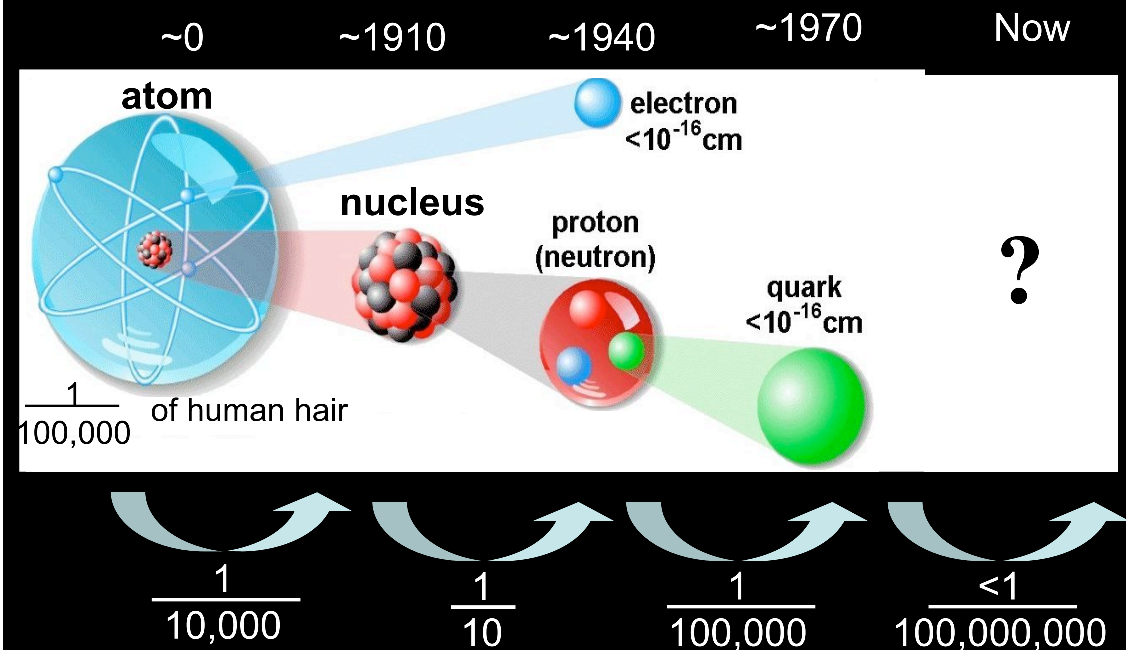
Exploring Nature's Fundamental Forces and Particles with the Large Hadron Collider

Beate Heinemann

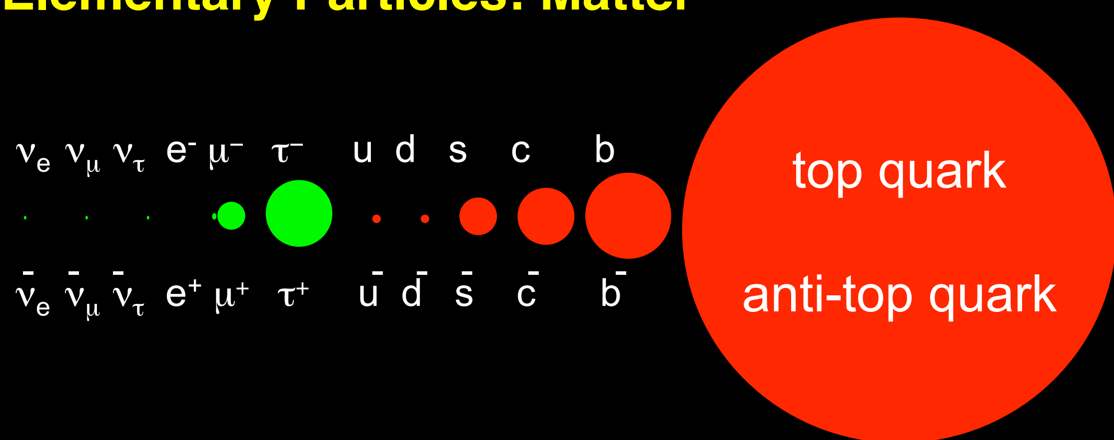
Who am I?

- I am a new associate professor here in Berkeley
- PhD (University of Hamburg / Germany)
  - at H1 experiment (with 300 people) at the ep collider HERA in Hamburg, Germany
  - I measured the structure of the proton and probed the electroweak interaction
- Postdoc (University of Liverpool / UK)
  - CDF experiment (with 700 people) at the Tevatron $p\bar{p}$ collider near Chicago
  - I did measurements that test the strong interaction the electroweak interaction and searched for new particles
- Now
  - working here on the ATLAS experiment (with 2000 people) at the Large Hadron collider

