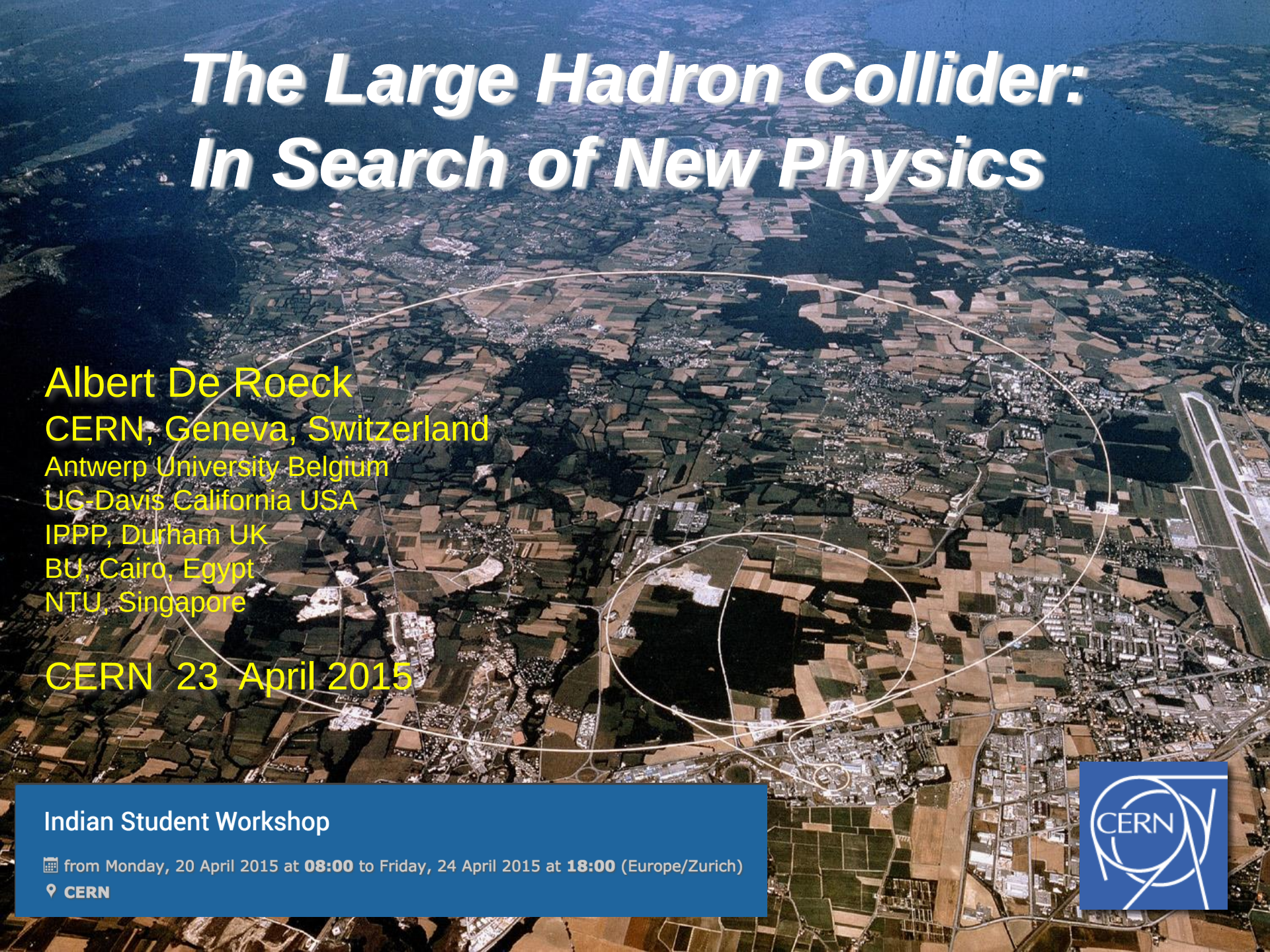
The Large Hadron Collider: In Search of New Physics



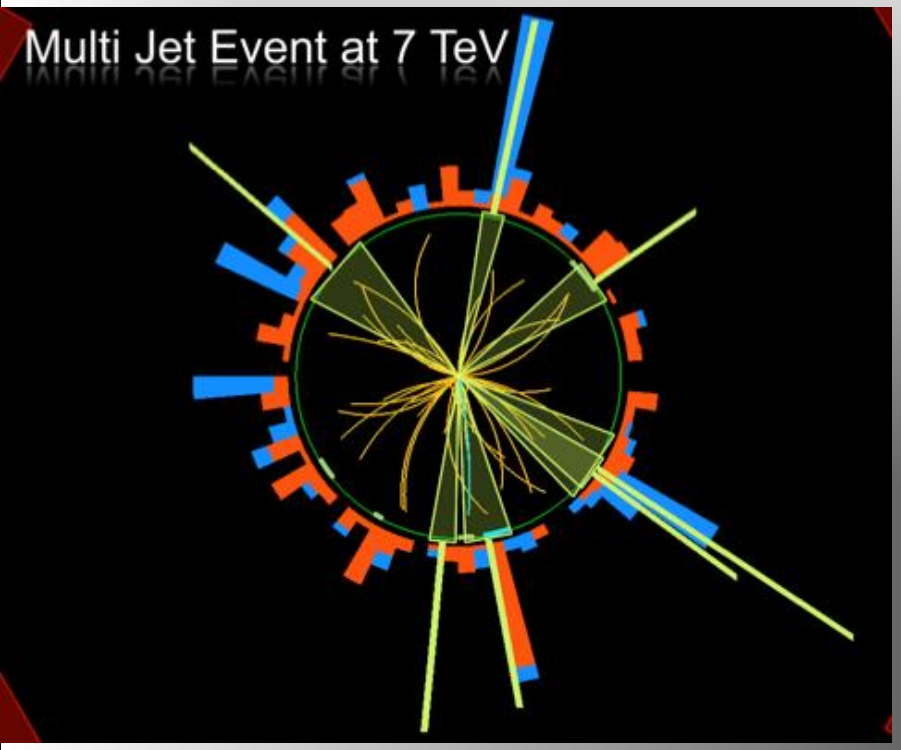
Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
IPPP, Durham UK
BU, Cairo, Egypt
NTU, Singapore

CERN 23 April 2015

Indian Student Workshop

from Monday, 20 April 2015 at **08:00** to Friday, 24 April 2015 at **18:00** (Europe/Zurich)

CERN



Outline

- Introduction
- Higgs discovery
- New Physics Searches
  @ the Large Hadron Collider
  -Dark Matter?
  -Supersymmetry?
  -Extra space dimensions?
  -Black Holes?
  -Matter Substructure?
- Summary


What is the world made of?
What holds the world together?
Where did we come from?

Accelerators are Powerful Microscopes

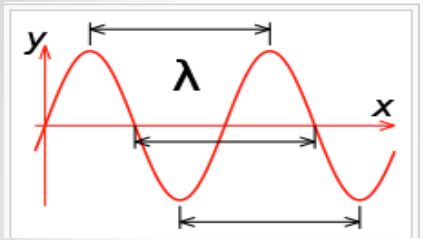
They make high energy particle beams that allow us to see small things.

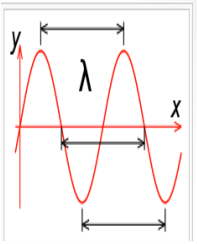
$$\lambda = \frac{h}{p}$$

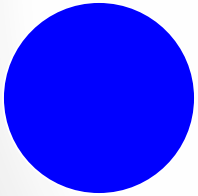
Planck constant

wavelength

momentum ~ energy



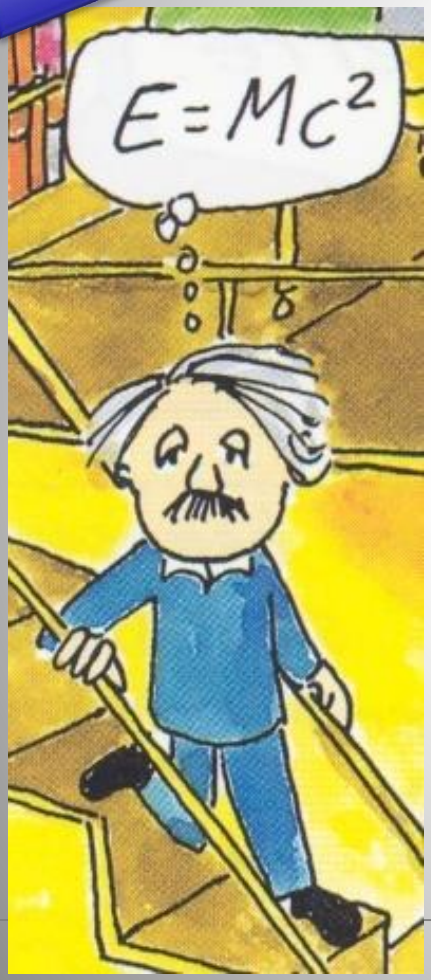




seen by low energy beam of particles (poorer resolution)

seen by high energy beam of particles (better resolution)

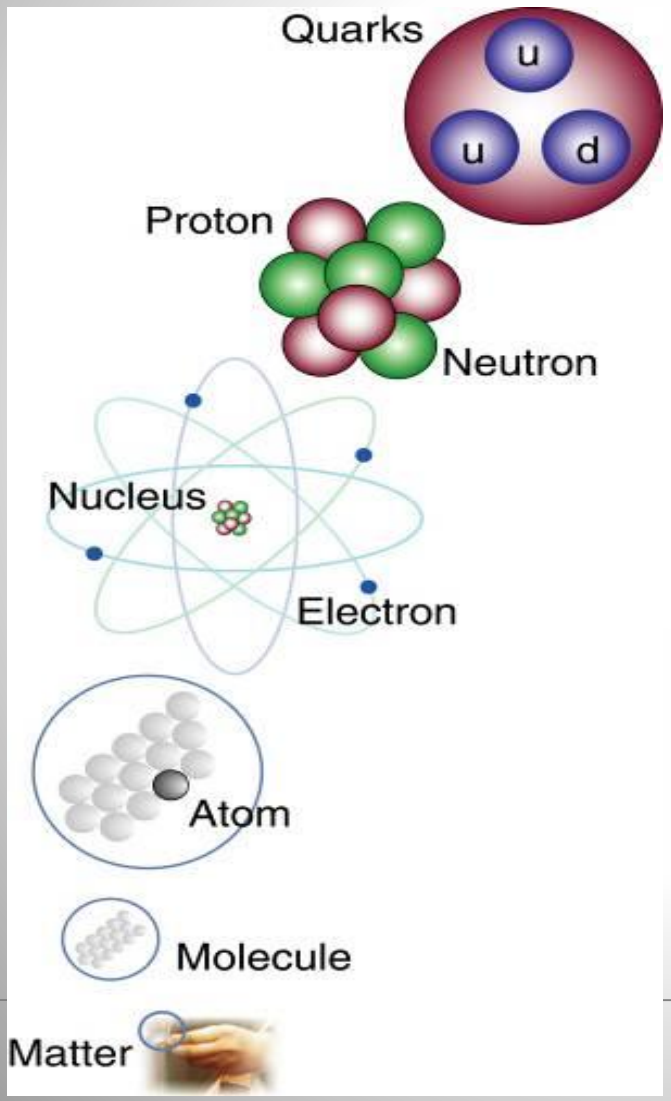
We can create particles from energy



- Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.
- Produce particles that may have existed at the beginning of the Universe, right after the Big Bang

The Structure of Matter

Matter



Quarks and electrons are the smallest building blocks of matter that we know of today.

Are there still smaller particles?

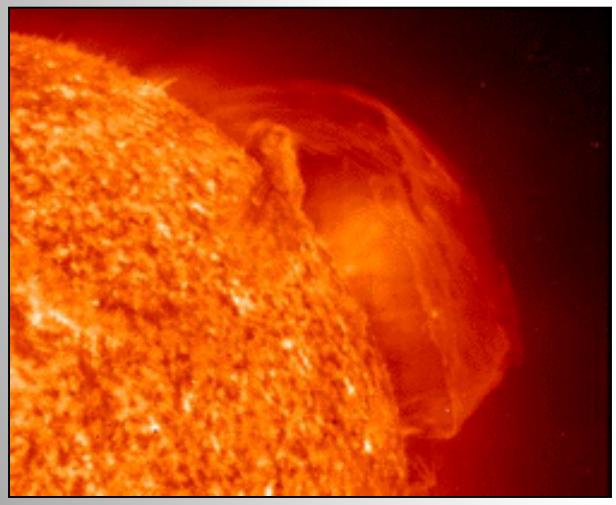
The Large Hadron Collider will address this question!

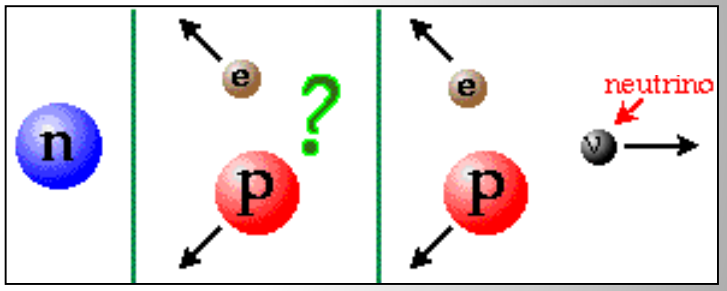
The Fundamental Forces of Nature

Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity





together they make the Sun shine

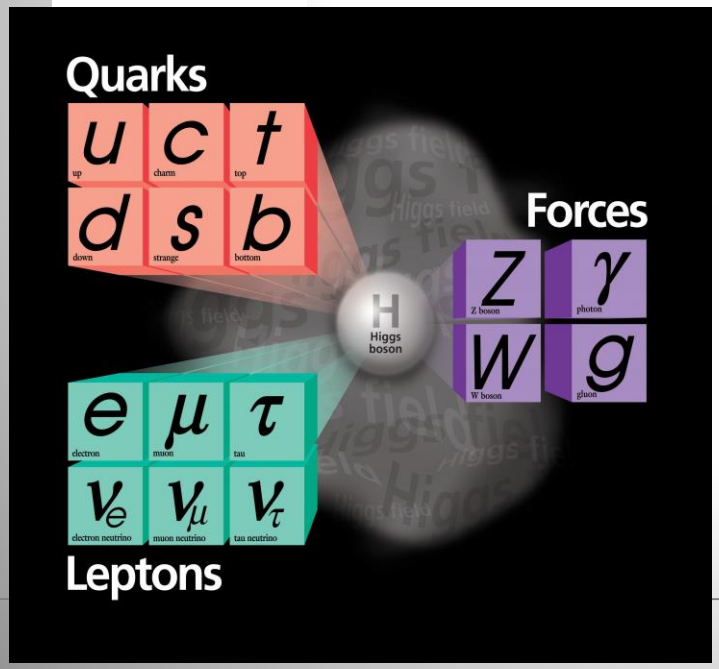
Gravity: holds planets and stars together

The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:

Fermions Bosons

Matter particles



Force particles

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin

The Hunt for the Higgs

Where do the masses of elementary particles come from?

