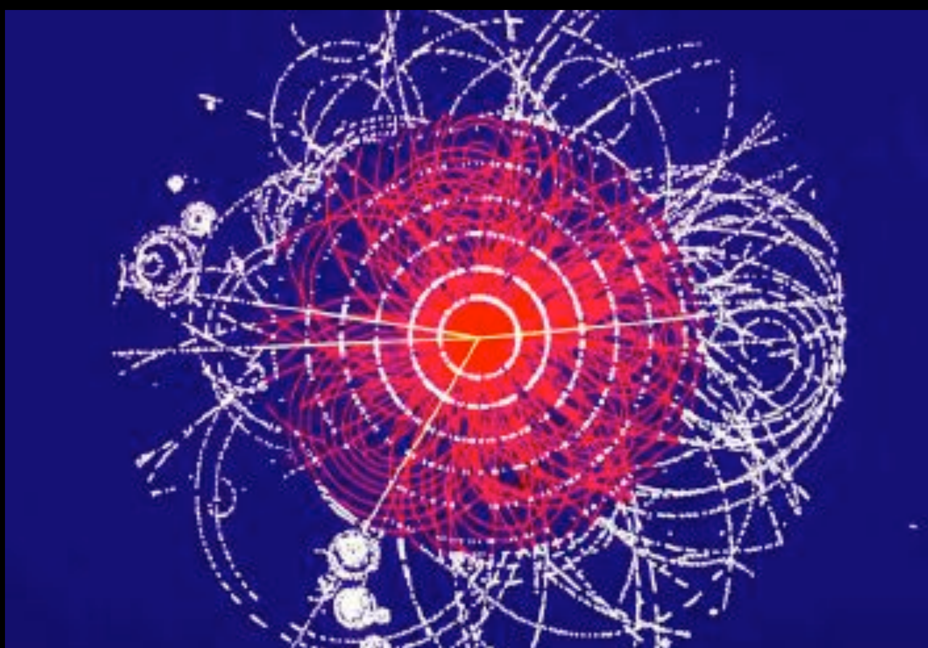
Detector Mass in Perspective

CMS is 30% heavier than the Eiffel tower

Tracking Detectors

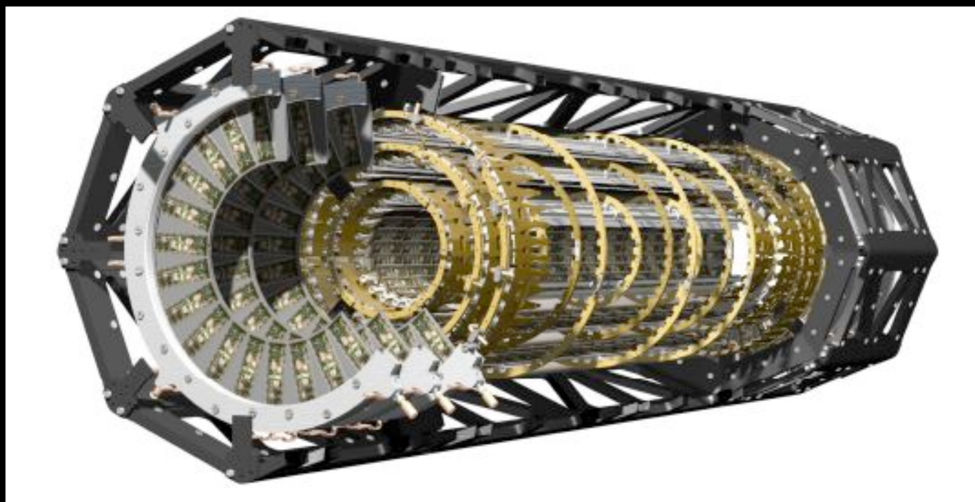


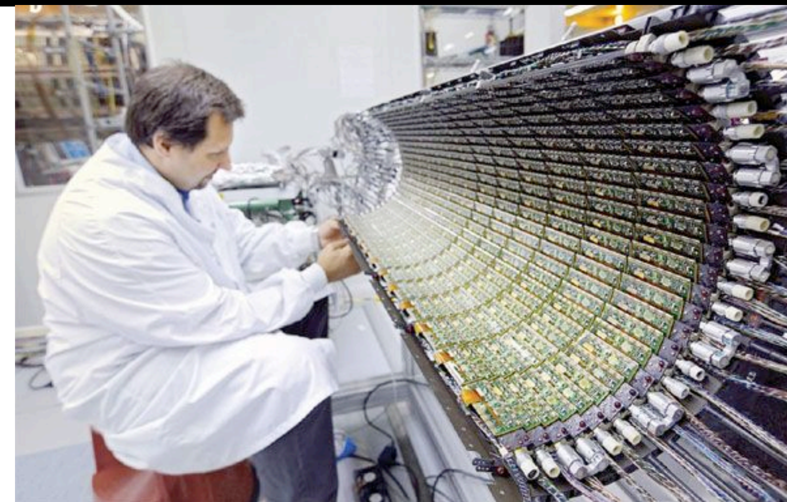




- **Tracking detectors**
  - ATLAS: TRT, silicon strips + pixels
  - CMS: silicon strips + pixels
- **CMS silicon area: 200 m^2**
  - Size of a football field