We learned a lot in the last century

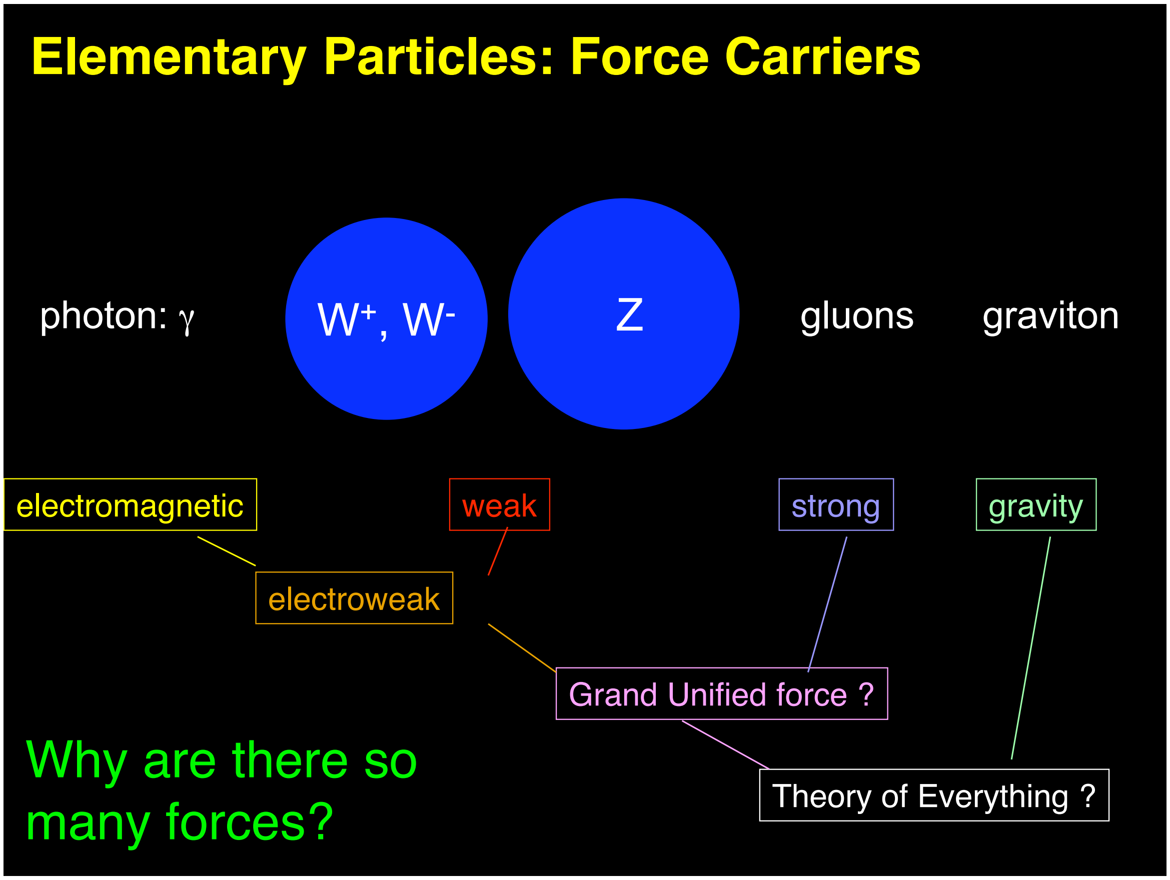


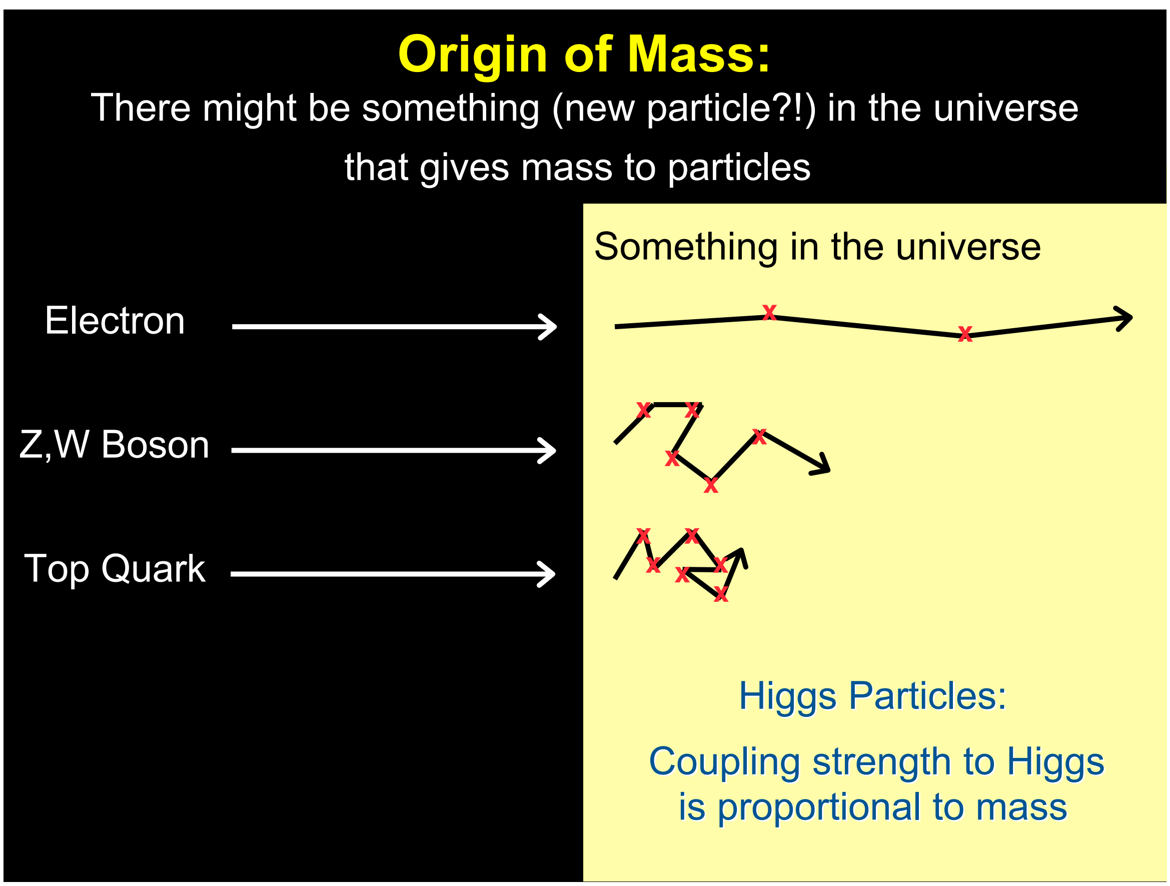
Elementary Particles: Matter



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

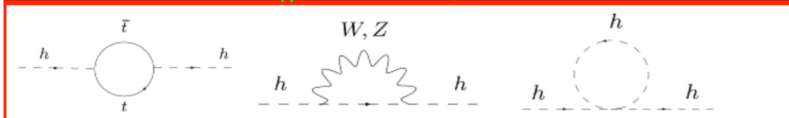
Why are there so many leptons and quarks?
And why do they have so different masses?


