Introduction to Particle Physics

Swedish Teacher program 2022

Lecture III

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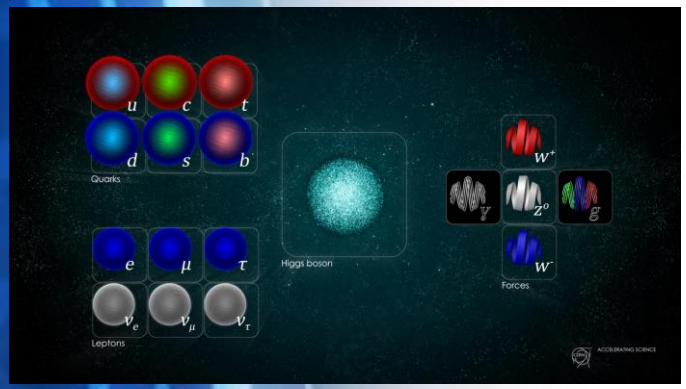
Beyond the SM

- Limits of the SM
- Grand unified theories (GUT)
  (speculative)
- Theories of Everything (ToE)
  (Merely speculative !)

Standard Model + General Relativity = Universe ?



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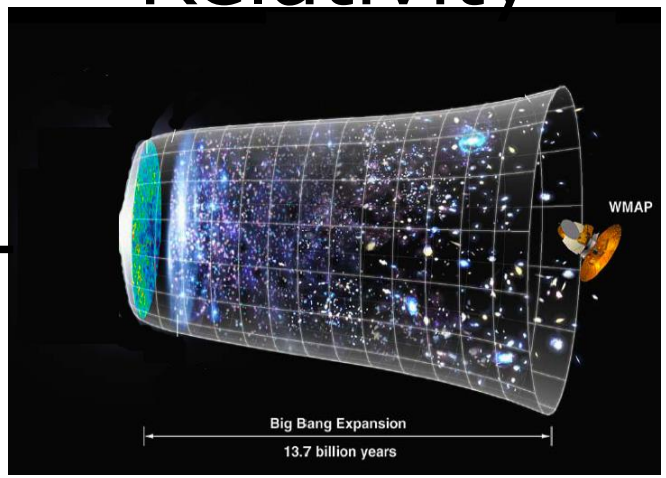
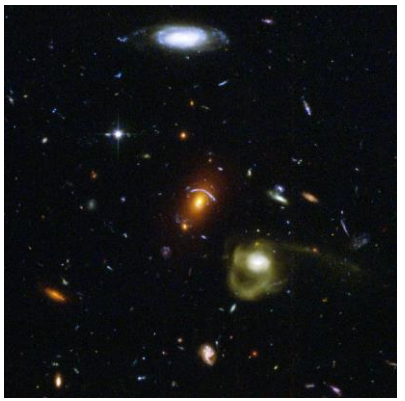




Not yet !

