Particle Theory in the age of the LHC

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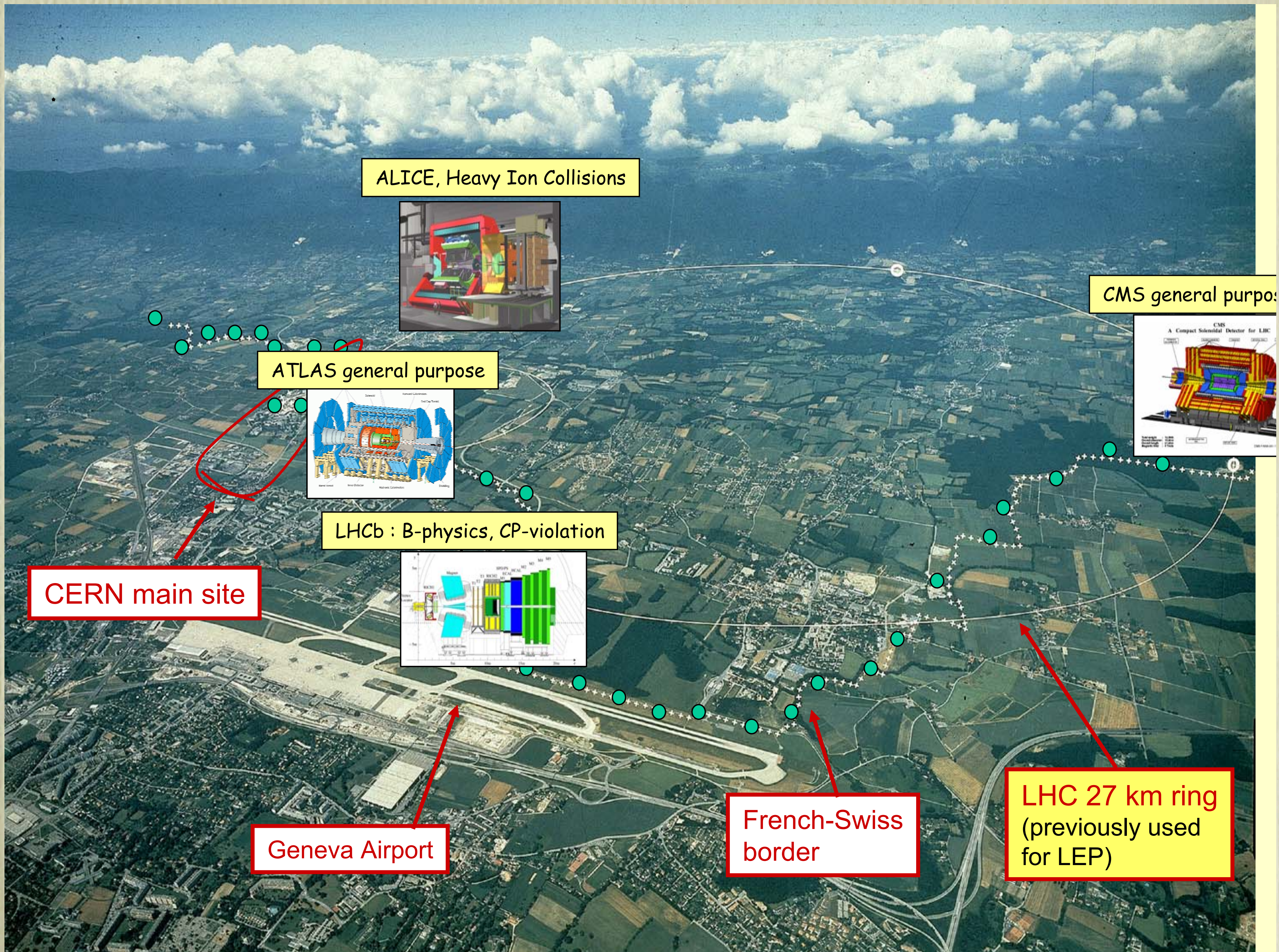
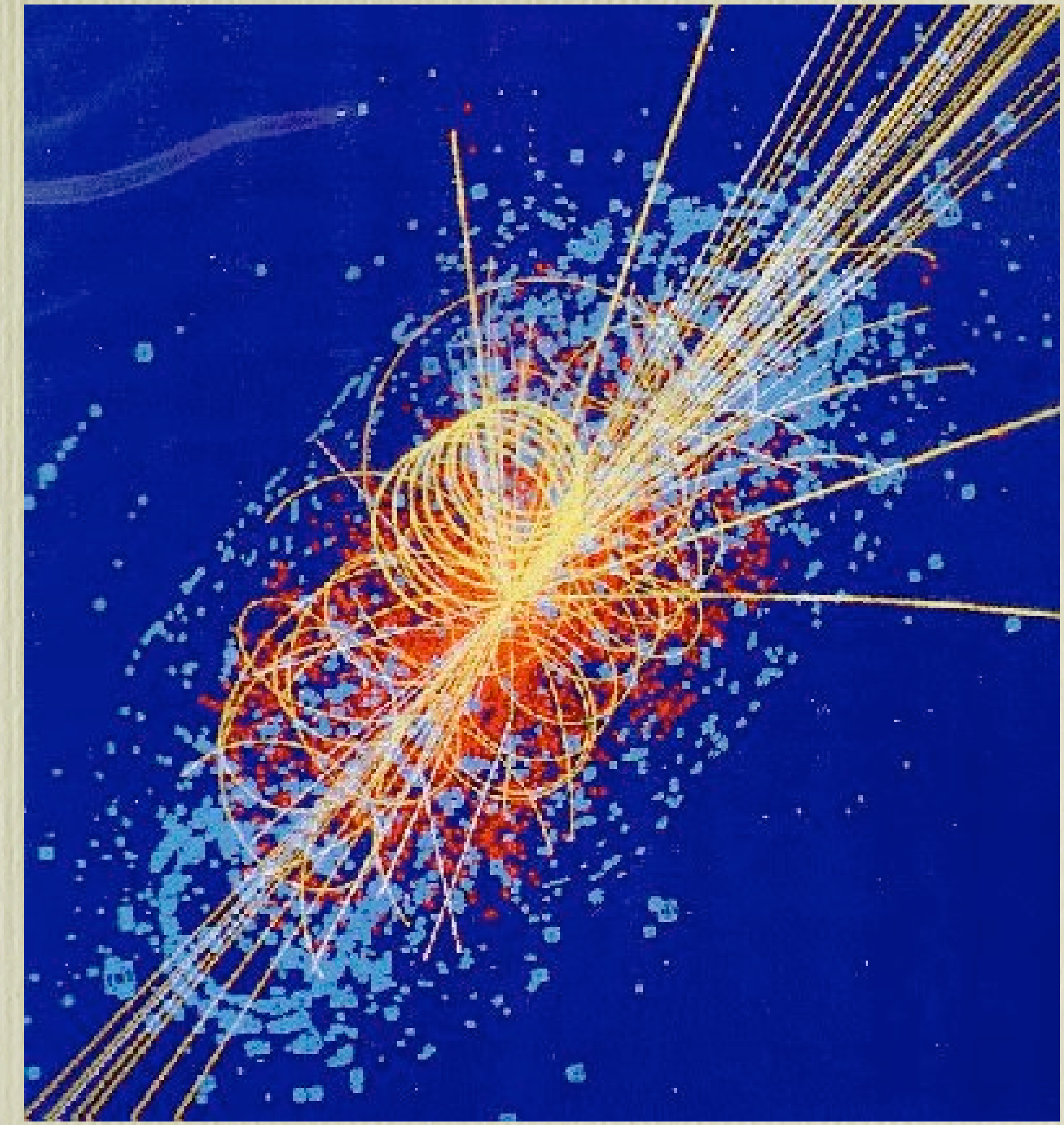
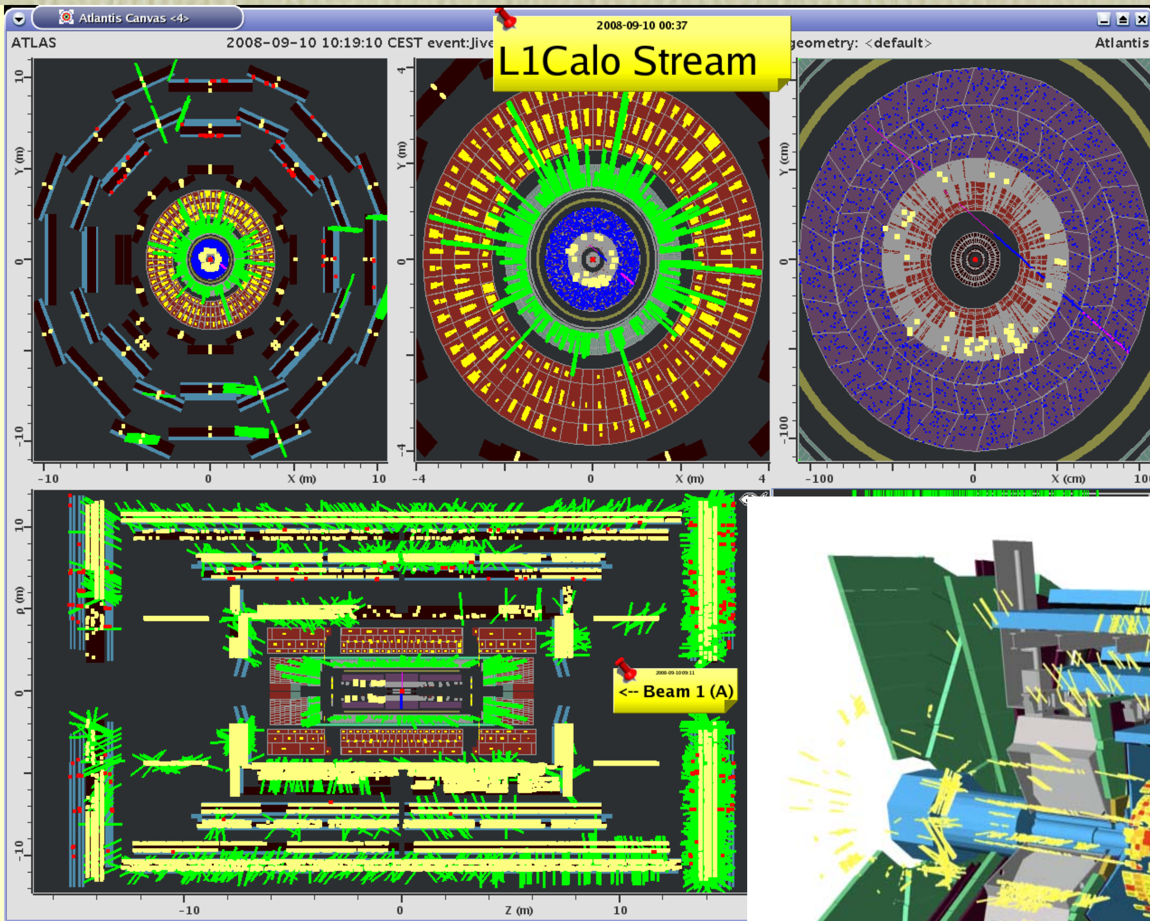