Elementary Particles: Force Carriers
photon: γ
W+, W-
Z
gluons
graviton
electromagnetic
weak
strong
gravity
electroweak
Grand Unified force ?
Theory of Everything ?
Why are there so many forces?


Origin of Mass:
There might be something (new particle?!) in the universe that gives mass to particles
Something in the universe
Electron
Z,W Boson
Top Quark
Higgs Particles:
Coupling strength to Higgs is proportional to mass

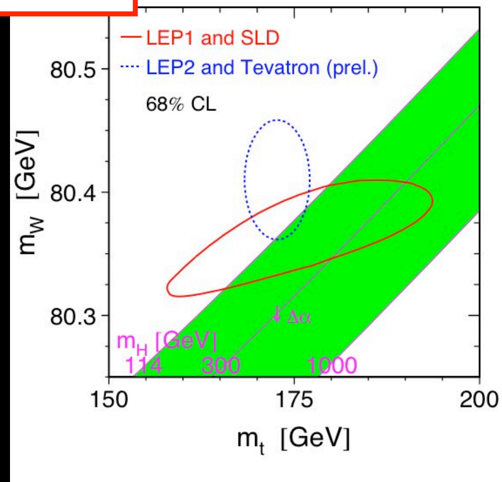
What we know about the Higgs

- LEP e^+e^- collider:
  - Excluded $m_H<114$ GeV/c^2



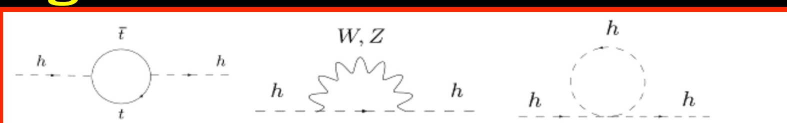
$m^2_H \approx (200\text{ GeV})^2 = m^2_H{}^{tree} + \delta\, m^2_H{}^{top} + \delta\, m^2_H{}^{gauge} + \delta\, m^2_H{}^{higgs}$

- Indirect constraints:
  - Masses of top quark, W boson and Higgs boson related:
    - $m_W \propto m_{top}^2$, $m_W \propto \ln(m_H)$
  - $m_H<144$ GeV at 95% CL
    - if Standard Model is correct



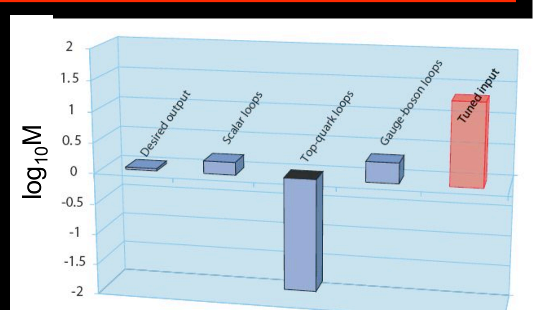
Higgs mass is between 114 and ~144 GeV or SM is invalid

Fine tuning in the Standard Model



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

- Large fine-tuning required:
  - Huge ad-hoc correction to achieve m_H=100 GeV:
    - $10^{19}-10^{17}=100$
  - It's incredible:
    - Like thickness of human hair (50 μm) compared to distance from earth to sun (1.5×10^{11} m)
    - Like knowing a position of something to better than 1nm on the equator (4×10^7m)



C. Quigg

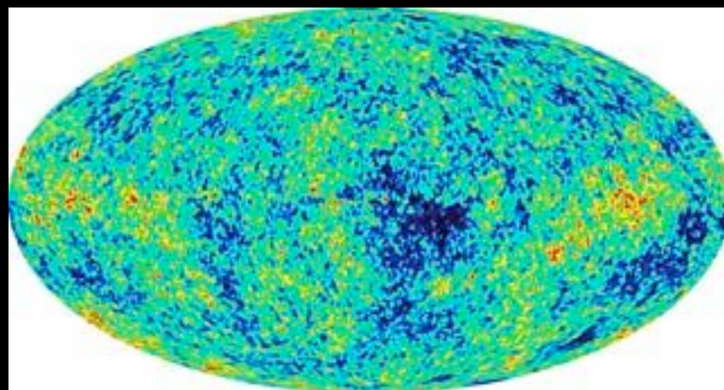
Even a problem if new physics mass > 5 TeV!

"Hierarchy problem":

Can be solved by new physics with M<5 TeV

WMAP satellite

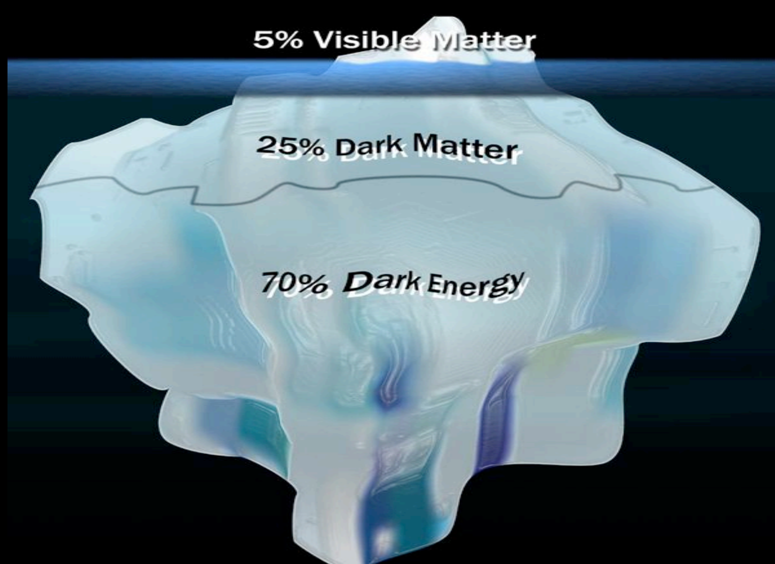
- Probes Cosmic Background radiation from Big Bang:
  - T ≈2.7 K
  - Colors specify the temperature