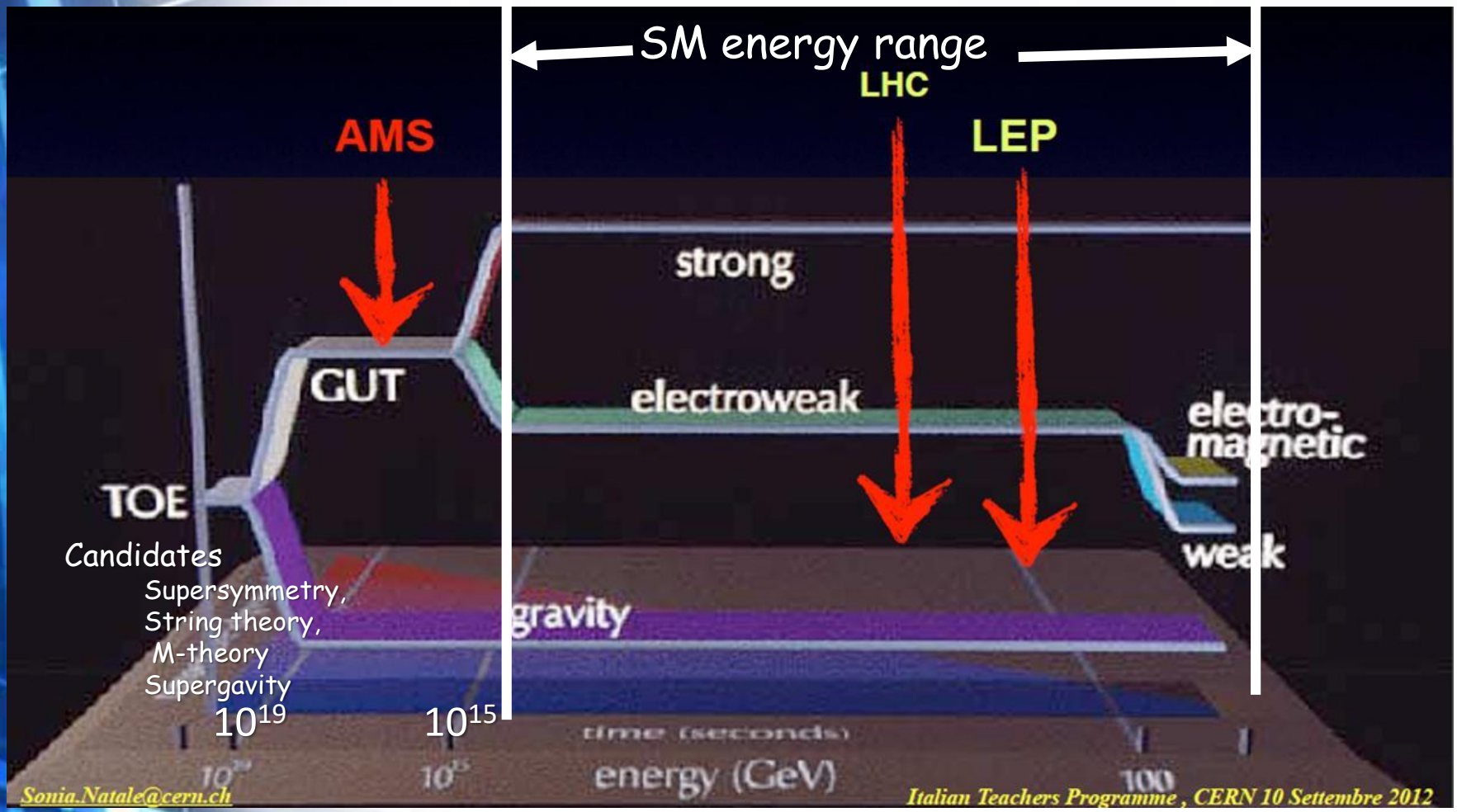
What the SM doesn't explain

- Dark matter: galaxy rotate too fast! It exists some extra matter not visible, 23% of total mass-energy. Which type of matter?
- Dark energy: it is accelerating the universe expansion, there is injection of energy. 73 % of total energy. What is its origin?
- We are in the 0.4% of the observable 4% mass-energy!
- SM doesn't incorporate the neutrino oscillation (then neutrino mass);
- Origin of mass;
- matter-antimatter asymmetry;;
- ....

Beyond the SM: Grand Unified Theories and Theory of Everything

A romantic dream for an unified description of the Universe ?

Energy scale for GUT and ToE



GUT what?

Grand Unified Theories !

- Theories with the objective of unifying the gauge interactions (EW and QCD) into one universal interaction;
- The unification energy is expected at around 10^{14} GeV! LHC energy 10^{4} GeV. No new physics in the 10 decade increase of energy (if true, bad news for the FCC program!)

A GUT candidate is labelled SU(5)

GUT Candidate: SU(5)

- The gauge bosons in the symmetry group SU(5) are the leptoquarks (sometime called diquark bosons)
  - It accommodates all the fermions of one generation;
  - There are 24 gauge bosons, the first 12 are $W^{\pm}$, Z^{0}, γ and 8 gluons the other 12 are the leptoquars;
  - The gauge boson can transform q → e^{-} or q → antiq!!
- The proton isn't any longer stable! $\tau \approx 4*10^{28}$ y.
- But IMB Experiment set $\tau > 5*10^{31}$ y !
- SU(5) may account for asymmetry baryon/antibaryon via a baryon non conserving interaction;

No GUT theory accommodates for gravity!

