Particle Theory Beyond the Standard Model

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The world physics community has spent > 4B dollars (including 600M from American taxpayers) on the "Large Hadron Collider" (LHC)

WHY?

Purpose of LHC

- Find the Higgs boson
- Make discoveries beyond Standard Model of Particle Physics
  - Many searches for “new physics” optimised at about 100-1000 fb^{-1} at (7+7 TeV) (2015?)
  - If we are lucky, new discoveries could be made this year, at (3.5+3.5 TeV).
- What is the Standard Model?

Particle Physics sacred principles

- All interactions are local (occur at a space-time point)
- Quantum mechanics is correct
- Special relativity (actually 4d Poincare invariance) is correct

▷ these assumptions imply that particle physics is completely described by (effective) quantum field theory

QFT

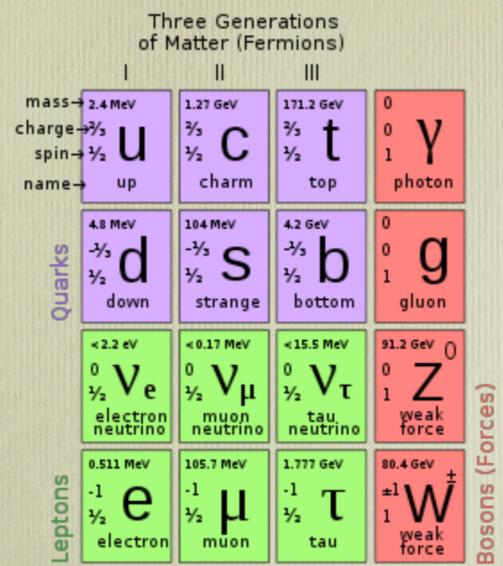
- Quantum: easier to teach how to DO than how to describe the first principles
  - Define set of observables and a procedure for computing PROBABILITY DISTRIBUTION for correlations between observations
  - several equivalent procedures (path integrals, Heisenberg, Schroginger picture)
  - several equivalent(?) interpretations of the meaning of these procedures (many worlds, Copenhagen, decoherence)

QFT, cont

- Field: (like E and M) Localized observable
(e.g. "is there an electron with a certain spin at this point in space at this time", rather than "what is the spin of the electron")
- Bosonic fields, like E and M, called forces, but quantized packets of field energy, like photons, have particle properties
- Fermion fields, like the electron field, cannot give macroscopic observables, but also have quantized packets of field energy with particle properties

Standard Model of Particle Physics

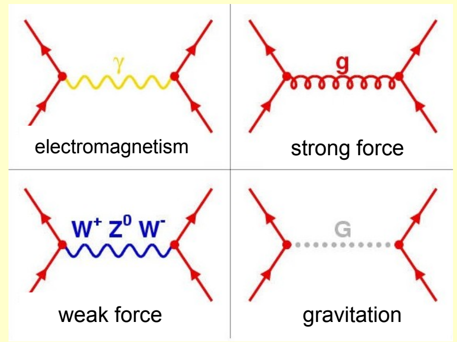
i: Fermionic Particles



ii: Forces mediated by Bosonic Particles

(ii) Forces / Interactions:

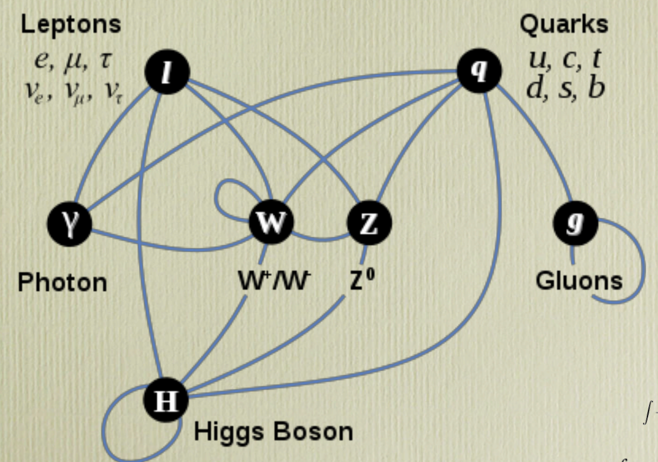
mediated via the exchange of
field quanta /bosons