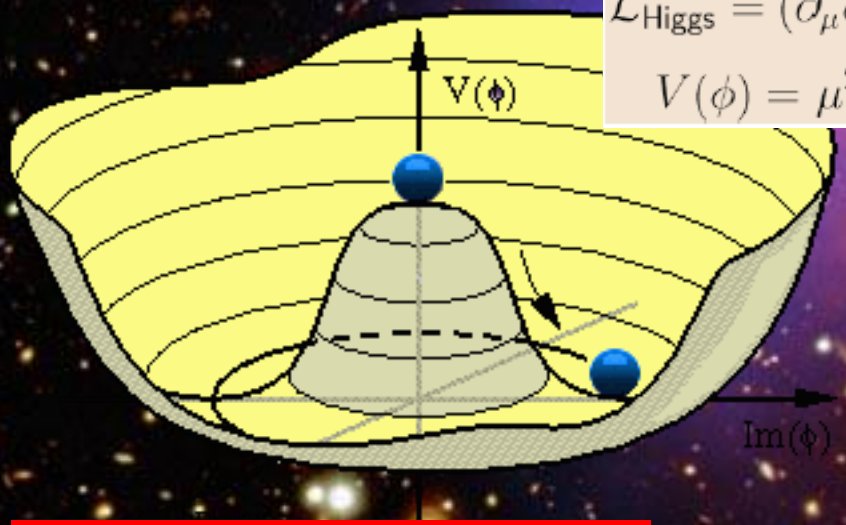
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



Scalar field with at least one scalar particle

Note: NOT the mass of protons and neutrons

It could be anywhere from 114 to ~700 GeV

The Higgs Field and the Cocktail Party

By David Miller

Imagine a cocktail party

This is the Higgs field

Enters a famous person…

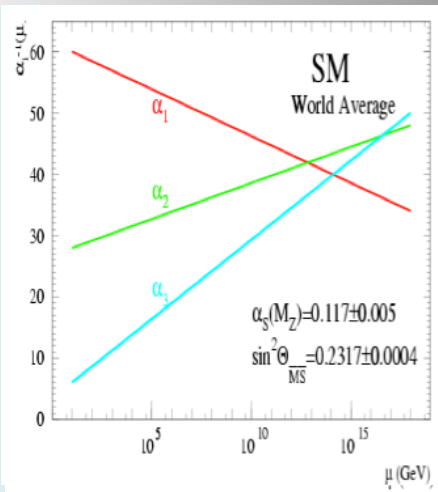
He is slowed down on his way to the drinks!!

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

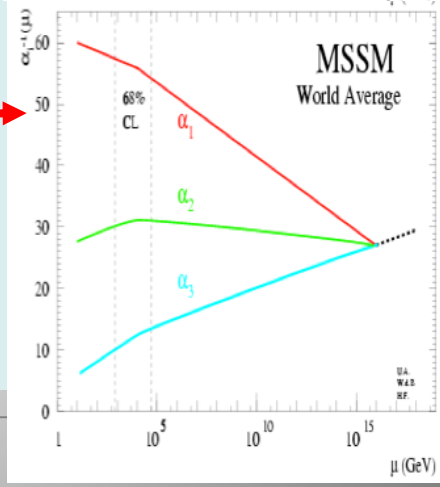
Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy? 19 parameters!
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy



Most popular extensions around 2000

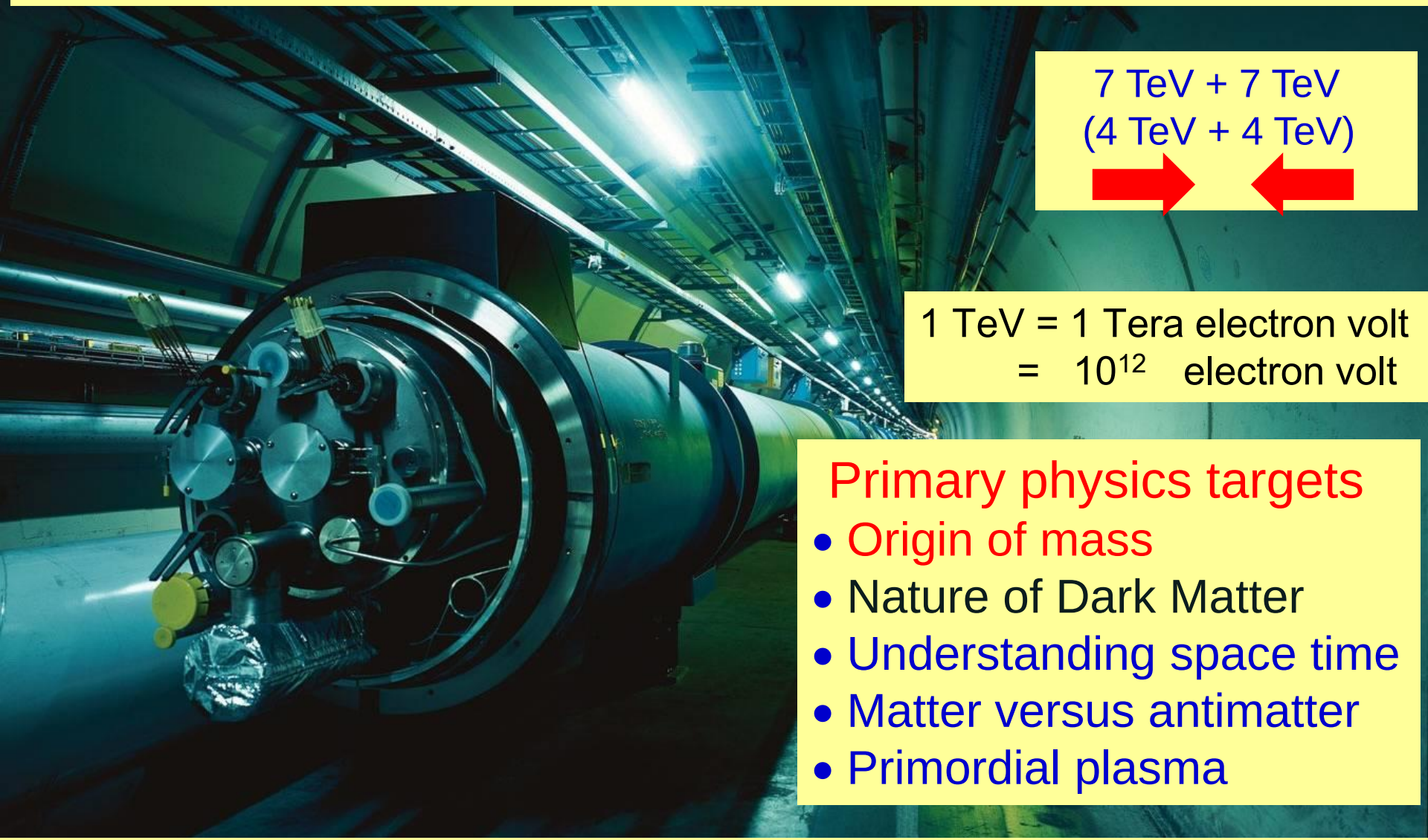
- Supersymmetry
- Extra space dimensions



Many other ideas: More symmetry and gauge bosons, composite Higgs models, L-R symmetry, quark & lepton substructure, Little Higgs models, Technicolor, Hidden Valleys, Vector-like quarks...