ALICE, Heavy Ion Collisions
CMS general purpos
ATLAS general purpose
LHCb : B-physics, CP-violation
CERN main site
Geneva Airport
French-Swiss border
LHC 27 km ring (previously used for LEP)

What the LHC does

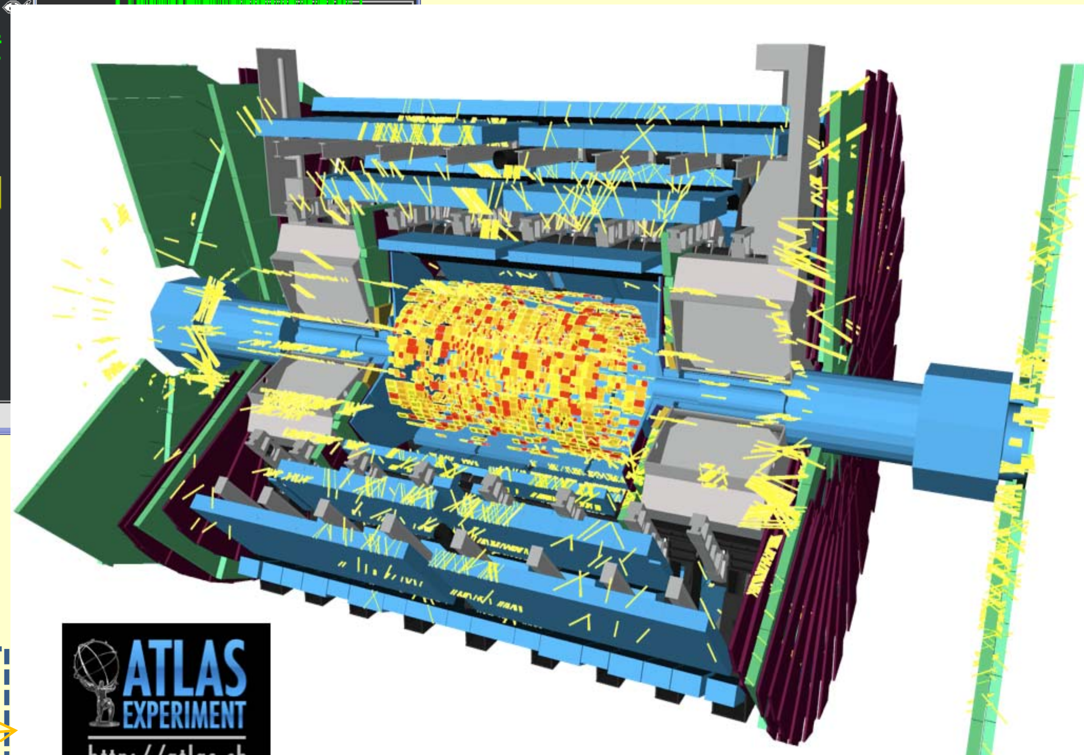
- Collides 5-7 TeV proton beams, total energy - 10- 14 TeV
- $E=mc^2$
- Energy converted to many massive particles
- Detectors record properties. Any new kinds?



An excellent start: first beams – September 10, 2008

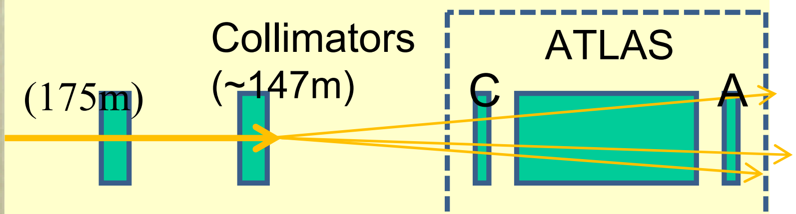


The very first beam-splash event from the LHC in ATLAS on 10th September 2008, 10:19



