# Introduction to Particle Physics

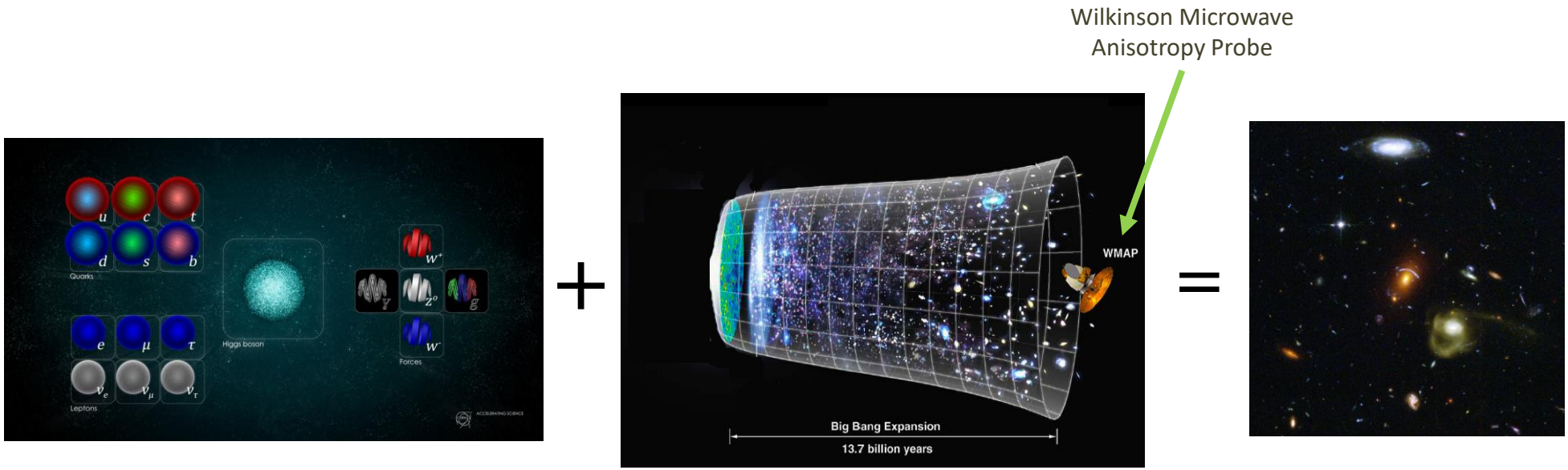
SWEDISH PHYSICS TEACHERS 2024

# Lecture 3

## Beyond the SM

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

# Standard Model + General Relativity = Universe ?




## Actually, not yet !

- dark matter
- dark energy

# What the SM doesn't explain

**Dark matter**: galaxy rotate too fast! It exists some extra matter not visible. It accounts for 23% of the total mass-energy. Which type of matter?

**Dark energy**: the universe expansion is accelerating. As a consequence, 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 (hierarchy problem);

matter-antimatter asymmetry.