Higgsless models rather disfavoured these days

The Large Hadron Collider = a proton proton collider



7 TeV + 7 TeV
(4 TeV + 4 TeV)

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

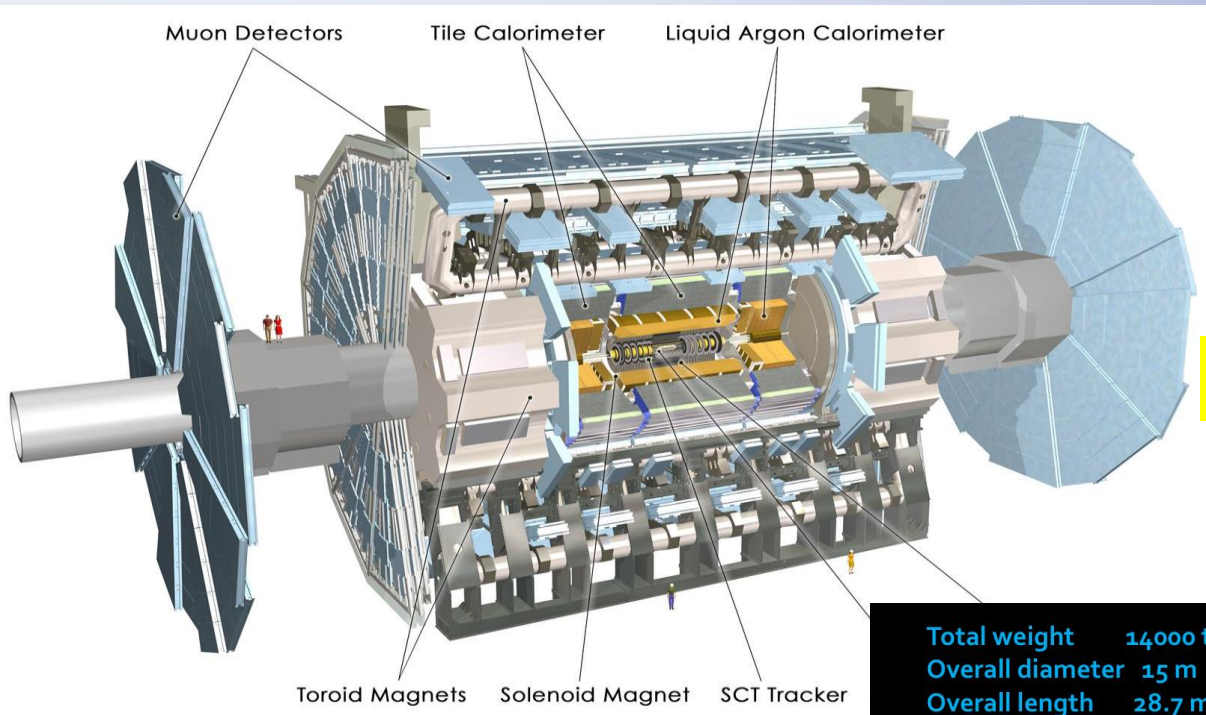
Primary physics targets

- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

The LHC is a Discovery Machine

The LHC will determine the Future course of High Energy Physics

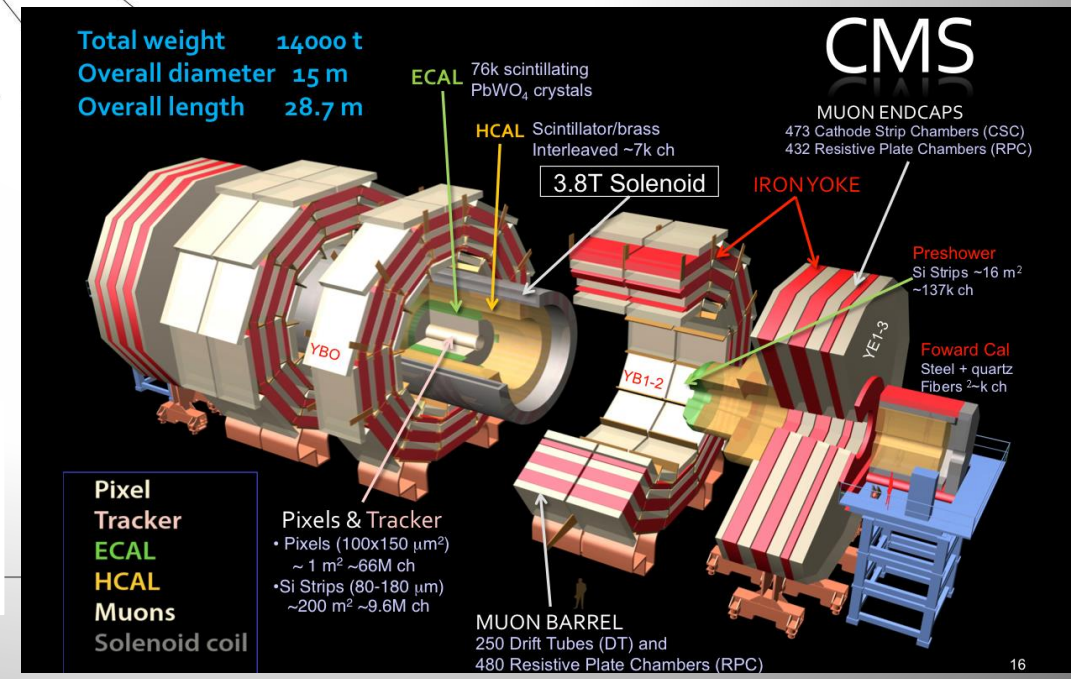
The Higgs Hunters @ the LHC



LHC: pp collisions at 7/8 TeV

The ATLAS experiment

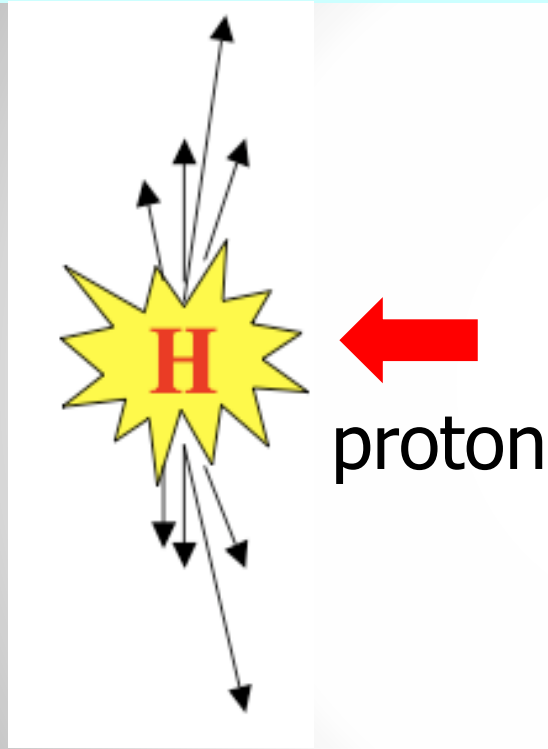
The CMS experiment



These experiments are likely to become DARK MATTER HUNTERS in 2015 and beyond…

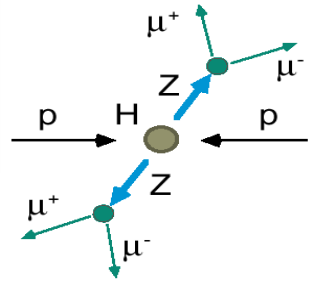
2012: A Milestone in Particle Physics

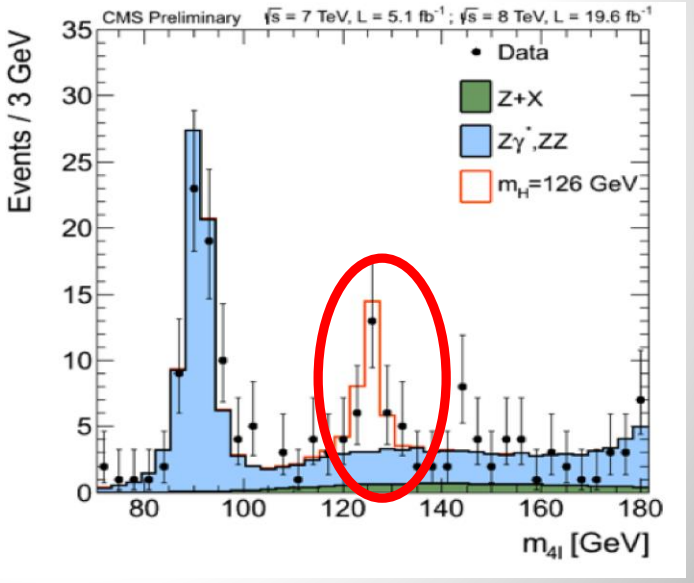
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it



proton

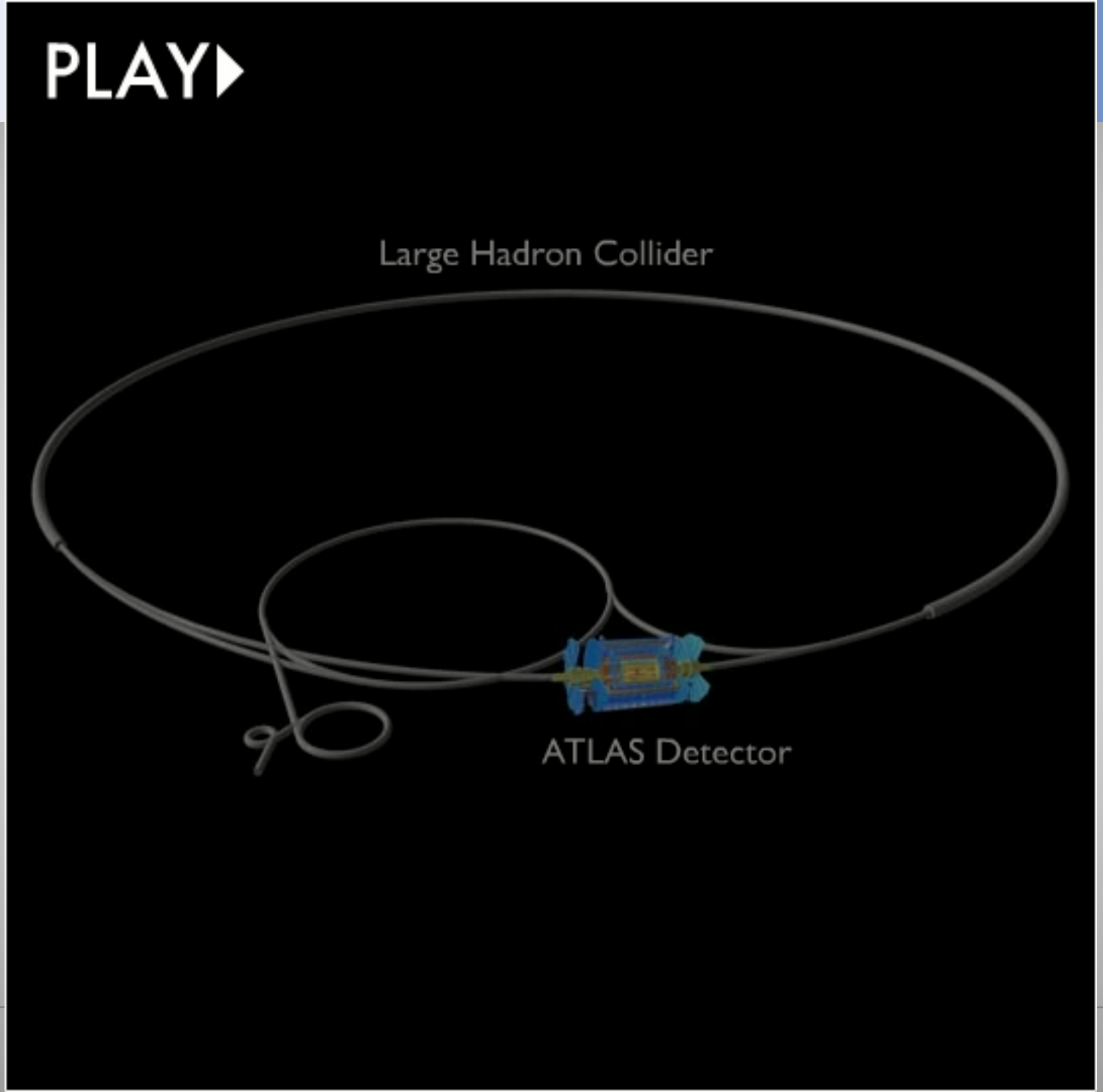
proton



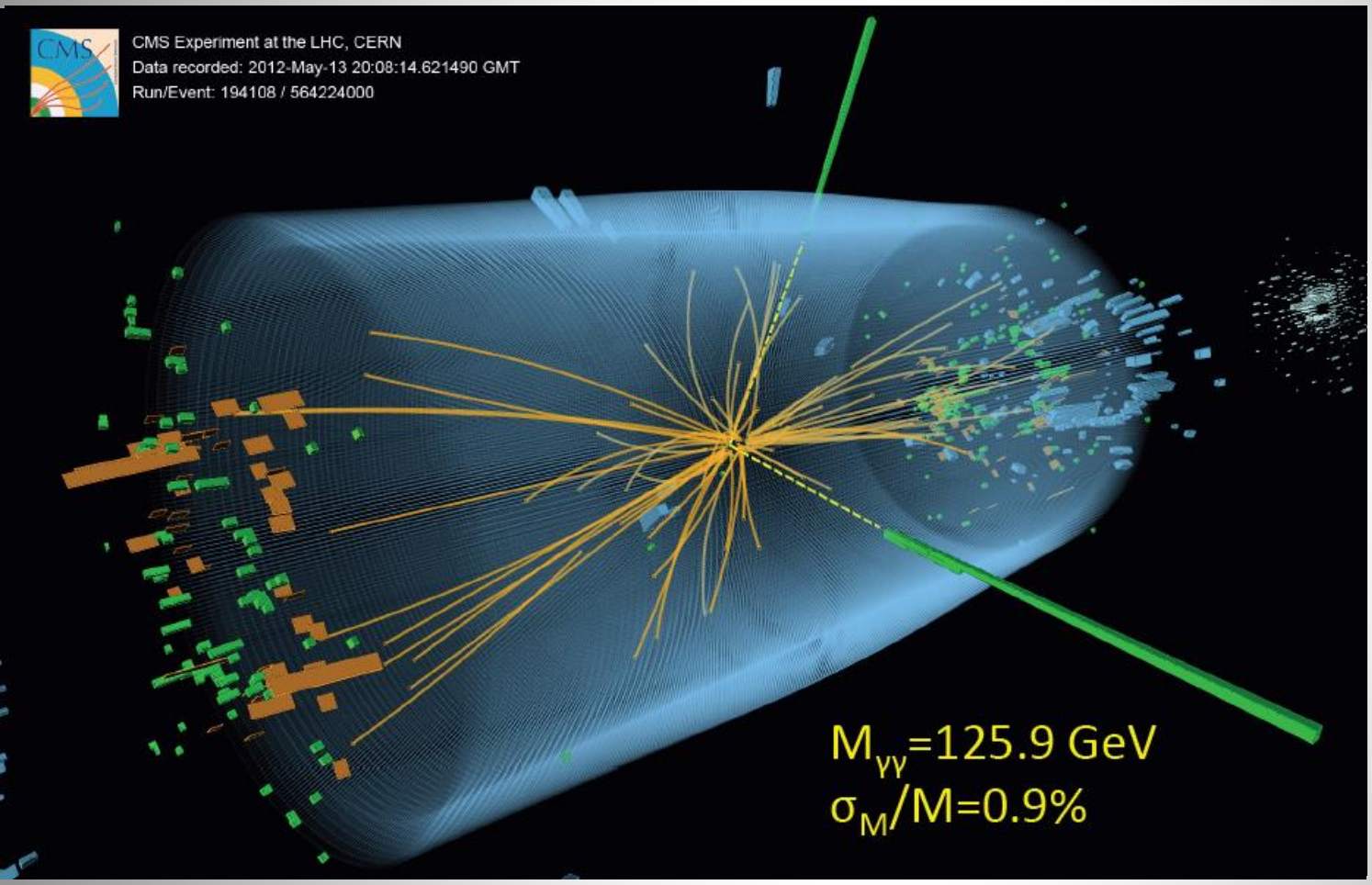


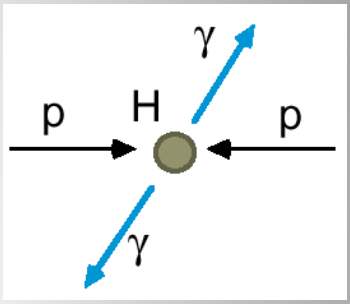
2013

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model


PLAY
Large Hadron Collider
ATLAS Detector

A Collision with two Photons

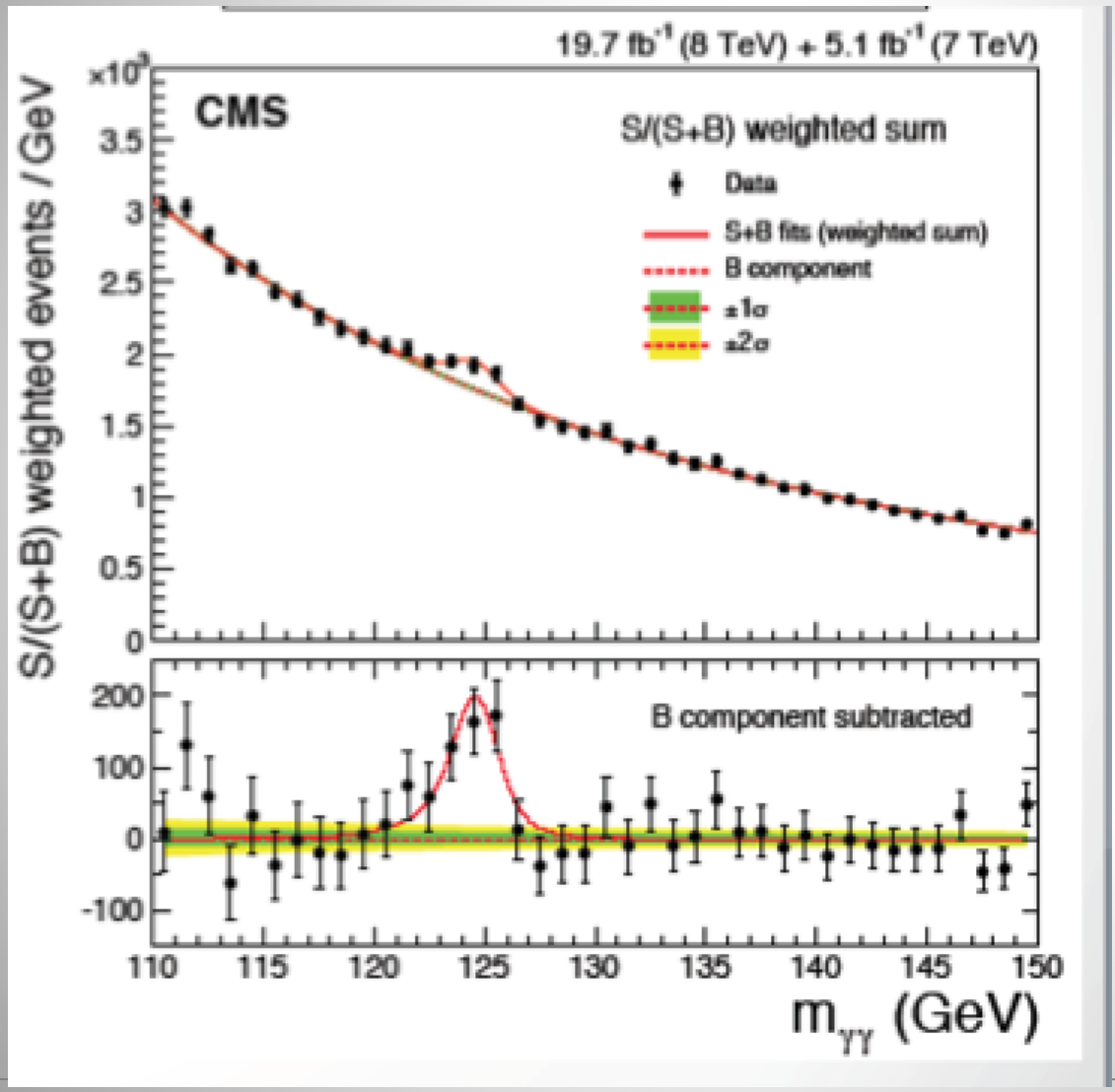


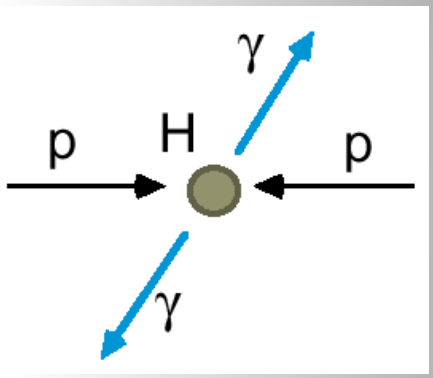


A Higgs or
a 'background'
process without
a Higgs?