$m_\gamma = 0$, $m_g = 0$

$M_W = 80.398 \pm 0.025$ GeV / c^2
$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

Summary of interactions



$$\int -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\mathrm{tr}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}\mathrm{tr}G_{\mu\nu}G^{\mu\nu}$$

$$\mathcal{L}_{\mathrm{EW}} = \sum_{\psi} \bar{\psi}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{1}{2}Y_{\mathrm{W}}B_{\mu} - g\frac{1}{2}\vec{\tau}_{\mathrm{L}}\vec{W}_{\mu}\right)\psi$$

$$S_{\mathrm{Higgs}} = \int d^4x \left[(D_{\mu}H)^{*}(D^{\mu}H) + \lambda(|H|^2 - v^2)^2\right].$$

Why go Beyond the Standard Model?

Status of the Standard Model

- Extended to allow for neutrinos to have mass
- Gravity is ignored, can only approximately be incorporated ("Effective theory")
- accounts well for most observations of the known particles

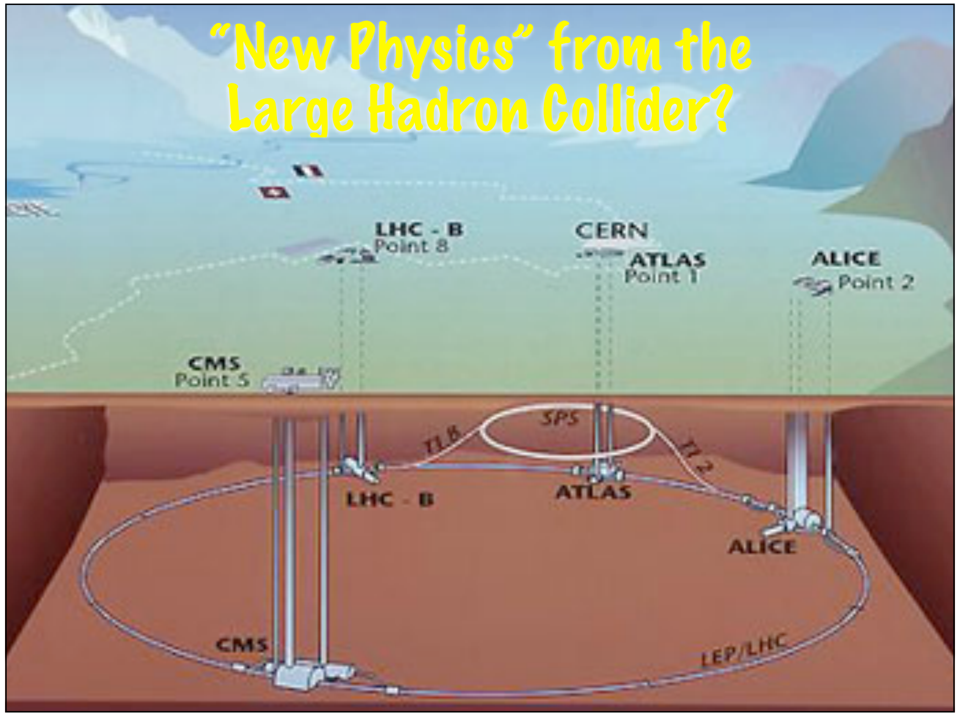
“Alive, but looking good?”

Evidence for BSM is overwhelming

- Triviality of SM
- Gravity,
- Inflation,
- Baryons,
- Dark Matter,
- Neutrino Mass,
- Accelerating Universe ...

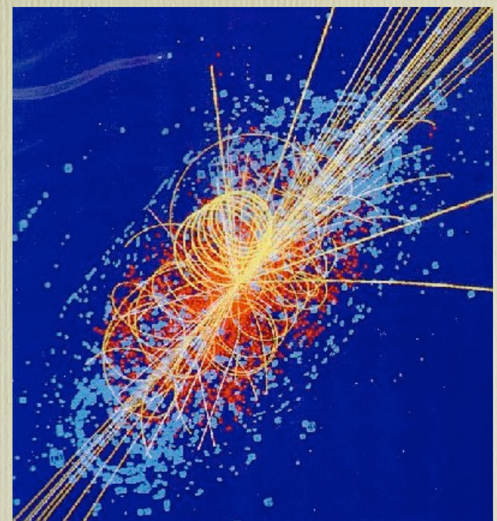
but weird and hard to interpret

“New Physics” from the Large Hadron Collider?