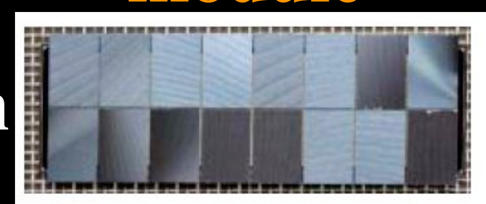
The ATLAS Pixel Detector



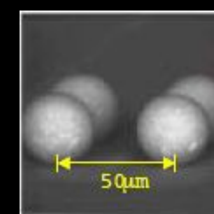


module

2 cm

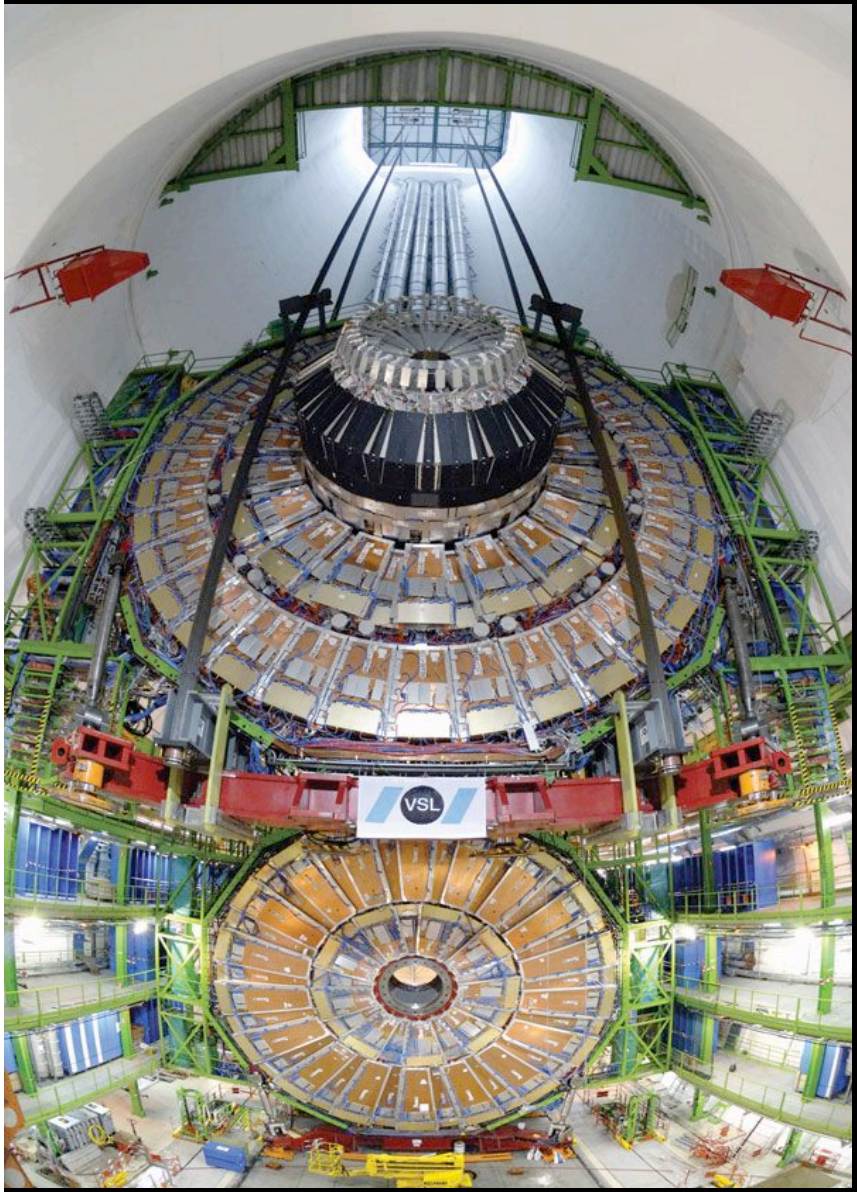


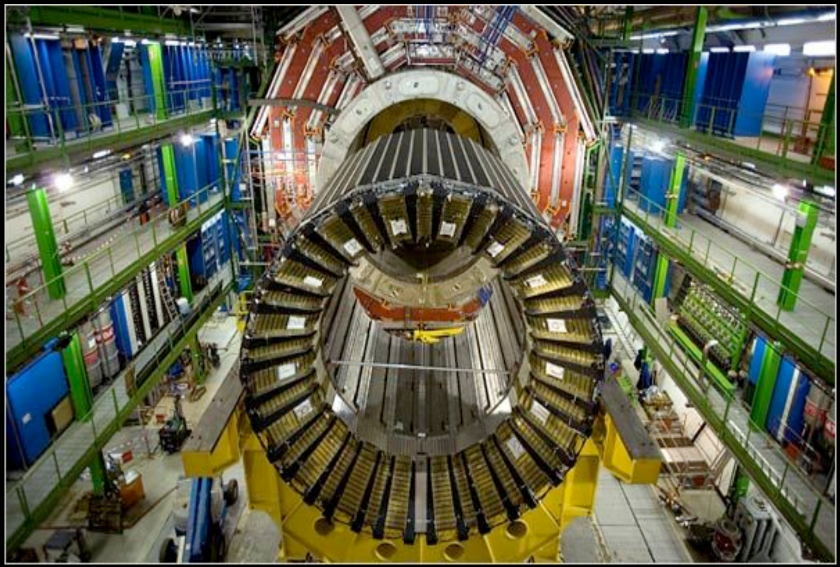
6 cm

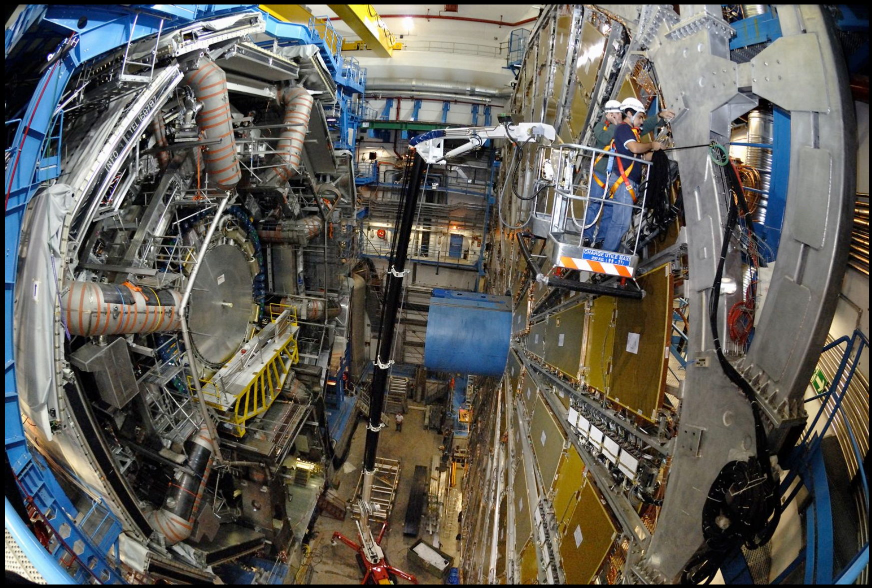


- Cylinder: L=1.4 m , R=12.25 cm
- 80,000,000 individual pixels arranged in modules:
  - 16 chips per module, 2880 pixels per chip => 46080 pixels/module
  - Distance between pixels: 50 µm (“pitch”)
- Designed and built largely in the US