Theory of Everything

- Theory with the objective to unify the Electroweak and Strong interactions with the gravity;

- Candidates:
  1. Composite models
  2. Supersymmetry (SUSY)
  3. Kaluza-Klein theories
  4. String models
  5. M-theories

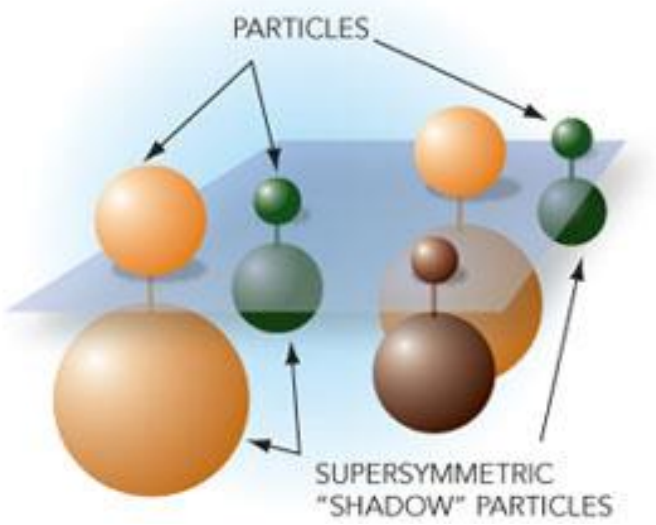
(1) Composite structure

- Electron and quark are assumed as composite structure,
- so far no evidence from the cross section trend that assumes the fermions as point-like objects!!

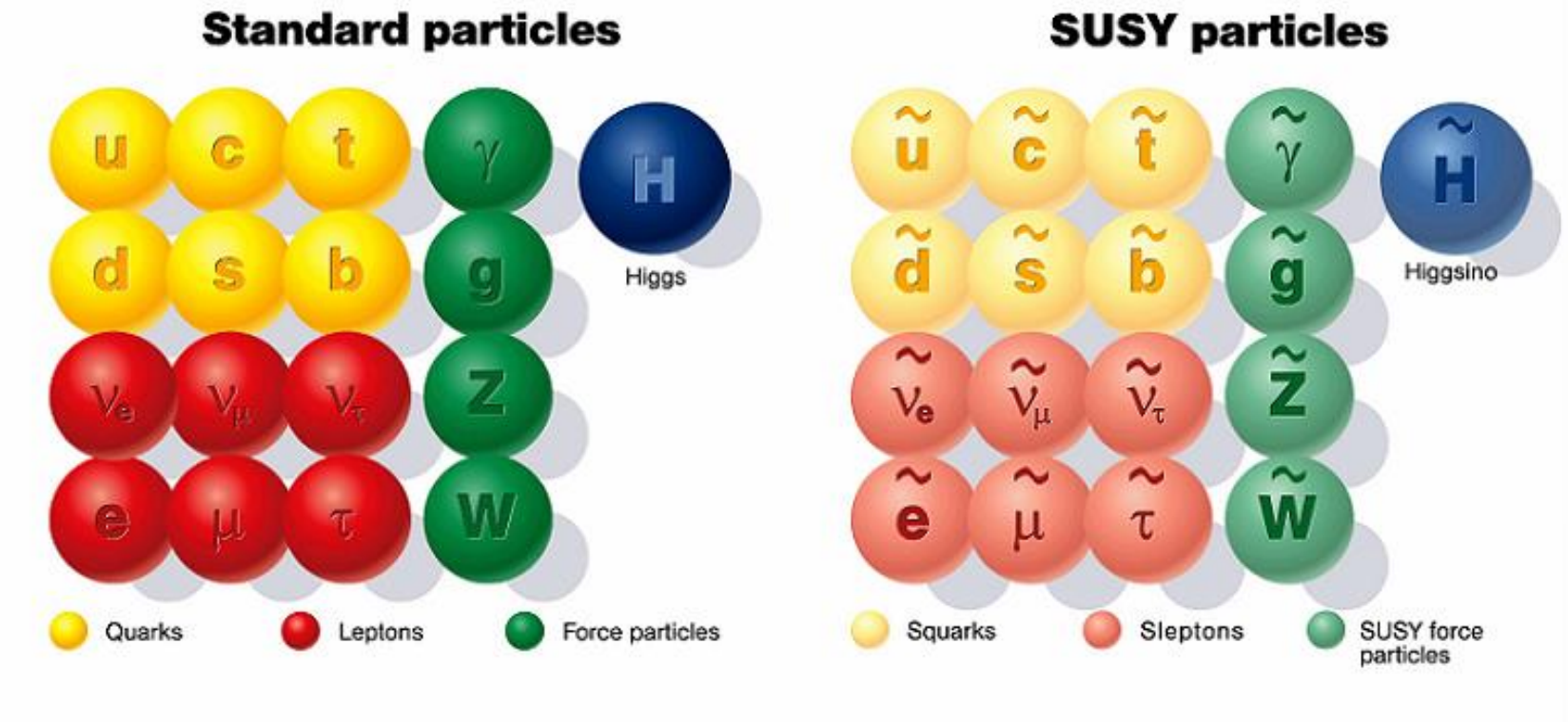
(2) SUPERSYMMETRY (SUSY)