What the LHC does

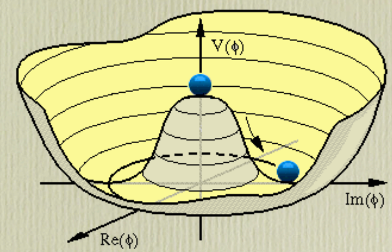
- Collides proton beams, Designed for 7+7=14 TeV
- $E=mc^2$
- Energy converted to many massive particles
- Detectors record properties. Any new kinds?



A New Start

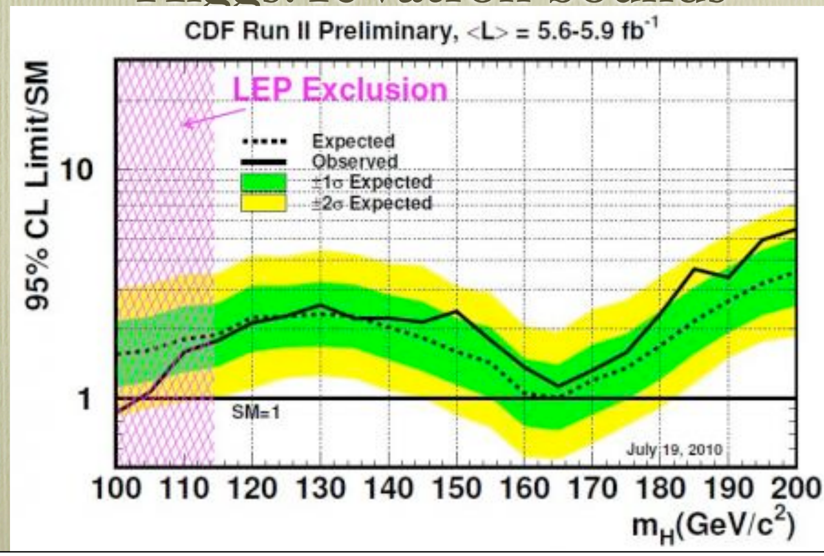
- March 29, 2010: First Collisions at 7 TeV! (half design energy) 16 years after construction approved, 18 months after accident aborts first run.