Muon Systems and Calorimeters





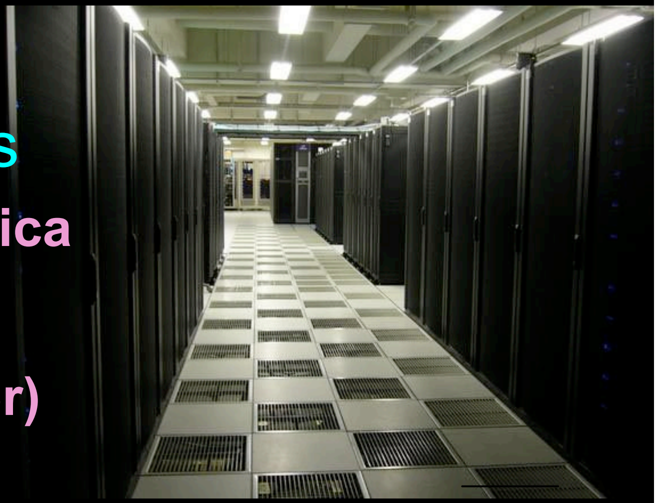


2000 Physicists from all over the World

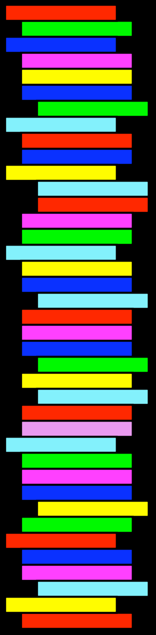
(including 400 PhD students)
+ many technician and engineers

Enormous Data Volumes

- **Pushing the computing limits!**
  - 1 second of LHC data: 1000 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:
    - **All the words spoken by humankind since its appearance on earth**



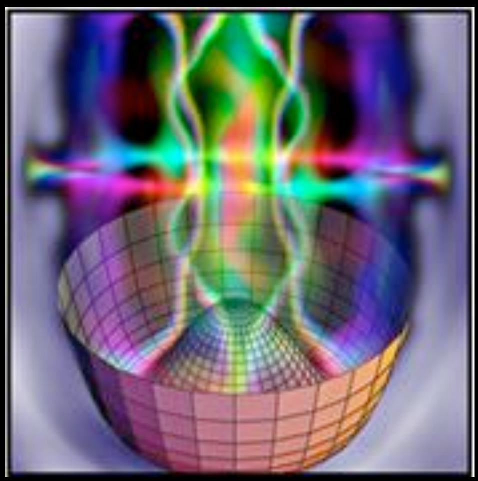
- **Solution: the "Grid"**
  - Global distribution of CPU power
    - More than 100 CPU farms worldwide share computing power



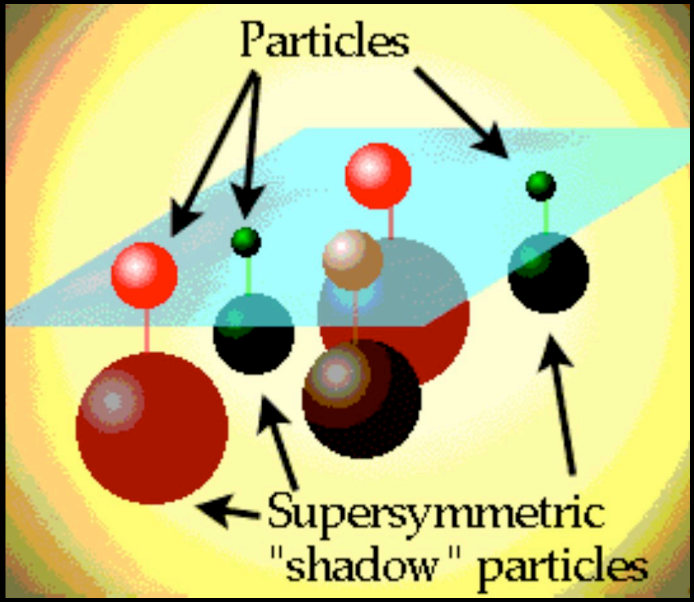
Searches for the Higgs Boson and Supersymmetry