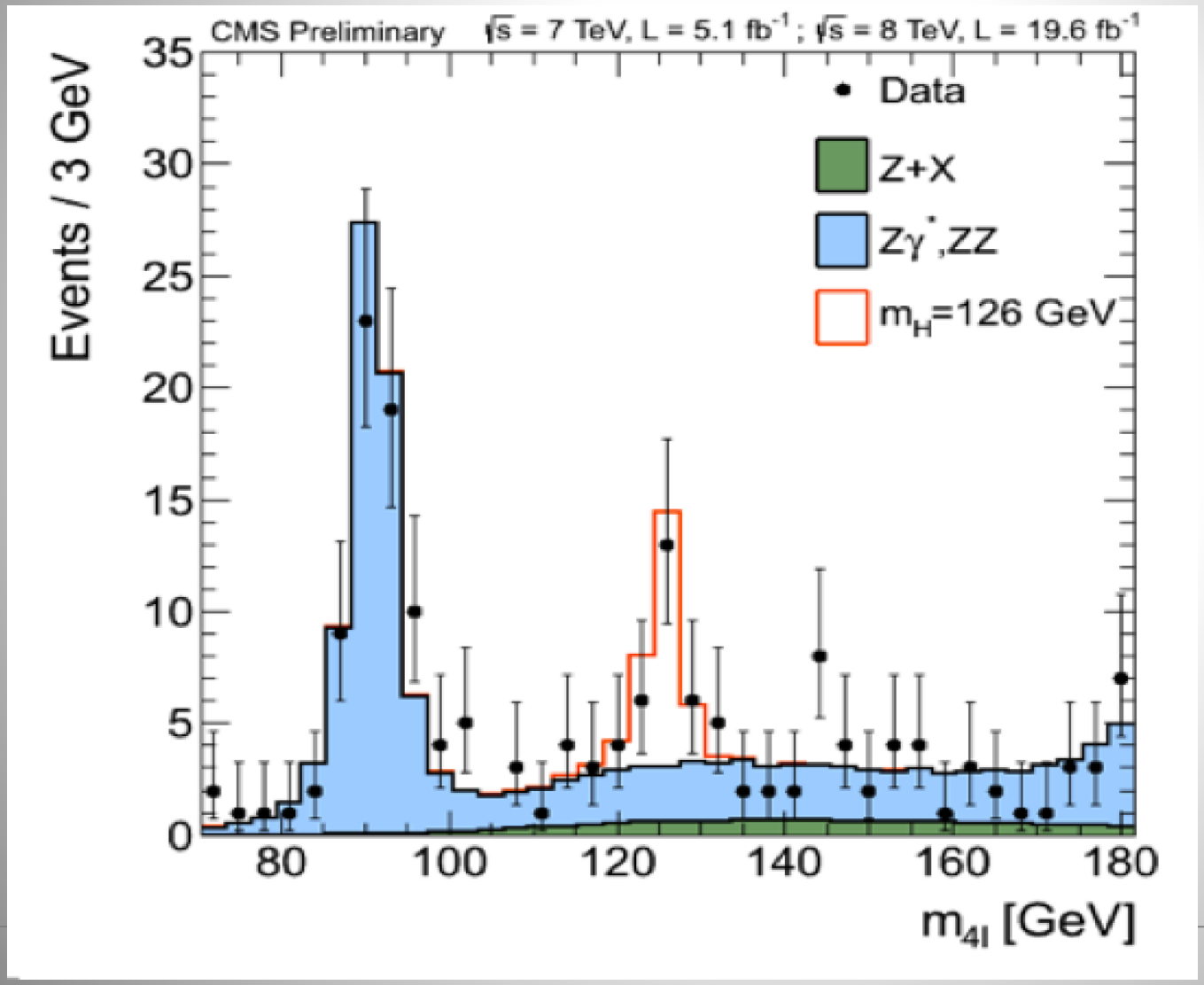
Note: the LHC is a Higgs Factory: 1 Million Higgses already produced
15 Higgses/minute with present luminosity

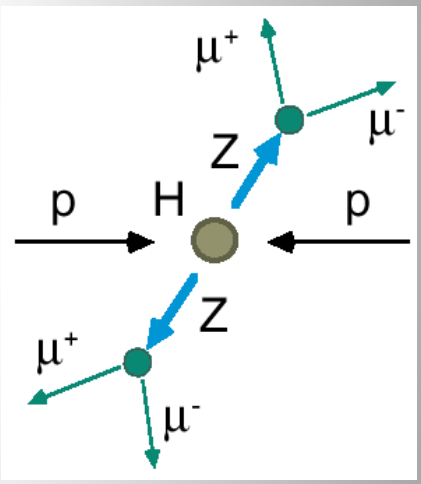
Discovery of the Higgs Boson...





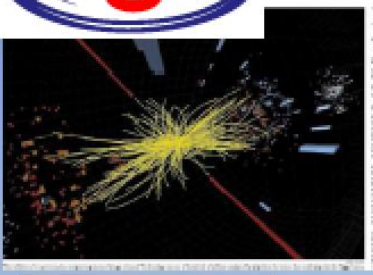
Discovery of the Higgs Boson...

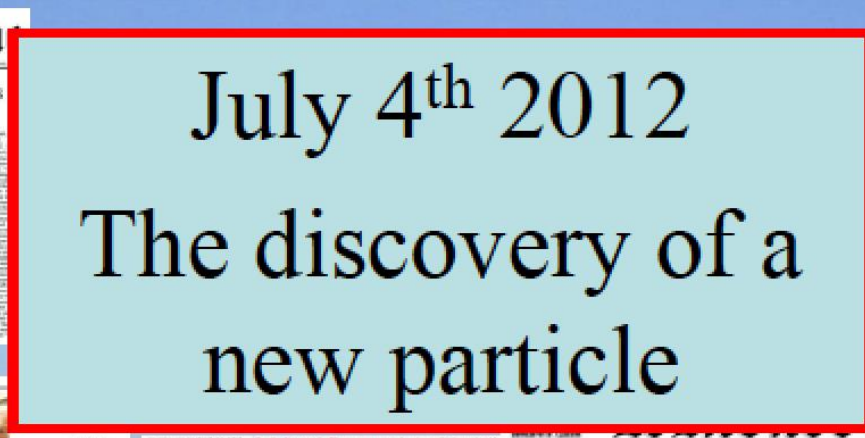




July 4th 2012

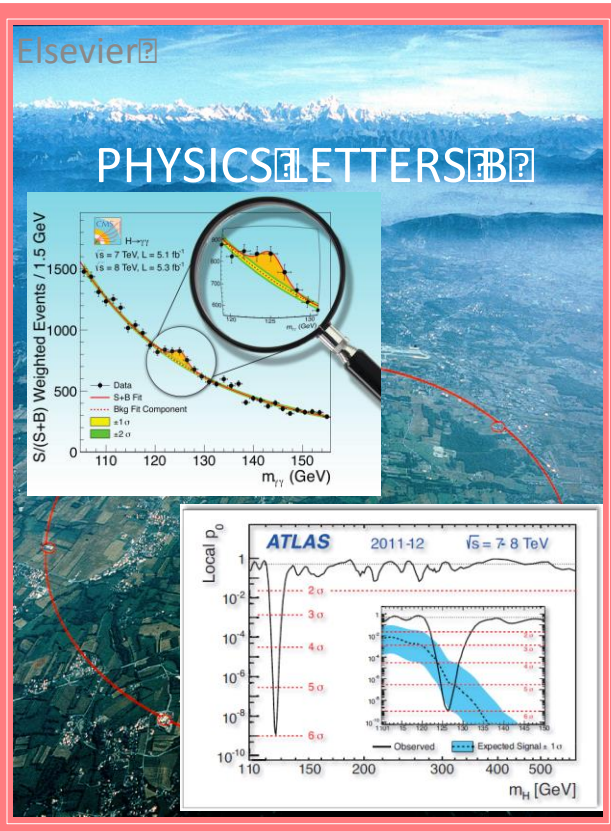
The discovery of a new particle





Most cited paper so far...

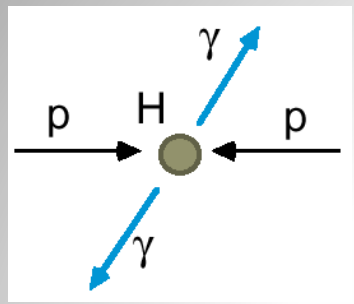
Special Physics Letters B edition with the ATLAS and CMS CMS papers on the Higgs Discovery



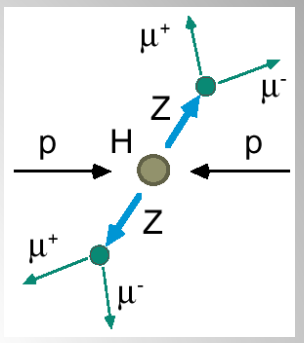
Cited about 4200 times so far...

Also...

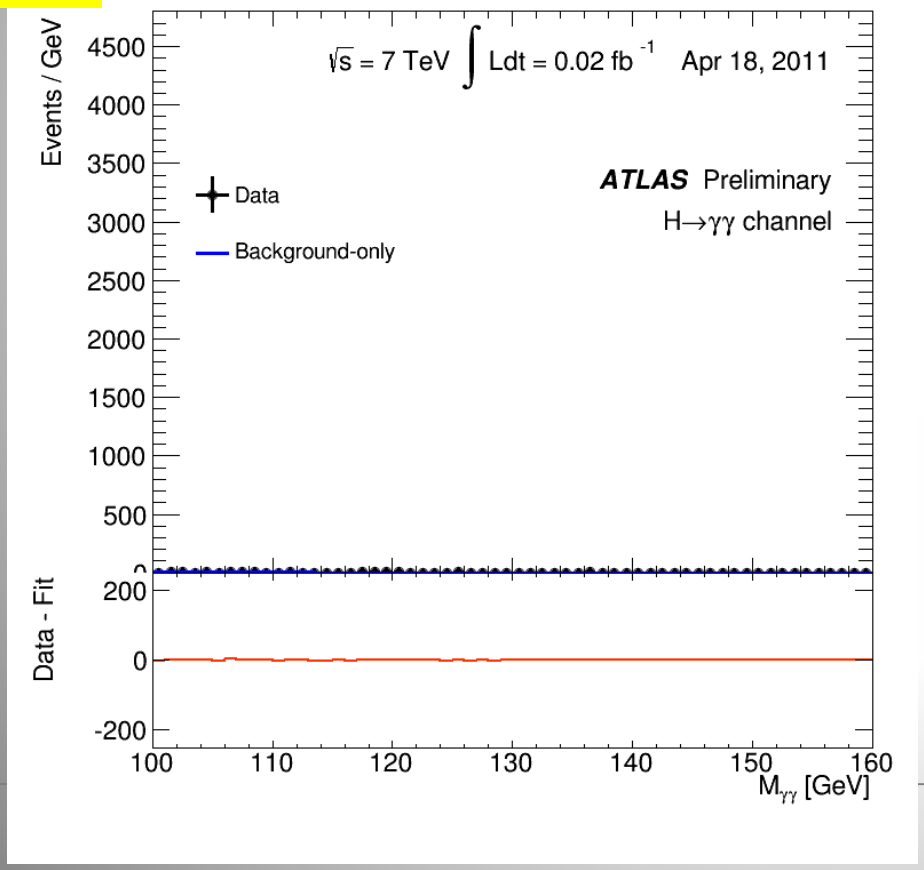
The Birth of a Particle



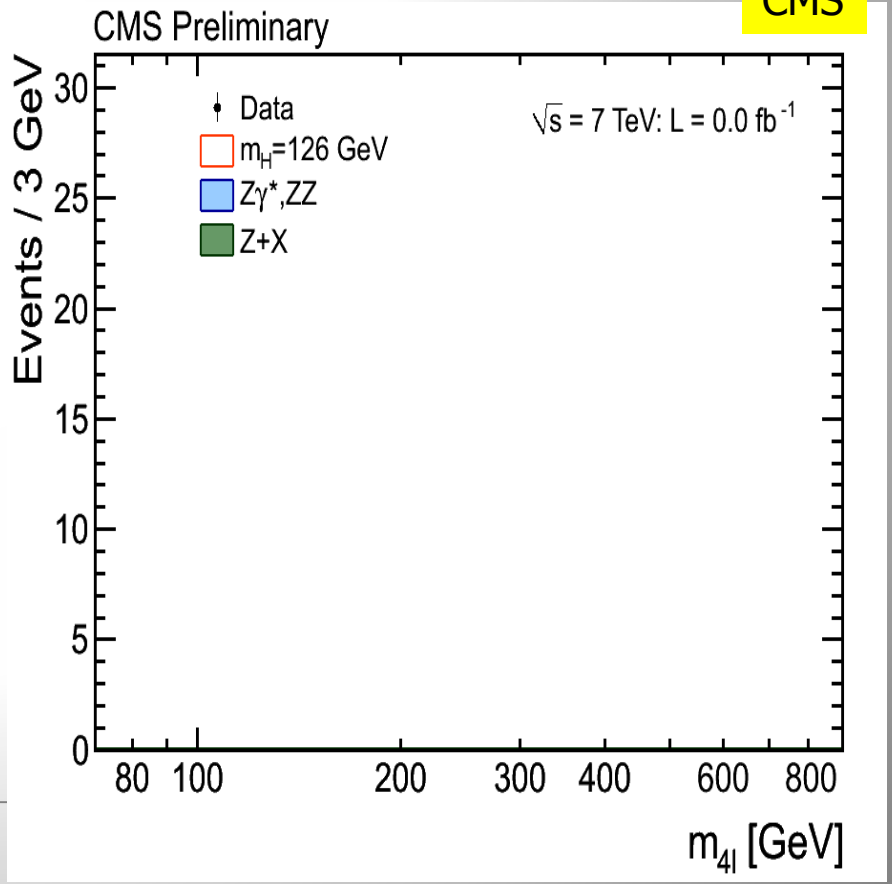
"History" of the data accumulation during the last two years



