Theoretical High Energy Physics in the LHC Era

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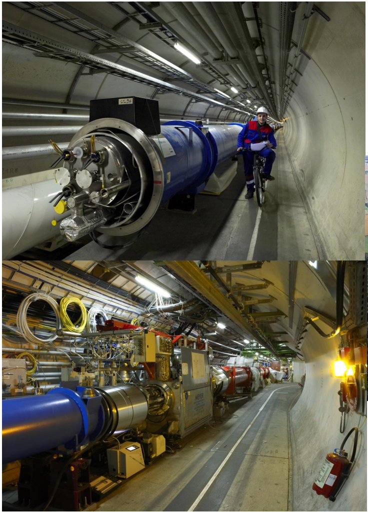
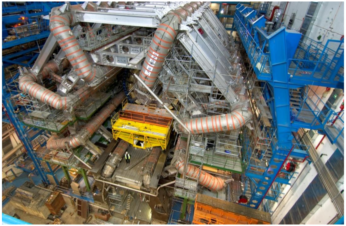
We have begun a very exciting era in particles physics. The Large Hadron Collider has completed a very successful run. This machine has opened an unexplored energy/distance scale, the “Terascale", energies of order 1000’s of GeV, corresponding to distances of order 10^{-17} cm.
It has discovered the Higgs boson(*)

The LHC at CERN:

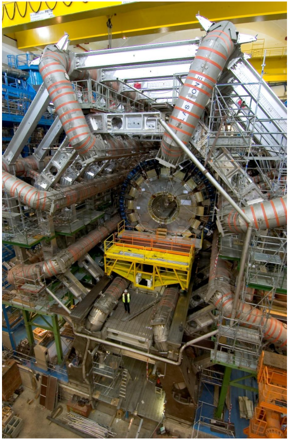


2 in 1 superconducting dipole magnet being installed in the CERN tunnel

ATLAS, one of the two large detectors at the LHC (Other: CMS; ALICE will study heavy ion collisions)

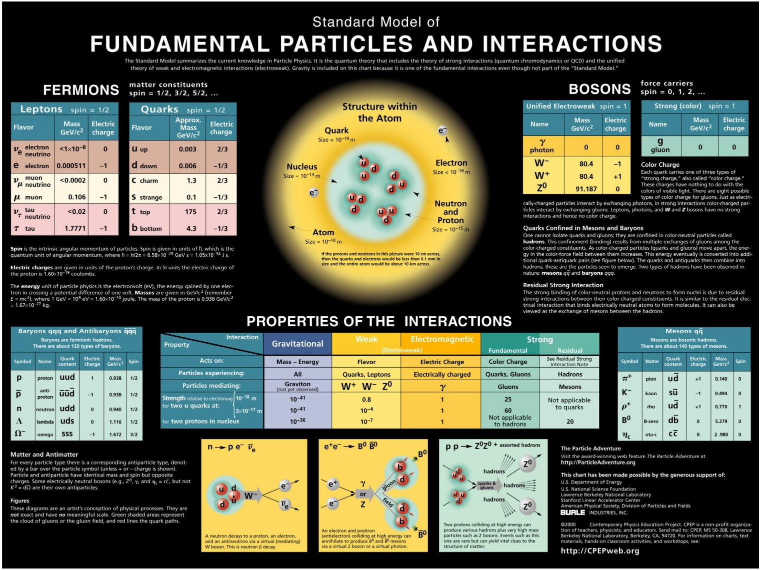


Muon superconducting Toroids in the ATLAS Detector at the LHC



Why is the terascale interesting? After all, we have an exquisite understanding of the basic laws of physics up to energy scales of order a few hundred GeV, embodied in the *Standard Model*. There have been strong arguments that new phenomena must show up in this energy regime. Many expect (hope?) that the Standard Model will be subsumed in a new structure in this energy range.