- (Lack of) isotropy tells us about particles in universe

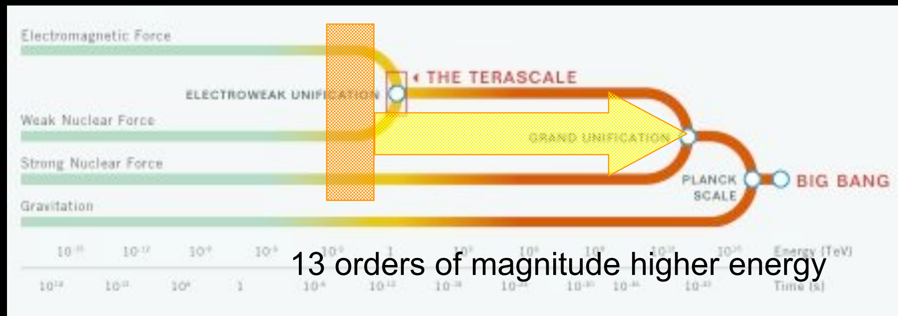
Nobel Prize 2006 to George Smoot for ancestor COBE

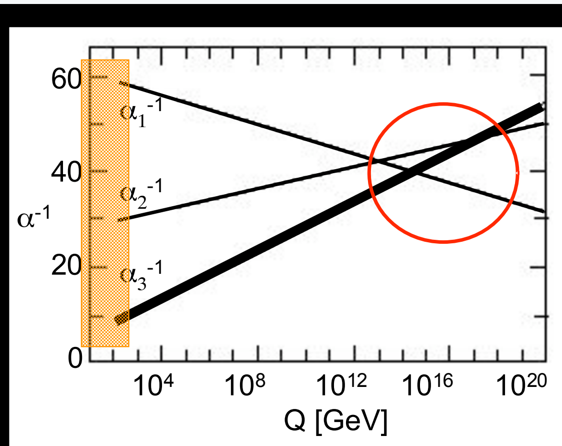
Cosmology Data



- We only know (very precisely) 5% of all matter!

What is Dark Matter and what is Dark Energy?





The Standard Model fails to unify the strong and electroweak forces.

Supersymmetry (SUSY)

- Double number of elementary particles:
  - SM fermion => SUSY boson
  - SM boson => SUSY fermion
- Many Advantages:
  - Removes asymmetry between bosons and fermions
  - Can explain cold dark matter:
    - Lightest SUSY particle (LSP) is stable
  - Unification of strong, electromagnetic and weak force at 10^{16} GeV
  - Stabelizes Higgs sector
- Disadvantages:
  - Not observed any SUSY particles yet => symmetry must be broken

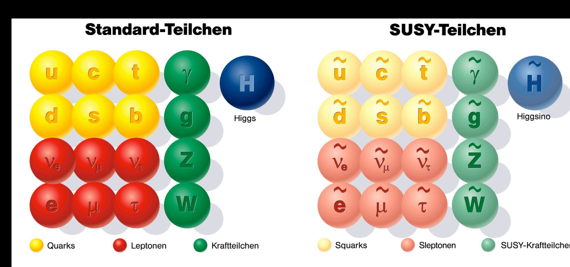
Symmetry between
fermions (matter) and bosons (forces)
“Undiscovered new symmetry”

e → e+, e-

superparticle → e, $\tilde{e}$

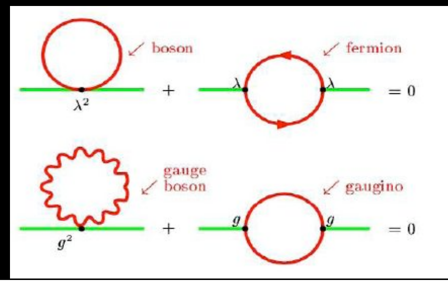
spin 1/2 spin 0

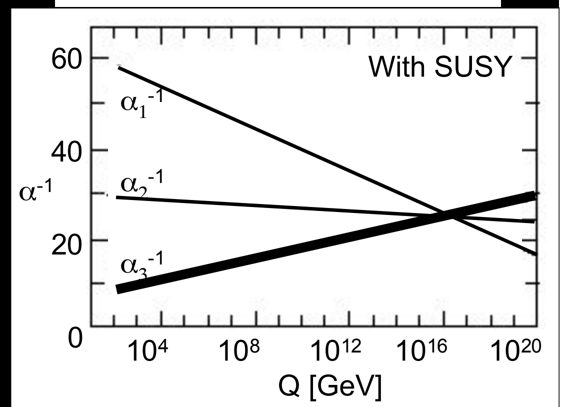
$M_e \neq M_{\tilde{e}}$



How SUSY Solves the problems

- If Mass ≤ a few TeV
  - Cancellation of fermion and boson diagrams
    - No divergence
    - No ad-hoc fine-tuning needed
  - Changes slop of coupling constants:
    - Exact unification of three forces!
  - Lightest SUSY particle ("LSP") fits very well as dark matter

