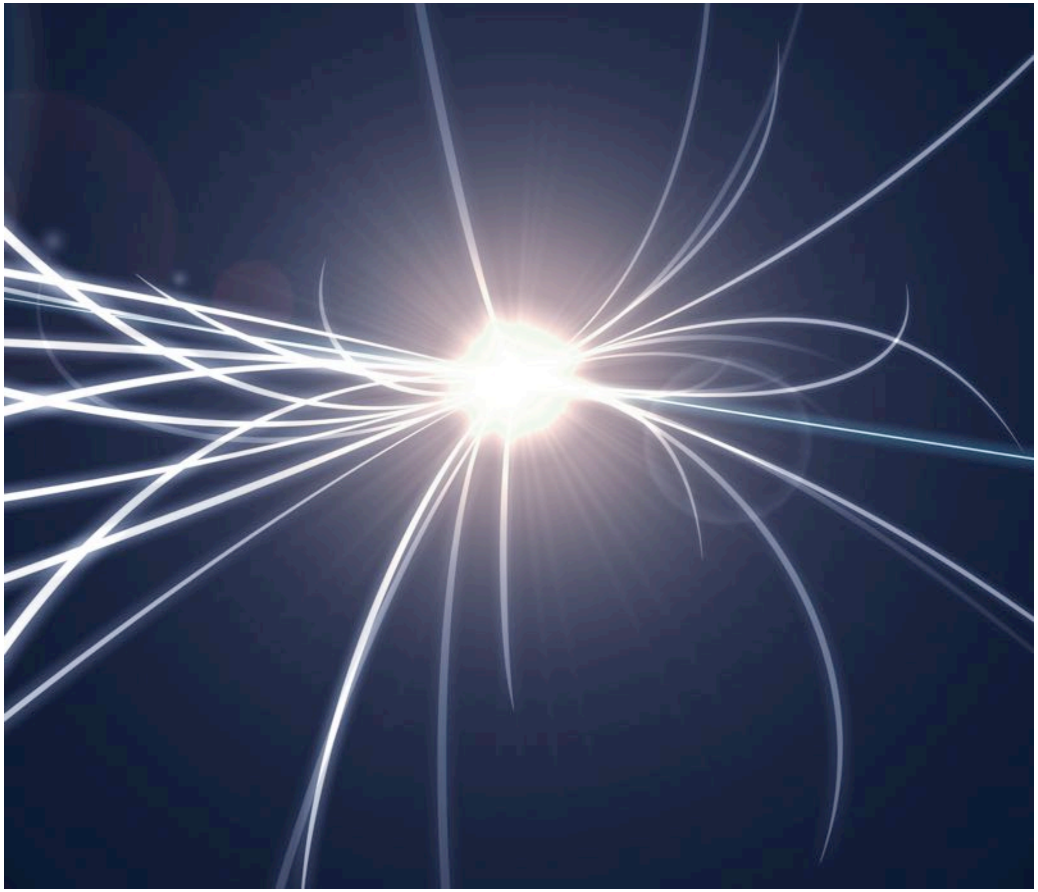
Particle Physics: What's Next?

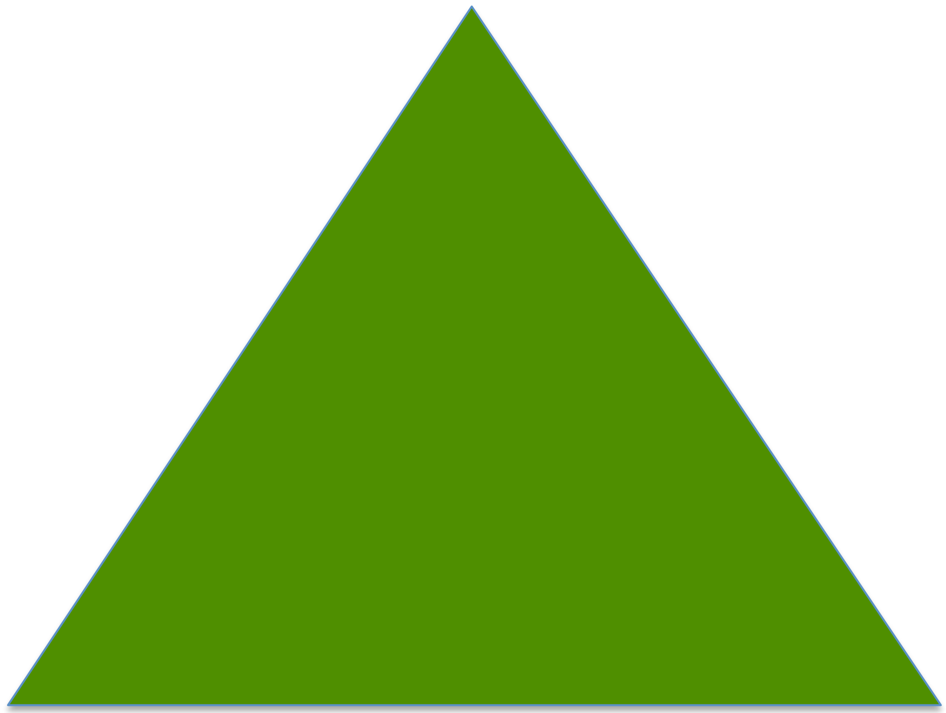


Jonathan Bagger
TRIUMF

January 20, 2016

Modern Physics

Classical Mechanics



Quantum Mechanics $\longleftrightarrow$ Special Relativity

Relativistic Quantum Field Theory

Relativistic Quantum Field Theory

- Space + Time = Spacetime

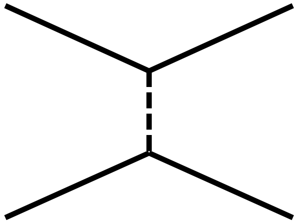
$$(x^i, t) \rightarrow x^\mu$$

- Fields

$$\phi(x^\mu)$$

- Particles are ripples in fields

- Interactions between fields are local



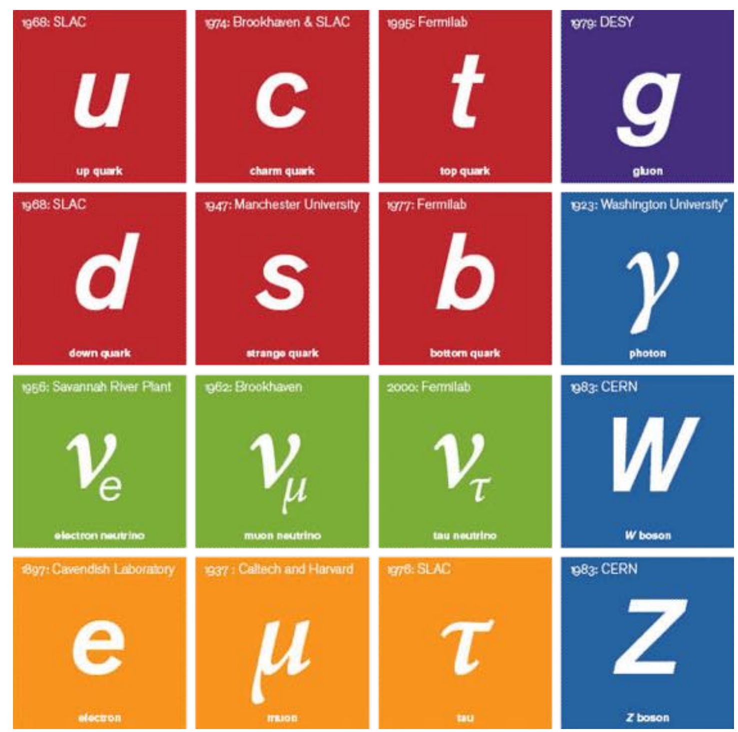
Feynman Diagrams!

Standard Model

- The framework works!

- The Standard Model gives a complete and consistent description of ordinary matter and its interactions, in terms of