- SUSY can include the Gravity;
- A connection between particles (spin 1/2) and fields (spin 1) exists
- Fermions (quarks and leptons) interact through the exchange of gauge bosons (gluons, photon, $W^{\pm}$ and Z°);
- "SUPERSYMMETRY" predicts a complete symmetry between particles of matter and carriers-of-force :

Spin ½ (fermions)	Spin 0, Spin 1 (bosons)
electron	selectron (S=0)
quark	squark (S=0)
photino	photon (S=1)
gluino	gluon (S=1)
gaugino (Wino, Zino)	W, Z (S=1)



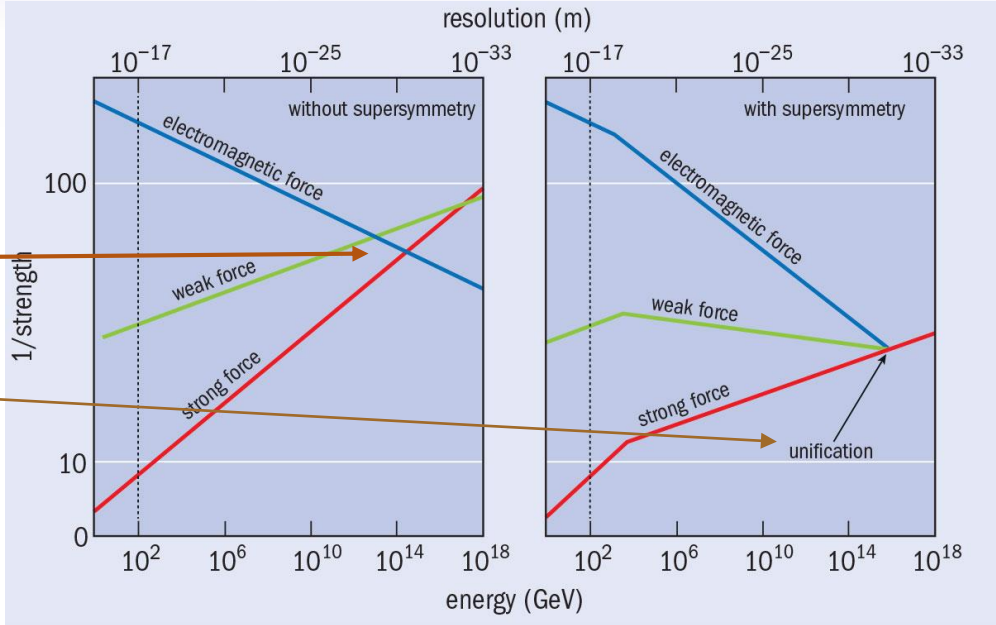
SUSY at one glance



Why 3 interactions?

Forces "run" with energy ….. and don't agree at high energy

SUSY can modify their evolution to join up → unification @ 10^{14} GeV



SUSY can explain the cosmological matter-antimatter asymmetry;

Lightest supersymmetric particle = dark matter ;

Unfortunately, so far no evidence of supersymmetric particles in ATLAS and CMS search!!