1. The Higgs boson: the higgs is responsible for the masses of the leptons (electron, muon, tau) and the quarks*, as well as the intermediate vector bosons. The Standard Model is not too precise about its properties. Prior to the LHC experiments, we had a lower limit on its mass (about 114 GeV), as well as some plausible range for its mass. Now a particle which appears to be this boson has been discovered with mass approximately 125 GeV.
2. Hierarchy: this is one phenomenon which points to dramatic new physics in this energy range.
3. Dark matter: About 20% of the matter of the universe exists in some form which interacts only very weakly with ordinary matter and radiation. Many ideas for understanding (2) provide a candidate for the identity of this (assumed) particle, which could be studied at the LHC.



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

Structure within the Atom

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
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American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see:

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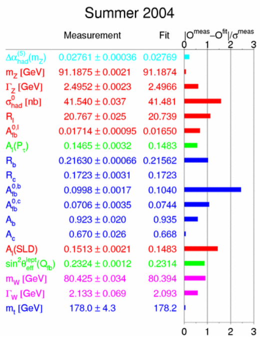
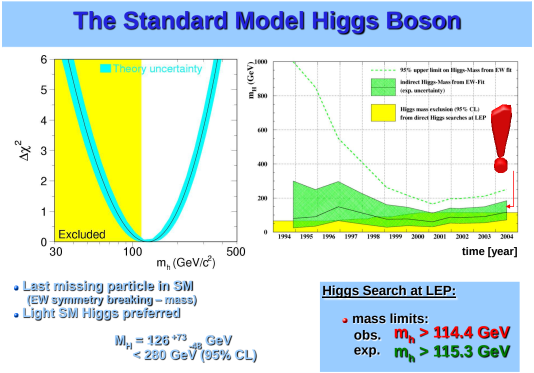


Summer 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2



The Standard Model Higgs Boson

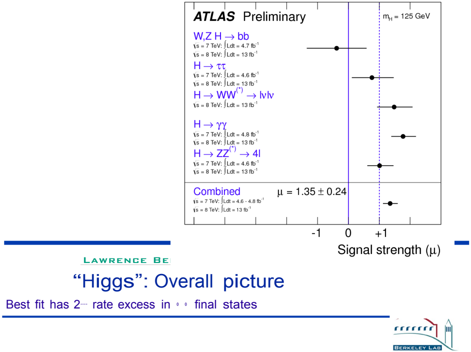
- Last missing particle in SM
  (EW symmetry breaking – mass)
- Light SM Higgs preferred

$M_H = 126^{+73}_{-48}$ GeV
< 280 GeV (95% CL)

Higgs Search at LEP:

- mass limits:
  obs. $m_h > 114.4$ GeV
  exp. $m_h > 115.3$ GeV

Higgs Discovery



“Higgs”: Overall picture

Best fit has 2 rate excess in final states

The Hierarchy Problem

What particle physicists call the “hierarchy problem" was first formulated by Dirac as the “problem of the large numbers". In modern language, the question is: why is the scale of gravitation, $M_p = 10^{19}$ GeV $\gg m_H, m_W$.
Said this way, a problem of *dimensional analysis*.
At least once in physics, such a problem has been encountered before. Lorentz theory of the electron:

$$\Delta E = \frac{e^2}{a} = \delta m_e$$

How large can a be? From modern experiments,

$$a < 10^{-17} cm \Rrightarrow \delta m_e > 1000 \text{ GeV} = 2 \times 10^6 m_e$$

For 3/4 century, we know the resolution of this puzzle (Weiskopf): *the positron*.

In QED, Lorentz's correction to the mass exists, but it is largely canceled by quantum mechanical corrections involving emission, absorption of photons (Feynman diagrams with virtual photons, but Weiskopf found in old fashioned perturbation theory).

The result is:

$$\frac{\delta m_e}{m_e} = \frac{3\alpha}{4\pi} \ln(m_e a)$$

which, even for $a = 10^{-32}$ cm, is a small fractional correction.

For those who take 217 with me next year, you'll learn how this works.