  – Spin ½ quarks and leptons
  – Spin 1 gauge bosons
  – Spin 0 Higgs boson

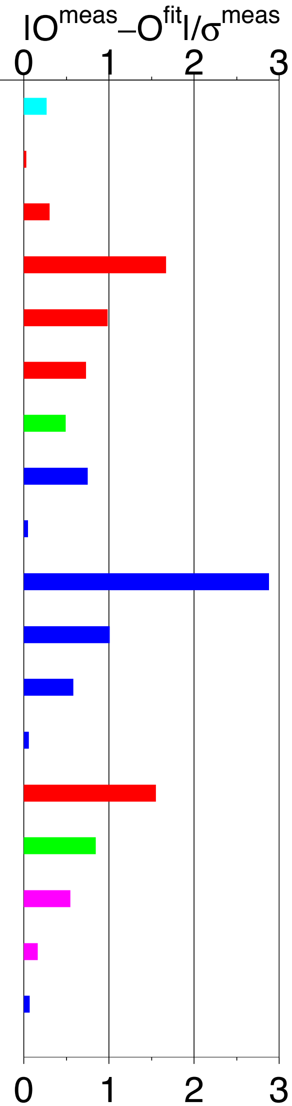


Bosons and fermions

CERN – LEP

Standard Model

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

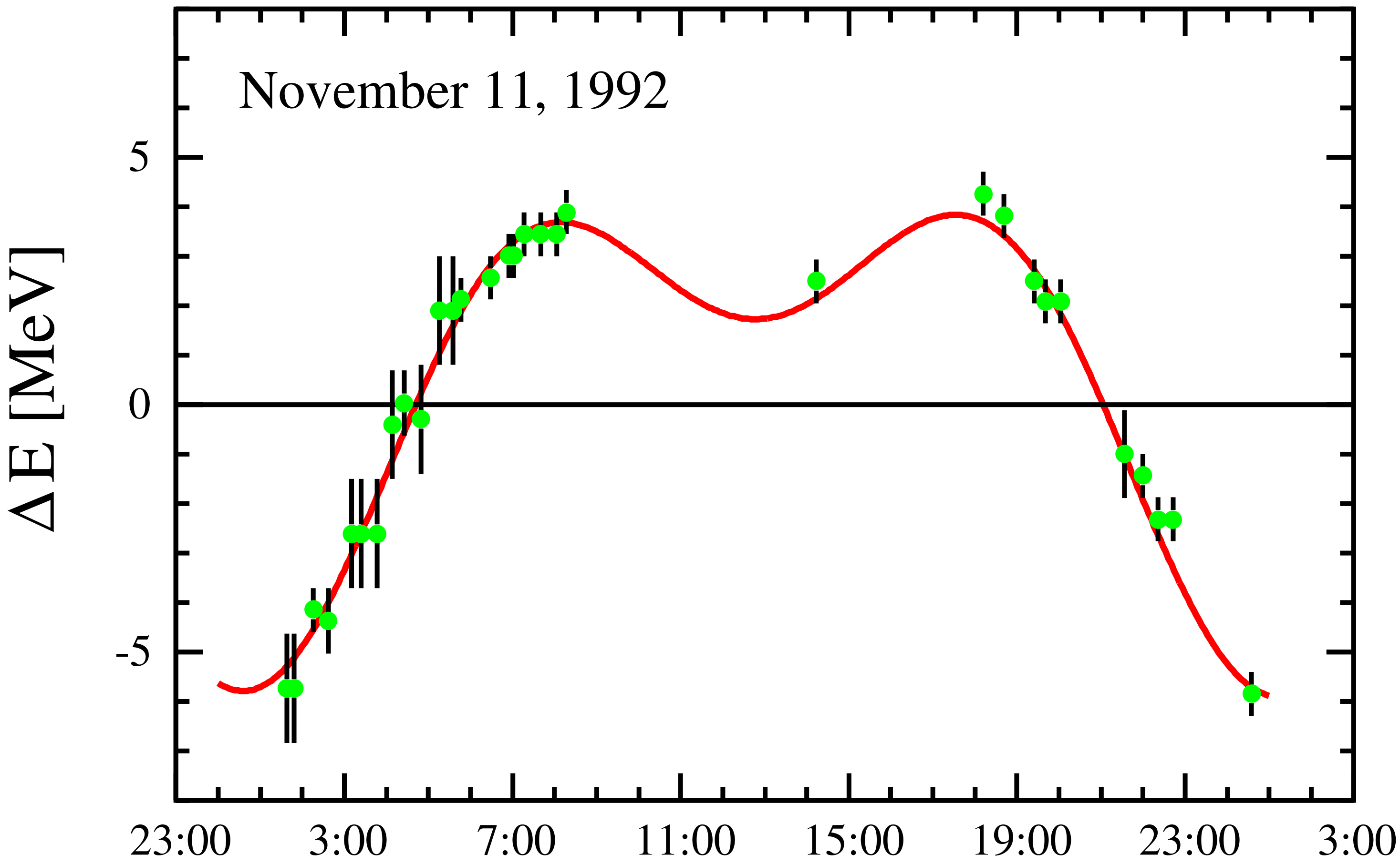


March 2012

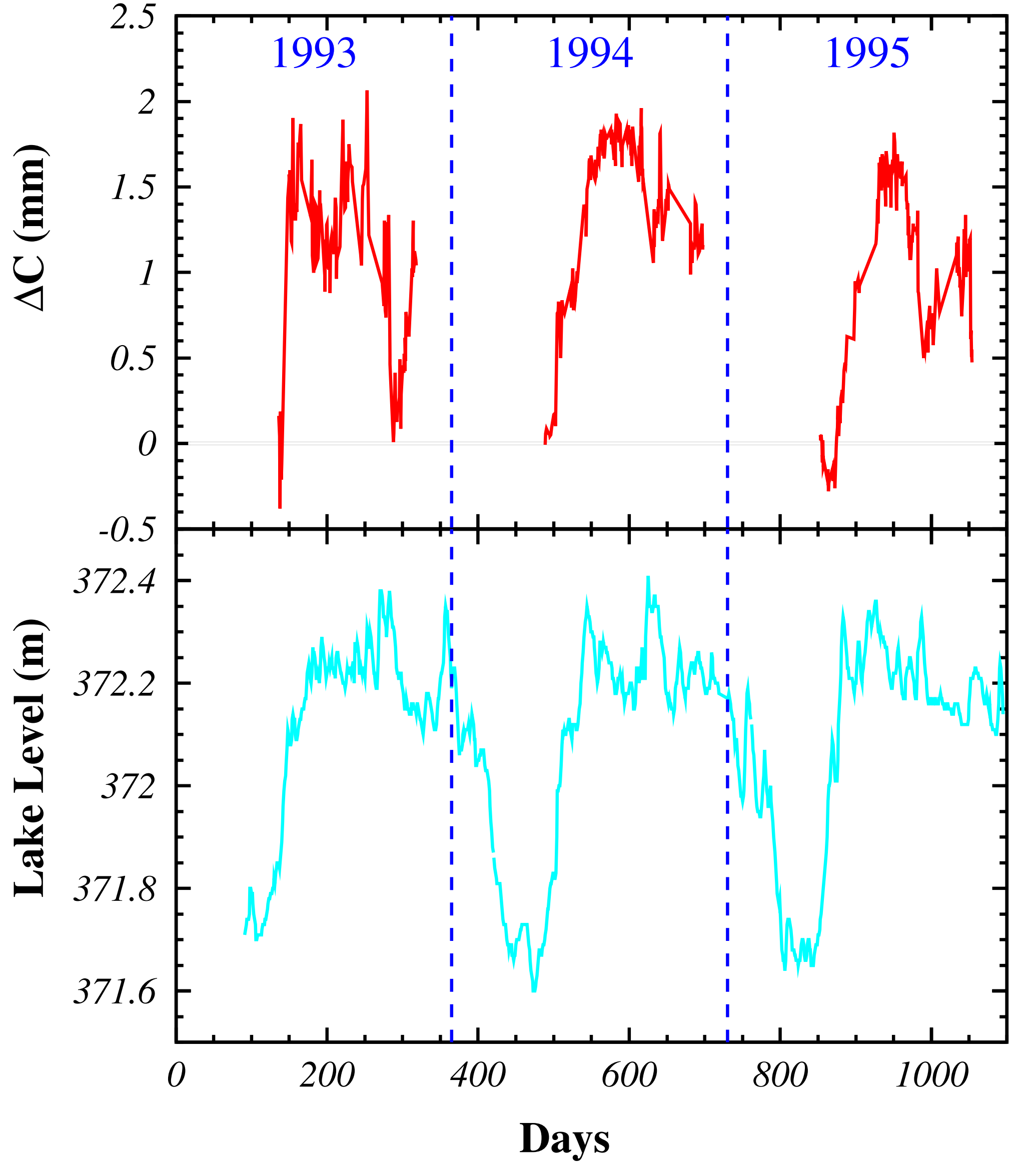
Part-per-mil precision!