Supersymmetric BEH bosons

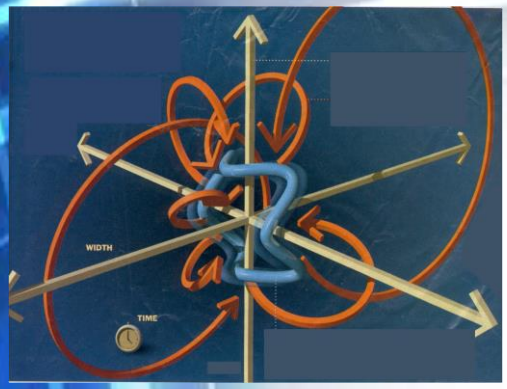
- If the supersymmetry exist then 5 Higgs bosons should exist (three neutral and two electrically charged)
- In this case the BEH boson discovered at LHC, could be one out of the three neutral;
- No such SUSY partner has been observed so far. So if they exist, they must have a mass > 1 TeV (energy explored at LHC);

(3) Kaluza-Klein theories

- (1920-1926) The idea was to add a fifth space dimension to the space-time of the General Relativity(GR);
- The fifth dimension is curled-up and has no effect on usual physics;
- It is possible to define a field with components that in the four dimensions satisfy the field equation of the GR and with the other components which satisfy the Maxwell's relations;
- Electromagnetism and GR are connected!!
- The success of the Electroweak unification has revived the interest on this theory and an integer number of dimensions have been added: work in progress.

(4)String theory as ToE ?

Superstrings in 9+1 dimensions?



Particles are not point-like but little strings vibrating in a 9+1 dimensional space
L ~10^{-35} m (Planck length)

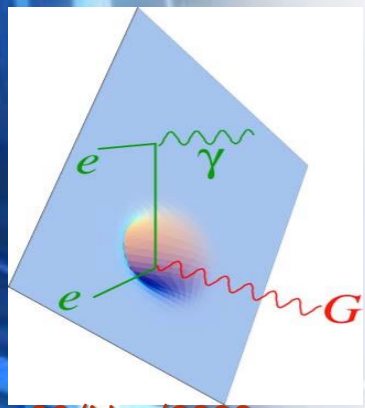
Standard model particles: different vibration modes, open/closed strings
GRAVITON-like particle contained (unification of SM and gravity possible)

BUT: why did 6 dimensions disappear? how did they disappear?
is there a unique way to go from 10 to 4 dimensions?

Axions, Magnetic monopoles Majorana neutrinos, Dyons (MM with e charge), weakly interacting massive particles (WIMPS) are proposed
So far no experimental observations!!

Quantum Gravity

In turn the observation of gravitational waves 2016-2017 can help in the quantization of the gravity (QFT!) A possibility to study the graviton properties (gauge boson of spin2);

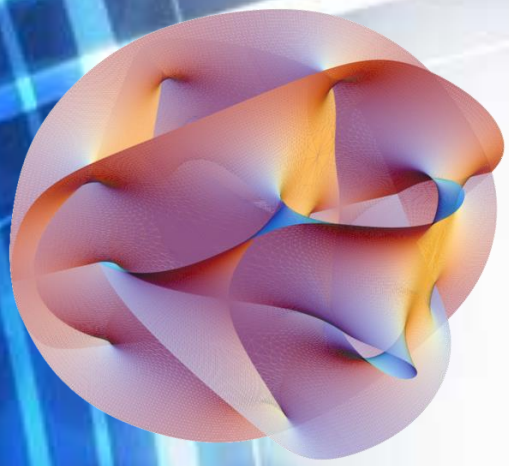


Why QG weakness? more than 3 macroscopic dimensions of space?

Is the graviton propagating in 4- or more dimensions of space?

Micro-black holes ?

(5) M-theory as ToE ?



This image of the en:Calabi–Yau manifold appeared on the cover of the November 2007 issue of en:Scientific American.

*) http://en.wikipedia.org/wiki/M-theory

M-theory*): p-brane in 11 dimension for the unification of SM+Gravity in a Theory of Everithing (ToE)

A p-brane is a physical object that generalizes the notion of a point particle to higher dimensions. For example, a point particle can be viewed as a brane of dimension zero, while a string can be viewed as a brane of dimension one.