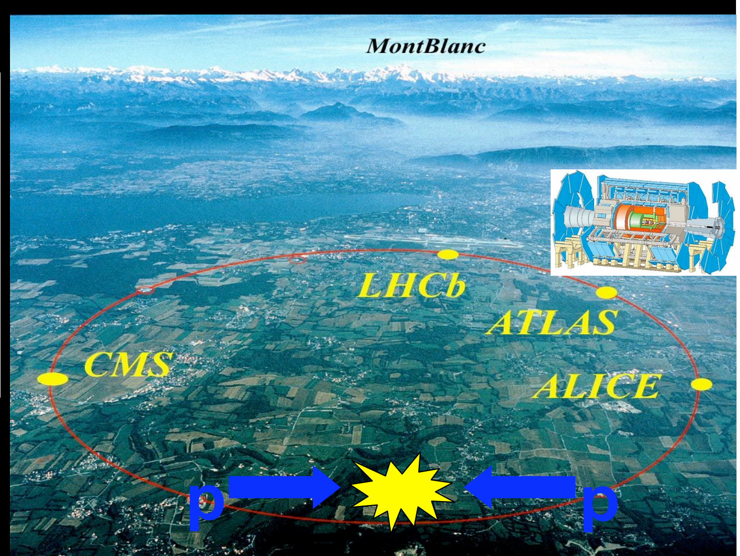




Coincidence !?! => We will find out at the LHC

The Large Hadron Collider (LHC)

(time difference 9h)

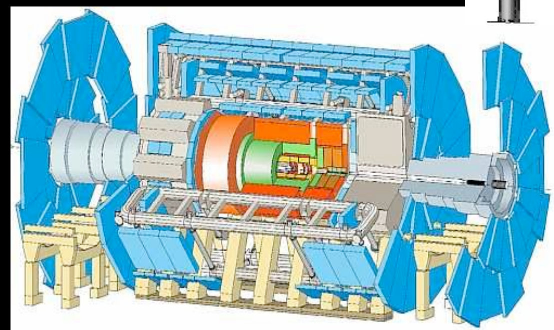


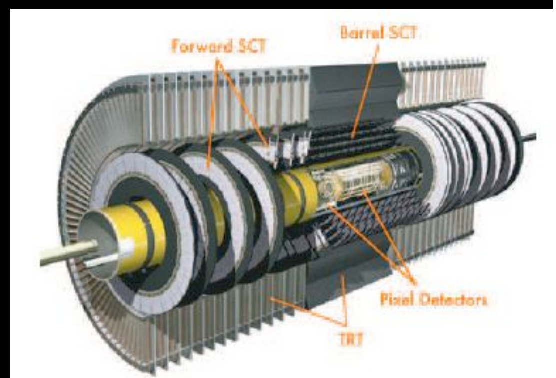
$\sqrt{s} \approx 14$ TeV

Operation begins in summer 2008

The ATLAS Detector

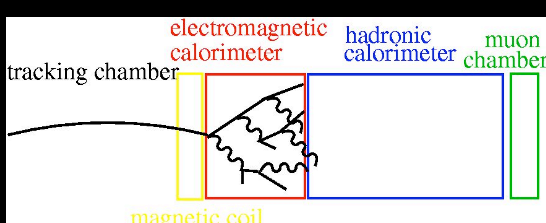
- General:
  - Weight ≈7000 tons
  - Length=42m, height=22m
  - Consists of many subcomponents
- Muon measurements:
  - Muon spectrometer
- Energy measurements
  - Electromagnetic calorimeter
  - Hadron calorimeter
- Charged particle momenta
  - Solenoid provides B-field
  - Transition Radiation Tracker (TRT)
  - Silicon strips (SCT)
  - Silicon pixels (80M pixels)
    - Largely designed and built in Berkeley