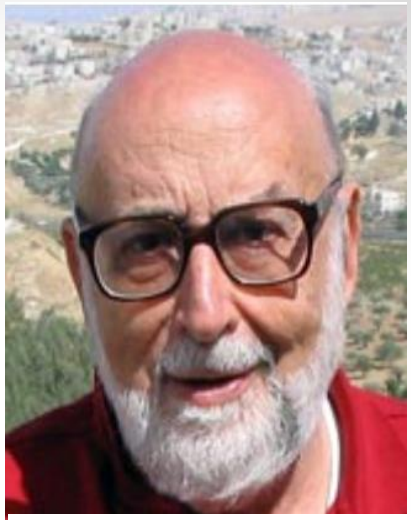
ATLAS



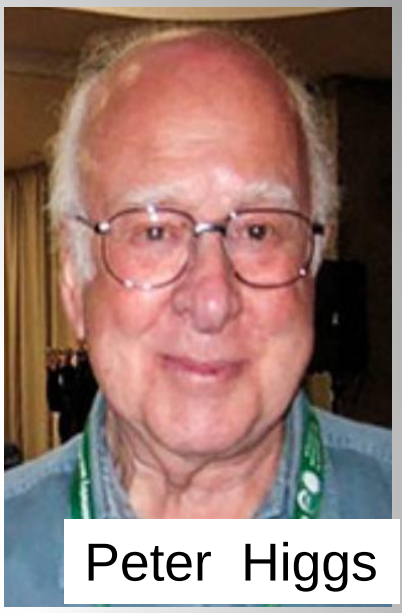
CMS



Tuesday 8 October 2013

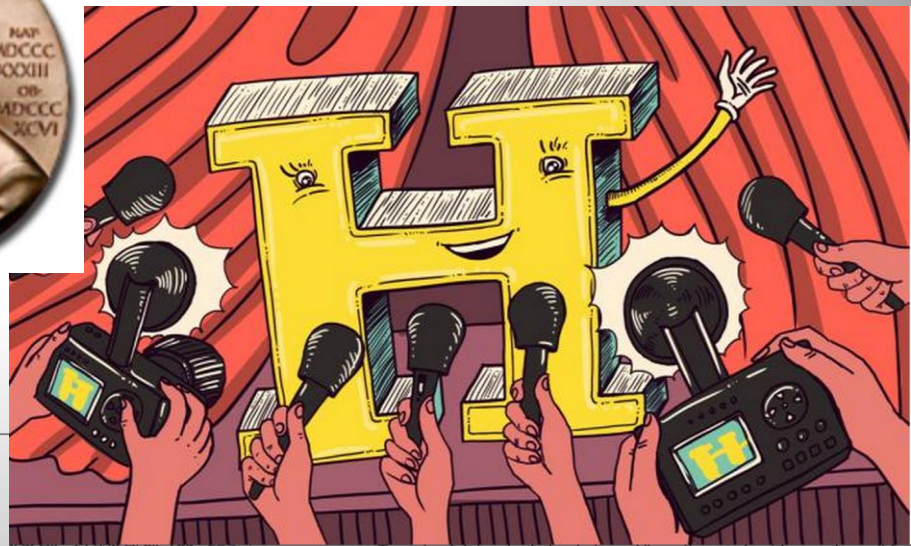


Francois Englert



Peter Higgs

Congratulations!!!!

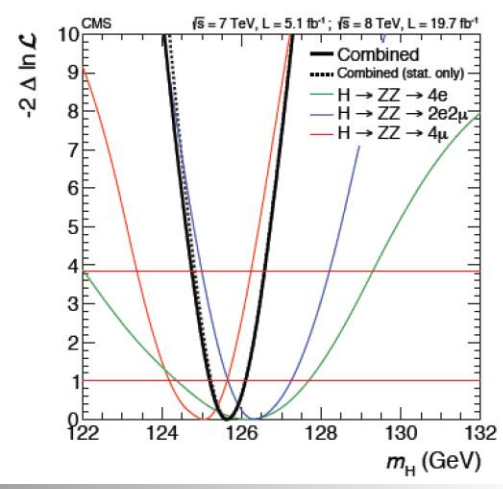


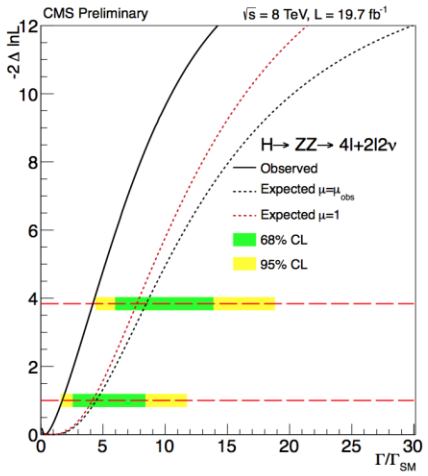
...and December 2013

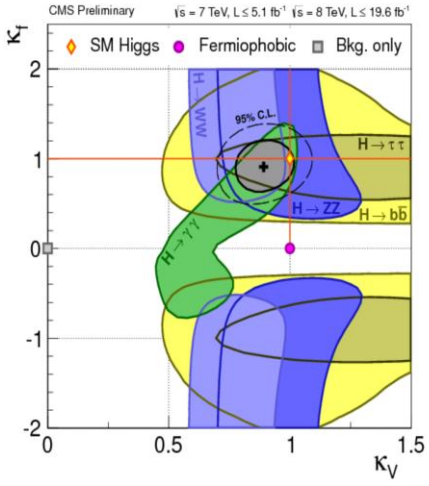
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

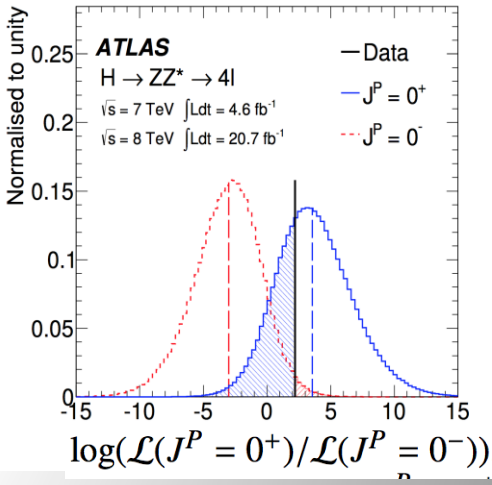
A Higgs…

We know already a lot on this Brand New Higgs Particle!!









Mass =
125.0 ±0.2 GeV

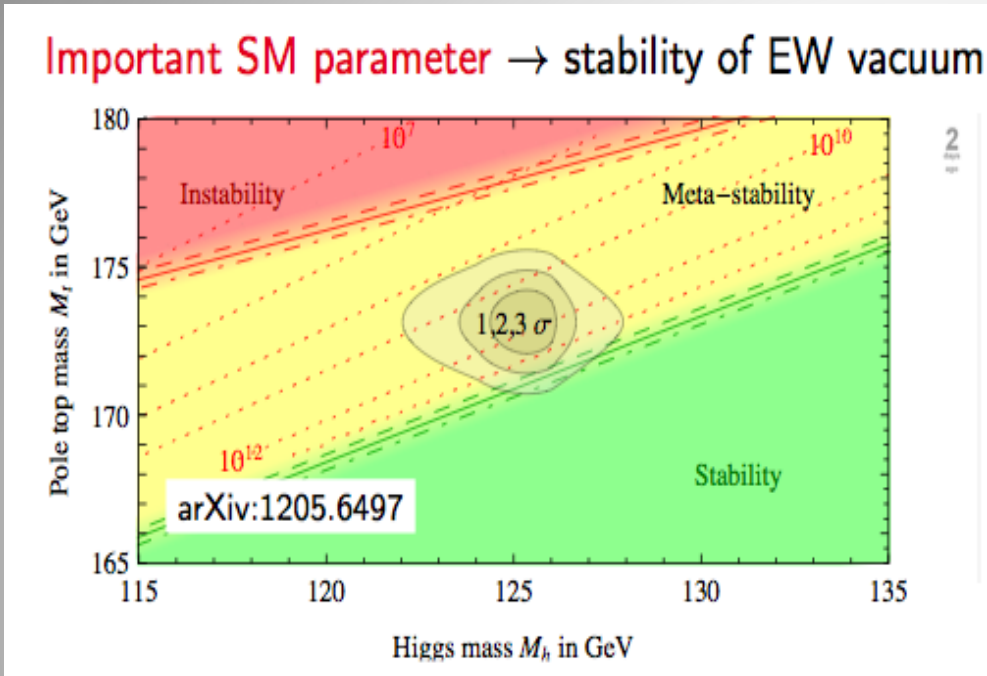
Width =
< 22 MeV
(95%CL)

Couplings are within 20% of the SM values

Spin =
0^+ preferred over 0^-,1,2

Note: We study the properties of the Higgs carefully, and check if these in Fact are as expected from the Standard Model. We also look for new "Higgses"

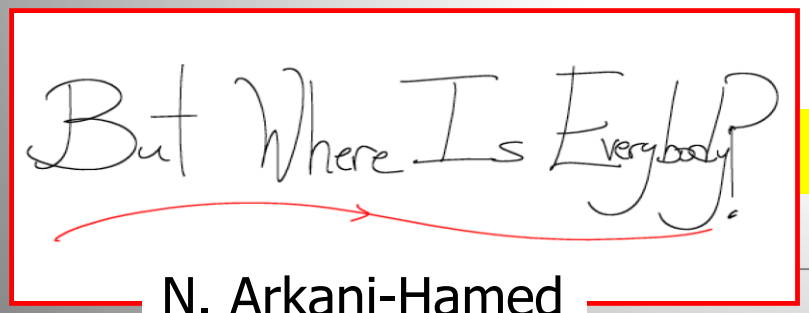
Consequences for our Universe?



Precise measurements of the top quark and first measurements of the Higgs mass:

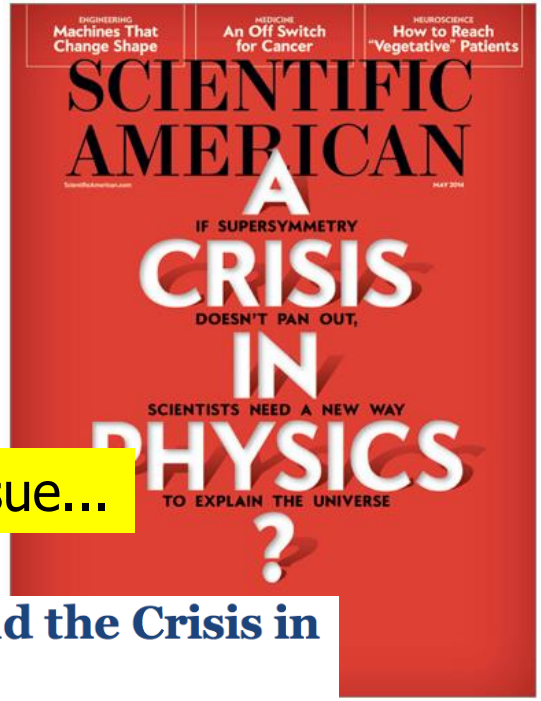
Our Universe meta-stable ?
Will the Universe disappear in a Big Slurp? (NBCNEWS.com)

New Physics inevitable?
But at which scale/energy?



N. Arkani-Hamed

...The May 2014 Issue...



Supersymmetry and the Crisis in Physics

The Future: Studying the Higgs…

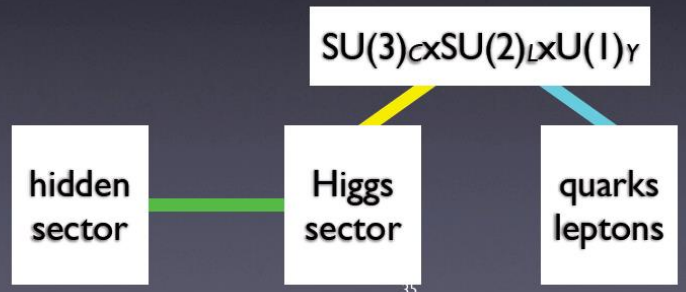
- More LHC Data 2015-2022
- LHC upgrade !
- Experiment upgrades!!
- (Other/new machines?)