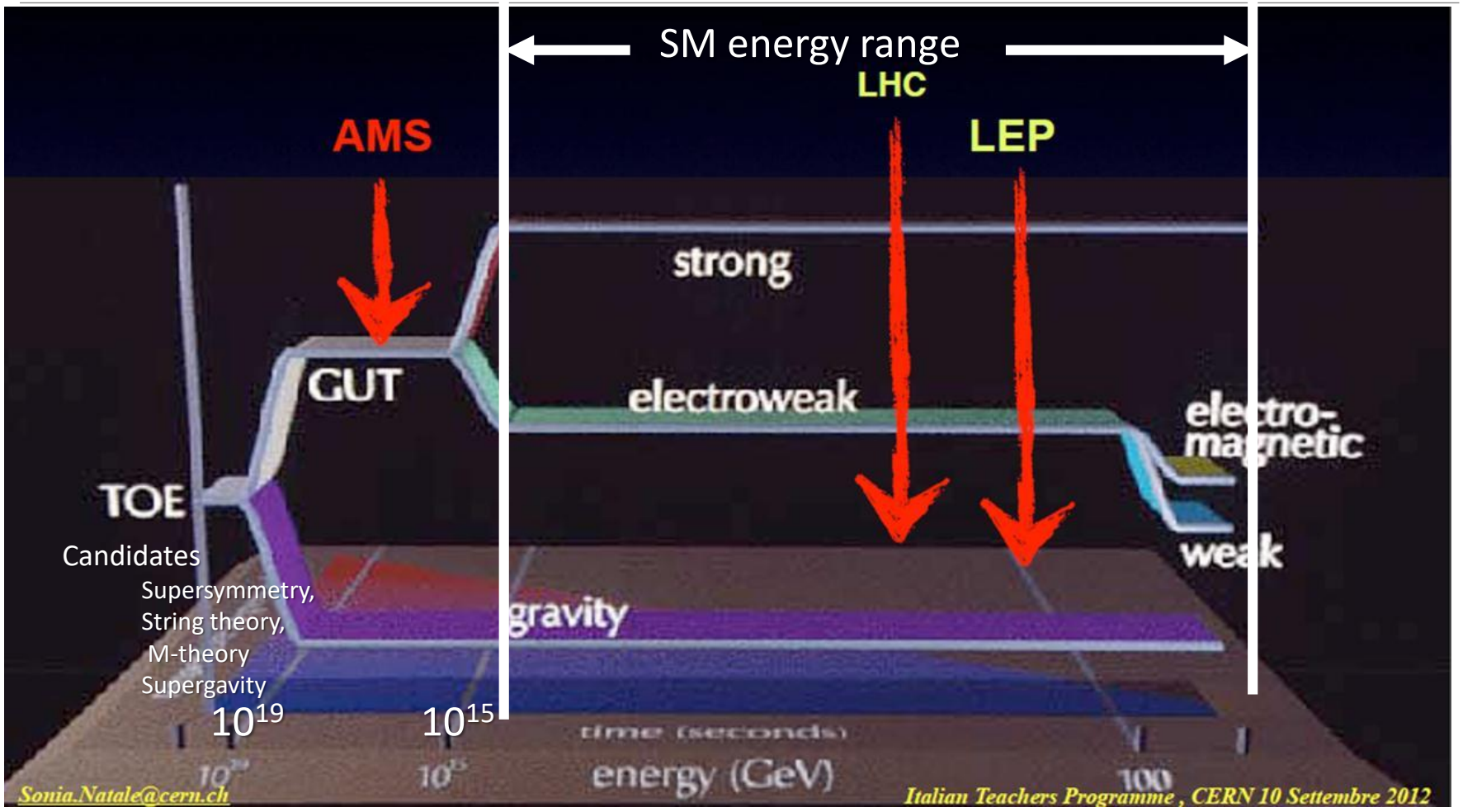
# Grand Unified Theories and Theory of Everything

GUT (Grand Unified Theory): ElectroWeak and Strong Interaction unified in a common theory. So far, they are described within the same mathematical scheme (SM), but not in a "unified physics". EW it is.

TOE (Theory Of Everything)= GUT + General Relativity (GR)!
So far GR is not yet a quantum theory of the interaction (QFT), it is "analytical description of space geometry" in presence of masses/(energy)

GUT and TOE, a scientific challenge …and maybe a romantic dream, for a unified description of the Universe

# Energy scale for GUT and ToE




BigBang → today

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# Theory of Everything

Theory with the objective to unify a GUT (EW+SI) with gravity described as QFT!