For the Higgs, there is no such cancelation, and the problem is even worse, since the mass-squared in a relativistic theory of scalars behaves as $1/a^2$. More generally, why isn't

$$m_H^2 = \mathrm{C}\ M_p^2$$

with C an $\mathcal{O}(1)$ constant?

Three (two?) solutions proposed:

1. The Higgs boson composite, with size $a \sim 10^{-16} - 10^{-17}$ cm.; “Technicolor" (also “little Higgs"...)
2. The underlying scale of fundamental physics is at 1 TeV (“large extra dimensions", “warped extra dimensions" (ADD,RS). If these ideas are correct, we are on the threshold of discovering large extra dimensions of space, the scale of string theory, or equally exciting possibilities. (“dual" to technicolor?)
3. A new symmetry of nature; much like Lorentz invariance, which underlies the cancelation for electrons, it leads to a similar cancelation. This symmetry is known as *Supersymmetry*.

Of these ideas, supersymmetry has been the most popular (8700 titles in the INSPIRE database, as opposed to 3900 for warped dimensions, 3800 for large extra dimensions, about 1500 for technicolor). Warning!!! Not a Scientific Study

Supersymmetry

Various symmetries are familiar in nature:

1. Translations, rotations, Lorentz boosts (“Poincare symmetry") (Manifest)
2. Isotopic spin, Gell-Mann’s “eightfold way" Broken, “explicitly" – the underlying interactions preserve them only approximately
3. Chiral symmetry of the strong interactions – spontaneously broken
4. Gauge symmetries of the Standard Model – some manifest (electromagnetism), some “Higgsed" (massive vector bosons), some “confined" (QCD)

Supersymmetry: a hypothetical symmetry relating fermions and bosons. Must be broken, since otherwise for every known fermion, there would be a boson of the same mass, and vice versa.

Implications for hierarchy:

1. Higgs bosons naturally light; mass of order the breaking scale of the symmetry.
2. Superpartners of the ordinary particles should have masses of order 100's of GeV or somewhat larger.

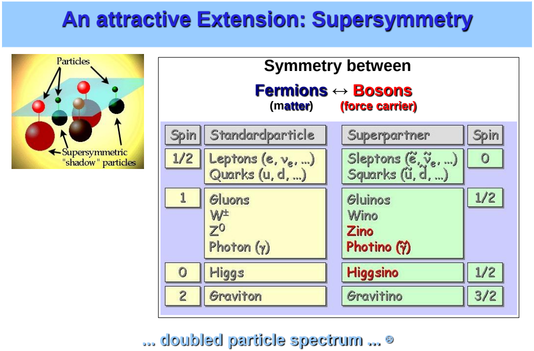
Superpartners

If these ideas are correct, for every particle we know in nature, there will be a “superpartner". E.g.

1. electron → selectron ($e \to \tilde{e}$; similarly $\mu \to \tilde{\mu}, \tau \to \tilde{\tau}$)
2. neutrino → sneutrino($\nu_e \to \tilde{\nu}_e$; similarly $\nu_\mu \to \tilde{\nu}_\mu, \nu_\tau \to \tilde{\nu}_\tau$)
3. $q \to \tilde{q}$
4. photon → photino ($\gamma \to \tilde{\gamma}$); similarly $g \to \tilde{g}$, etc.)

Spectrum and Interactions

The interactions of the particles are fixed by supersymmetry, but the spectrum is not. Lightest supersymmetric particle typically stable: candidate for dark matter.