Some Example Analyses

Finding the Higgs boson:
-with photons
-with Z-bosons



Finding a Supersymmetric World



Rates of Processes

- Much increased rates compared to previous collider

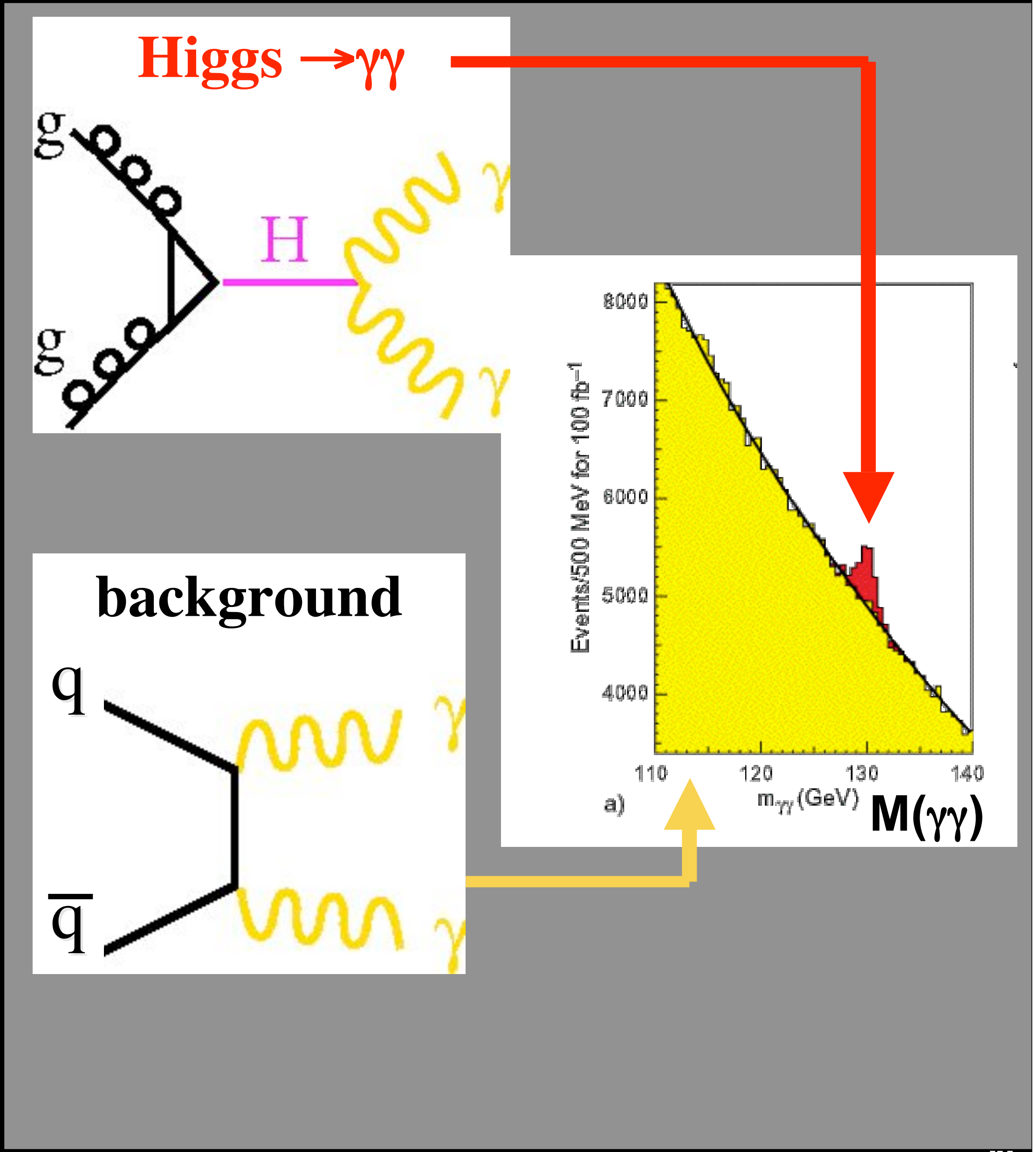
Process (mass)	Tevatron $\sqrt{s}$ =2 TeV	LHC $\sqrt{s}$=14TeV	Ratio
$W^{\pm}$ (80 GeV)	2600	20000	~10
tt (2x172 GeV)	7	900	~100
gg->H (120 GeV)	1	40	~40
$\tilde{\chi}^{+}_{1}\tilde{\chi}^{0}_{2}$ (2x150 GeV)	0.1	1	~10
$\tilde{q}\tilde{q}$ (2x400 GeV)	0.05	60	~1000
$\tilde{g}\tilde{g}$ (2x400 GeV)	0.005	100	~20000
Z' (1 TeV)	0.1	30	~300

- Discovery opportunity early
  - Biggest jump in energy since SppS that discovered W's and Z's

Finding the Higgs Boson (with photons)

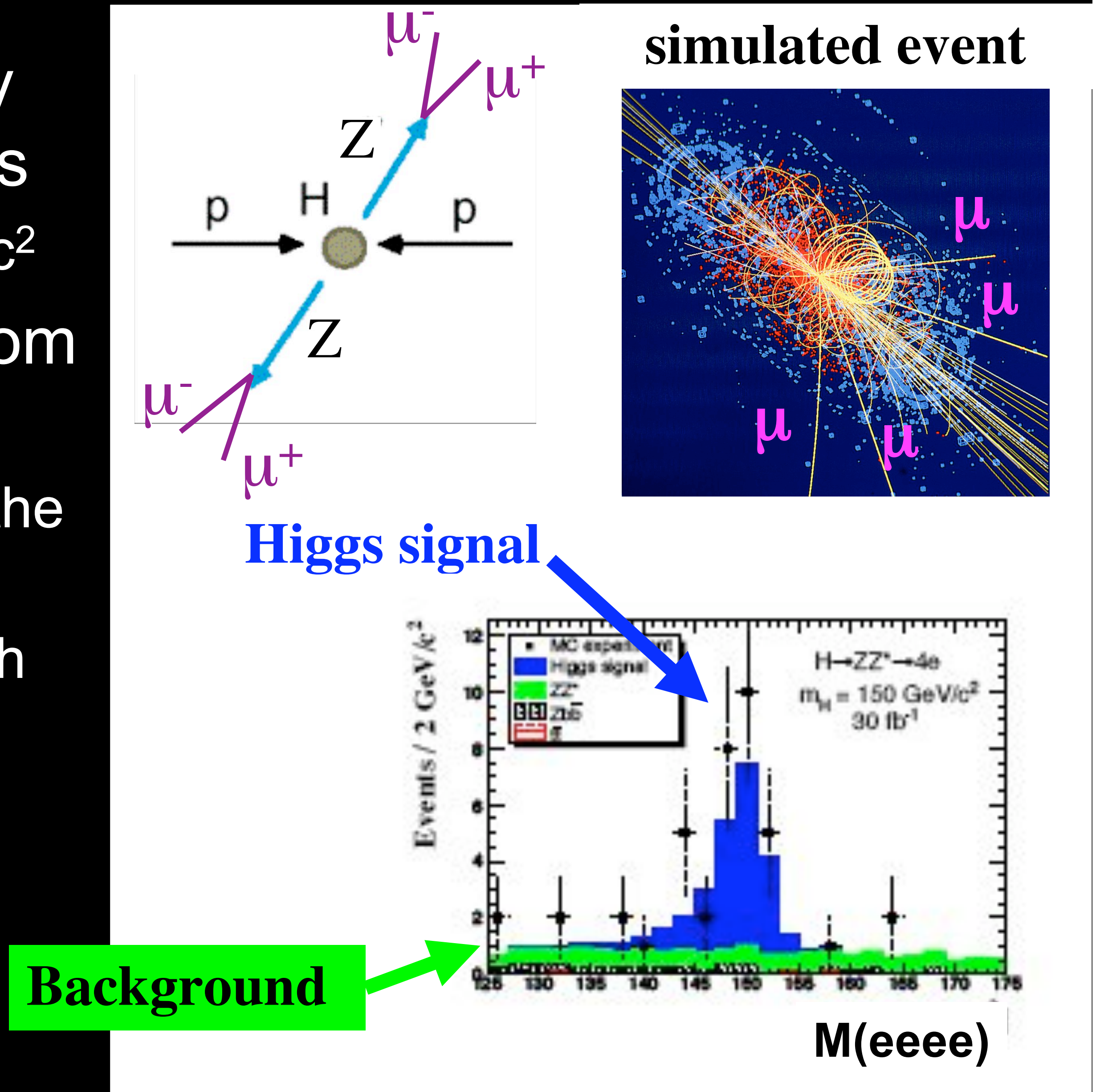
- Find 2 high energy photons
  - If M(H)<130 GeV/c^2
- Separate signal from backgrounds
  - Backgrounds can look exactly the same
  - but for γ's from Higgs:

$$M(H)=M(\gamma\gamma)=\sqrt{[(E_1+E_2)^2-(p_1+p_2)^2]}$$

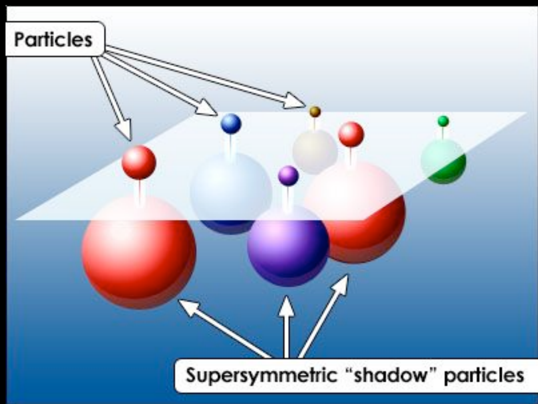


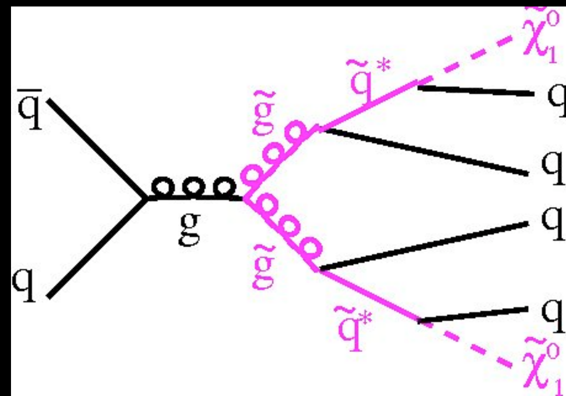
Finding the Higgs Boson (with Z's)

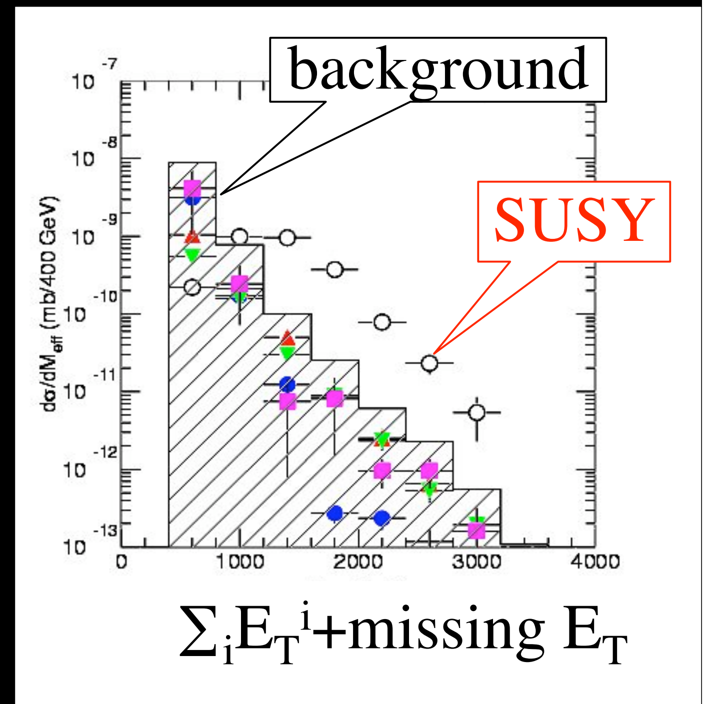
- Find 4 high energy muons or electrons
  - If $M(H)>130$ GeV/c^2
- Separate signal from backgrounds
  - Again calculating the invariant mass
  - Backgrounds much smaller than in diphoton case:
    - Easier!

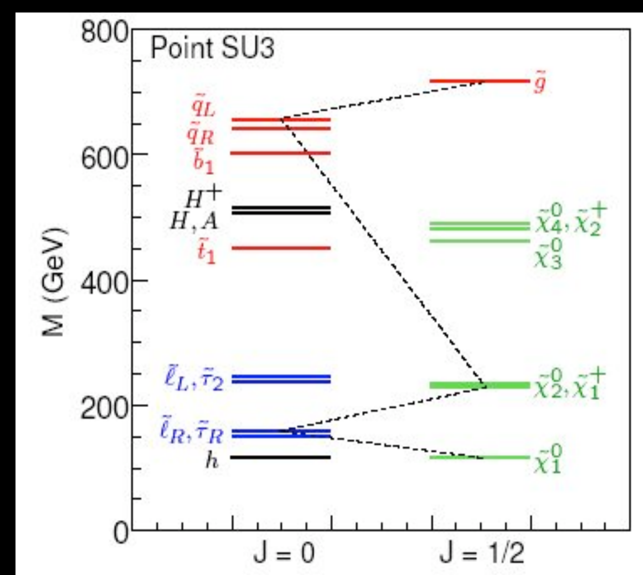


Finding a Supersymmetric World









- **Supersymmetric particles decay into ordinary particles:**
  - Measure decay products
  - Dark matter particle ($\tilde{\chi}_1^0$) escapes detector unseen:
    - Momentum balance tell us presence of dark matter particles (“missing E_T”)
- **Search strategy:**
  - Search for many high energy particles plus large missing E_T