OPAL

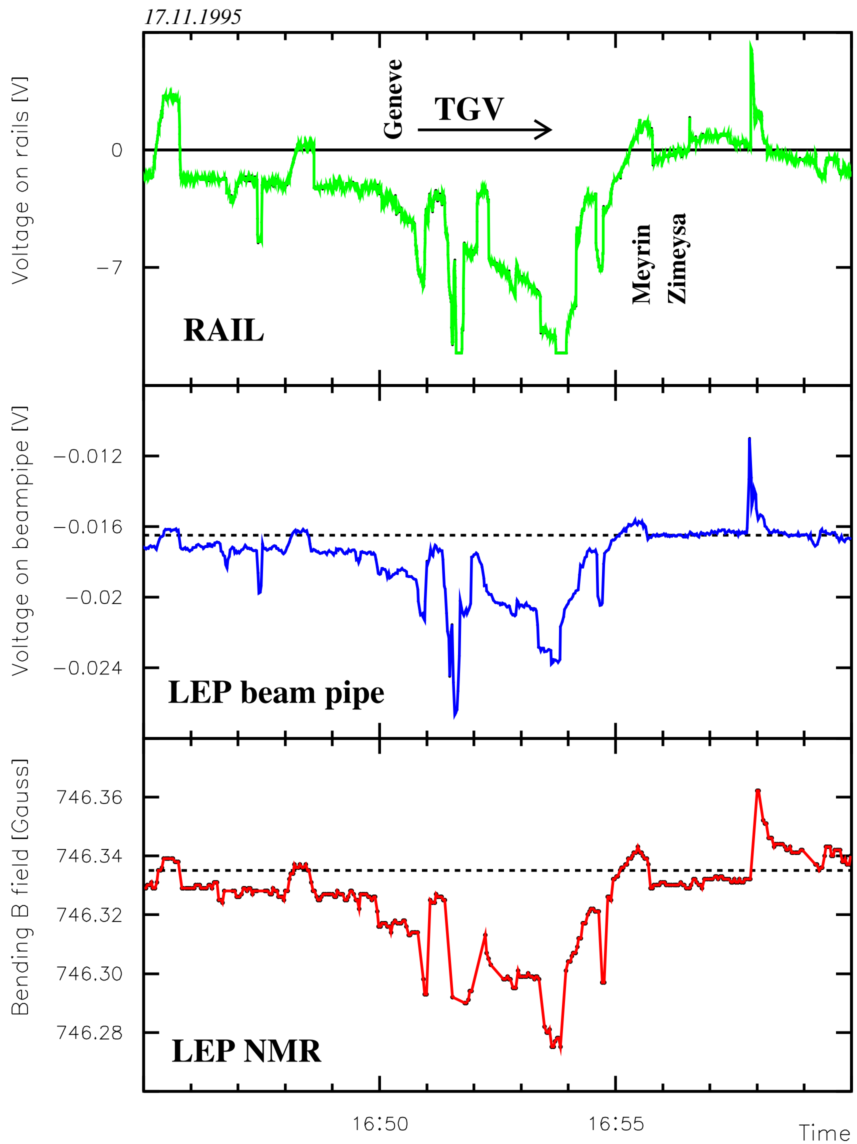
Standard Model: Tide Effect



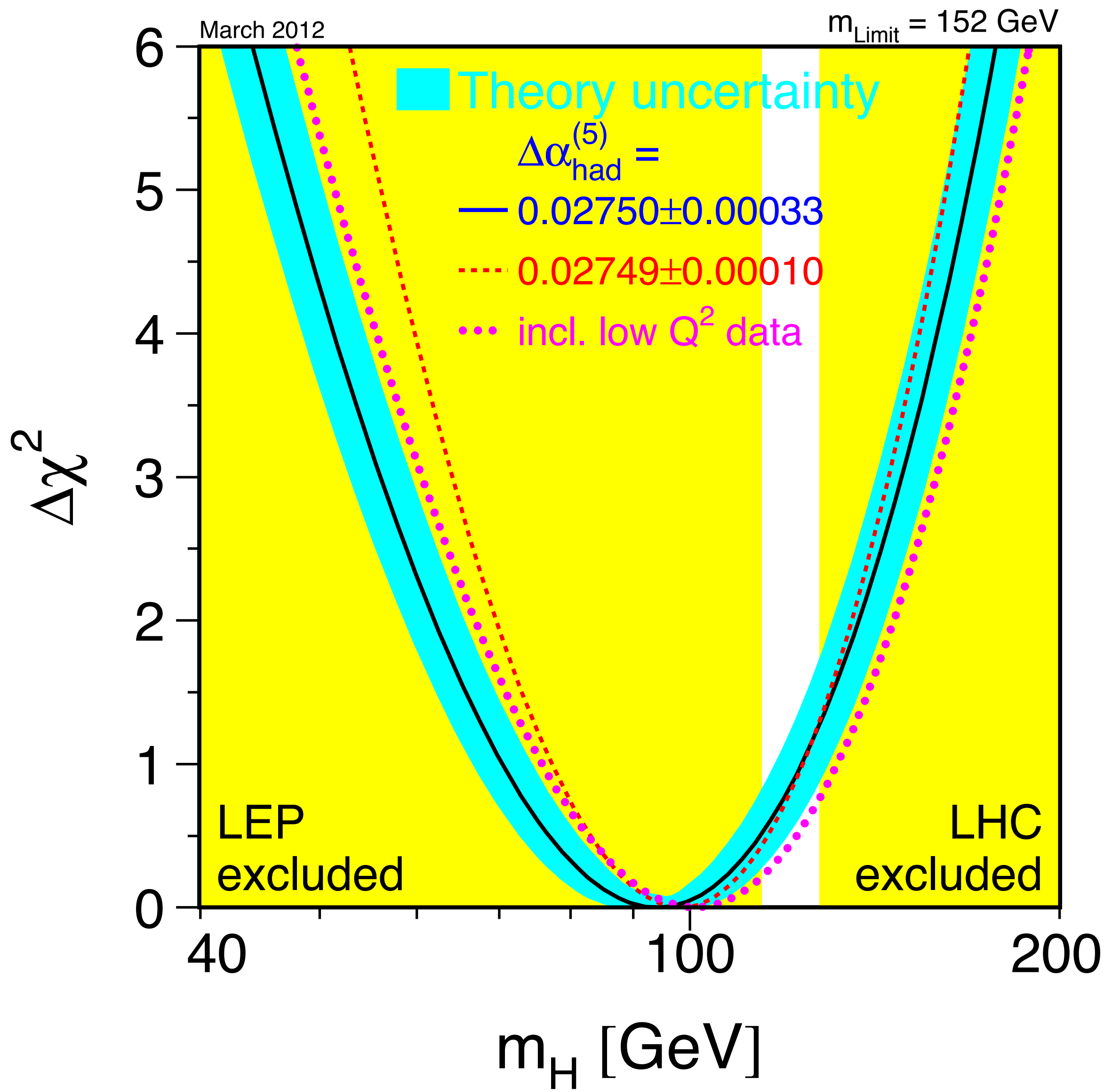
Standard Model: Lake Effect



Standard Model: TGV Effect



Higgs Boson



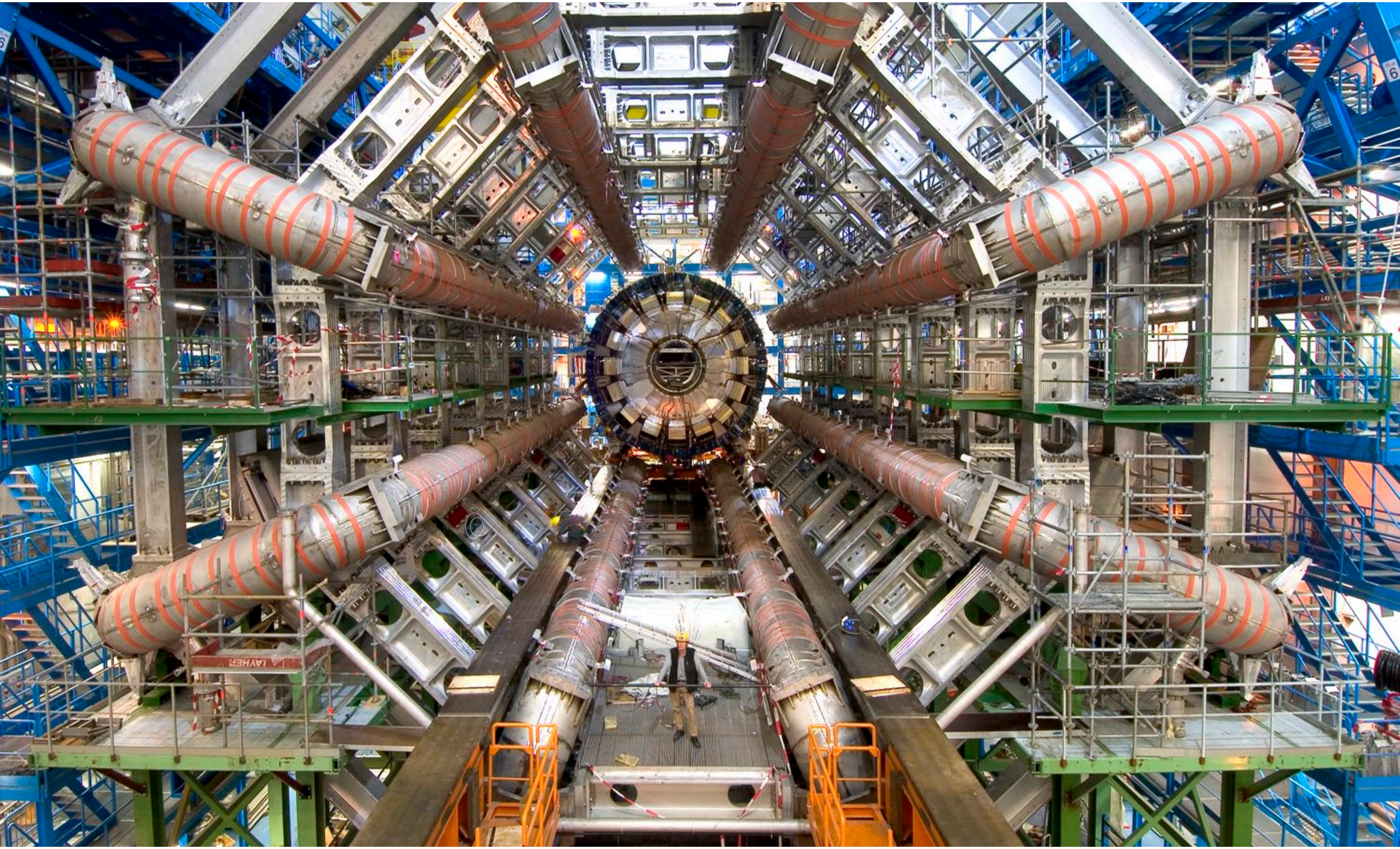
Higgs Boson

Direct and indirect measurements

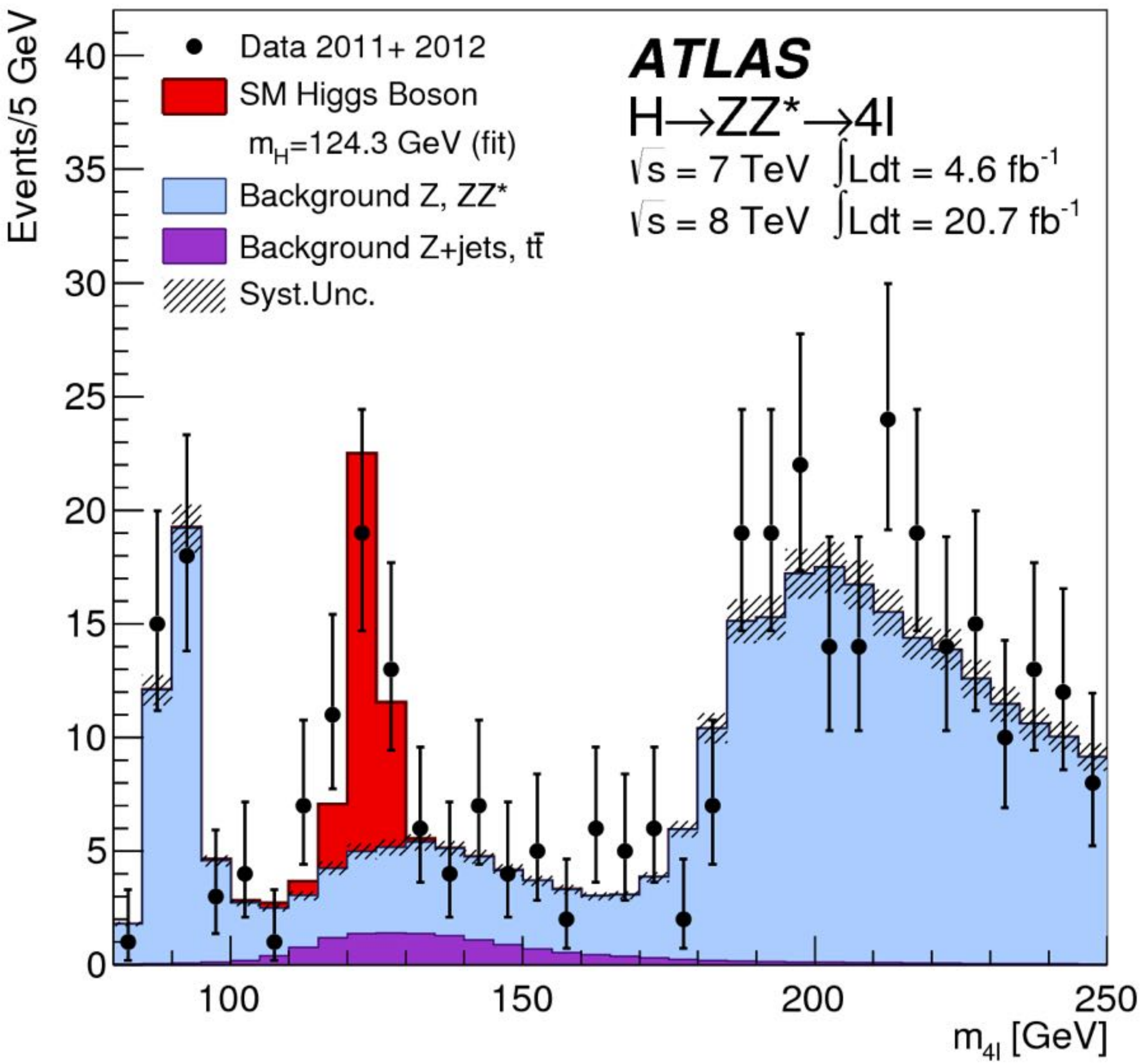
March, 2012

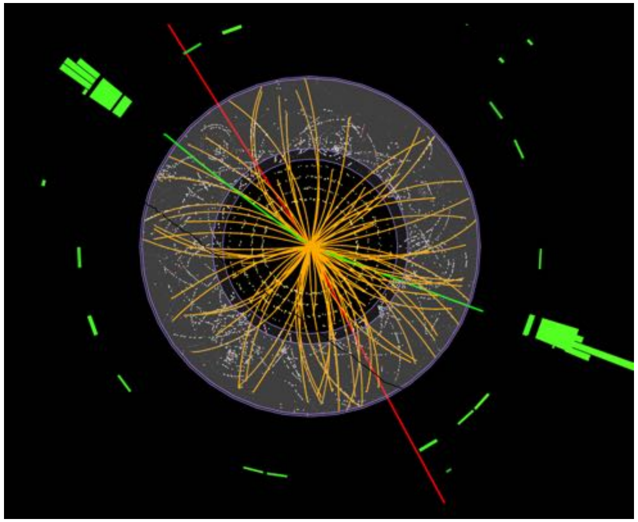
LEP EWWG

LHC – ATLAS



Higgs Boson





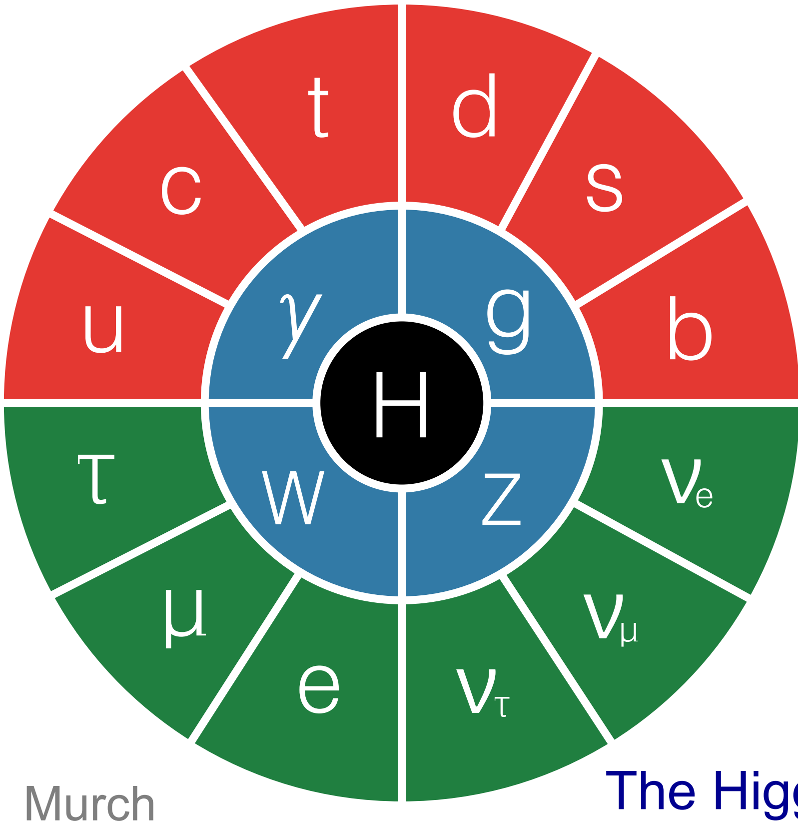
Higgs Boson

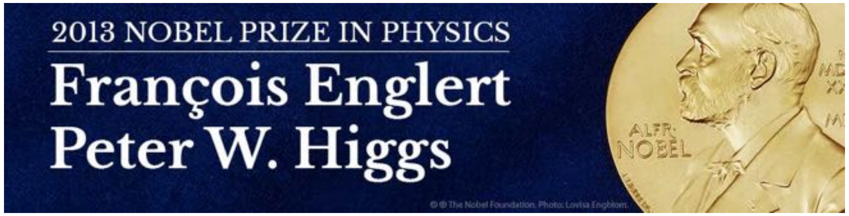
e, mu final state

July 4, 2012