Many questions are still unanswered:

- What explain a Higgs mass ~ 126 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤

Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors"



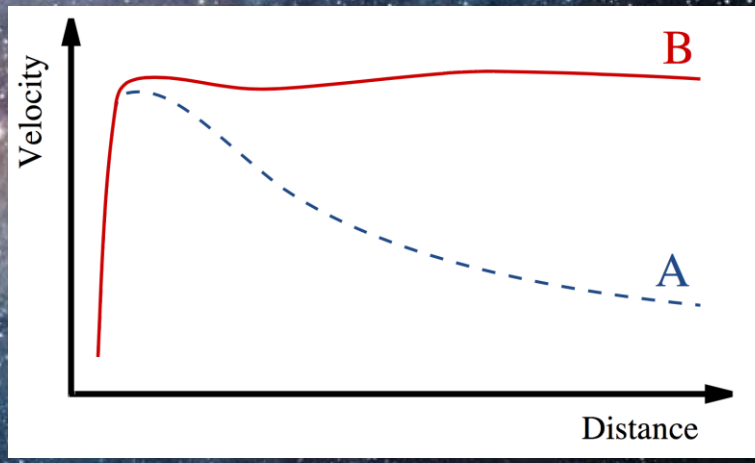
Next Questions…

Dark Matter at the LHC?

Are we Supersymmetric?

Dark Matter in the Universe

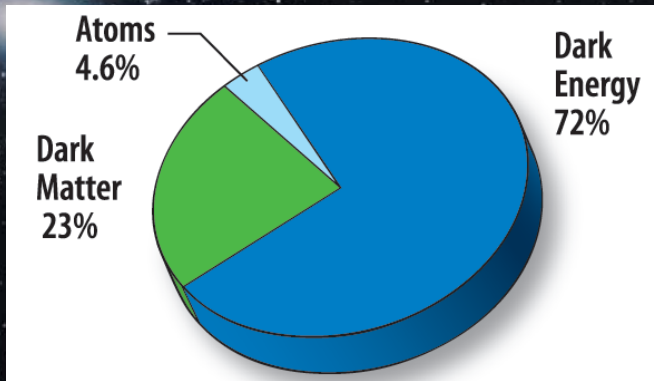
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?

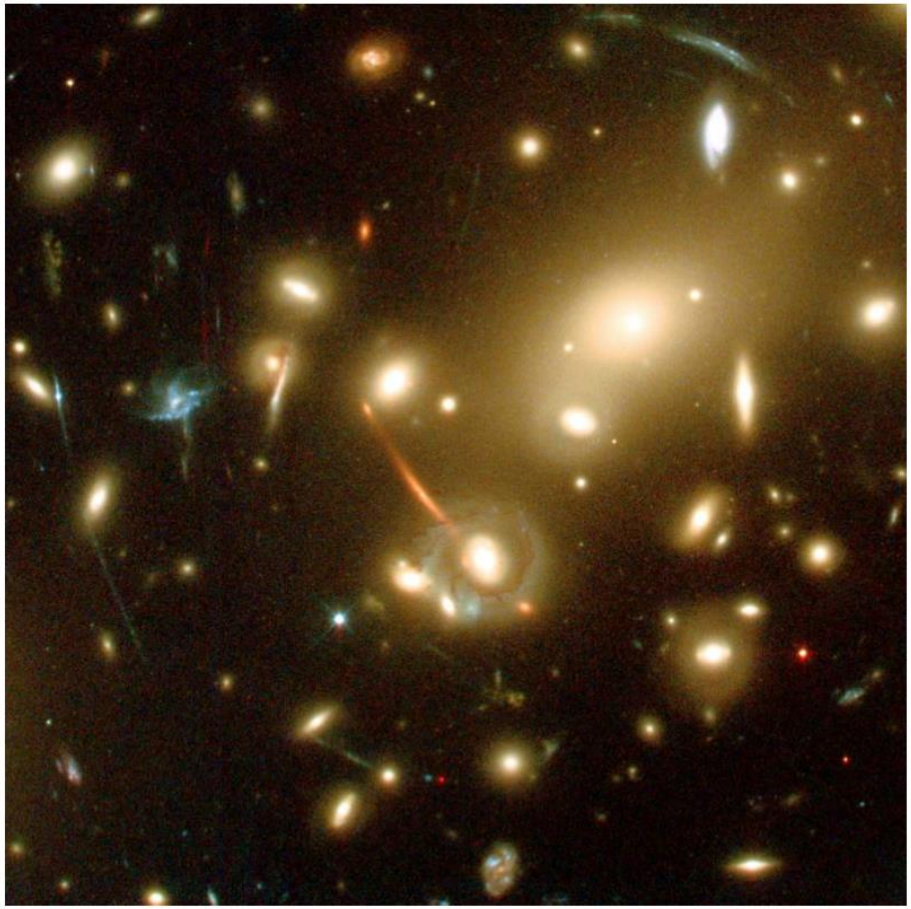

F. Zwicky 1898-1974


Vera Rubin ~ 1970

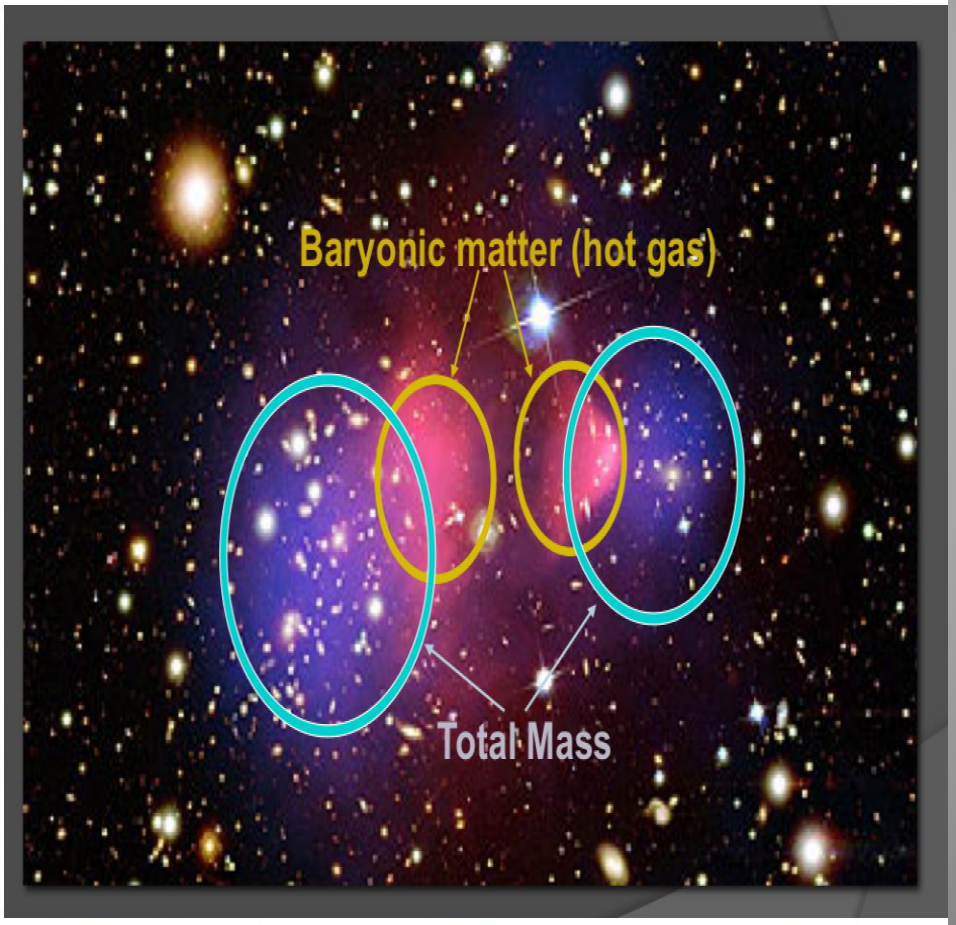


More Evidence for Dark Matter

- Gravitational Lensing
  - much more lensing than can be explained by visible mass



- Bullet Cluster; colliding galaxies
  - Composite x-ray, visible image, 10x DM

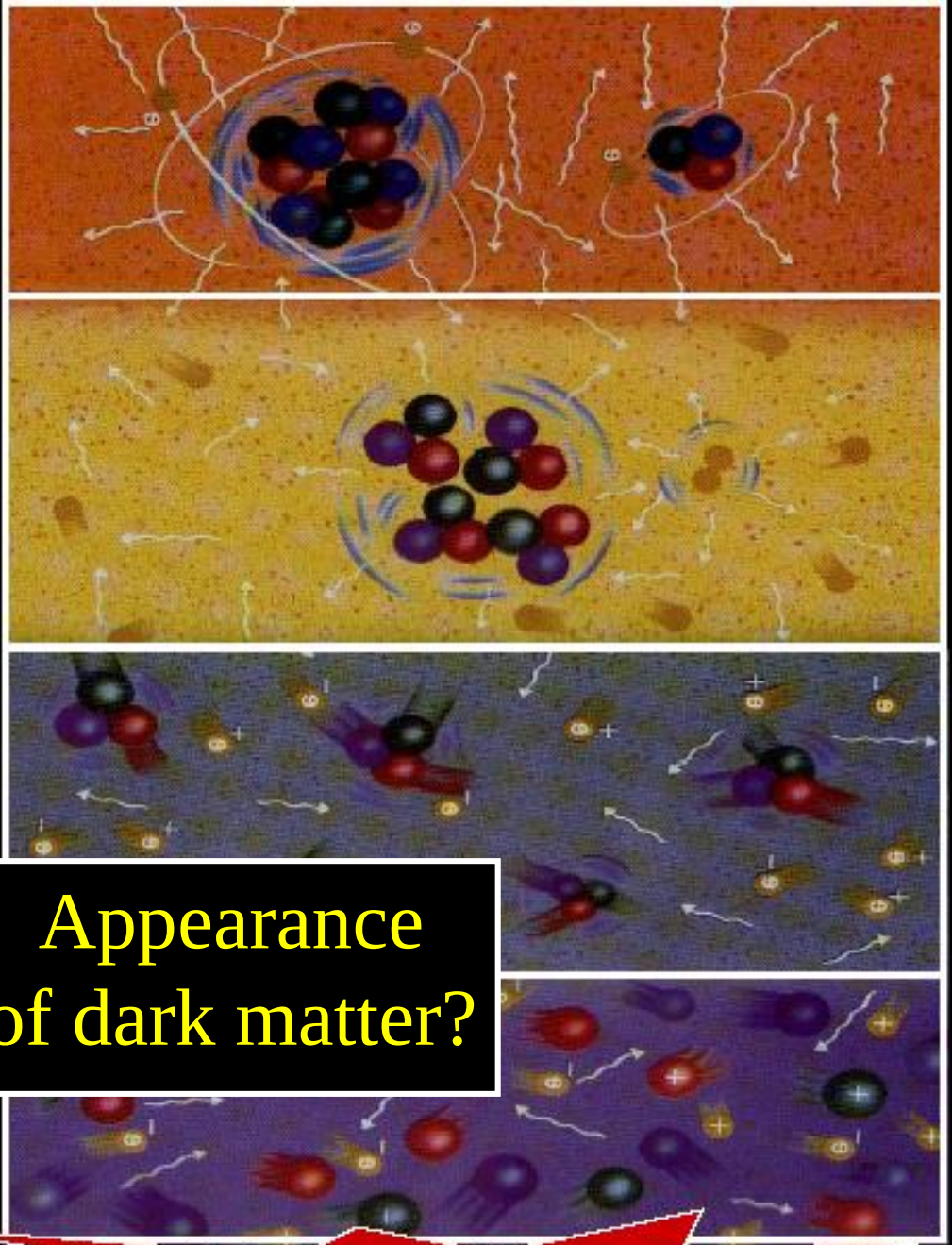


300,000 years

3 minutes

1 micro-second

1 pico-second



Appearance of dark matter?

BANG!