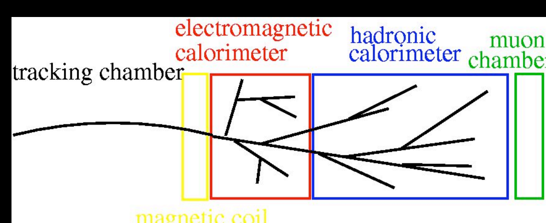


Detector designed to distinguish particle types

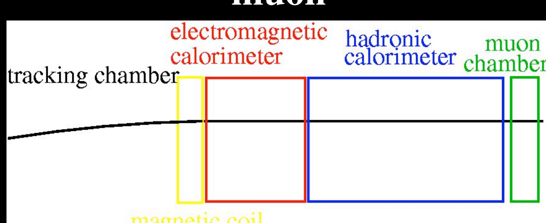
electron



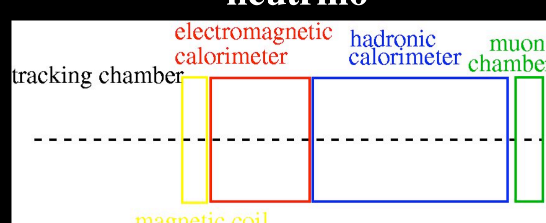
charged pion or proton



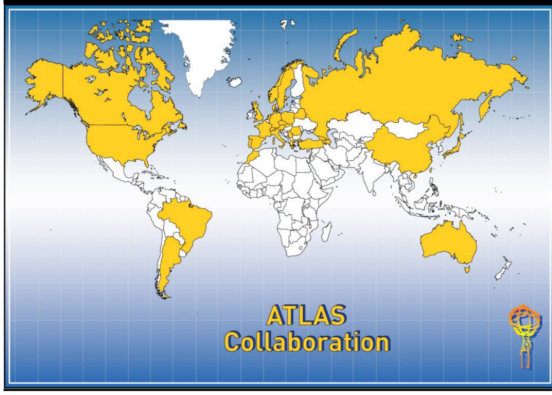
muon



neutrino



ATLAS Collaboration

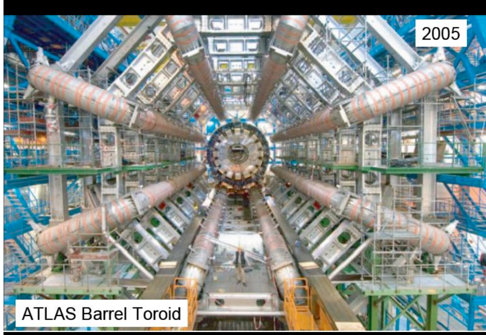


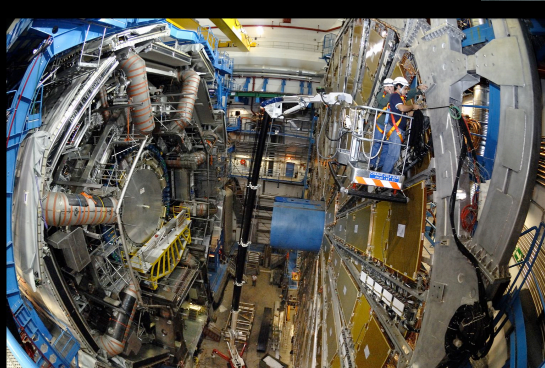
35 Countries
165 Institutions
2000 Scientific Authors total

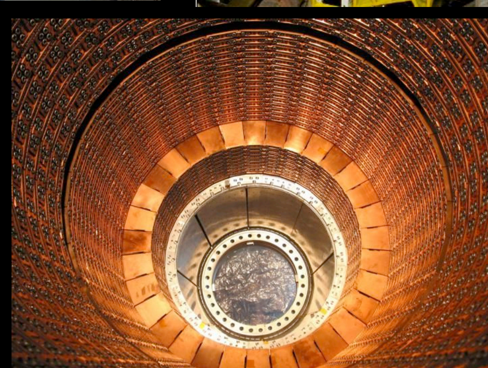
Very international enterprise

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, **Berkeley LBL and UC**, HU Berlin, Bern, Birmingham, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Regina, Ritsumeikan, UFRJ Rio de Janeiro, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Yale, Yerevan

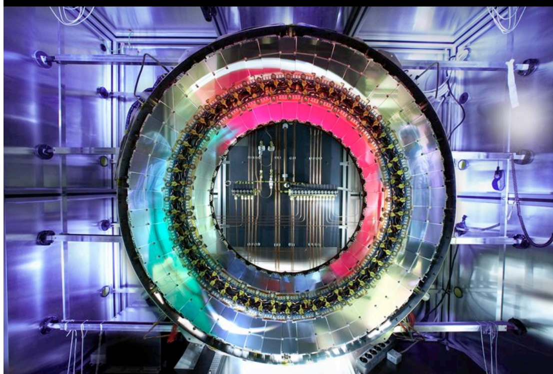
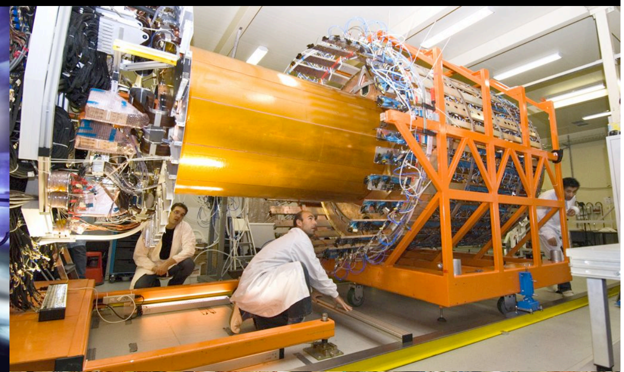
ATLAS Muon System and Calorimeters