Standard Model

- It is hard to understate the importance of the Higgs discovery
- It completely changes the picture





The Higgs is the linchpin of the Standard Model

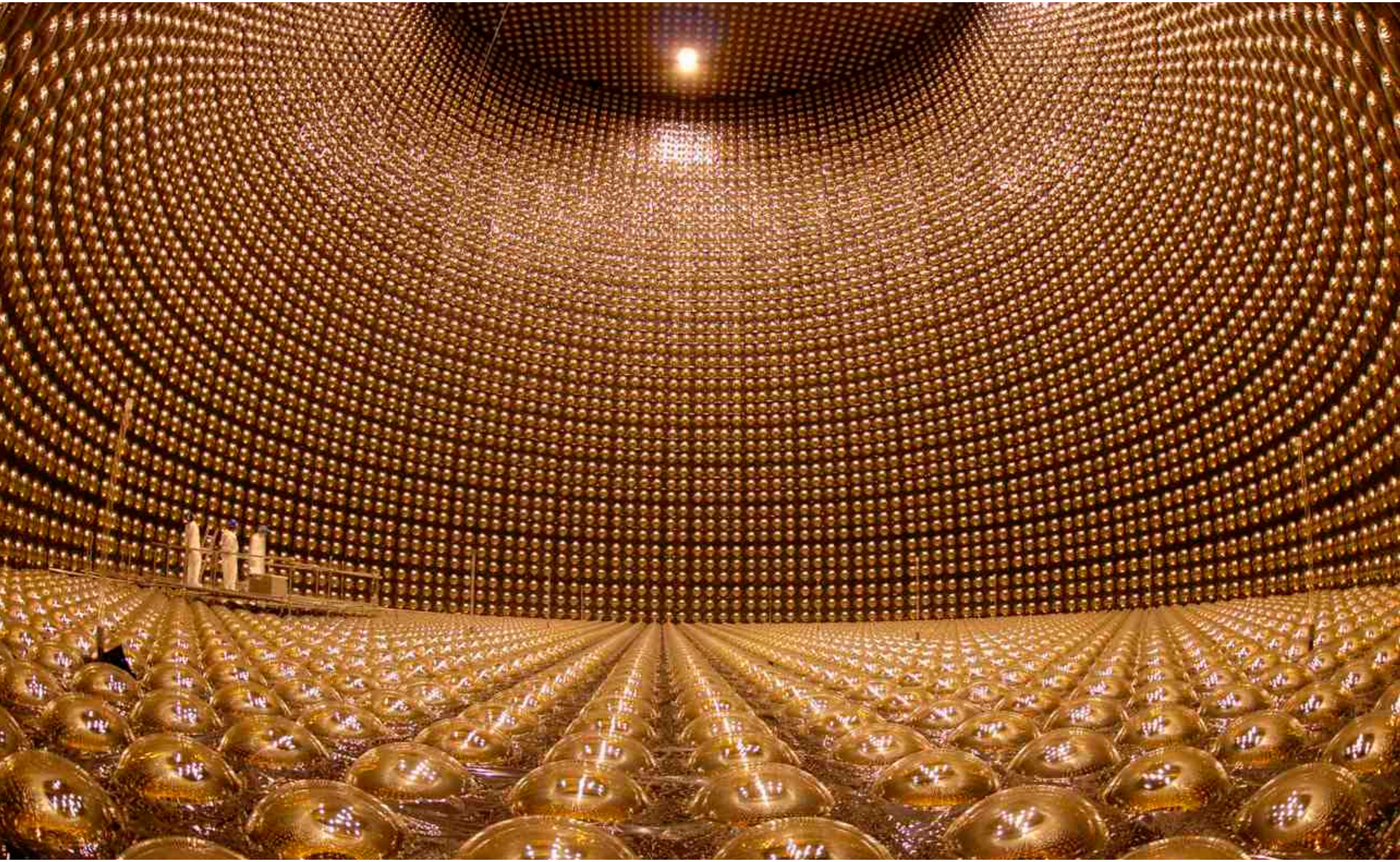
Standard Model

- The discovery of the Higgs marks turning point for the field

- With it, the Standard Model is complete
  - It provides a complete and quantitative description, in terms of relativistic quantum field theory, for ordinary matter – the quarks, leptons and gauge bosons
  - It has been tested to better than the part-per-mil level