ATLAS EXPERIMENT http://atlas.ch

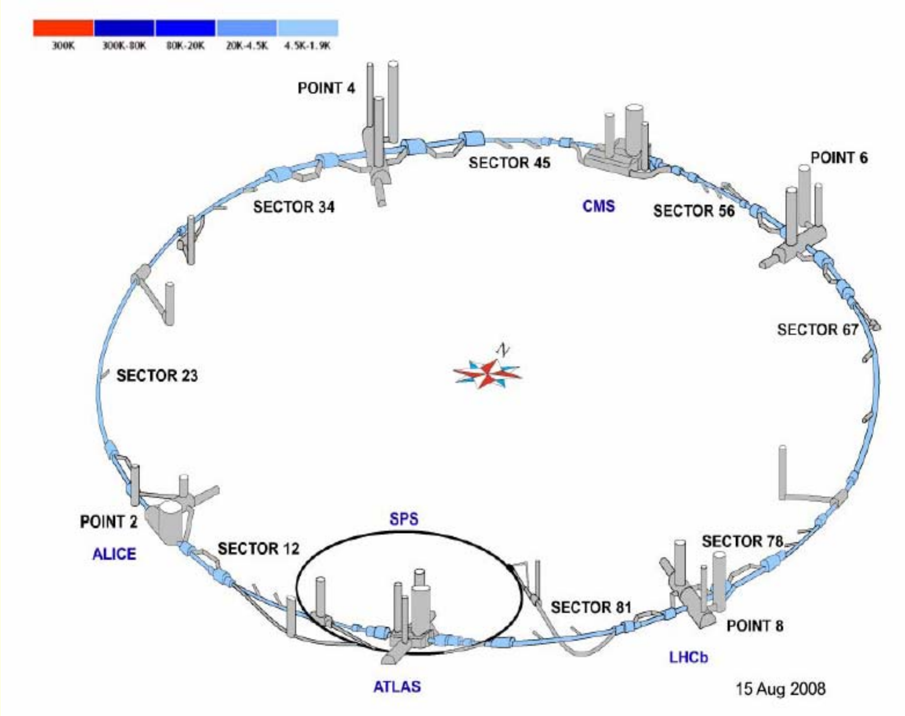
first beam event seen in ATLAS



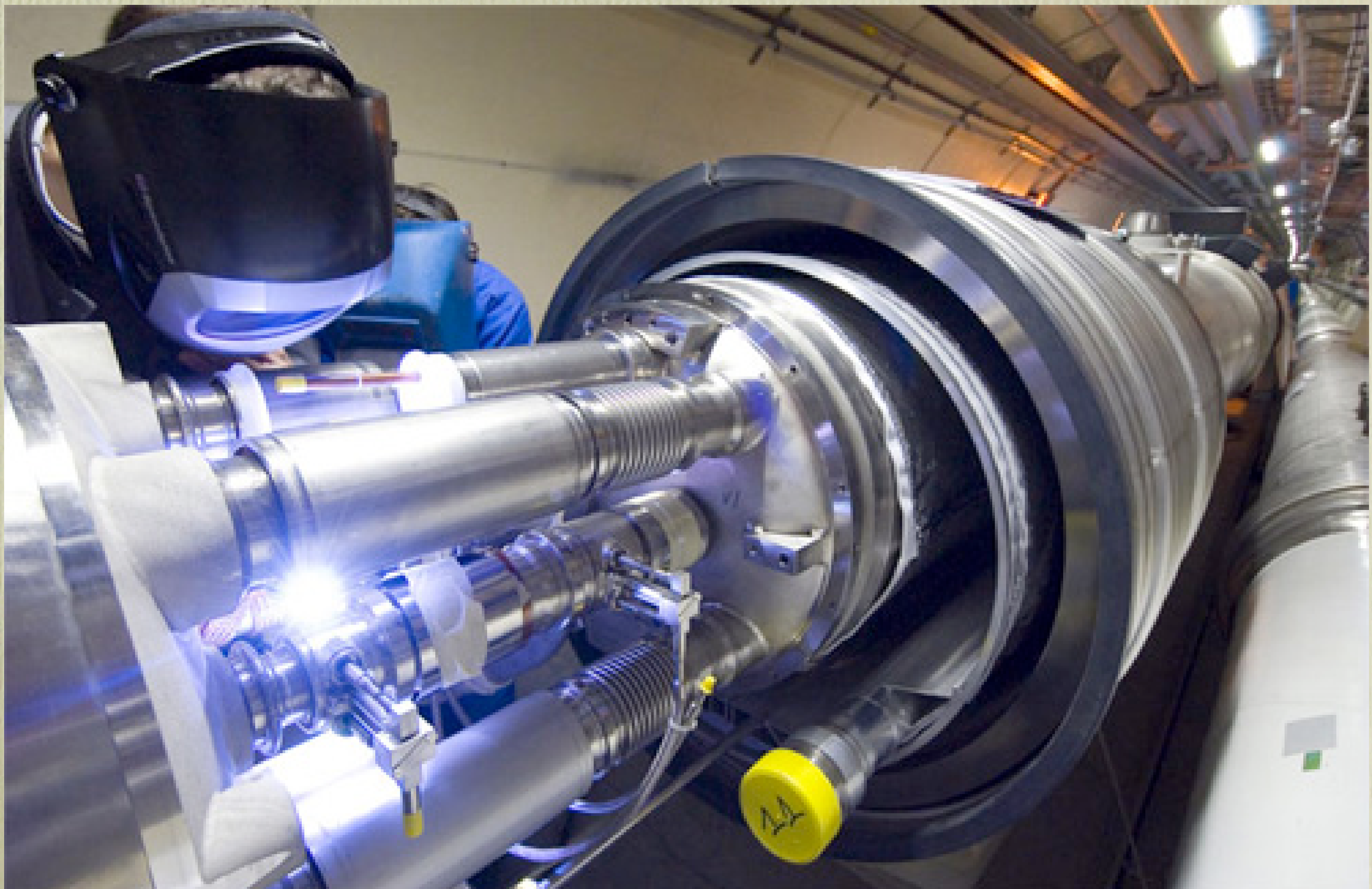
The Event on 19. Sep 2008

- the present understanding
- ongoing repair work
- plans for 2009

a quench of about 100 superconducting magnets, that heated up as much as 100 C. About one ton of liquid helium leaked out, causing about 100 of the supercooled electromagnets to heat up and fail.



Results of Accident



The CERN Management today confirmed the restart schedule for the Large Hadron Collider resulting from the recommendations from the Chamonix workshop. The new schedule foresees first beams in the LHC at the end of September this year, with collisions following in late October. A short technical stop has also been foreseen over the Christmas period. The LHC will then run through to autumn next year, ensuring that the experiments have adequate data to carry out their first new physics analyses and have results to announce in 2010. The new schedule also permits the possible collisions of lead ions in 2010.

This new schedule represents a delay of 6 weeks with respect to the previous schedule which foresaw LHC "cold at the beginning of July". The cause of this delay is due to several factors such as implementation of a new enhanced protection system for the busbar and magnet splices, installation of new pressure relief valves to reduce the collateral damage in case of a repeat incident, application of more stringent safety constraints, and scheduling constraints associated with helium transfer and storage.

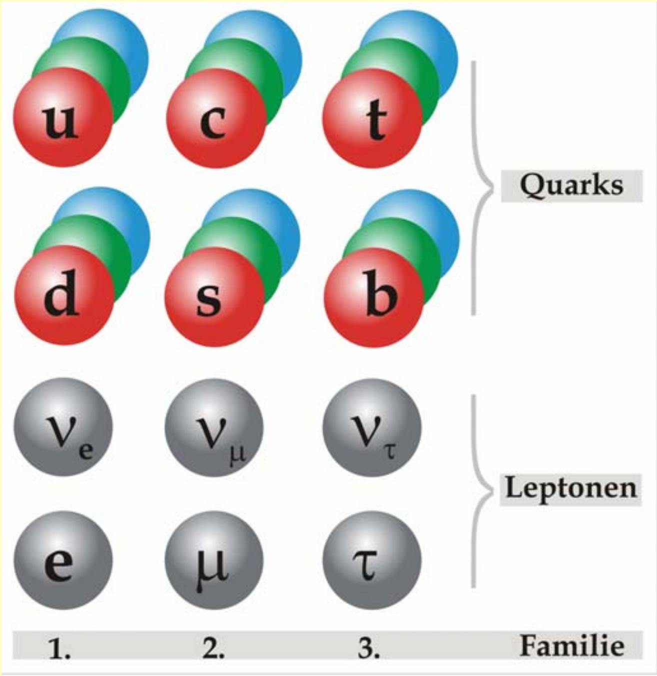
In Chamonix there was consensus among all the technical specialists that the new schedule is tight but realistic.

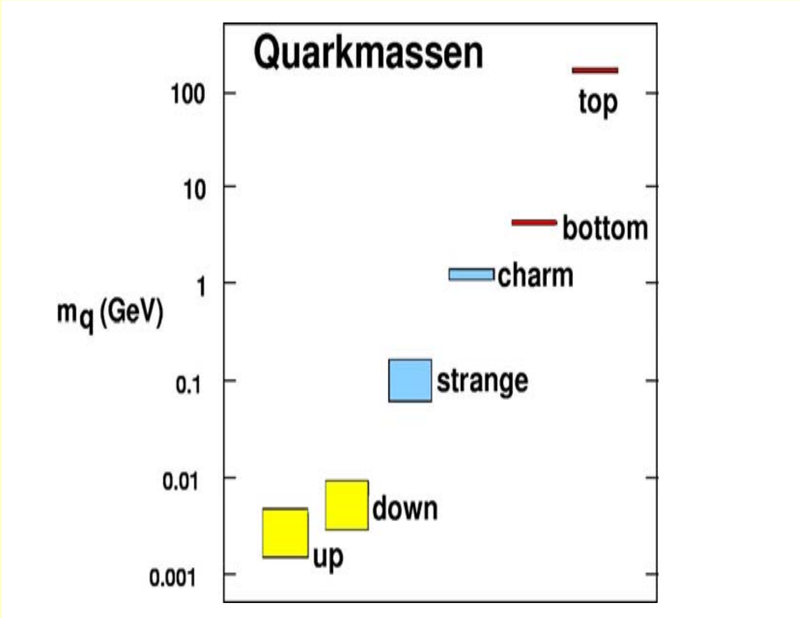
Purpose of LHC

- Make discoveries beyond Standard Model of Particle Physics
- What is the Standard Model?