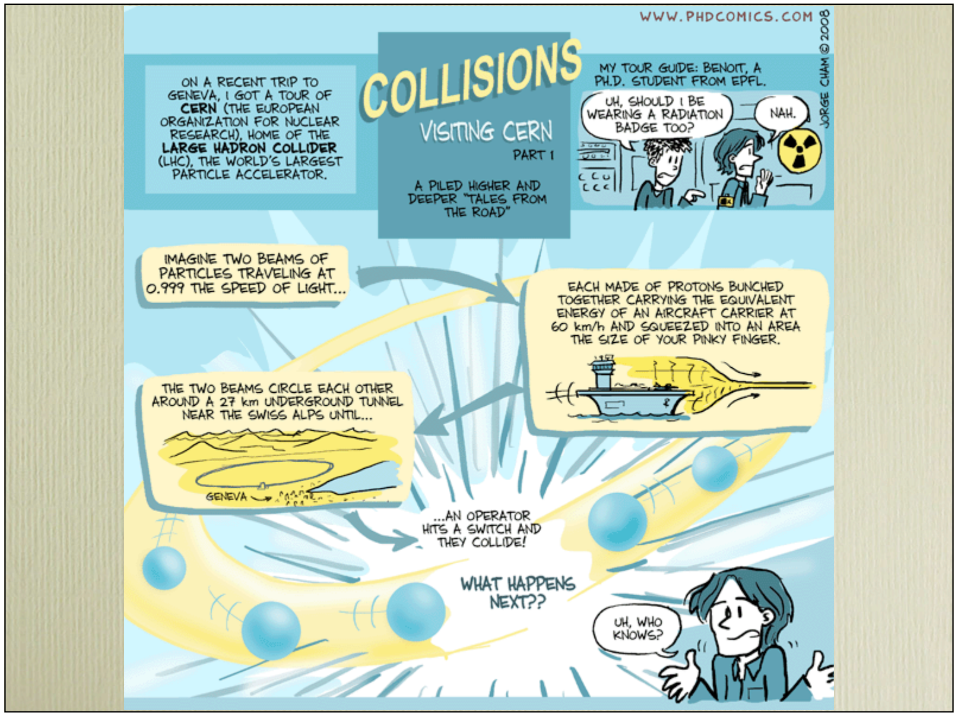
The hunt for the Higgs Boson



The Standard Model Vacuum is a WEAK SUPERCONDUCTOR due to a CONDENSATE of Higgs bosons. Couplings with this condensate give W and Z bosons, and the quarks and leptons, their mass. Excitations of the vacuum are the long sought Higgs. The Higgs mass is an unknown parameter but must be less than 1000 GeV/c².

The hunt for the Higgs:TeVatron bounds

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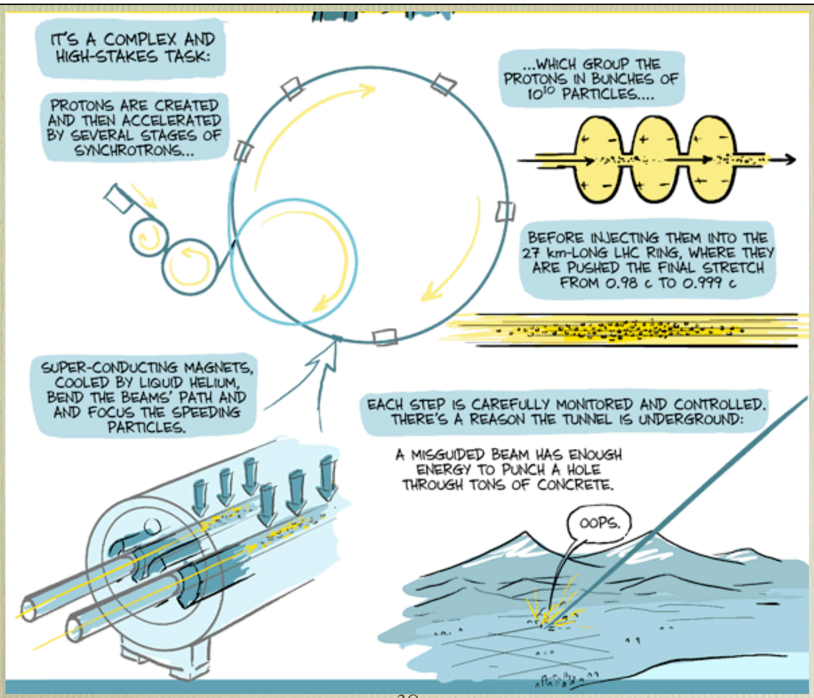
COLLISIONS
VISITING CERN
PART 1
A PILED HIGHER AND DEEPER "TALES FROM THE ROAD"
ON A RECENT TRIP TO GENEVA, I GOT A TOUR OF **CERN** (THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH), HOME OF THE **LARGE HADRON COLLIDER** (LHC), THE WORLD'S LARGEST PARTICLE ACCELERATOR.
MY TOUR GUIDE: BENOIT, A PH.D. STUDENT FROM EPFL.
UH, SHOULD I BE WEARING A RADIATION BADGE TOO?
NAH.
IMAGINE TWO BEAMS OF PARTICLES TRAVELING AT 0.999 THE SPEED OF LIGHT...
EACH MADE OF PROTONS BUNCHED TOGETHER CARRYING THE EQUIVALENT ENERGY OF AN AIRCRAFT CARRIER AT 60 km/h AND SQUEEZED INTO AN AREA THE SIZE OF YOUR PINKY FINGER.
THE TWO BEAMS CIRCLE EACH OTHER AROUND A 27 km UNDERGROUND TUNNEL NEAR THE SWISS ALPS UNTIL...
GENEVA
...AN OPERATOR HITS A SWITCH AND THEY COLLIDE!
WHAT HAPPENS NEXT??
UH, WHO KNOWS?