Branes are dynamical objects which can propagate through spacetime according to the rules of quantum mechanics. They have mass and can have other attributes such as charge. A *p*-brane sweeps out a (*p*+1)-dimensional volume in spacetime called its *worldvolume*. Physicists often study fields analogous to the electromagnetic field which live on the *worldvolume* of a brane.

Beyond SM:
Scientific program at LHC 2015 -...

ATLAS and CMS on SUSY and extra dimensions

ATLAS and CMS

are investigating about the origin of mass, extra dimensions of space, microscopic black holes, and evidence for dark matter candidates in the Universe..

Supersymmetry

Events with substantial missing energy with high-energy electrons or muons will be indications for the production and decay of super-partners

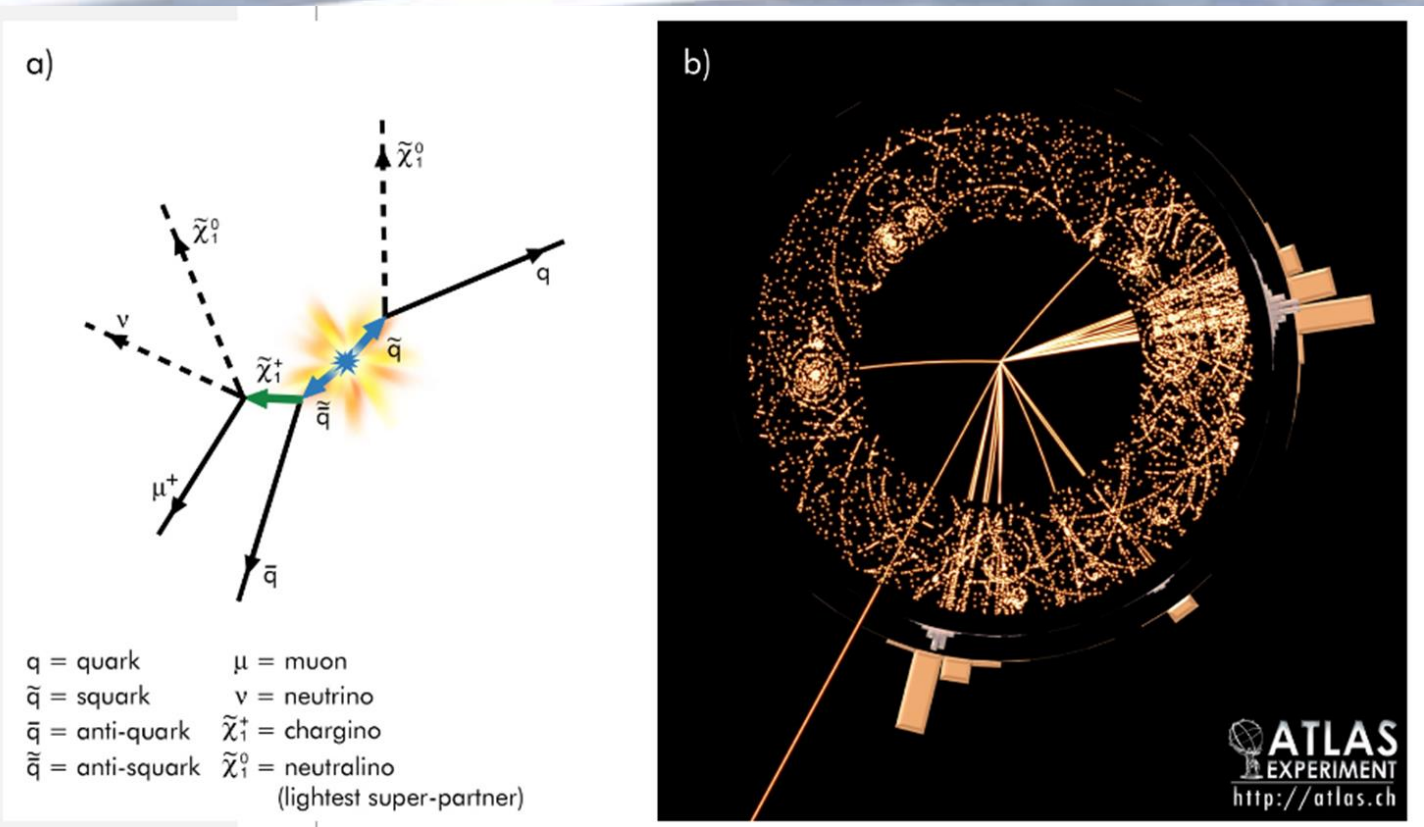


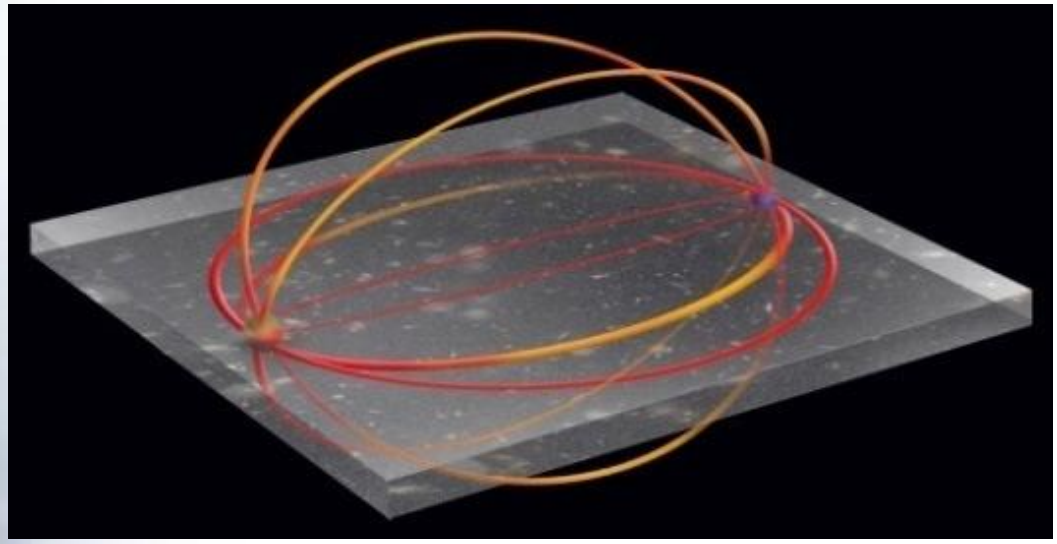
Fig. 1a): In this example, the collision of two protons results in the production of a squark and an antisquark (the super-partner of the quark and its antiparticle). These decay into lighter particles, one of which (a "chargino", written as $\tilde{\chi}_1^+$) also decays into still more particles. The chargino and squark are written with a tilde over them, which indicates that they are super-partner particles. The decays happen so quickly that no tracks are left in the ATLAS detector from the squark and chargino. In the end, two of the neutralinos $\tilde{\chi}_1^0$ (lightest super-partner particles) survive, because there are no lighter super-partners into which they can decay.

Fig. 1b): This figure shows an example of the momentum imbalance resulting from collision events such as in Fig. 1a). The two incoming (colliding) protons were perpendicular to this image, and the collision happened at the center. The visible particles are those that came out of the collision at the center. The solid bars on the outside show the areas where most of the energy went. It is clear that most of the momentum (and energy) went to the bottom and right. This imbalance was due to the lightest super-partner particles (and the neutrino) going undetected to the upper left. They leave no tracks and deposit no energy. This momentum imbalance is a signature for new particles.

ATLAS and CMS probing Extra dimensions for gravity

ATLAS Experiment may see evidence that extra dimensions exist via collision events in which a graviton particle disappears into other dimensions. ATLAS would detect a large imbalance of energy in the event.