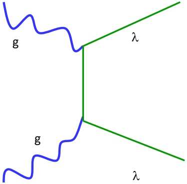
An attractive Extension: Supersymmetry

Symmetry between

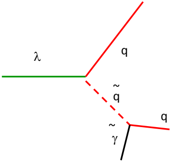
Fermions ↔ **Bosons**
(matter) (force carrier)

Spin	Standardparticle	Superpartner	Spin
1/2	Leptons (e, ν_e, ...) Quarks (u, d, ...)	Sleptons ($\tilde{e}$, $\tilde{\nu}_e$, ...) Squarks ($\tilde{u}$, $\tilde{d}$, ...)	0
1	Gluons $W^{\pm}$ Z^0 Photon (γ)	Gluinos Wino Zino Photino ($\tilde{\gamma}$)	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

... doubled particle spectrum ... ☹



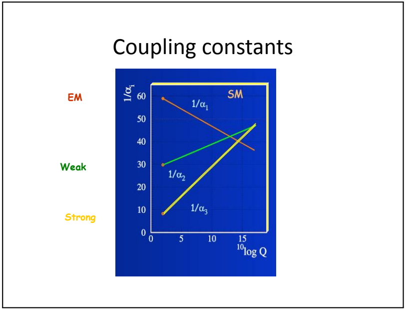
Gluons scatter and produce gluinos



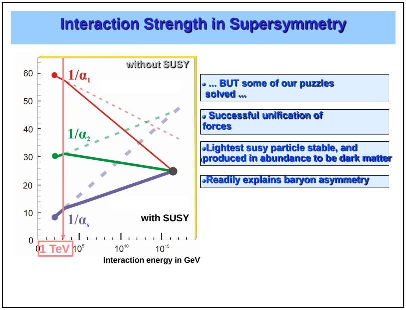
Gluino decays to quark and photino

Even without discovery, two dramatic predictions (outcomes of the basic hypothesis):

1. Dark Matter Candidate (often, not always)
2. Unification of couplings.



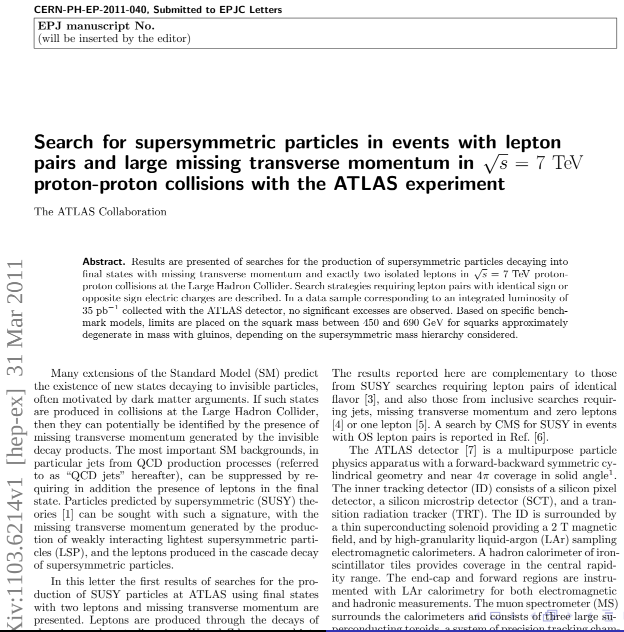
Coupling constants



Interaction Strength in Supersymmetry

- ... BUT some of our puzzles solved ...
- Successful unification of forces
- Lightest susy particle stable, and produced in abundance to be dark matter
- Readily explains baryon asymmetry

Extensive searches have already been conducted for these particles, limits set on masses.



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EPJ manuscript No.
(will be inserted by the editor)

Search for supersymmetric particles in events with lepton pairs and large missing transverse momentum in $\sqrt{s} = 7$ TeV proton-proton collisions with the ATLAS experiment

The ATLAS Collaboration

Abstract. Results are presented of searches for the production of supersymmetric particles decaying into final states with missing transverse momentum and exactly two isolated leptons in $\sqrt{s} = 7$ TeV proton-proton collisions at the Large Hadron Collider. Search strategies requiring lepton pairs with identical sign or opposite sign electric charges are described. In a data sample corresponding to an integrated luminosity of 35 pb^{-1} collected with the ATLAS detector, no significant excesses are observed. Based on specific benchmark models, limits are placed on the squark mass between 450 and 690 GeV for squarks approximately degenerate in mass with gluinos, depending on the supersymmetric mass hierarchy considered.