The Standard Model of Particle Physics

(i) Building blocks of matter: Quarks and Leptons





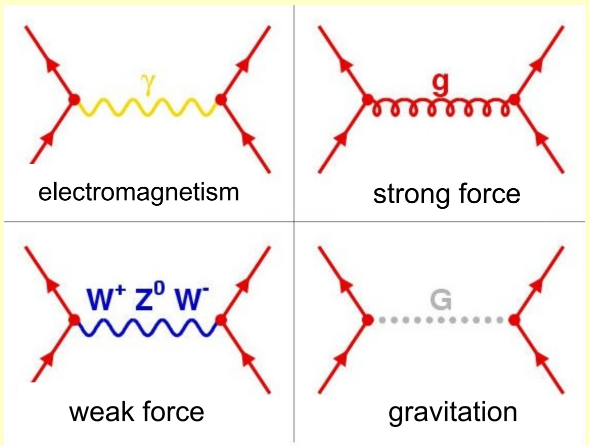
m (e) = 0.000511 GeV/c^2
m (τ) = 1.8 GeV/c^2

m (u) = 0.005 GeV/c^2
m (t) = 172.5 GeV/c^2

In comparison: m (p) = 0.938 GeV/c^2

(ii) Forces / Interactions:

mediated via the exchange of field quanta /bosons



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

M_W = 80.398 ± 0.025 GeV / c^2
M_Z = 91.1875 ± 0.0021 GeV / c^2

(iii) Higgs sector

New (scalar) field is introduced;
Needed to break (hide) the electroweak symmetry

⇒ **Higgs particle**

Theoretical arguments: $m_H < \sim 1000$ GeV/c^2

Theoretical description:

Gauge theories of electroweak and Strong interactions

(i) Electroweak theory

S. Glashow
A. Salam
S. Weinberg

(ii) Quantum Chromodynamics

D.J. Gross
H.D. Politzer
F.E. Wilcek

Problem: symmetry requires massless gauge bosons

SM theoretical inputs

- All interactions are local
- Quantum mechanics is correct, at least up to energy scales > 1 TeV (length scales down to 10^{-17} cm)
- Special relativity (actually 4d Poincare invariance) is correct on these same scales

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

SM theoretical inputs (II)

- There are gauge forces, mediated by exchanges of gauge bosons
- The gauge group is $SU(3)_c \times SU(2)_W \times U(1)_Y$

$SU(3)_c \times SU(2)_W \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{em}$ via the Higgs mechanism

Higgs is origin of mass for Weak bosons, quarks, leptons

- Gravity is ignored

Why go Beyond the Standard Model?

theorists engage in two types of activity:

- playing around with new/old/stolen ideas for going beyond the standard paradigm
(easy, fun, richly rewarded, but potentially useless)

- calculating things within the standard paradigm
(useful, but difficult, tedious, and poorly rewarded)

Evidence for BSM is overwhelming

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

but weird and hard to interpret

the importance of mystery

one cannot help but be in awe
when he contemplates the mysteries of eternity,
of life, of the marvelous structure of reality.
It is enough if one tries merely to comprehend
a little of this mystery every day.

A. Einstein

status of theories beyond the standard model

- The BSM models were created by man
- They evolved
- They rebelled
- There are many copies
- And they have a plan

Robust
Elegant
Multi-
functional
not fine-tuned
viable

What model builders aim for

Typical BSM model

barely
viable,
fine-tuning
reduced
at cost of
additional
structure

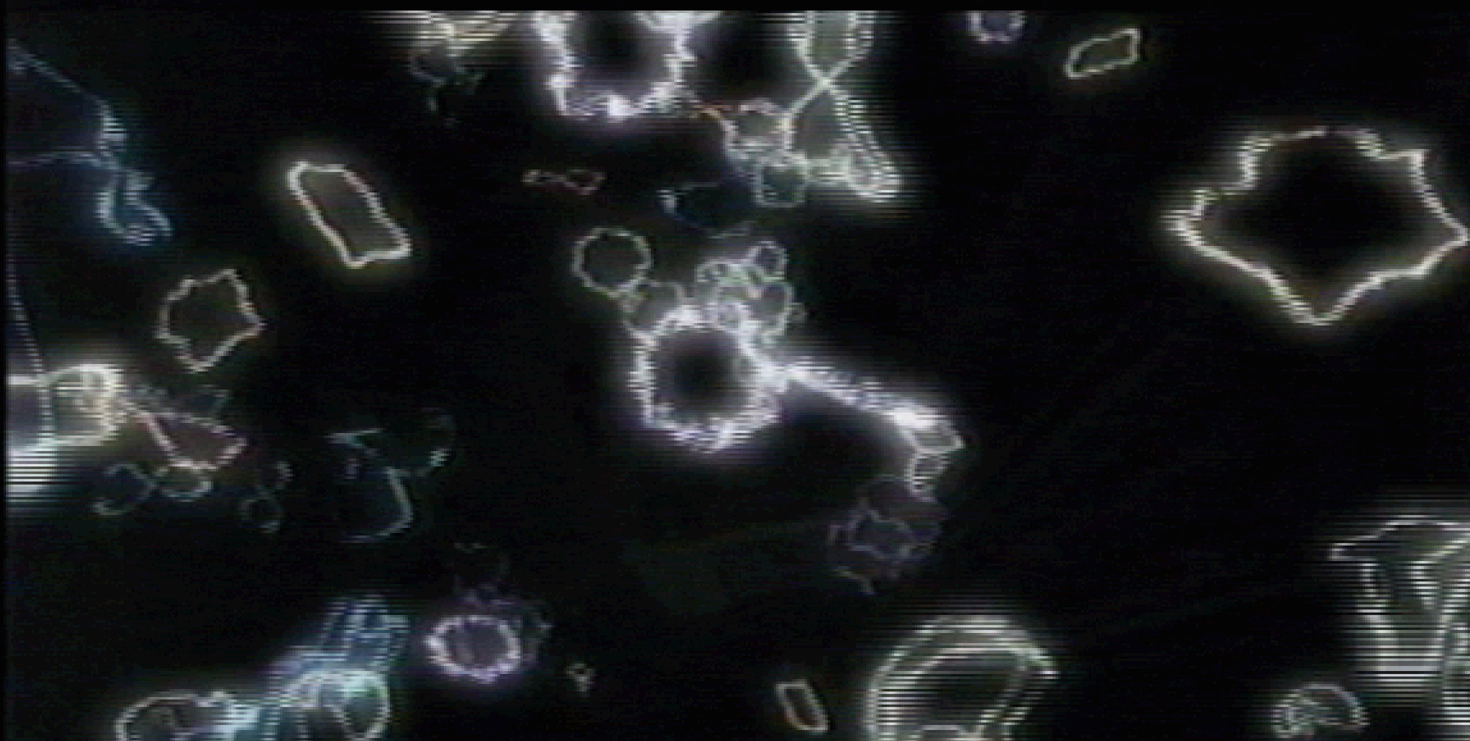
"Alive, but looking good?"