- However, there are other important phenomena that the Standard Model does address
  - We know there is more to the story…

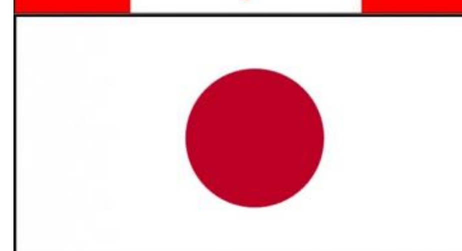
Neutrino Mass



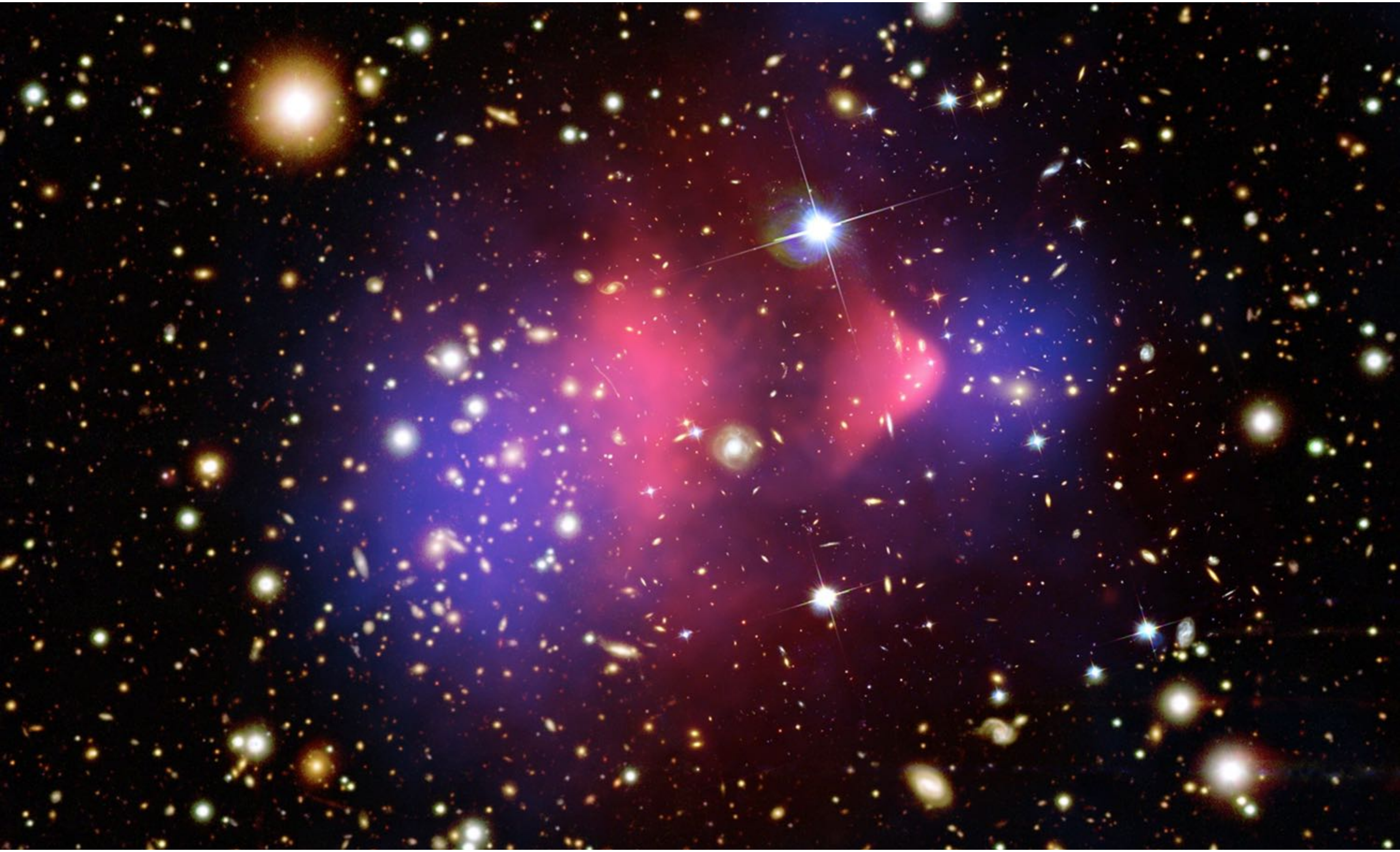
Super Kamiokande

Neutrino Mass

2015 Nobel Prize in Physics



Dark Matter

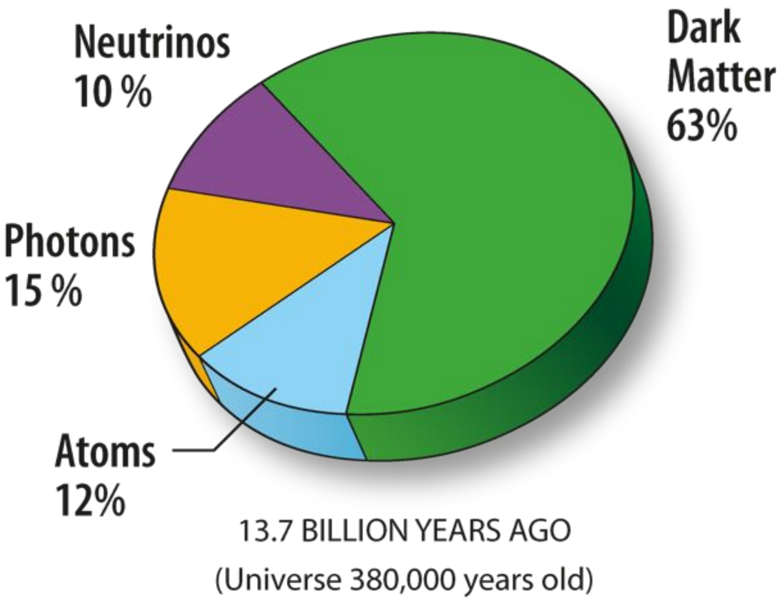


Bullet Cluster

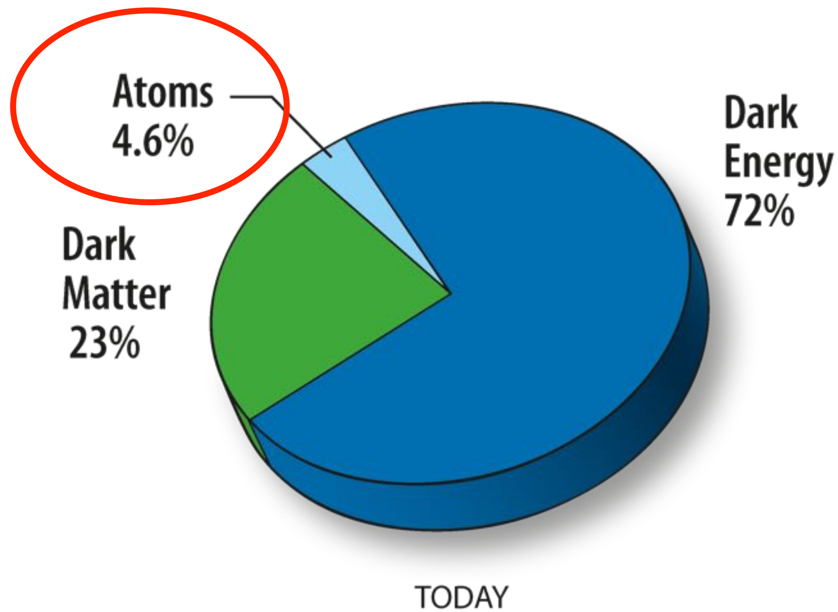
Dark Energy

2011 Nobel Prize in Physics

Composition of the Universe

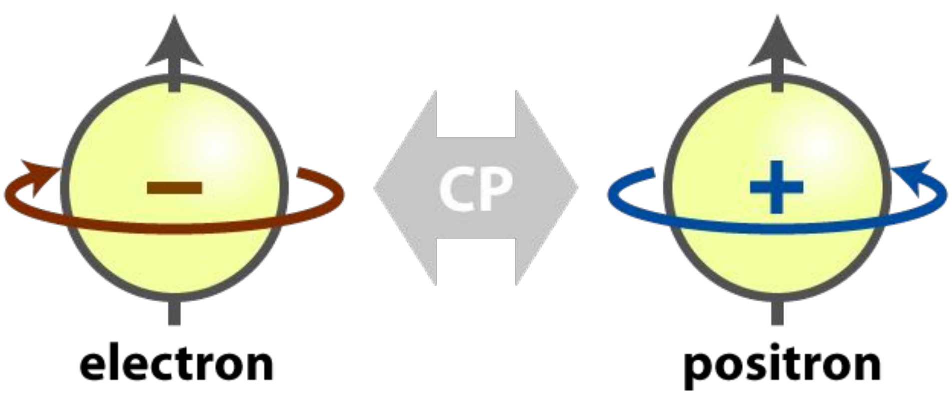


As measured by WMAP
(and Planck)