Candidates:

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

# (1) Composite structure

Electrons and quarks 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)

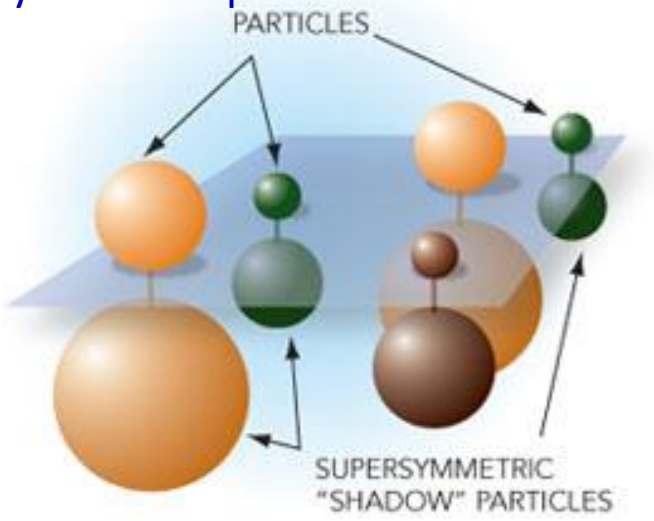
- SUSY can include the Gravity as QFT;

- A connection between fermion fields (spin 1/2) and boson fields (spin 1, force carriers particles) exists;

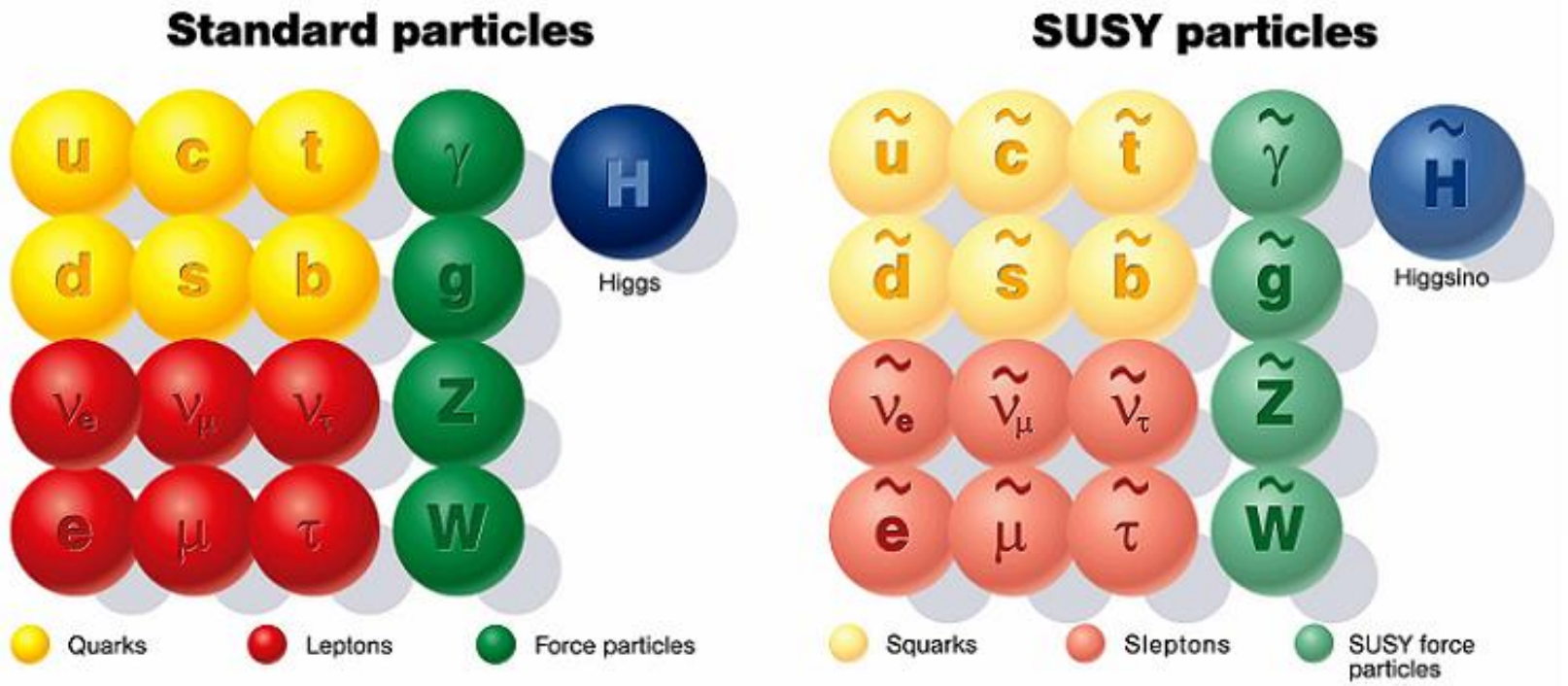
- We know that fermions (quarks and leptons) interact through the exchange of gauge bosons (gluons, photon, $W^{\pm}$ and $Z^{\circ}$ );