Guidance from String Theory

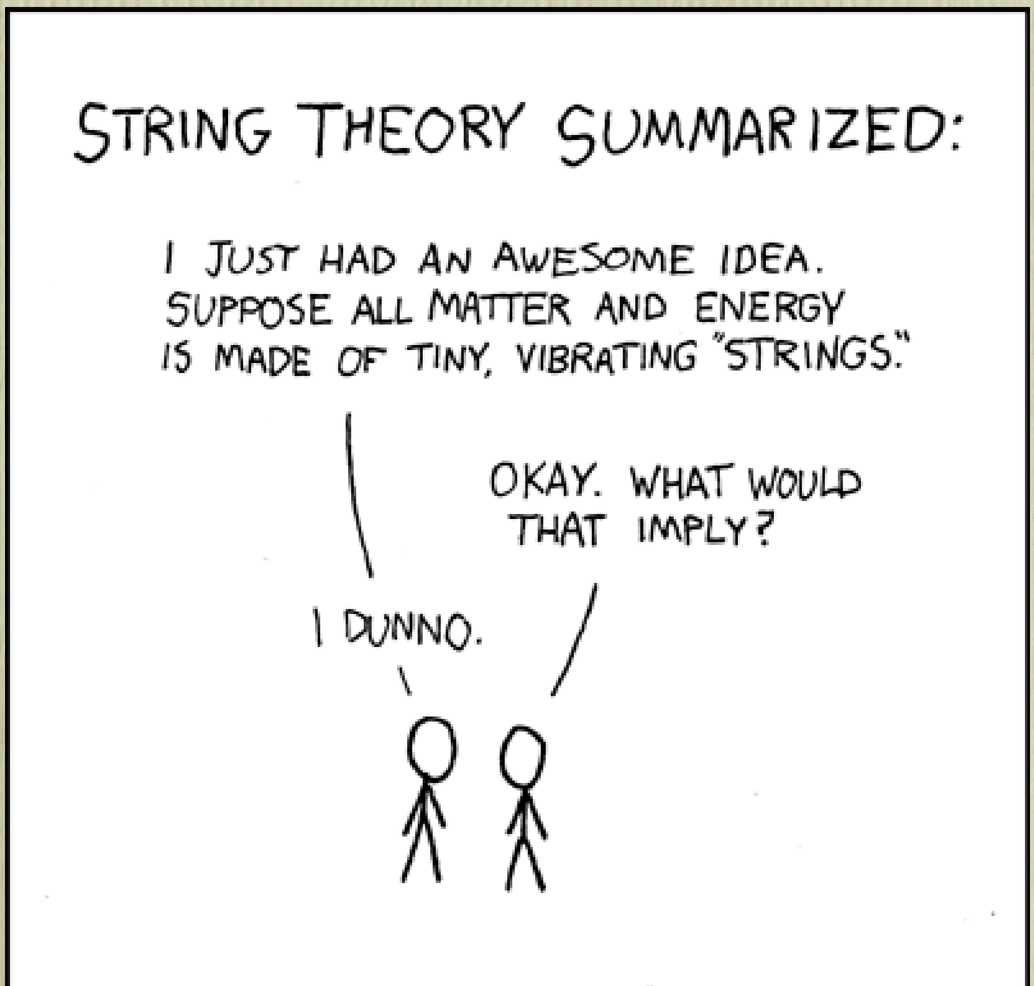
- Chasing Einstein's dream: *"NATURE IS CONSTITUTED SO THAT IT IS POSSIBLE TO LAY DOWN SUCH STRONG DETERMINED LAWS THAT WITHIN THESE LAWS ONLY RATIONALLY COMPLETELY DETERMINED CONSTANTS OCCUR, NOT CONSTANTS THEREFORE THAT COULD BE CHANGED WITHOUT COMPLETELY DESTROYING THE THEORY."*

in string theory

electrons, quarks, photons, gravitons, neutrinos, etc are all different vibrations of one kind of microscopic string: the superstring



Implications



Predictions from Strings?

Yes! New Dimensions, SUSY,Branes, New forces, lots of new scalars

“String theory is often called the "Theory of Everything" (TOE). However, since so far it makes no predictions observed by experiment, a better name might be the

"Theory of Everything Not Appearing in Laboratories"

(TOENAIL).”-W. Siegel

String Theory Finally makes a viable prediction

The Anthropic Landscape!

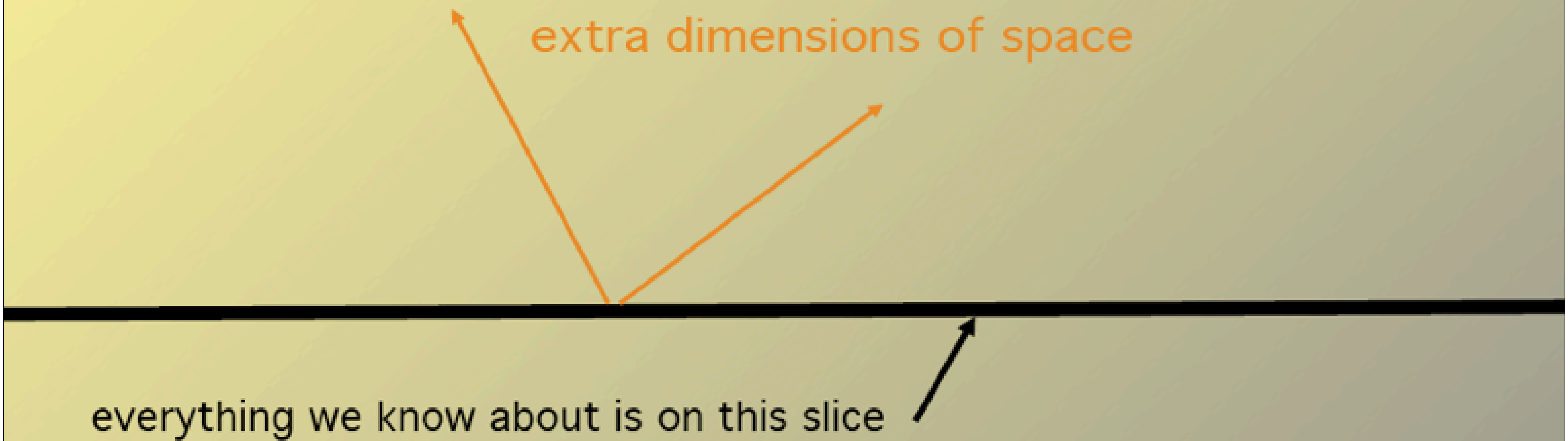
- (maybe finetuning is ok)

Answers from Experiment

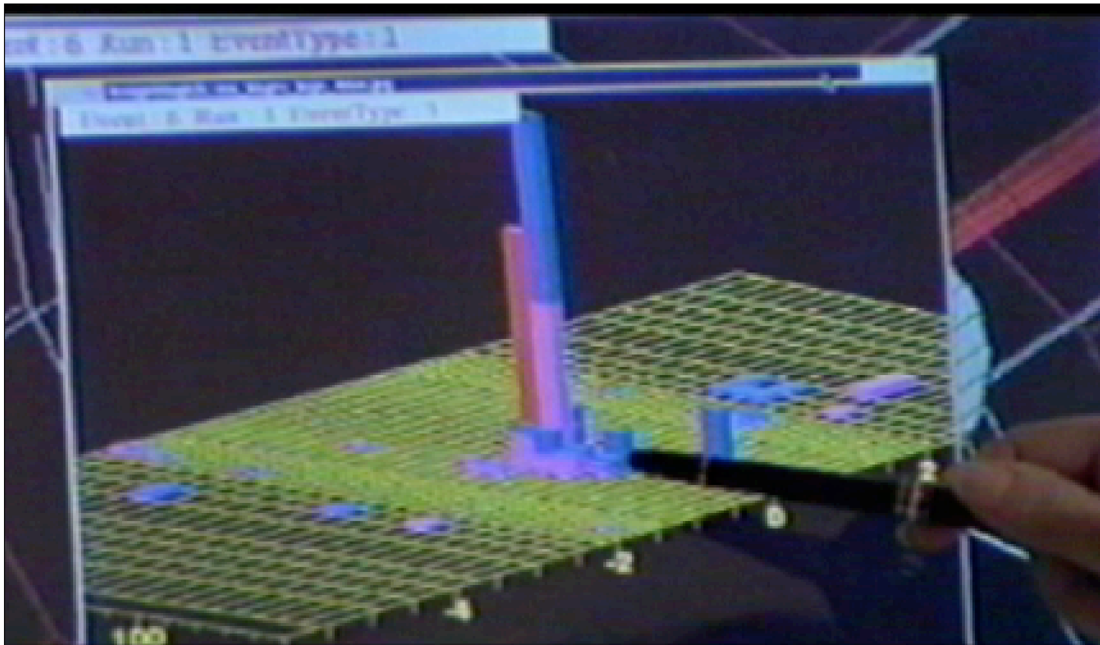
- LHC may discover
  - Supersymmetry
  - Xtra Dimensions
  - Dark Matter
  - “Unparticles”
  - ????