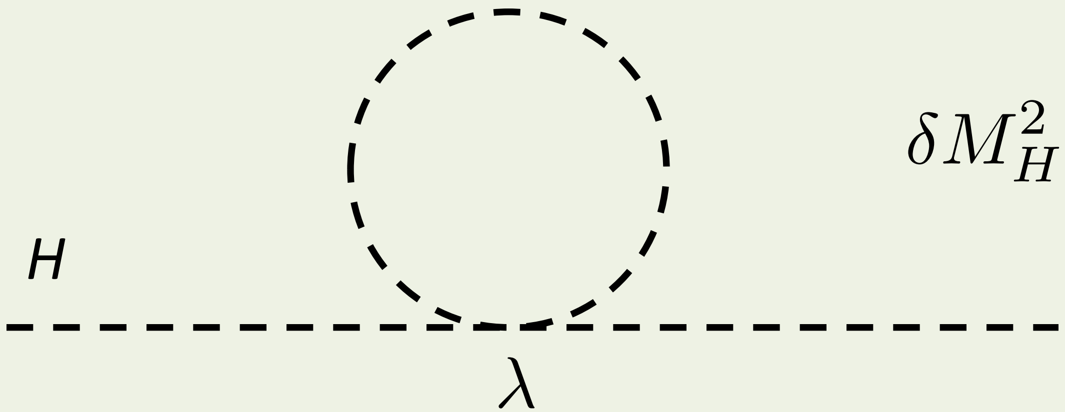


CP Violation

- If our present Universe – composed of matter but not antimatter – evolved from an initial Big Bang, there must be a small asymmetry in the laws of physics between matter and antimatter
- This asymmetry is called CP violation
- There is not enough CP violation in the Standard Model to account for the present matter density of the Universe



Hierarchy Problem



$$\delta M_H^2 \sim \lambda M_P^2$$

The Higgs mass is unstable

Keeping the Higgs boson mass at 125 GeV requires fine tuning of about 1 part in 10^{34}

What does this tell us?

We can't stop!

There is more to the story …

Spacetime

- Spacetime coordinates are bosons, obeying

$$[x^\mu, x^\nu] = 0$$

- Relativistic quantum field theory is invariant under the Poincaré group of spacetime transformations

$$x'^\mu = \Lambda^\mu{}_\nu \, x^\nu + a^\mu$$

- The structure of the Poincaré group is encoded in its Lie algebra

$$[P_\mu, \; P_\nu] = 0 \qquad [P_\mu, \; M_{\nu\rho}] = \eta_{\mu\nu} P_\rho - \eta_{\mu\rho} P_\nu$$

$$[M_{\mu\nu}, \; M_{\rho\sigma}] = \eta_{\nu\rho} M_{\mu\sigma} - \eta_{\mu\rho} M_{\nu\sigma} - \eta_{\nu\sigma} M_{\mu\rho} + \eta_{\mu\sigma} M_{\mu\rho}$$

Supersymmetry?

- In supersymmetry, spacetime has fermionic coordinates θ^α that obey the anticommutation relation

$$\{\theta^\alpha, \theta^\beta\} = 0$$

- Supersymmetry transformations are fermionic translations of the fermionic coordinates

$$\theta'^\alpha = \theta^\alpha + \epsilon^\alpha$$

- The structure of the supersymmetry group is encoded in its super Lie algebra

$$\{Q_\alpha, Q_\beta\} = \gamma^\mu_{\alpha\beta} P_\mu$$

Anticommutators instead of commutations for fermions!

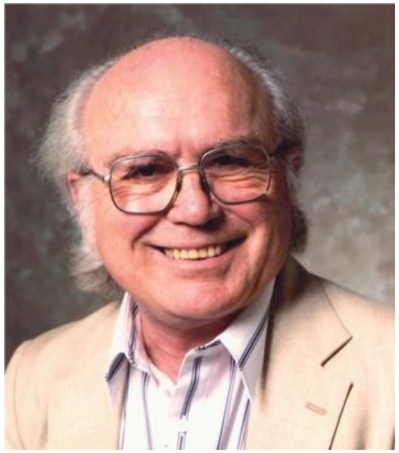
Supersymmetry!

- Supersymmetry is the unique extension of the Poincaré algebra consistent with the axioms of relativistic quantum field theory

- Therefore it is possible to make consistent supersymmetric quantum field theories. Do they describe nature?

Noether

Wess and Zumino



Superfields

- Supersymmetric fields are functions of x^μ and θ^α

$$\Phi(x^\mu, \theta^\alpha)$$

- Their power series expansions contain bosons and fermions

$$\Phi(x^\mu, \theta^\alpha) = \phi(x^\mu) \ + \ \theta^\alpha \, \psi_\alpha(x^\mu) \ + \ \ldots$$

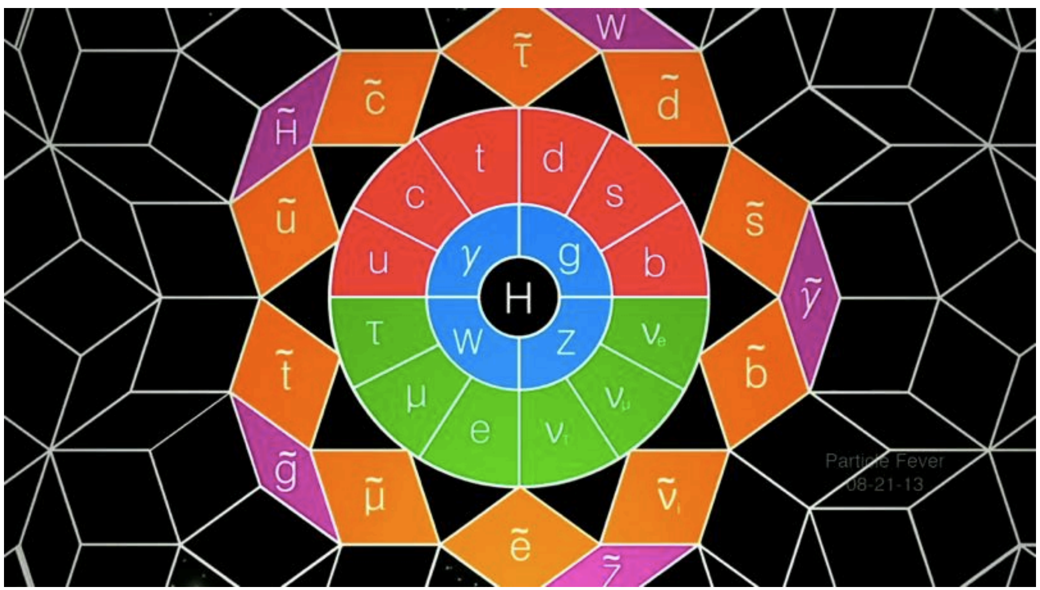
Boson Fermion

- For every fermion there is a boson, and vice versa!

Bose – Fermi symmetry!

Supersymmetric Standard Model

☐ Spin ½ Quarks	Spin 0 Squarks
☐ Spin ½ Leptons	Spin 0 Sleptons
☐ Spin 1 Gauge Bosons	Spin ½ Gauginos
☐ Spin 0 Higgs Bosons	Spin ½ Higginos



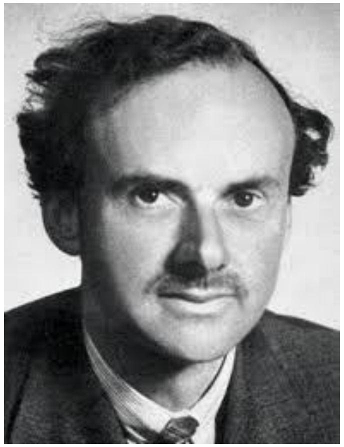
Murch

Twice the number of particles!

Antimatter

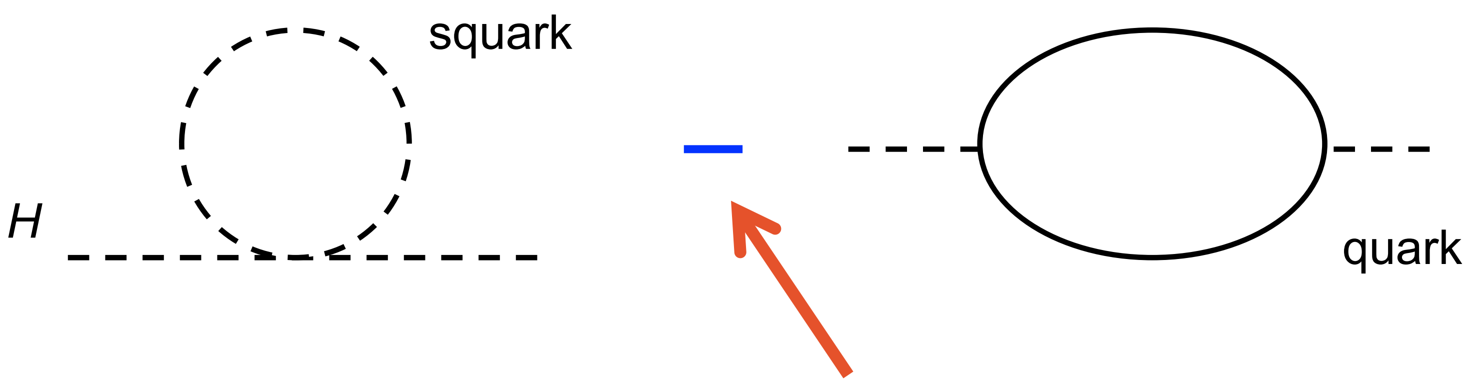
- Supersymmetry seems preposterous – but as we will see, it has all the right properties and addresses the key issues
- That's why theorists love it
- But doubling the number of particles?
  - In fact, something like this has happened before
  - Dirac combined relativity and quantum mechanics, and showed that every particle has its own antiparticle
  - Twice the number of particles!