=> do spectroscopy of Supersymmetric World

Many Other Possibilities…

Current Status of the LHC

Original LHC Startup Plan

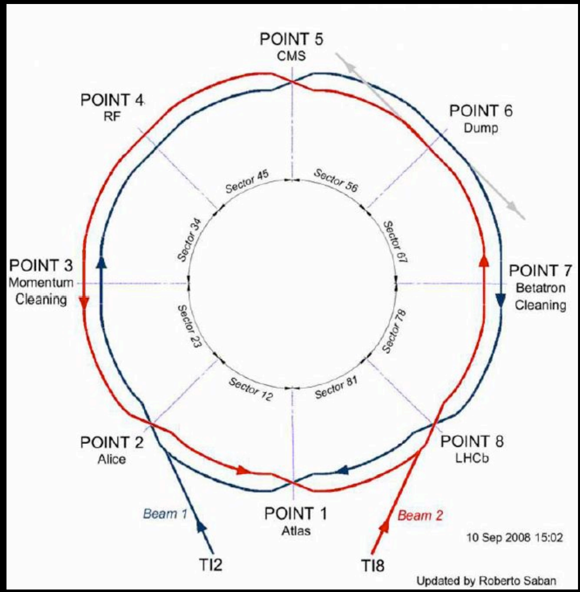
- September 10th 2008:
  - First circulating beam at 450 GeV
- 2-4 weeks later
  - Collisions of beams at 450 GeV
- November-December ‘08
  - Collide beams at 5 TeV
    - 7 of the 8 sectors had been commissioned up to 5.5 TeV
- December ‘08 - June ‘09
  - Shutdown to commission machine to design energy
- June ‘09-November ‘09
  - A few fb^{-1} of luminosity at $\sqrt{s}$=14 TeV
- Then… continue to improve each year

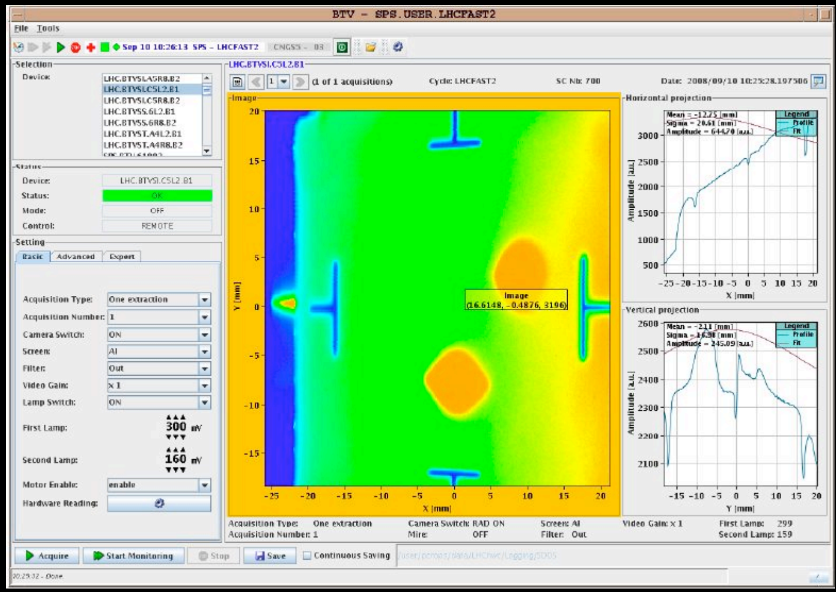
September 10th 2008

- First beam circulation broadcasted live on TV worldwide
- Worked very well: accomplished within <1h

Beam circulation

- The machine physicists were amazed how well it all worked
  - Lot's of optimism spread in the community
  - The machine looked "great"





In the News…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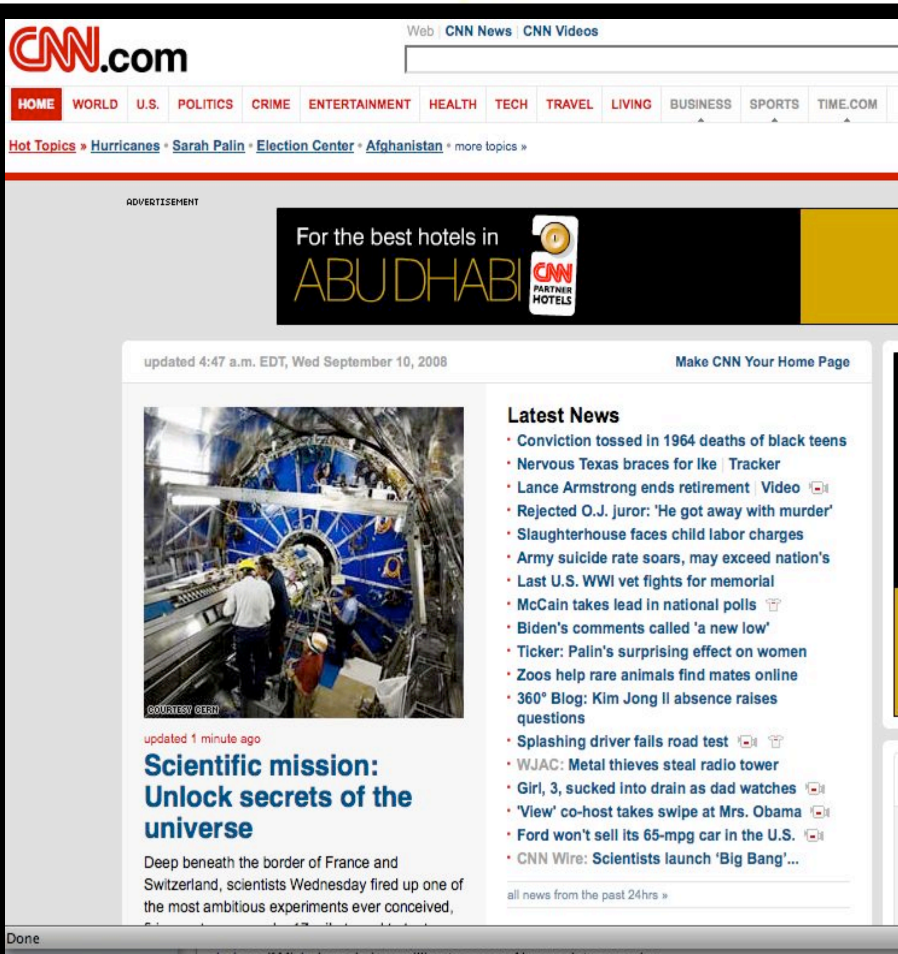
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Start für Teilchenbeschleuniger
Dem Urknall auf der Spur
In Genf ist der Teilchenbeschleuniger "Large Hadron Collider" (LHC) in Betrieb gegangen. Wissenschaftler wollen mit der weltgrößten Anlage im Atomforschungszentrum CERN den Urknall simulieren und die Materie erforschen. Kritiker des Experiments warnen vor Schwarzen Löchern. [mehr]
Quarks&Co: Das Mikroskop der Physiker [wdr]
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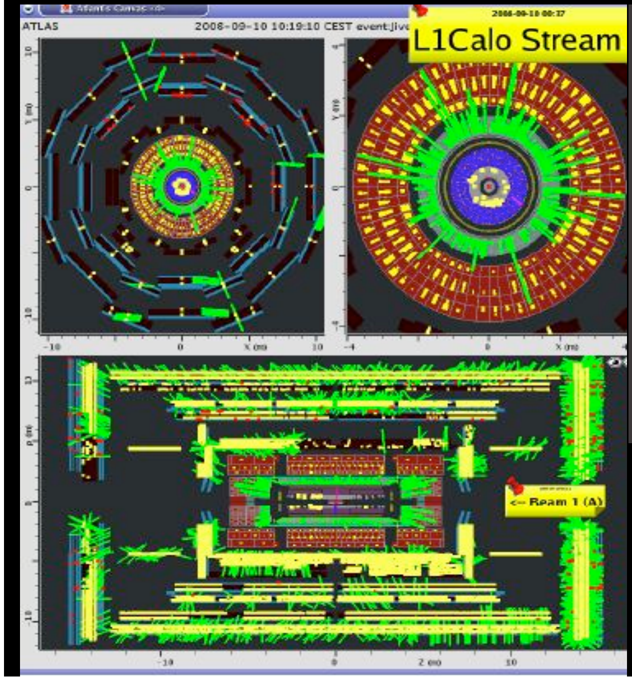
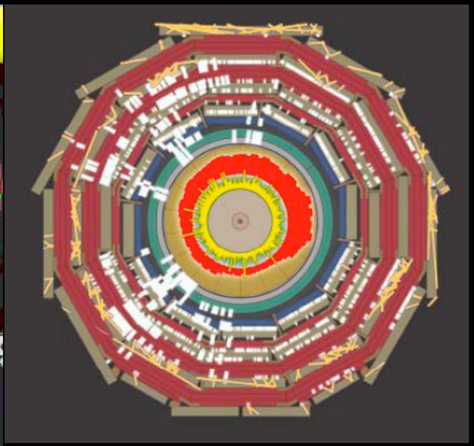
Bilder