the universe: traditional view
you are here

the universe: a bigger view

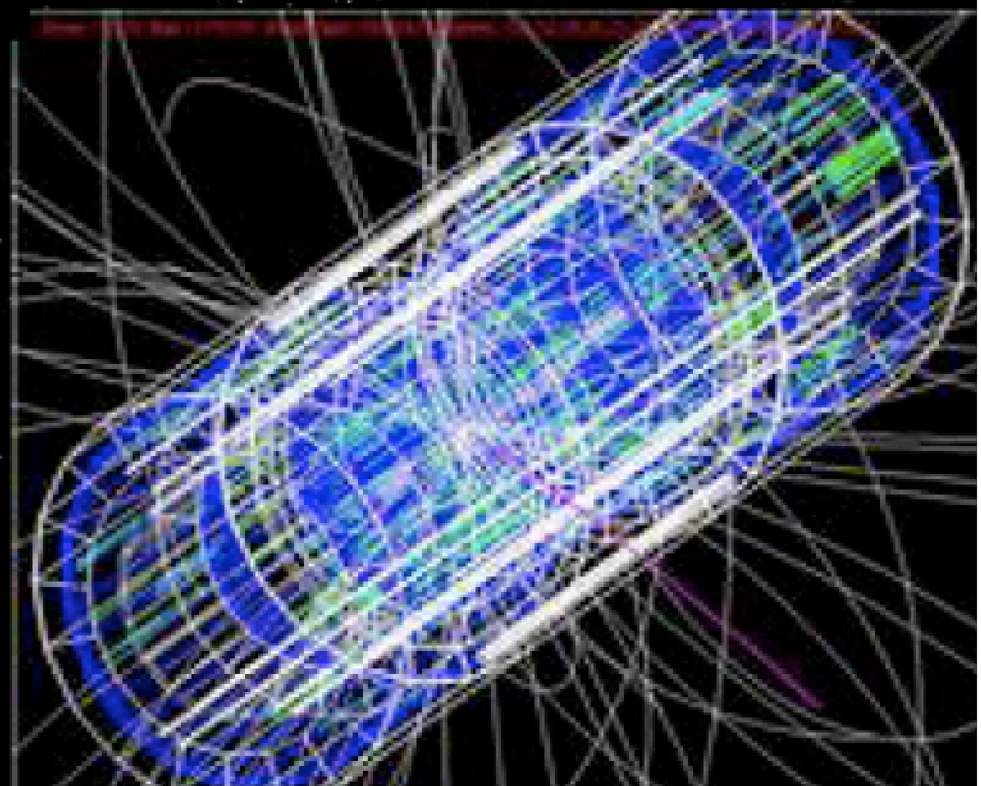


the rest is terra incognita

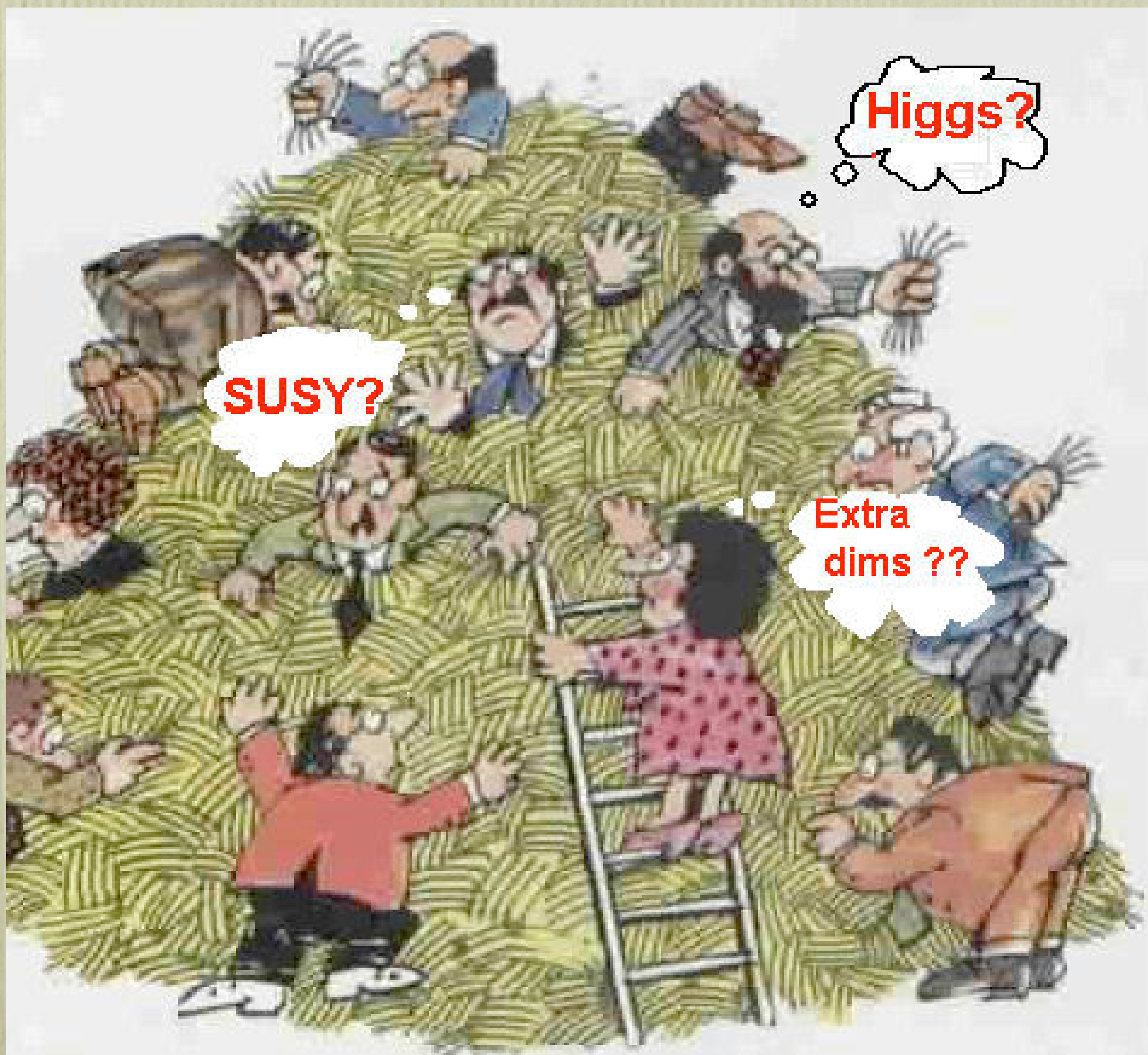


you have to sift through trillions of “events”