- "SUPERSYMMETRY" predicts a complete symmetry between particles of matter and Interaction carriers :

| 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) |



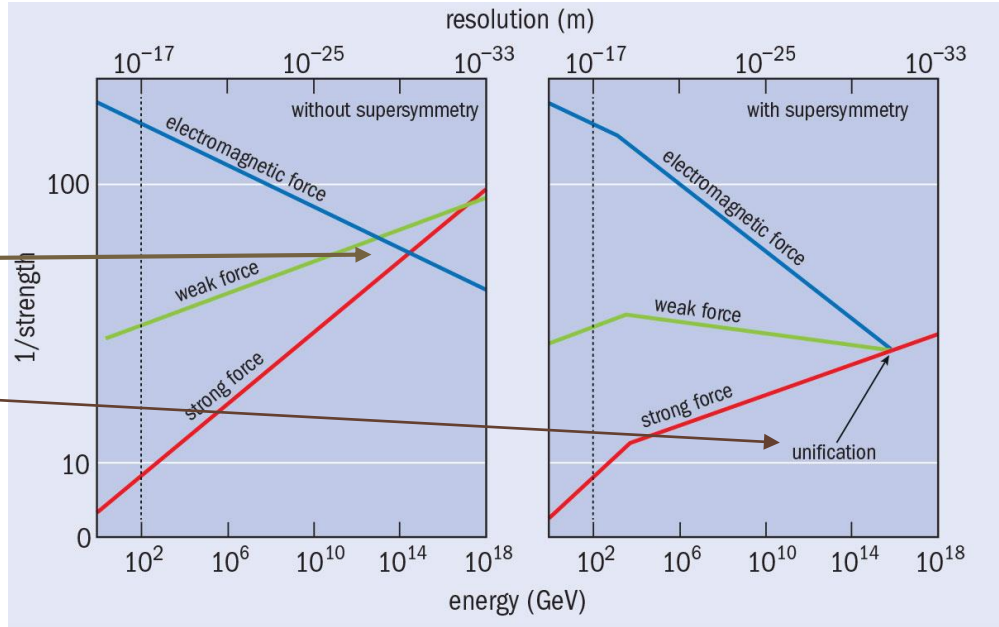
# SUSY at one glance



# Evolution of the 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 could explain the cosmological matter-antimatter asymmetry;

Lightest supersymmetric particle = dark matter ;

Unfortunately, so far, no evidence of supersymmetric particles neither in ATLAS nor in 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;

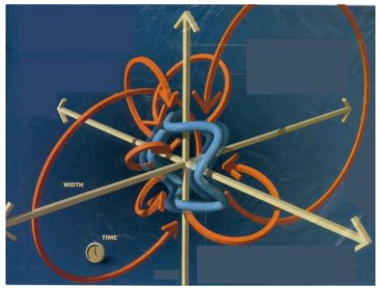
Electromagnetism and GR are connected but not as QFT!!

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.