1933 Nobel Prize in Physics



Hierarchy

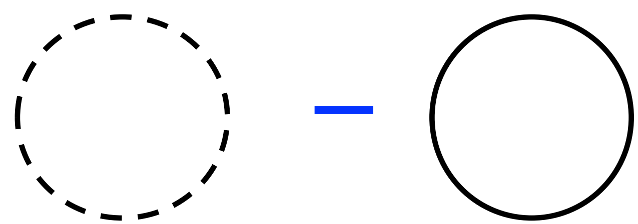
- Supersymmetry tames the hierarchy



- Loops cancel! For every bosonic loop, there is a countervailing fermionic loop, and vice versa
- Of course, this mechanism requires that the superpartner masses be near the Higgs mass…

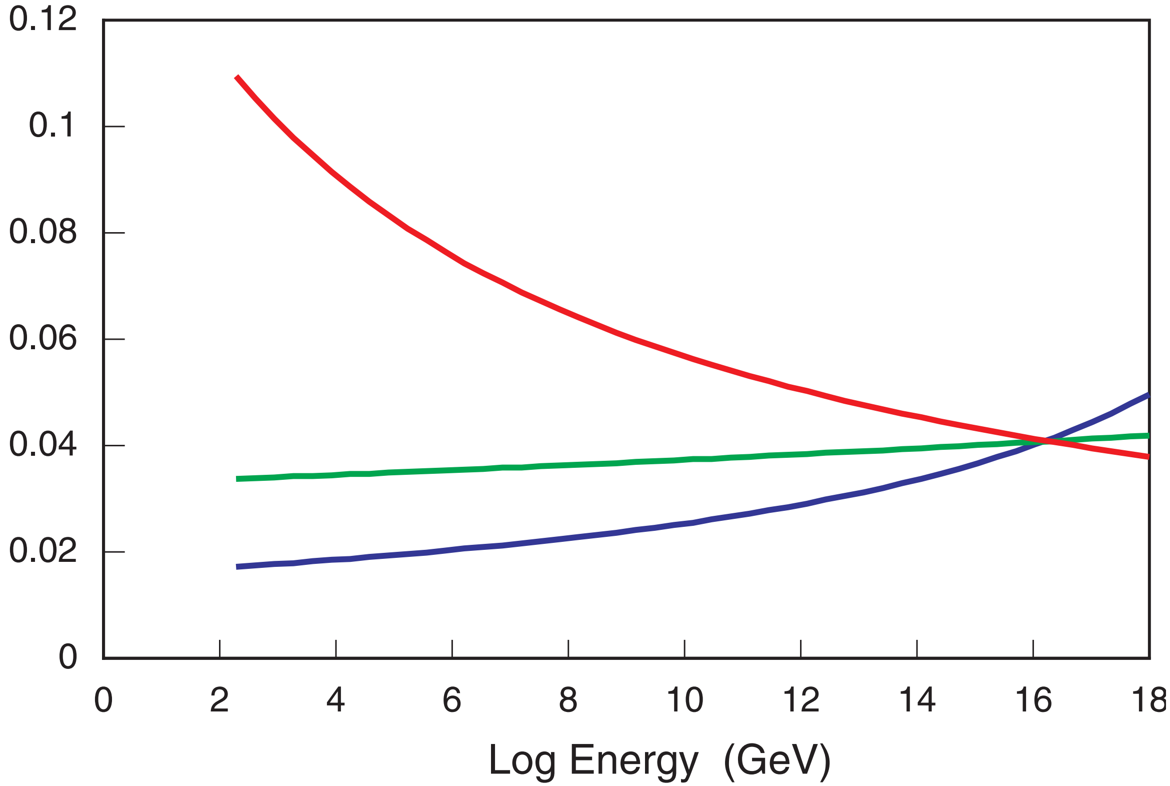
Other Virtues

- Supersymmetry
  - Accommodates neutrino masses
  - Explains the origin of the Dark Matter
    - The lightest supersymmetric particle can be stable
  - Includes new sources of CP violation
  - Helps stabilize the cosmological constant
    - Bose – Fermi symmetry reduces the fine tuning from one part in 10^{124} to one part in 10^{88} …



Grand Unification

- But best of all, supersymmetry supports the grand unification of the forces



$M_{GUT} \approx 10^{16}$ GeV

What's not to like?

Where is it?

- We've been looking for supersymmetry for a very long time …

Madonna was looking in 1985

And the Fermilab Tevatron started looking that very same year

In each case, to no avail …

Scandal!

January 5, 1993

With the Arts and Entertainment

Science Times

The New York Times

315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates the risks of Big Science, and its often sparse pickings.

By MALCOLM W. BROWNE

THREE HUNDRED AND FIFTEEN physicists worked on the experiment.

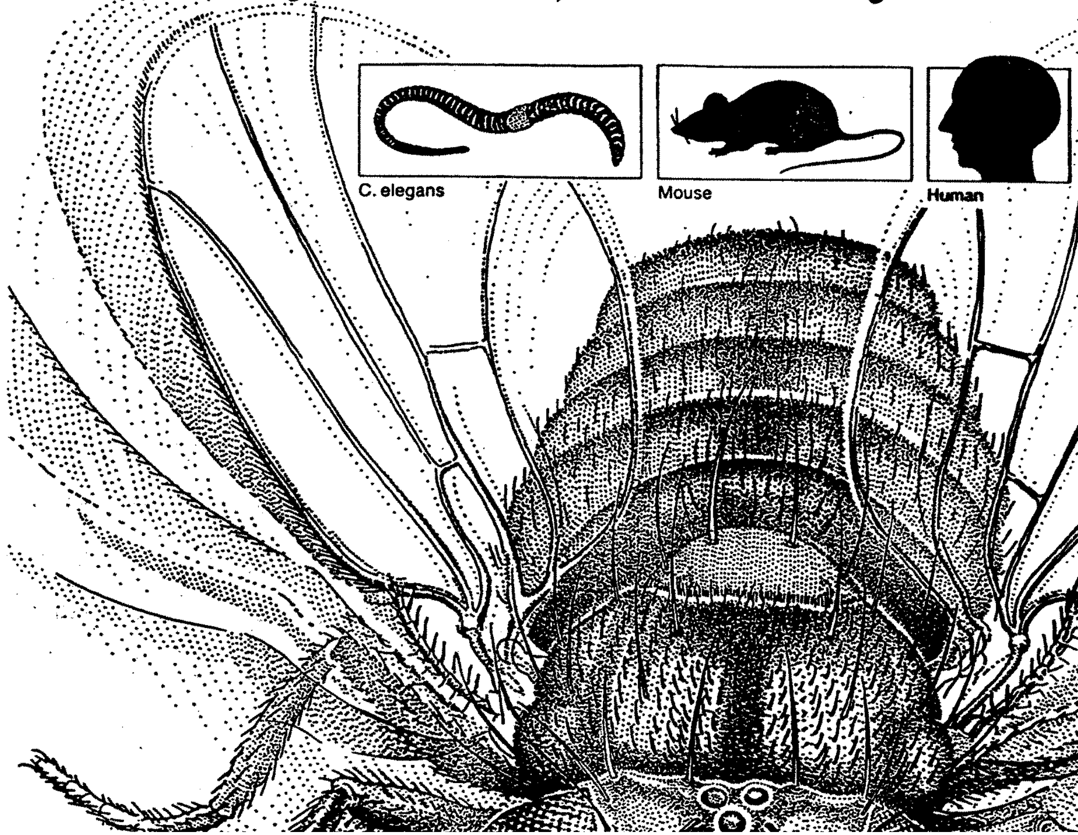
Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and political criticism.

To some, the elaborate trappings and null result of the latest Fermilab experiment seem to typify both the lofty goals and the staggering difficulties of "Big Science," a term coined in 1961 by Dr. Alvin M. Weinberg of

From Fly to Man, Cells Obey Same



CERN LHC

- The CERN LHC is supposed to be a supersymmetry factory
- With proton-proton collisions at an energy of 8 or 14 TeV, it has 4 – 7 times the reach of the Fermilab Tevatron
- Most of the collisions are glue-glue, so one expects the greatest discovery reach for the colored sparticles
- However, some of the collisions are quark-quark, so one also expects production of purely electroweak sparticles

The world is waiting with bated breath

- Will 3000 physicists fail to find supersymmetry?