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



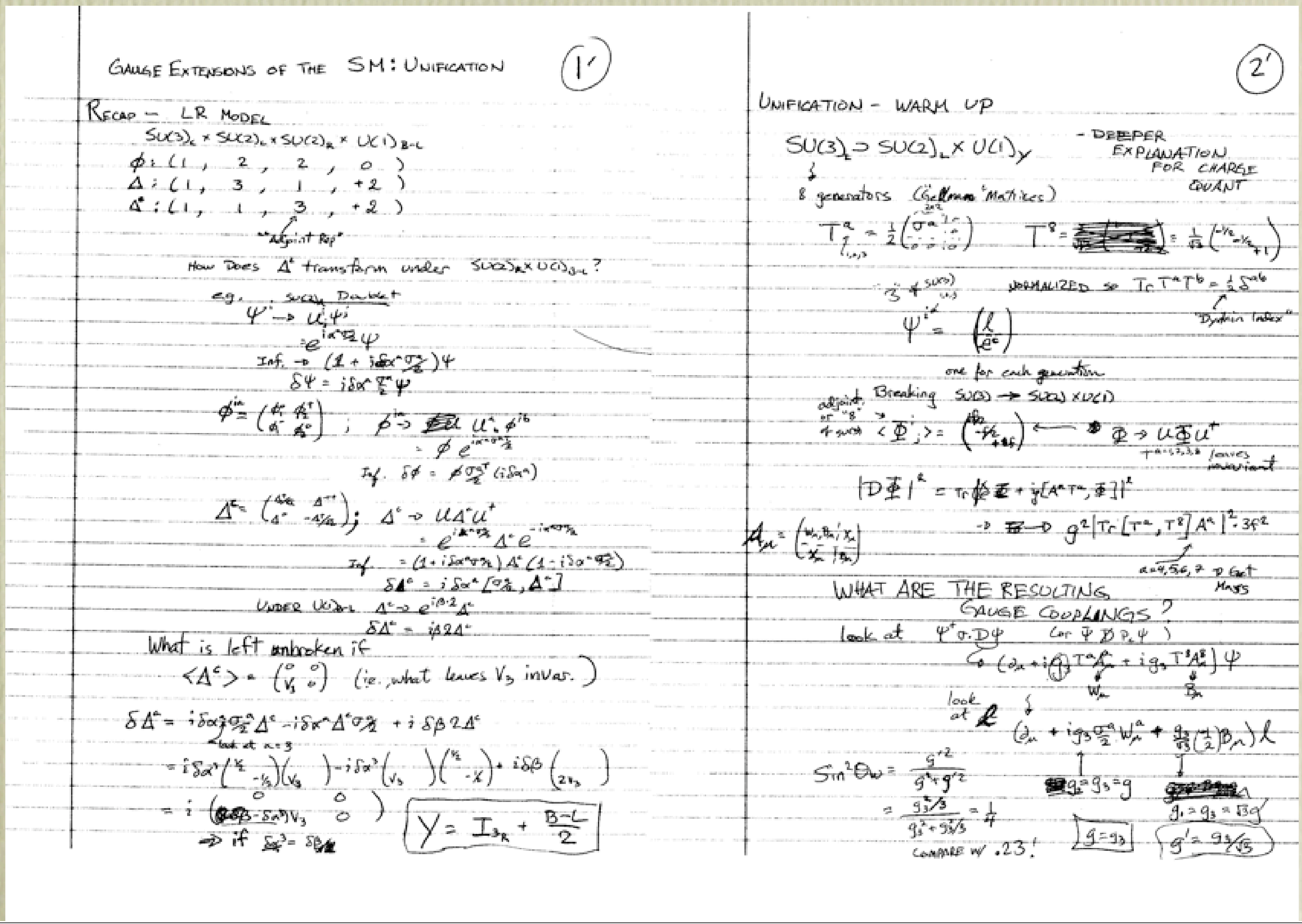
700 megabytes of data every second



the importance of Standard Model calculations

- the SM still rules (almost) all
- below the energy frontier, new physics means (mostly) rare processes, small discrepancies, small inconsistencies
- at the energy frontier, SM backgrounds are about to get 100-500 times worse (Steve Mrenna)

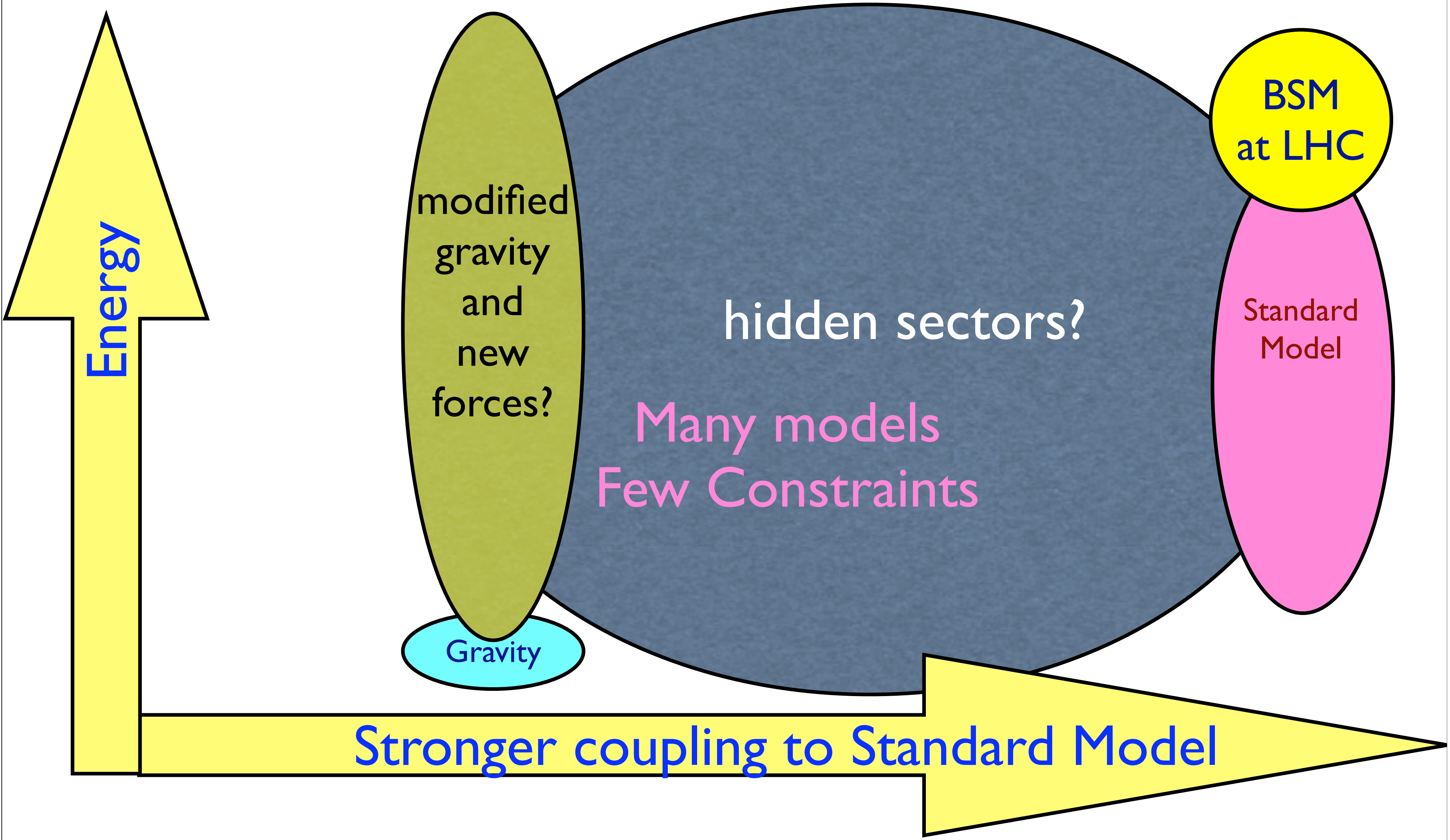
past 30 years: theorists busy extending sm (on paper)



Beyond the Standard Model Theory

- Predicts new kinds of particles
- or even “unparticles”
- New symmetries, principles, effects

Landscape of known and unknown unknowns



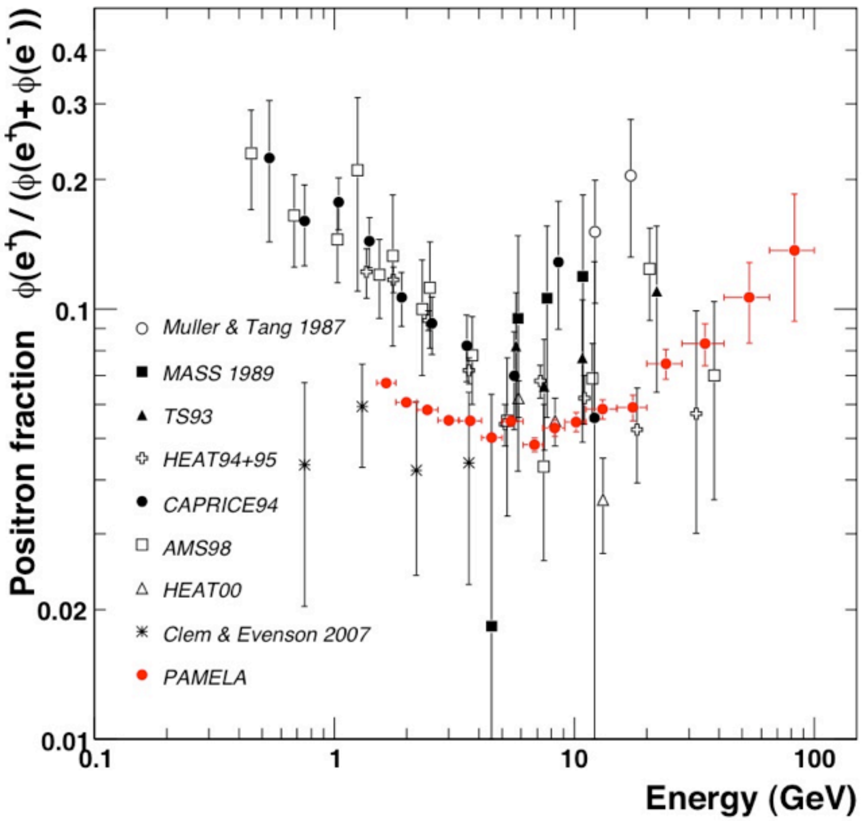


FIG. 3: **PAMELA positron fraction with other experimental data.** The positron fraction measured by the PAMELA experiment compared with other recent experimental data[24, 29, 30, 31, 32, 33, 34, 35]. One standard deviation error bars are shown. If not visible, they lie inside the data points.