Many extensions of the Standard Model (SM) predict the existence of new states decaying to invisible particles, often motivated by dark matter arguments. If such states are produced in collisions at the Large Hadron Collider, then they can potentially be identified by the presence of missing transverse momentum generated by the invisible decay products. The most important SM backgrounds, in particular jets from QCD production processes (referred to as "QCD jets" hereafter), can be suppressed by requiring in addition the presence of leptons in the final state. Particles predicted by supersymmetric (SUSY) theories [1] can be sought with such a signature, with the missing transverse momentum generated by the production of weakly interacting lightest supersymmetric particles (LSP), and the leptons produced in the cascade decay of supersymmetric particles.

In this letter the first results of searches for the production of SUSY particles at ATLAS using final states with two leptons and missing transverse momentum are presented. Leptons are produced through the decays of

The results reported here are complementary to those from SUSY searches requiring lepton pairs of identical flavor [3], and also those from inclusive searches requiring jets, missing transverse momentum and zero leptons [4] or one lepton [5]. A search by CMS for SUSY in events with OS lepton pairs is reported in Ref. [6].

The ATLAS detector [7] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle[1]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT). The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimeters. A hadron calorimeter of iron-scintillator tiles provides coverage in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large su-

Discovery of Higgs at 126 GeV

Uncomfortably large for susy (Haber, Banks, Dine). But maybe ok. Focus of much of my effort at present time (and that of students).
Even more problematic for alternatives to supersymmetry (but again, maybe ok – also subject of efforts in our group)

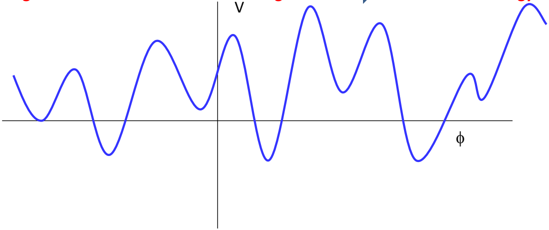
Another hierarchy

Another hierarchy (failure of dimensional analysis): the cosmological constant (dark energy). What solves this? Is there some other solution to hierarchy problems which we are not considering?

The Landscape

Following earlier suggestions of Bousso, Polchinski, Kachru, Kallosh, Linde, Trivedi: established the existence of a *vast* number of metastable states, perhaps 10^{500} or even more. (Compare spin glass). Uniform distribution of possible cc's.

Weinberg: in such a situation + existence of galaxies → observed dark energy!



Could the hierarchy problem be solved in a similar way? Some underlying distribution of possible Higgs masses; anthropic selection?

This view has been advocated by Michael Douglas, Leonard Susskind.

Reasons for Optimism

1. It seems likely that even in string landscape, states with some amount of supersymmetry are common.
2. Metastable states with some supersymmetry are generically long-lived; others are not (G. Festuccia, A. Morisse, M.D.).
3. Among the supersymmetric states, low scale breaking of supersymmetry much more likely to lead to a sufficiently light Higgs (S. Thomas, E. Gorbatov, M.D.).

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Theory Projects of Current, Recent Students

1. Theoretical issues in quantum field theory (Pack, Ubaldi)
2. Supersymmetry model building (Mason, Kehayias, Bose)
3. Supersymmetry, Higgs and LHC (Monteux, Bose)
4. Cosmological questions: Dark matter candidates with, without supersymmetry (Ubaldi, Wu)
5. Cosmological questions: inflation, “moduli" (Pack; Bose, Monteux, Stevenson-Haskins)
6. Cosmological questions: vacuum stability, more general questions relating to dark energy (Morisse, Sun)
7. Cosmological questions: baryogenesis.

Other projects (postdocs; more senior collaborators)

1. Tunneling from a false vacuum (with Draper)
2. Proton decay and its implicates for the supersymmetry breaking scale (with Draper, Shepherd)
3. Understanding “anomaly mediation" in supergravity (with Draper; now with Komargodski)