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7,\ 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g},\ \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g},\ \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g},\ \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1,\ \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1,\ \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}_1^\pm)=2\ m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2,\ \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R},\ \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu),\ \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 $\mu s<\tau(\tilde{g})<$1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau},\ \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q},\ \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X,\ \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X,\ \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to W\tilde{\chi}_1^0,\ \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu,\ e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to W\tilde{\chi}_1^0,\ \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e,\ e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t,\ \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} 1 **Mass scale [TeV]**

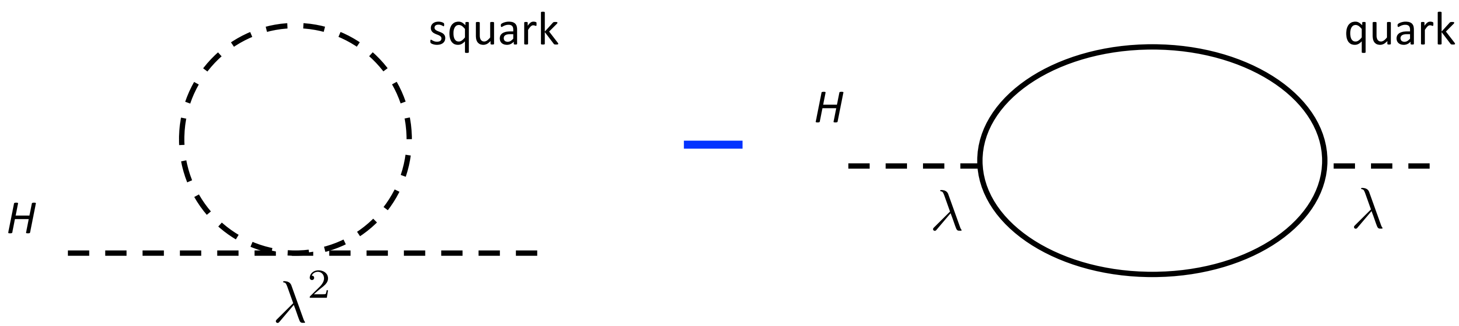
$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

So where is it?

Hmmmm…

- We need to step back and think again about naturalness



$$\delta M_H^2 \sim \lambda^2 M_{\mathrm{squark}}^2$$

- Inverse hierarchy: Light quarks allow heavy squarks!

Light stop, sbottom, Higgsinos, some gauginos
All others can be heavy!

LHC 14: Will lightening strike?

- It may well be that the next run of the LHC will discover supersymmetry

- With twice the energy, the reach will be significantly higher
  - The colored sparticles will be easiest to find
  - With time and luminosity, the reach for the electro-weak sparticles will also increase

Either – Or

- If supersymmetry is found, we celebrate – and also, get to work
- If supersymmetry is not found, it does not mean that supersymmetry is dead
- It will fade, perhaps, as a topic of phenomenological interest
  – But it will retain its mathematical relevance

Next Steps

- If supersymmetry is not found at the 14 TeV LHC, we need to press on a variety of fronts
  - We need to accumulate luminosity at the LHC, because in a proton machine, energy reach increases with luminosity
  - We need to make precision measurements to search for departures from the predictions of the Standard Model
    - This includes a host of measurements, from Higgs properties at the ILC to rare decays at higher luminosity but lower energy accelerators
    - At TRIUMF, it includes measuring the neutron EDM at the UCN facility under construction with Japan

Next Steps

- If supersymmetry is not found at the LHC …
  - We also need to keep searching for Dark Matter
    - Its discovery will provide a clue to what lies beyond
  - We need to understand gravity, and its interplay with the Standard Model
    - What is Dark Energy telling us?
  - We need to question all our assumptions …
    - Locality?
    - Uniqueness?
    - Naturalness?

Example: String Moduli

- It may well be that there is no new physics within reach, and the hierarchy problem is, in fact, a diversion
- For example: In string theory, coupling constants are determined by the vacuum expectation values of “modulus fields.” What sets those values?
- If there were just one Universe, it would take an act of providence to tune the expectation values to just the right values (and the cosmological as well)
- But if there were more than one Universe, the vevs could differ in each

“It’s only logical”

Inflation

- The inflationary paradigm provides a context in which this can happen

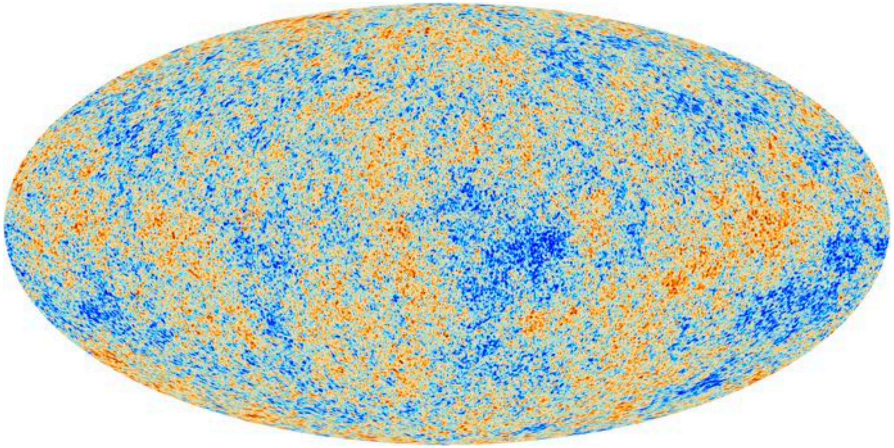
- According to inflation, our Universe grew from a tiny quantum fluctuation

- Other Universes are growing from other fluctuations, with different values of the moduli fields

- The Universes have very different properties from each other
  - Most would be inhospitable to life

Multiverse?

- Today, all the data from WMAP and Planck are consistent with the inflationary paradigm …
- Is our Universe just one part of a Multiverse? Are there other Universes? If so, how might we tell?
- And … if there were 10^{500} Universes, would it be so surprising if there were one that looked like ours?

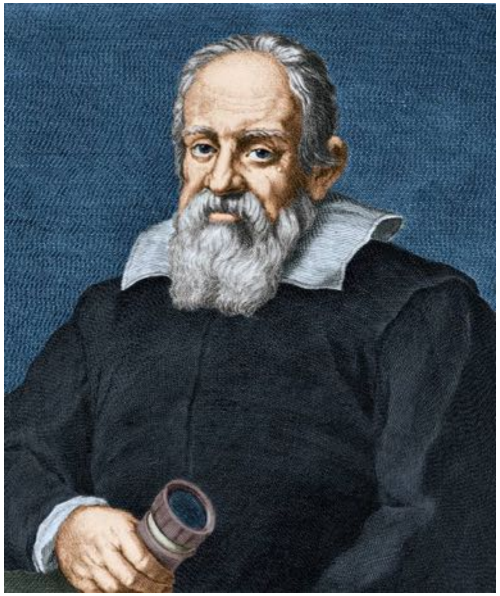


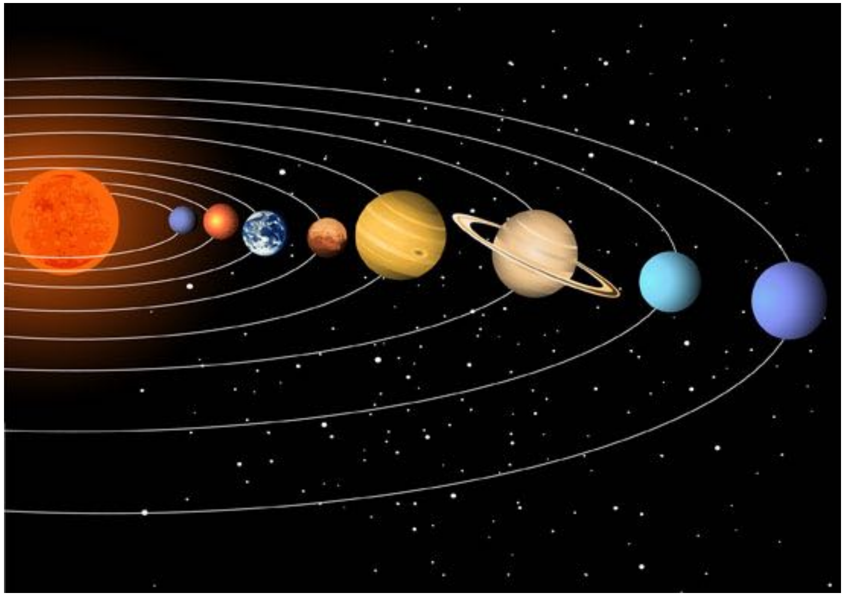
Planck

Earth in the Solar System

- Before the invention of the telescope, one might have asked why the Earth's orbit was sufficiently fine-tuned to support life

- One might have tried to construct a physical mechanism to place the Earth at exactly the right distance from the Sun

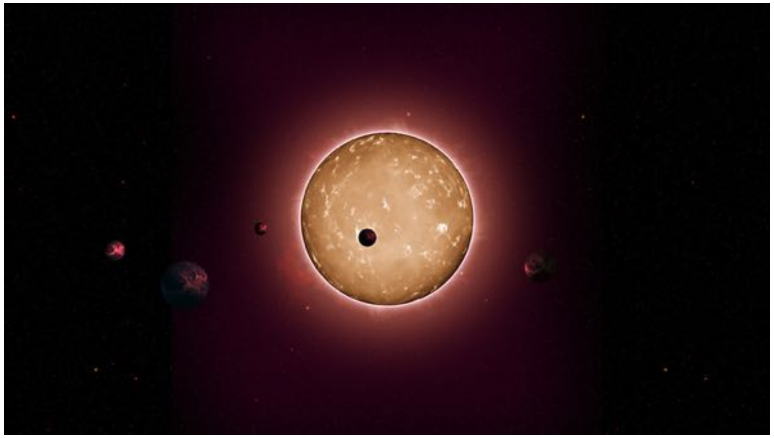




Kepler Satellite

- But today, we know that would be nonsense. The Kepler satellite is monitoring over 100,000 stars in our galaxy – and has found over 1,000 planets
- The visible Universe contains 10^{11} galaxies, each with 10^{11} stars. So there must be at least 10^{20} planets
- Armed with this knowledge, we understand that Earth's properties are an accident of history. They are not fine tuned
- Might that also be so for the Universe itself?

And how could we tell?



Kepler-444