Hints (or red herrings) from the sky?

measurements of positrons + electrons

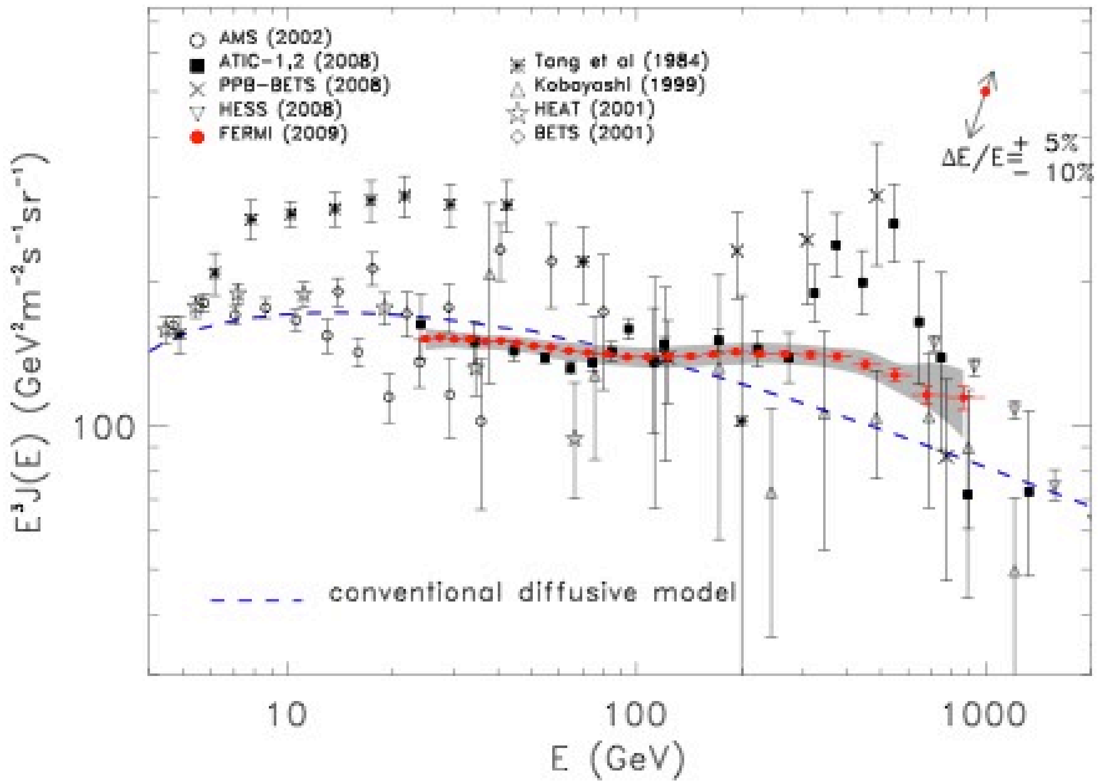
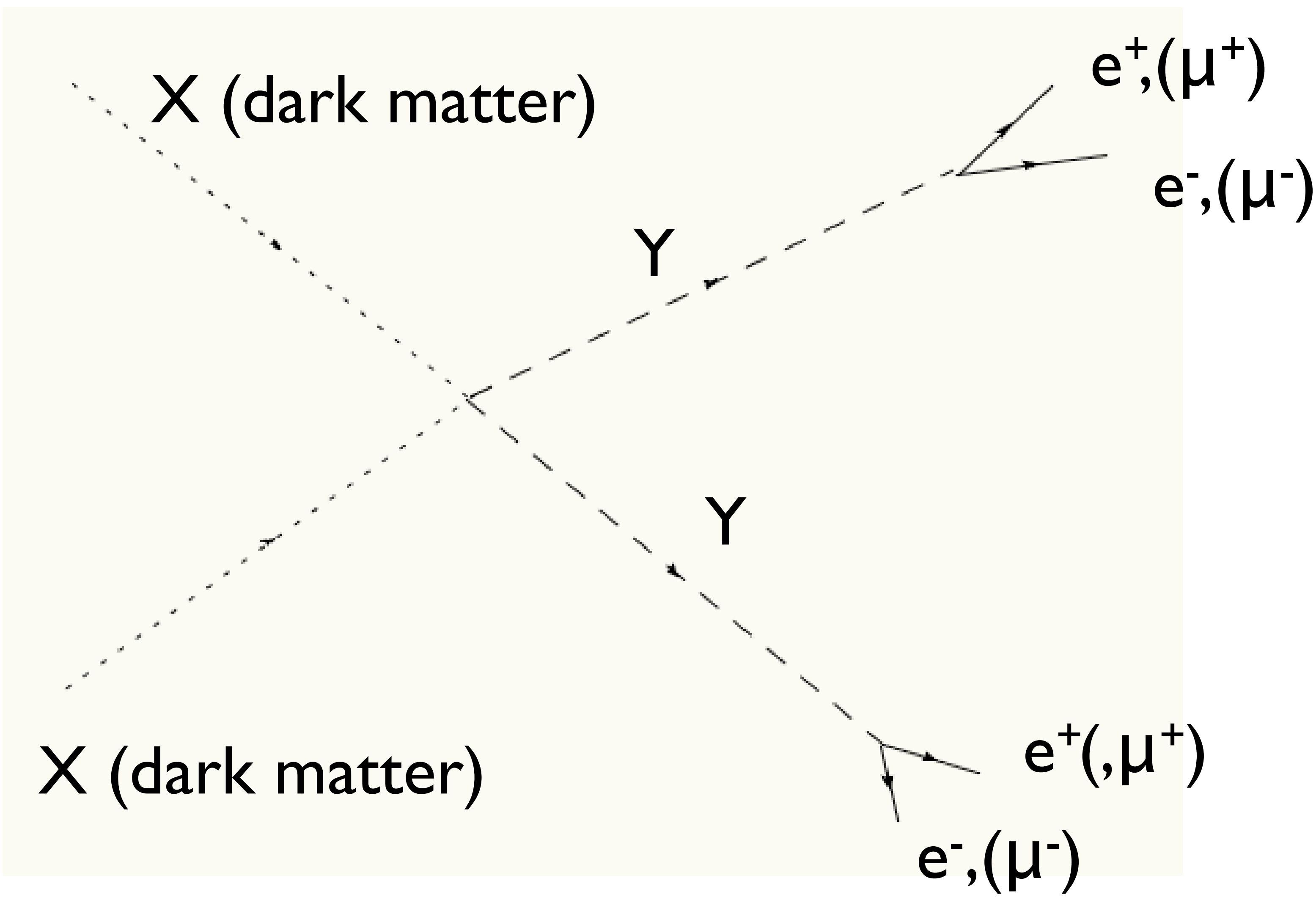


FIG. 3: (color) The Fermi LAT CR electron spectrum (red filled circles). Systematic errors are shown by the gray band. The two-headed arrow in the top-right corner of the figure gives size and direction of the rigid shift of the spectrum implied by a shift of $^{+5\%}_{-10\%}$ of the absolute energy, 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



Focus of Theoretical Physics in the age of the dawn of the LHC

- Doing useful, challenging Standard Model calculations
- thinking of new LHC signatures
- thinking of new ways to analyze LHC data and organize/present results to find new physics
- pursuing nonaccelerator anomalies: dark matter, neutrino oscillations, dark energy

1-2 years from now (hopefully)

- Theorists will be busy comparing new physics models against LHC data
- Certain to be multiple explanations for any anomaly
- Having a blast.