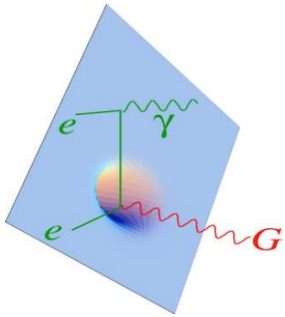
# (4)String theory as ToE ?

## Superstrings in 9+1 dimentional space?

The elementary entities are little strings vibrating in a 9+1 dimensional space, revealing its structure at l ~$10^{-35}$ m (Planck length );



The SM particles: would be described via different vibration modes, open/closed strings
Quantum Gravity: graviton-like particle is contained in the Superstring model



# (4)String theory as ToE ?

Superstrings in 9+1 dimentional space?

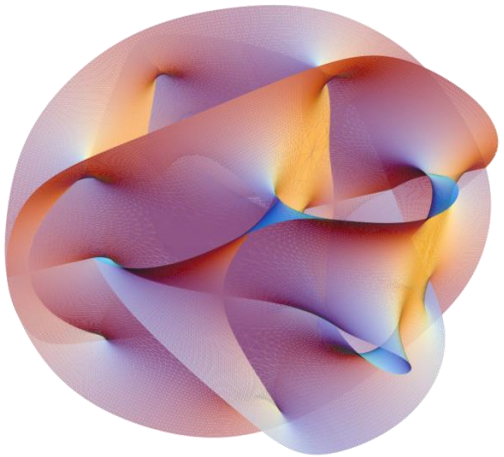
With superstring in 10 dimension, the unification of SM and Gravity (GR) is then possible!!

But, why 6 space dimensions disappeared? How did they disappear?
Is there a unique way to go from 10 to 4 dimensions where we live?

With superstrings, Axions, Magnetic monopoles, Majorana neutrinos, Dyons (MM with e charge), weakly interacting massive particles (WIMPS) can be proposed,…unfortunately, so far, no experimental observations!! ☹