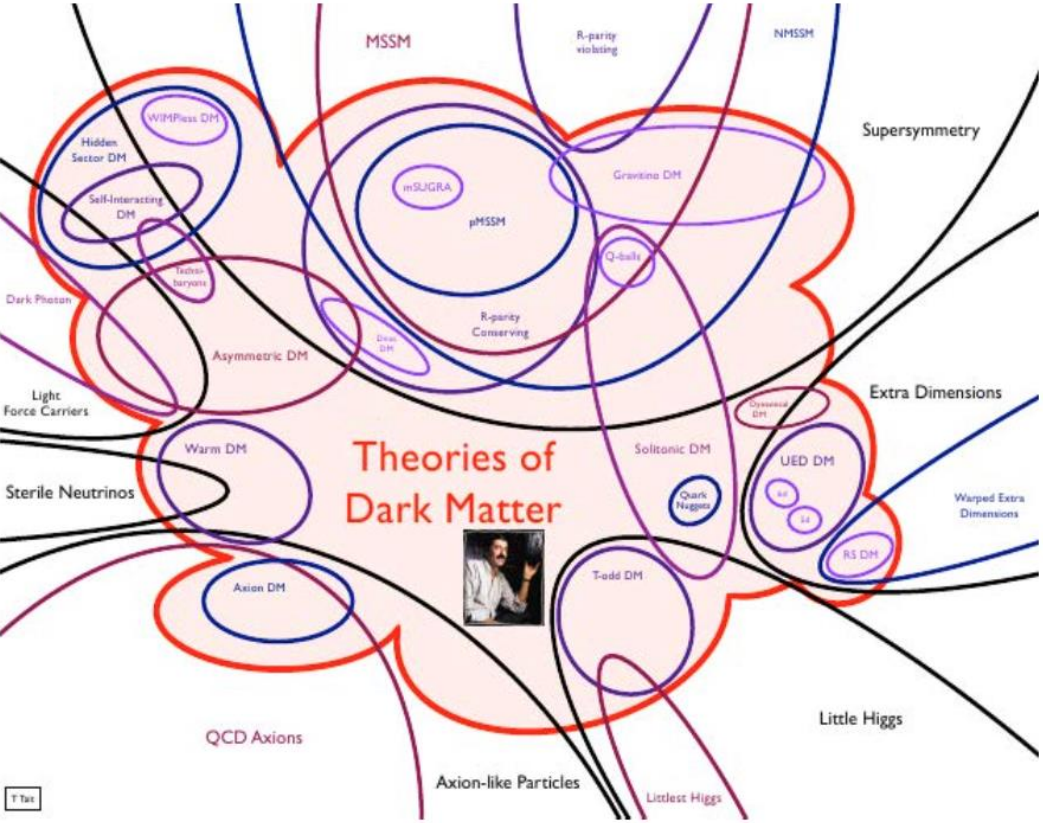
Formation of atoms

Formation of nuclei

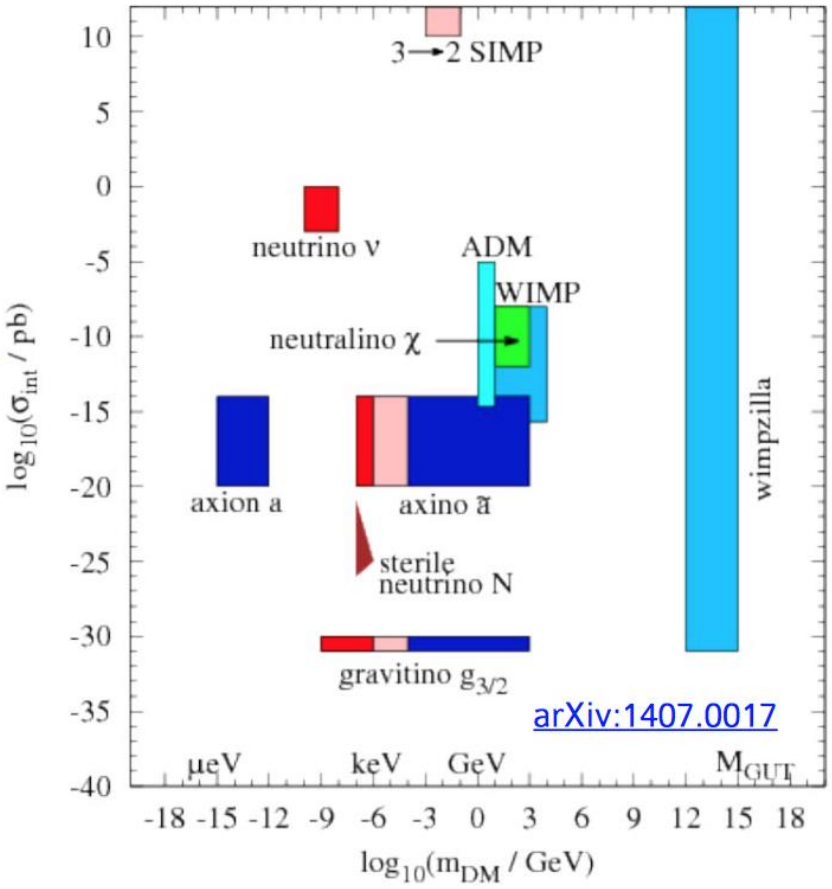
Formation of protons & neutrons

Appearance of mass?

Theories on Dark Matter



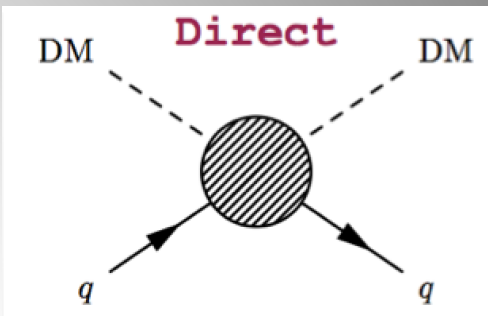
Tim Tait, DM@LHC 2013



(Our) **preferred DM candidate**
matches cosmological observations (e.g. thermal relic density):
dark, stable, cold, weakly interacting with SM particles,
mass of up to a few TeV → a **WIMP**

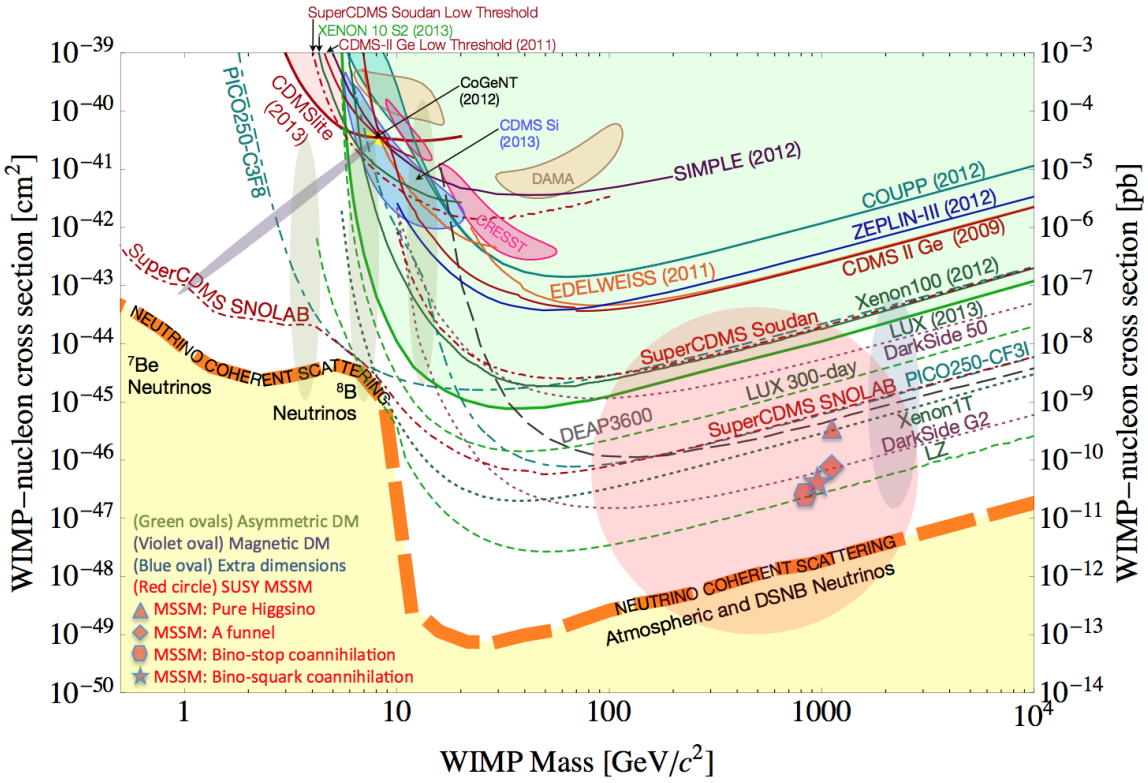
Direct Searches for Dark Matter

State of the art today:
Driven by the results of the LUX experiment

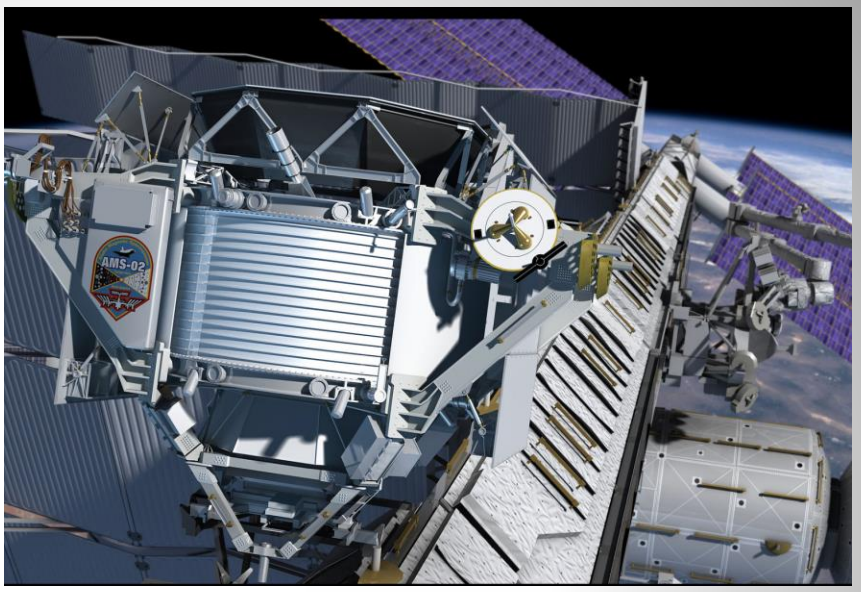


Intensive campaign of direct detection experiments since more than ~20 years

No (real) sign so far…

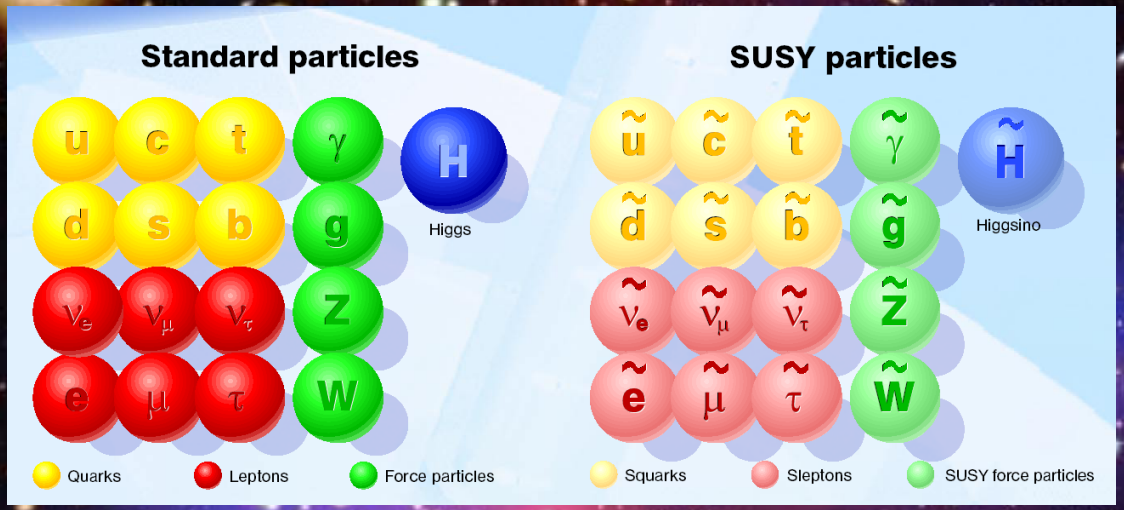


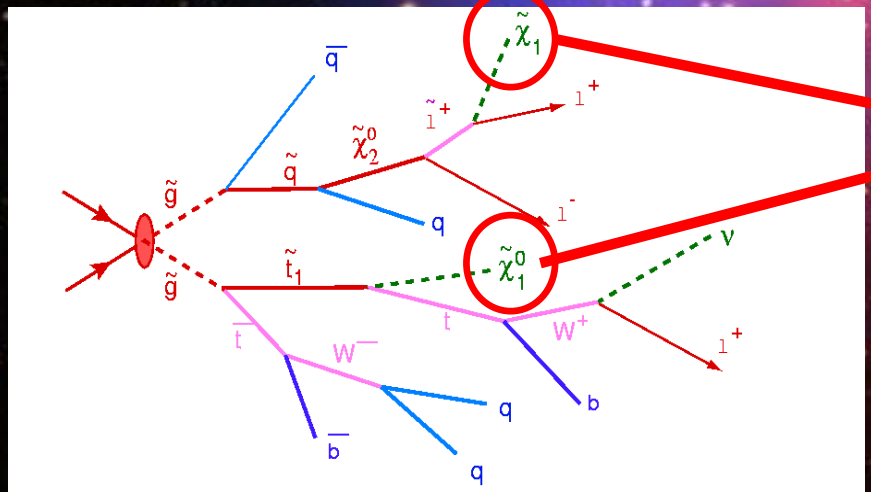
Dark Matter Searches in Space!



Visit the AMS control room at CERN today…

Supersymmetry: a new symmetry in Nature?





SUSY particle production at the LHC

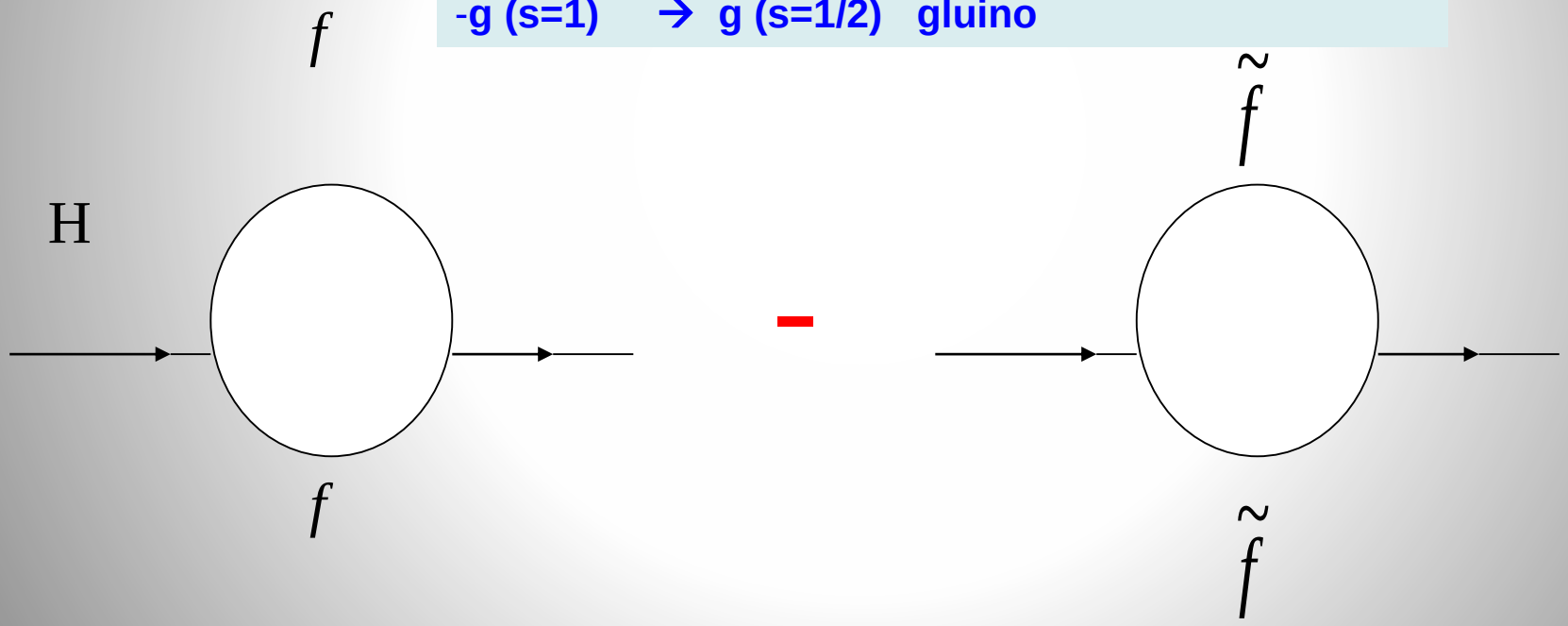
Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