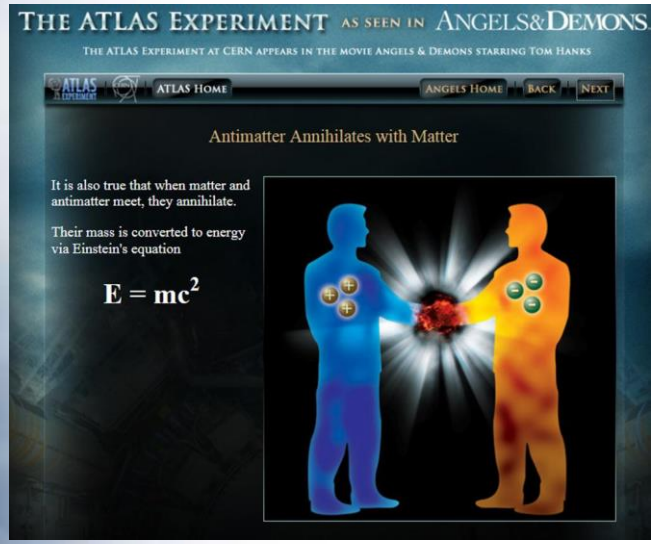
CMS: This is why the detector must be as "hermetic" as possible.

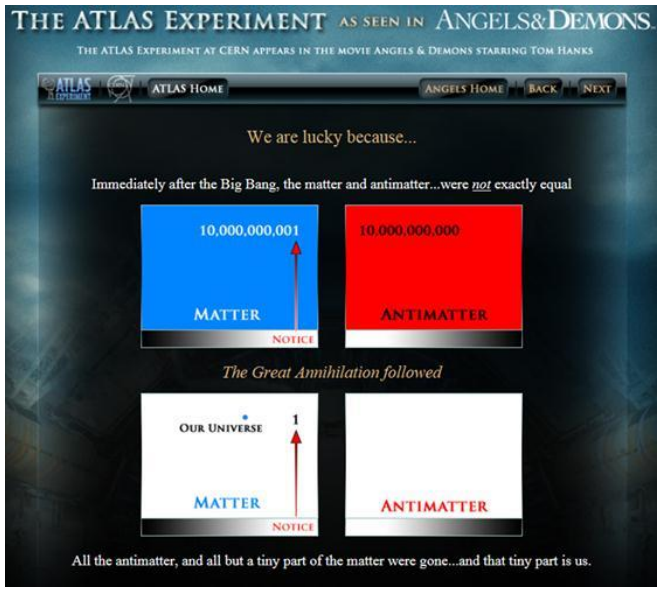


10^{-10} Matter-animatter asymmetry

LHCb (http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#EW2013) is dedicated to deeply investigate matter/antimatter asymmetry via decay of Beauty-particles (beauty-quark in) since weak interactions of matter differ subtly from those of antimatter. This may explain why the matter survived right after the Big-Bang.

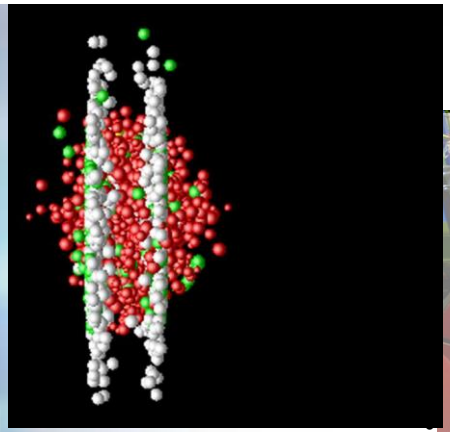
ATLAS and CMS as well contribute on this topic





ALICE probing the quark-gluon plasma

Two relativistic lead-ion collision in the laboratory frame



The long term goal of the ALICE experiment is to provide a precise characterization of the high-density (10^{11} kg/cm^3), high-temperature (5 10^{12} K)phase of strongly interacting matter;

To achieve this goal, high-statistics precision measurement are required. The general upgrade strategy for the ALICE detector is conceived to deal with this challenge with expected Pb-Pb interaction rates of up to 50 kHz during future operation of LHC

Summary Lecture III

- The SM doesn't account for dark matter, dark energy,..... And as input it requires several parameters. Nevertheless it accounts for many experimental observations!

- Theories beyond standard model try to unify Gravity and particle world:
  - GUT
  - Supersymmetry
  - Kaluza-klaine
  - String and M theories

  - Anyway so far no experimental evidence of predicted new particles...except the confirmation of the gravitational waves!! Data useful to study the graviton properties?

A long way to go! Young and smart students required!