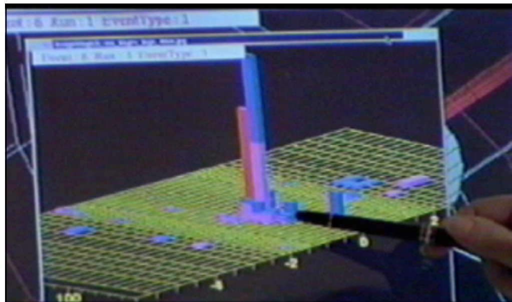

IT'S A COMPLEX AND HIGH-STAKES TASK:
PROTONS ARE CREATED AND THEN ACCELERATED BY SEVERAL STAGES OF SYNCHROTRONS...
...WHICH GROUP THE PROTONS IN BUNCHES OF 10^10 PARTICLES....
BEFORE INJECTING THEM INTO THE 27 km-LONG LHC RING, WHERE THEY ARE PUSHED THE FINAL STRETCH FROM 0.98 c TO 0.999 c
SUPER-CONDUCTING MAGNETS, COOLED BY LIQUID HELIUM, BEND THE BEAMS' PATH AND AND FOCUS THE SPEEDING PARTICLES.
EACH STEP IS CAREFULLY MONITORED AND CONTROLLED. THERE'S A REASON THE TUNNEL IS UNDERGROUND:
A MISGUIDED BEAM HAS ENOUGH ENERGY TO PUNCH A HOLE THROUGH TONS OF CONCRETE.
OOPS.

Plans for 2010-11

- The LHC will run at 3.5+3.5 TeV in 2010 and 2011, until the experiments collect an integrated luminosity of ~ 1 fb^{-1} .
  (now has 1/1000 of that, enough to rediscover the top quark!). TeVatron now has 9 fb^{-1}).
- Only a short technical stop is foreseen at the end of 2010-beginning of 2011. The 2010-2011 run will be followed by a long (~1 year) shut-down, to redo all splices to enable the machine to operate at design energy (7+7 TeV). A "final" plan can only be made around June, following experience with machine operation and performance at 3.5+3.5 TeV.

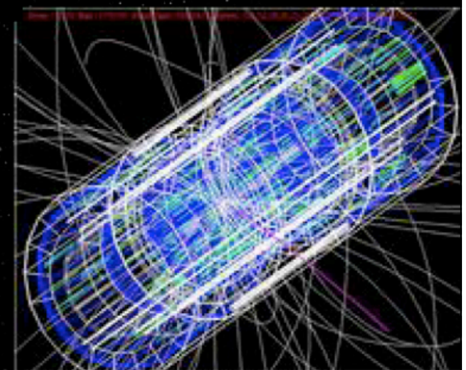
LHC numbers

- 27 km circumference
- at 7 TeV, protons accelerated to 99.9999991% speed of light
- each proton travels 11,245 times around ring/second
- collision energy equivalent to temperature over 1 billion times core of sun
- 120 tons liquid helium at 1.9 K
- power consumption: 120 MW
- cost: 4 billion $



you have to sift
through trillions
of “events”

to find the rare
events that have
new particles or
new physics



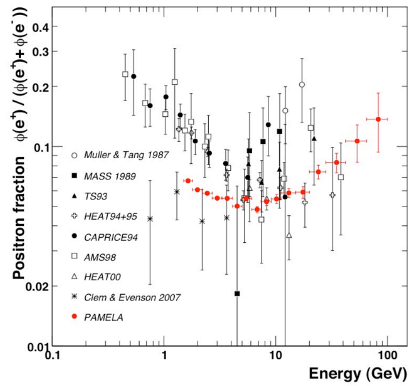


FIG. 3: **PAMELA positron fraction with other experimental data.** The positron fraction measured by the PAMELA experiment compared with other recent experimental data[24, 29, 30, 31, 32, 33, 34, 35]. One standard deviation error bars are shown. If not visible, they lie inside the data points.