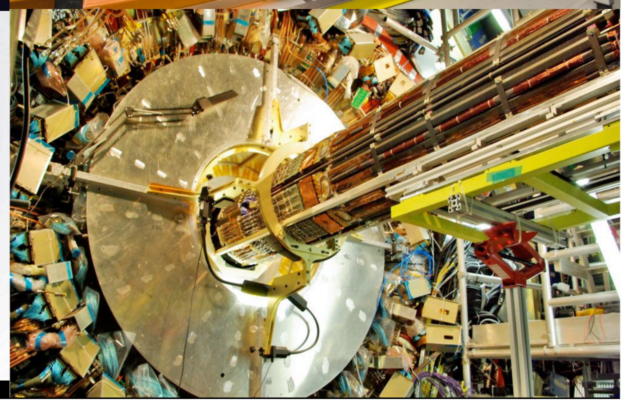




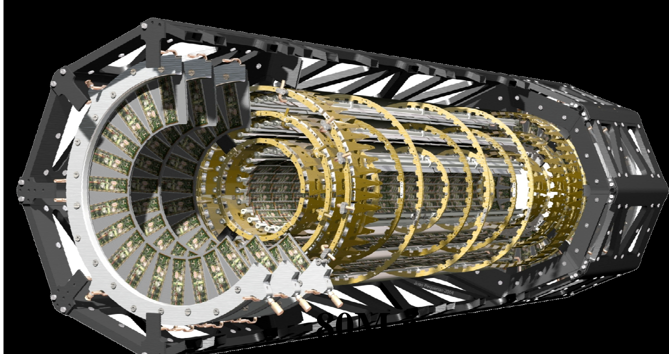


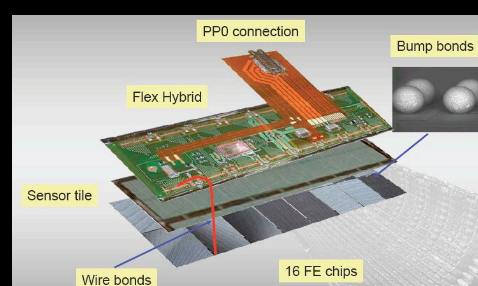
ATLAS Tracking Detectors

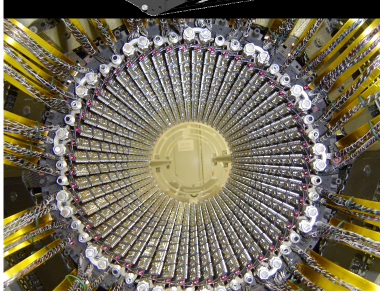





ATLAS Pixel Detector



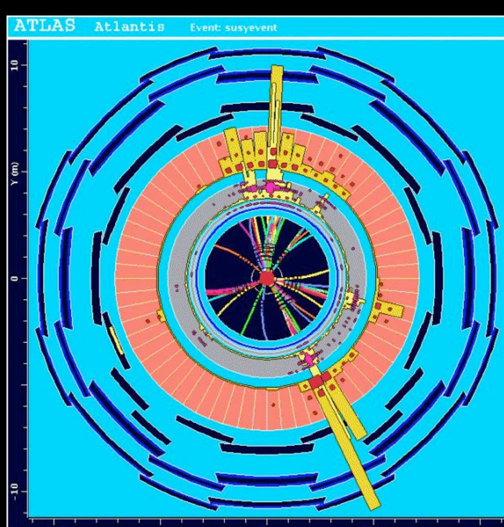


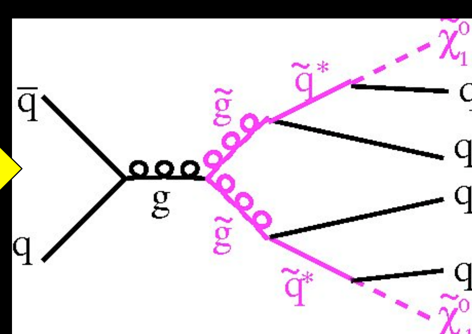


- 80 million pixels in 1744 modules:
  - 50x400 μm
  - High precision construction:
    - Support structure made of carbon fibre
  - Cooled to -10° C
- Novel readout chip
- 100's of meters of cables to get signal read out

A Part of the Berkeley Group

The Challenge

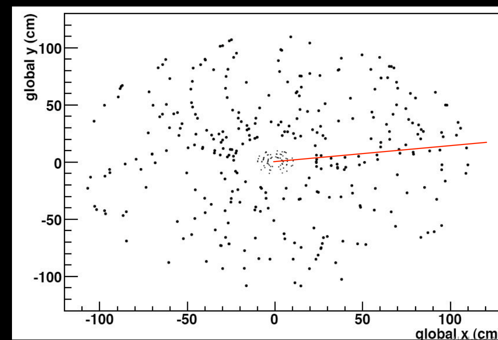


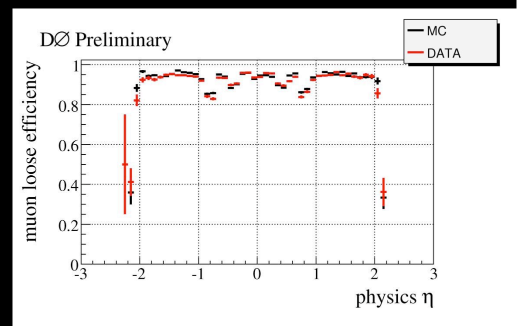


Measured hits in detector =>
understand the underlying physics

How does one do that?

- Reconstruction algorithms turn hits into measurements:
  - e.g. tracking algorithms turn hits into trajectories
- Simulations tell us expected signatures for physics processes
  - Tune simulation to accurately model detector
- Use simulation to study how signal and backgrounds behave
  - Develop analysis strategy and then apply it to real data



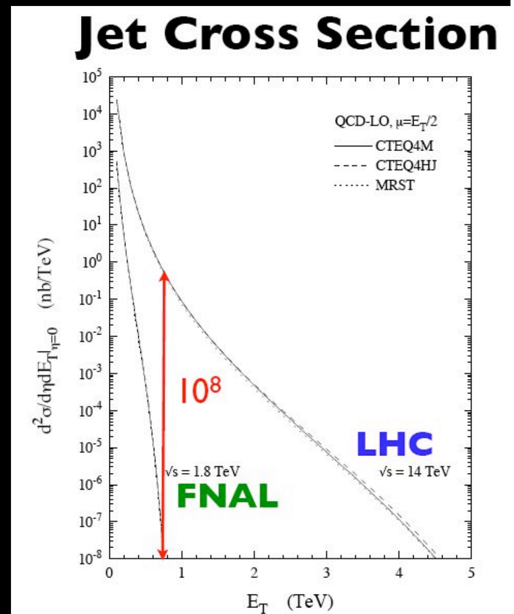


Main LHC Physics Goals

- Discover the Higgs boson
  - Or rule out its existence
    - Puts theorists into big trouble
- Discover new particles with M≈ 0.5-5 TeV
  - Maybe supersymmetry
    - discover dark matter in the laboratory
  - Maybe there is something else
    - Maybe something noone has thought of!
  - Maybe there is nothing
    - Puts theorists into big trouble
- Measure masses of the top quark and the W boson more precisely
- …