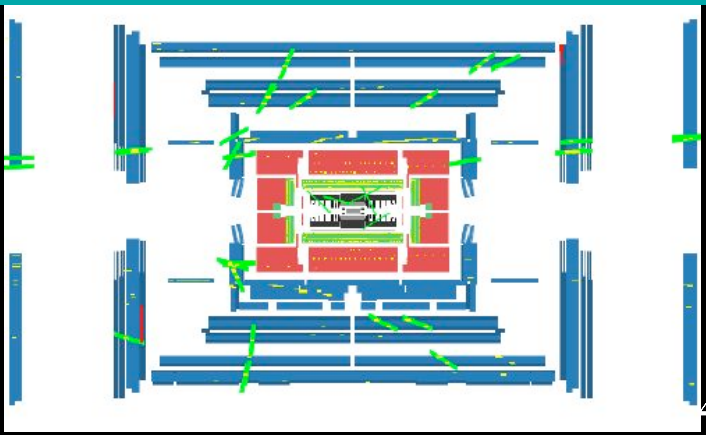
Excitement in ATLAS and CMS

"Splash events": from beam dump into collimators





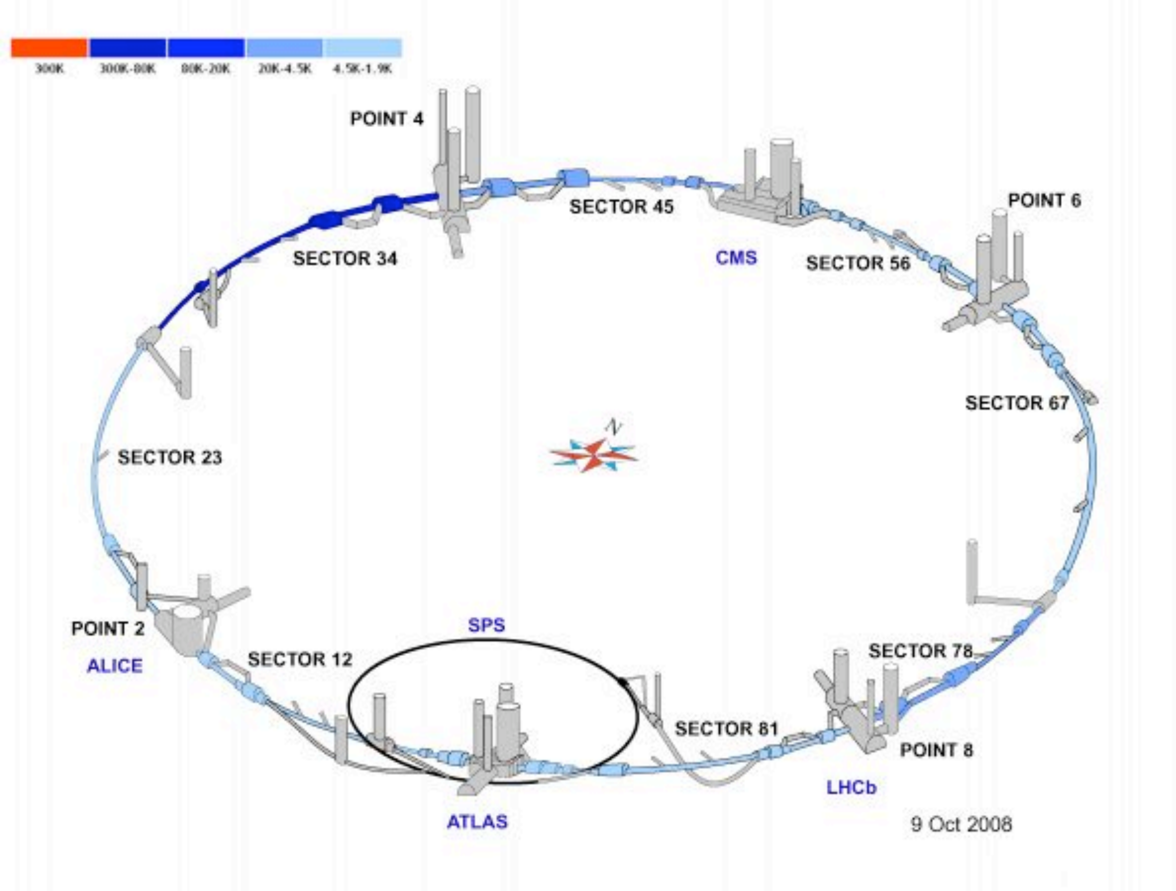
Beam halo muons From circulating beam



September 19th: the problem

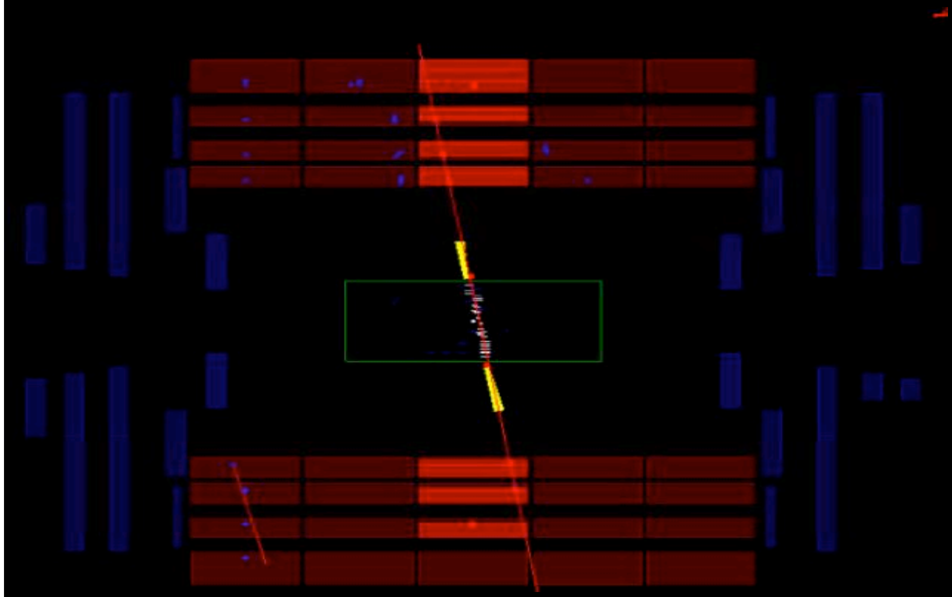
- Some (minor) problems occurred when trying to bring beams to collisions
  - Hope was to get collisions before September 24th
  - Meanwhile the remaining 8th sector (34) was commissioned up to 5.5 TeV
- Major incidence occurred in sector 34 probably due to faulty connection between two magnets:
  - Causing a quench of about 100 magnets
  - A large amount of helium was released into the tunnel
- Sector 34 is now being warmed up and the damage is being assessed
- Hope is to start up again in ~May or so
  - But not really known until cause fully understood

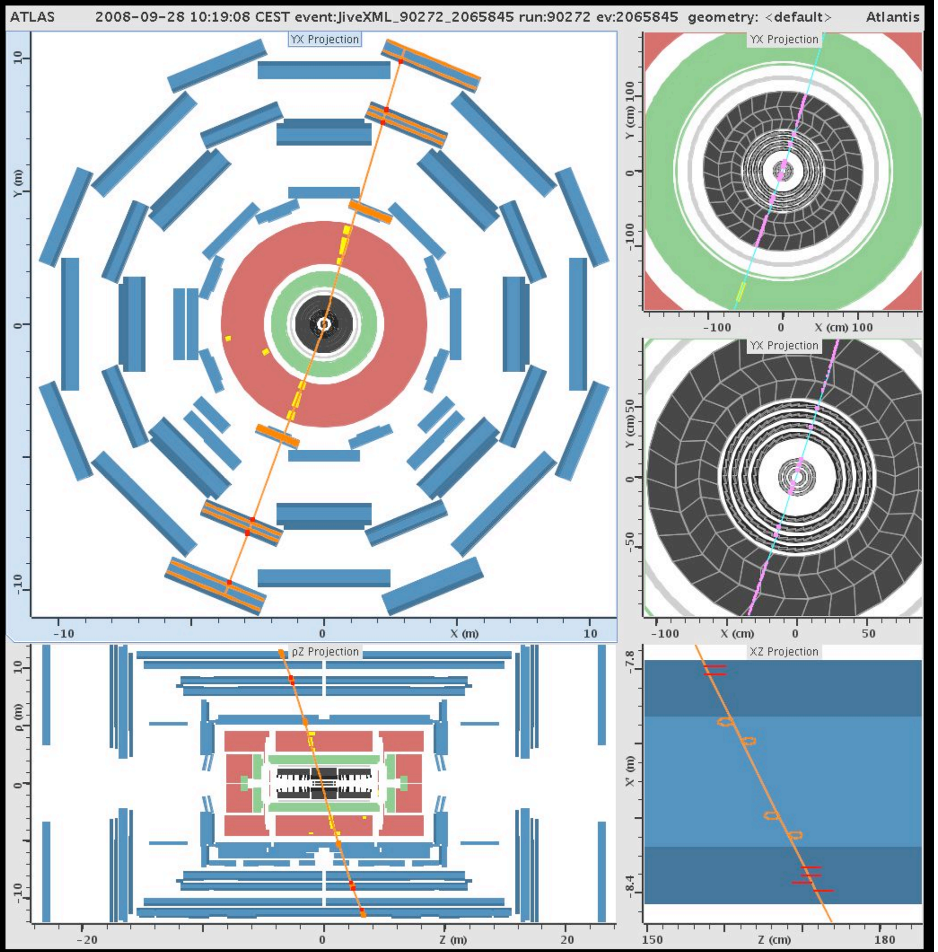
LHC Cooling Status



- Sector 34 now at 200 K
  - Expected to be at room temperature in 1-2 weeks
- Document on incidence was released today
  - no detailed schedule yet

Cosmic Muon Data





- **Experiments are currently running cosmic data taking**
  - **already understand response of detectors quantitatively**
  - **Be well prepared for beams**

Conclusions

- The LHC will finally probe the "TeV scale" ($r = 10^{-17}$ cm)
  - Known to be special since 1934
- The LHC will definitely answer some (and hopefully many) fundamental questions
  - What is the origin of mass?
  - Do supersymmetric particles explain the hierarchy problem and/or the Dark Matter?
  - …
- After a 15 year design and construction phase the LHC experiments first beam was seen
  - Major incidence with accelerator delayed collisions to next year
  - Cosmic muons used to understand and optimize detector performance
- Hopefully next year first physics analyses can be done
  - Discoveries will likely come 2-3 years later