Hints (or red herrings) from the sky?

measurements of positrons + electrons

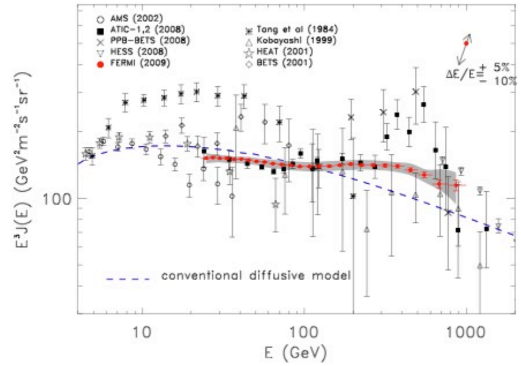
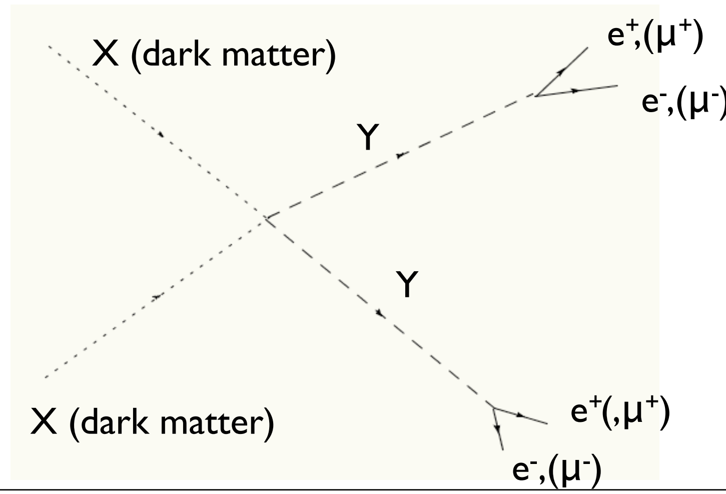


FIG. 3: (color) The Fermi LAT CR electron spectrum (red filled circles). Systematic errors are shown by the gray band. The two-headed arrow in the top-right corner of the figure gives size and direction of the rigid shift of the spectrum implied by a shift of $^{+5\%}_{-10\%}$ of the absolute energy, corresponding to the present estimate of the uncertainty of the LAT energy scale. Other high-energy measurements and a conventional diffusive model [1] are shown.

WIMP Annihilation via intermediate light boson



It's On: Early Interpretations of ATLAS Results in Jets and Missing Energy Searches

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The first search for supersymmetry from ATLAS with 70 nb^{-1} of integrated luminosity sets new limits on colored particles that decay into jets plus missing transverse energy. For gluinos that decay directly or through a one step cascade into the LSP and two jets, these limits translate into a bound of $m_{\tilde{g}} \geq 205\,\mathrm{GeV}$, regardless of the mass of the LSP. In some cases the limits extend up to $m_{\tilde{g}} \simeq 295\,\mathrm{GeV}$, already surpassing the Tevatron's reach for compressed supersymmetry spectra.

I. INTRODUCTION

Jets plus missing energy is one of the most promising channels in the search for physics beyond the Standard Model at hadron colliders. With the preliminary results from ATLAS on jets plus missing energy searches for supersymmetry [1], new limits on color octet particles that subsequently decay into a pair of jets and a long lived neutral particle can be set. Although only $70 \pm 8\ \mathrm{nb}^{-1}$ of integrated luminosity has been analyzed, that is already sufficient to infer new constraints on models with light colored particles.

The most robust bounds on new color octet particles come from LEP2's measurements of thrust. These measurements place a model independent lower bound on a

tron's searches for jets and missing energy in a more general setting [8]. Models where the gluino decays into jets plus the LSP have a model independent lower bound of $m_{\tilde{g}} \gtrsim 130\,\mathrm{GeV}$, with stronger constraints arising from spectra where the gluino and LSP have hierarchical mass splittings. This universal limit is far below the normally quoted 400 GeV limit on gluino-like objects. Given such limited current bounds – a 51 GeV hard lower limit on the gluino mass and an approximate 130 GeV lower limit from dedicated searches – the integrated luminosity accumulated at the LHC in its early running is already sufficient to extend the present reach for light colored octets.

Low luminosity searches allow modest cuts to be placed on missing transverse energy, helping the searches' effi-


Experimentalists
LHC
results
Theorists