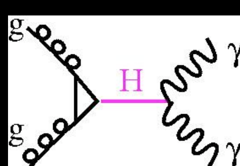
Physics Opportunities at LHC

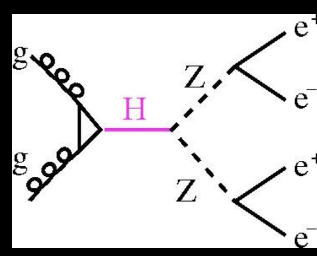
Cross Sections of Physics Processes (pb)	Tevatron	LHC	Ratio
$W^{\pm}$ (80 GeV)	2600	20000	10
$t\bar{t}$ (2x172 GeV)	7	800	100
gg->H (120 GeV)	1	40	40
$\tilde{\chi}^{+}{}_{1}\tilde{\chi}^{2}{}_{0}$ (2x150 GeV)	0.1	1	10
$\tilde{q}\tilde{q}$ (2x400 GeV)	0.05	60	1000
$\tilde{g}\tilde{g}$ (2x400 GeV)	0.005	100	20000
Z′ (1 TeV)	0.1	30	300

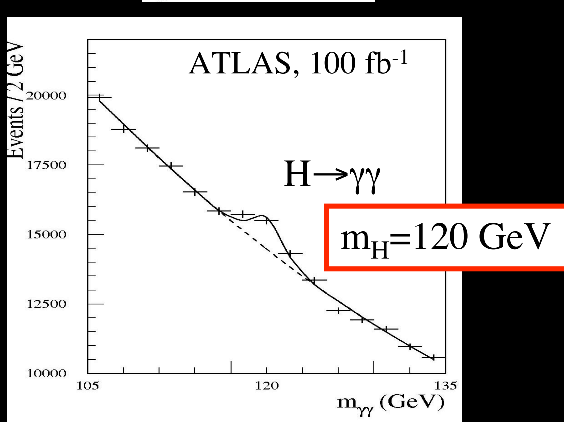


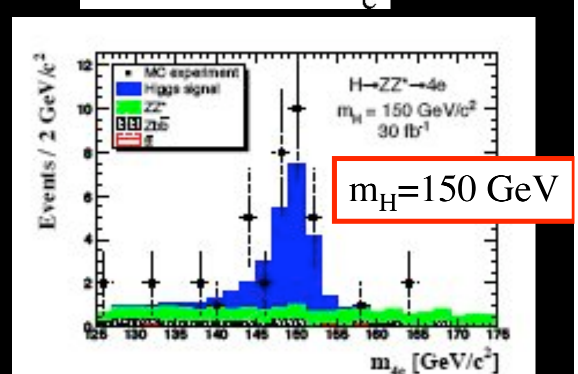
- Amazing increase for strongly interacting heavy particles
  - Opportunity!

Higgs Boson Searches



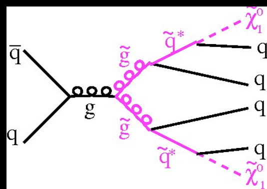


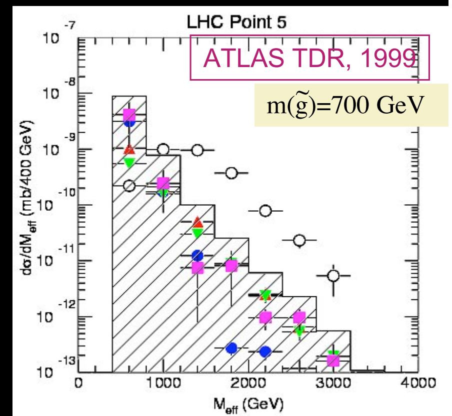




Requires quite a lot of data =>
Discovery not expected before 2010

Supersymmetry





- Best observation chance is to search for the SUSY partner of gluon (“gluino”)
  - Large production probability
  - Detection via many “jets” and missing energy

May already be discovered in 2009-2010!
=> then we have to look for more SUSY particles and measure all their masses

Current Students and Faculty on ATLAS

- Graduate Students
  - Andre Bach
  - Michael Leyton (@CERN)
  - Peter Loscutoff
  - Max Scherzer (@CERN)
  - Lauren Tompkins
  - Seth Zenz (@CERN)
- Faculty:
  - Marjorie Shapiro
  - Jim Siegrist
  - Me
- At LBNL:
  - 9 postdocs
    - 3 here, 6 at CERN
  - 10 senior scientists
  - 6 computing professionals
  - + engineers and technicians

You can talk to those students and/or work with us over the summer to get a better idea

Some Current Student Activities

- Compare different theoretical programs for calculating Standard Model backgrounded processes to SUSY search
- Study efficiency of the electron finding algorithm
- Study performance of track finding algorithms
  - In simulated events or cosmic ray muons
- Study and improve pixel detector resolution
- Design diagnostics software for pixel detector testing
- ....

Some Example Thesis Topics

- Current UCB students:
  - Measurement of the track multiplicity in Minimum Bias events
  - Search for a new particle decaying to two top quarks
  - Measurement of W+jets production
  - Measurement of Z+jets production
  - Measurement of the top cross section
- Future examples:
  - Search for the Higgs boson in the ZZ decay mode
  - Evidence for production of supersymmetric particles
  - Measurement of the Higgs boson mass in the diphoton decay
  - Measurement of the mass of the lightest supersymmetric particle
  - Observation of a new particle decaying to two leptons
  - Evidence for extra spatial dimensions
  - ....

Conclusions

- **There may soon be a revolution in our understanding of fundamental physics**
  - Good reasons to believe that spectacular discoveries will be made at the LHC
- The LHC will start in summer 2008 and then gradually take more and more data
  - I think the most exciting time will be around 2010-2011 when substantial data become available
- Berkeley is playing a central role in the ATLAS experiment
  - You will learn hardware, software and analysis skills and live in Europe for some time