# (5) M-theory as ToE ?

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

**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

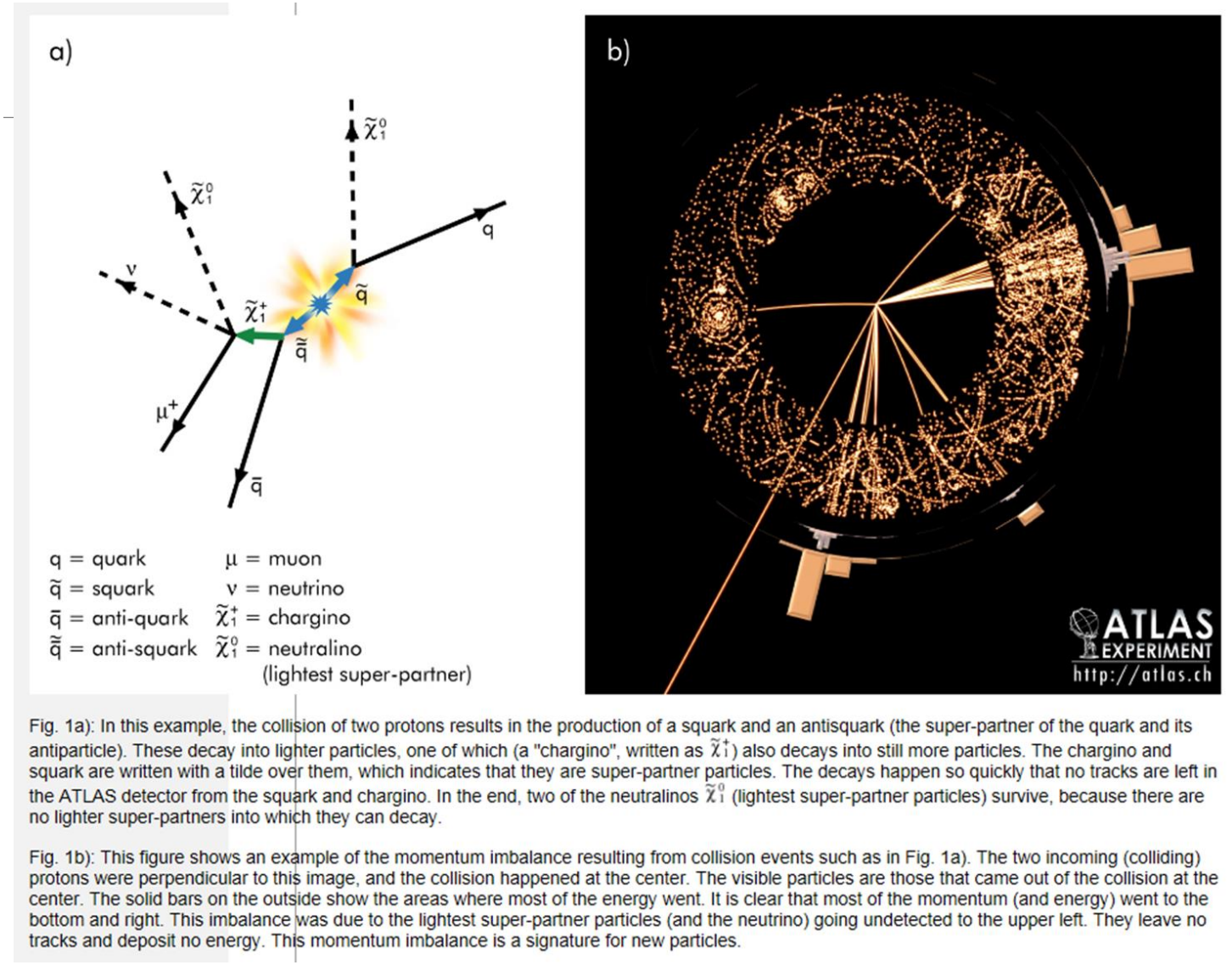


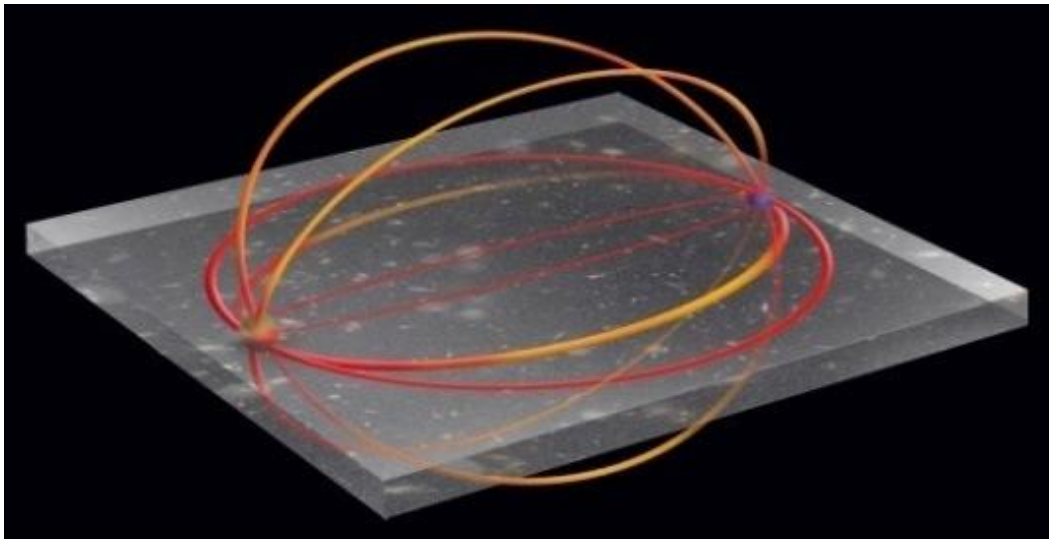

Fig. 1a): In this example, the collision of two protons results in the production of a squark and an antisquark (the super-partner of the quark and its antiparticle). These decay into lighter particles, one of which (a "chargino", written as $\tilde{\chi}_1^+$) also decays into still more particles. 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.

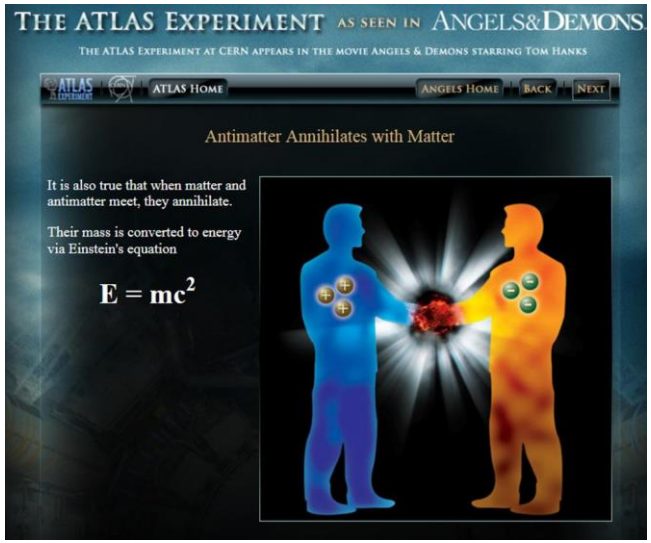
CMS: This is why the detector must be as “hermetic” as possible.

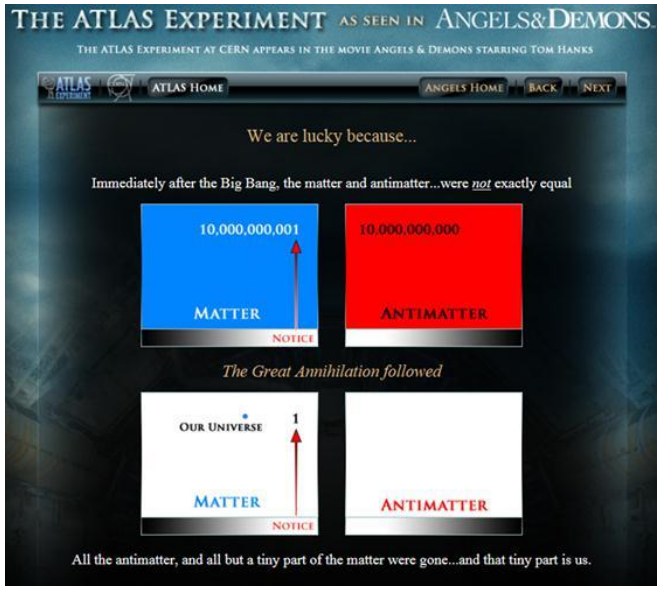


# $10^{-10}$ Matter-animatter asymmetry

*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.*

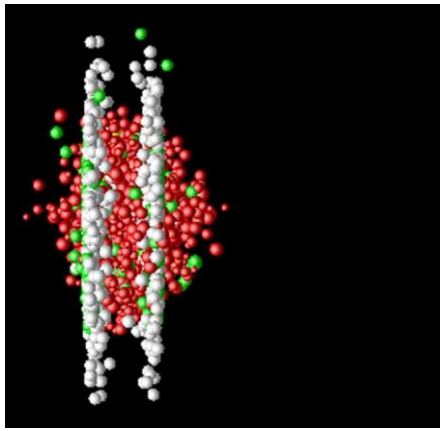
*ATLAS and CMS as well contribute on this topic*



# 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

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 the particle world:

- GUT
- Supersymmetry
- Kaluza-klaine
- String and M theories

Anyway so far no experimental evidence of predicted new particles;

But, 2015 confirmation of the gravitational waves!! Data useful to study the graviton properties!

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