Picture from Marusa Bradac

Supersymmetry

Supersymmetry (SUSY) → assumes a new hidden symmetry between the bosons (particles with integer spin) and fermions (particles with half integer spin). Stabelize the Higgs mass up to the Planck scale

-Each particle with spin S has a SUSY partner p with spin S -1/2
-q (s=1/2) → q (s=0) squark
-g (s=1) → g (s=1/2) gluino

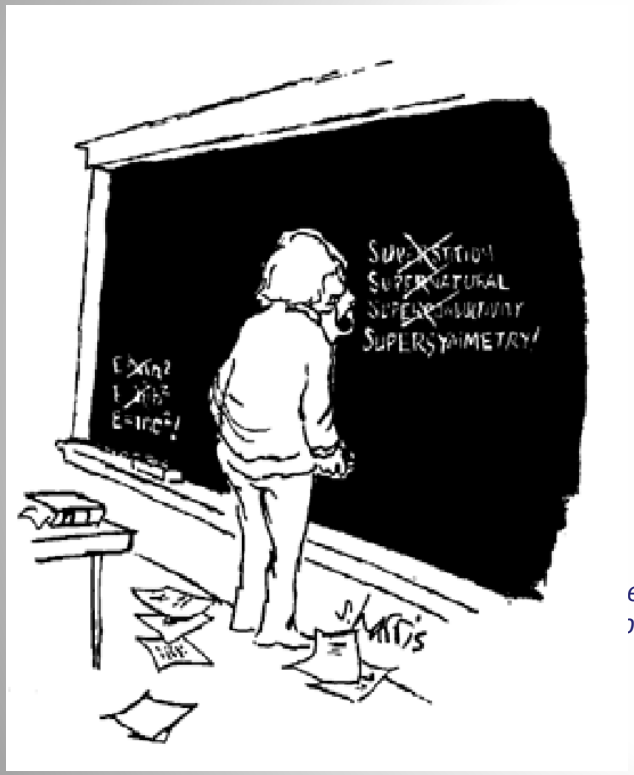


Fermion and boson loops cancel, provided $m_{\tilde{f}} \leq$ TeV.

Supersymmetry

A VERY popular benchmark…

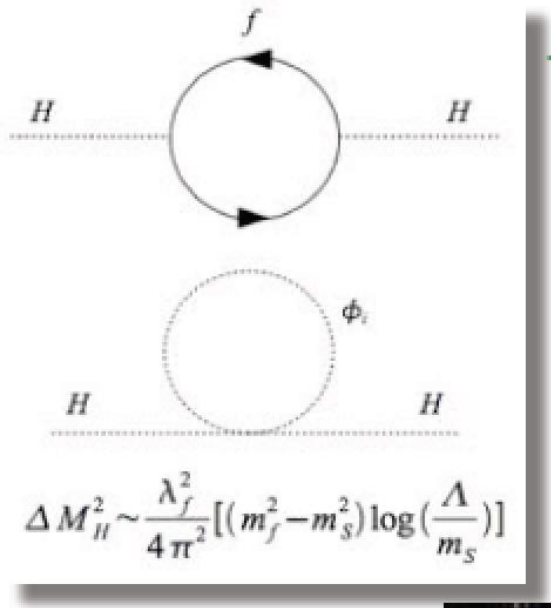
More than 10000 papers since 1990



"One day all these trees will be SUSY phenomenology papers"

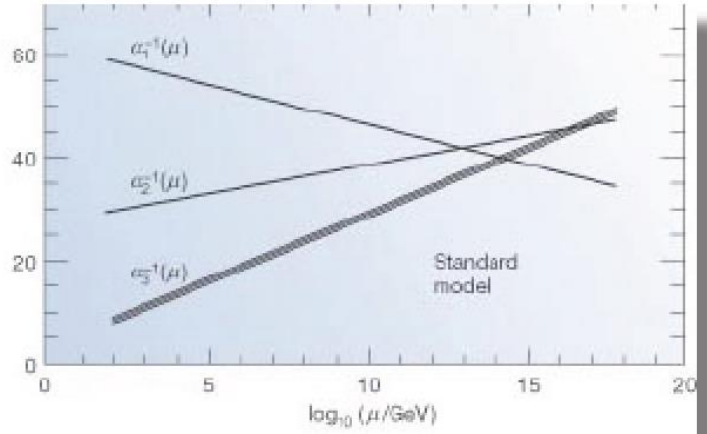
Considered as a benchmark for a large class of new physics models

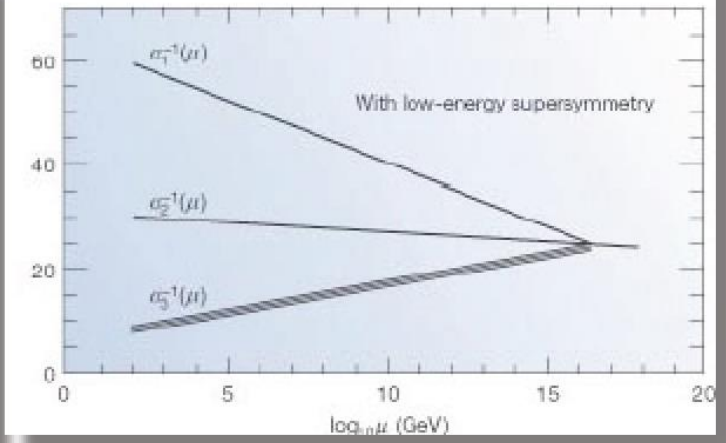
Summary: Why SUSY is good for you!!



- Elegant solution to the hierarchy problem (i.e., why the Higgs mass is not at the Planck scale)

- Gauge unification

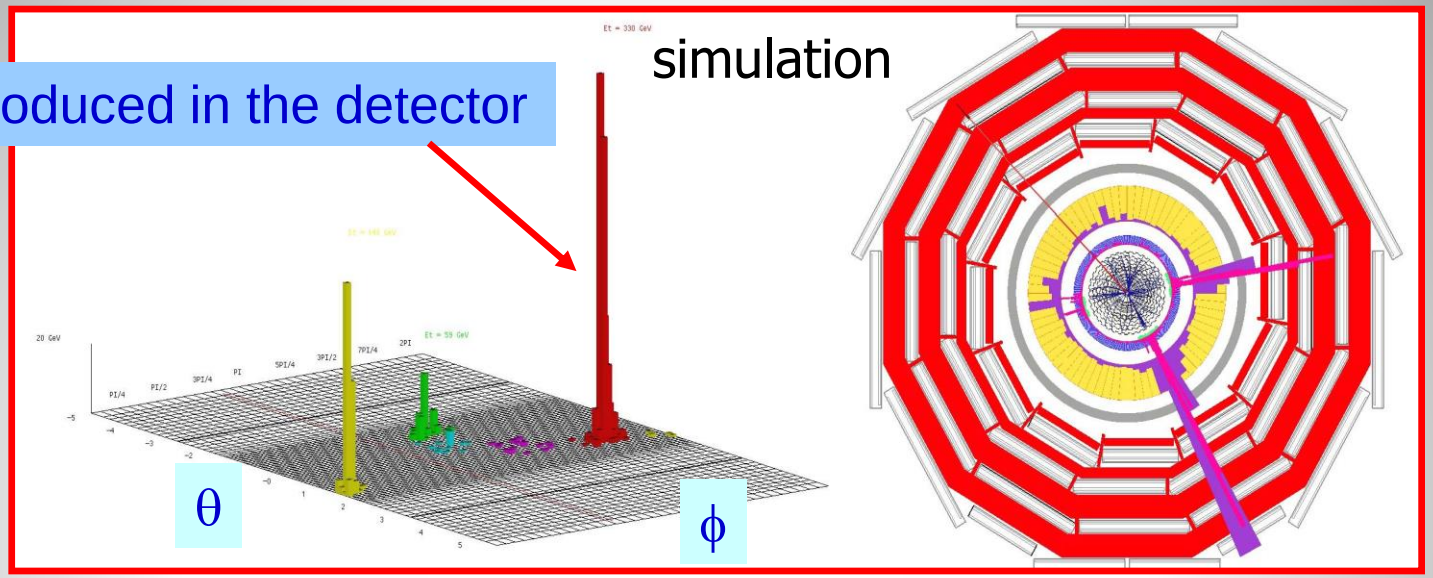


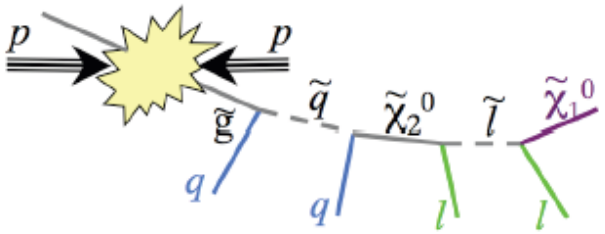


- Dark matter candidate with the right abundance

Detecting Supersymmetric Particles

Energy produced in the detector



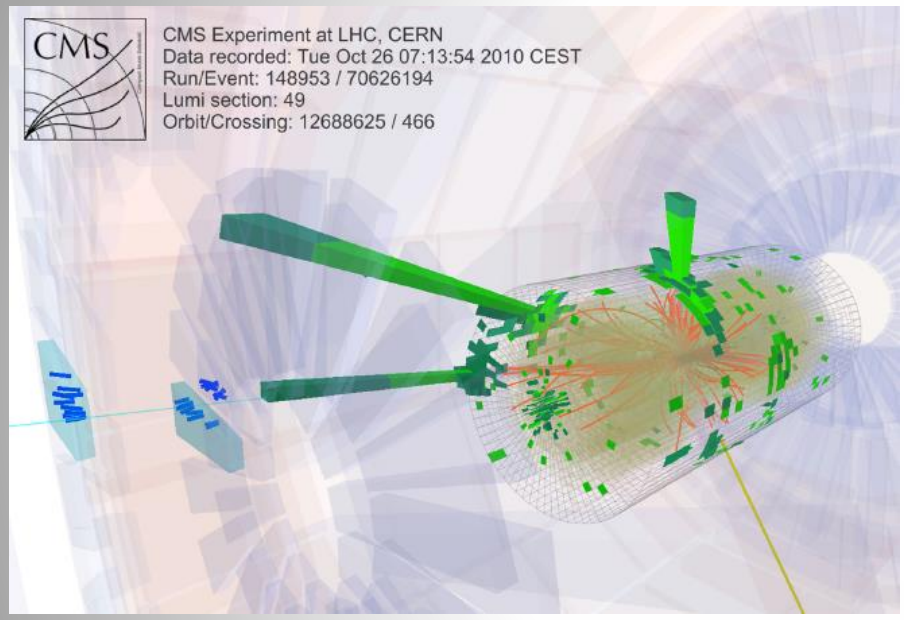


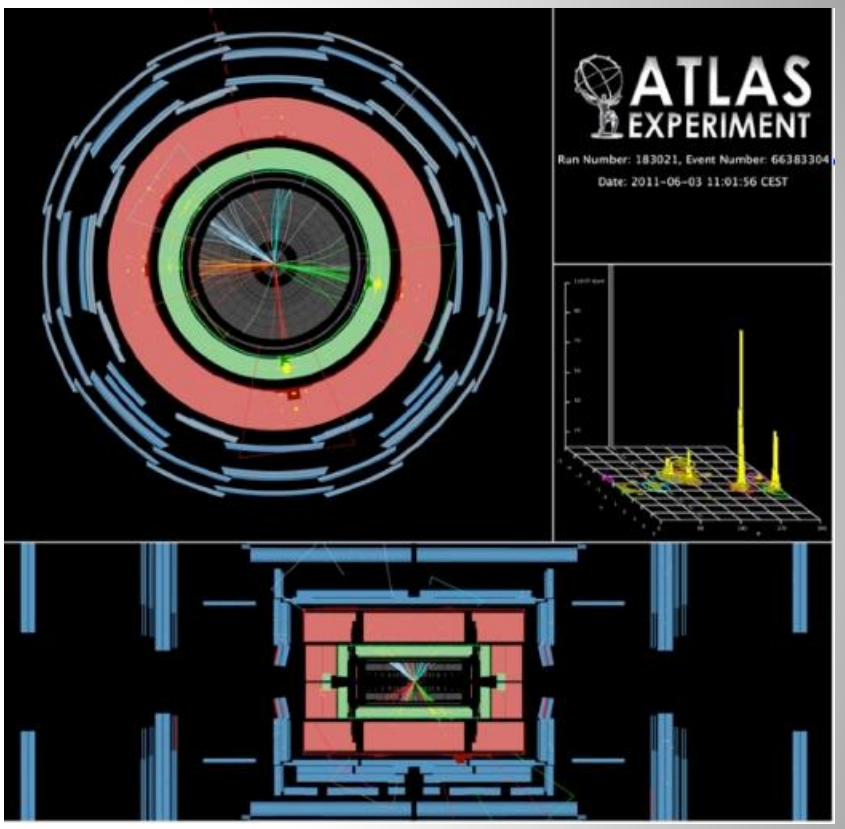
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

Very prominent signatures in CMS and ATLAS

…Some Interesting Collisions…

…already in 2010…

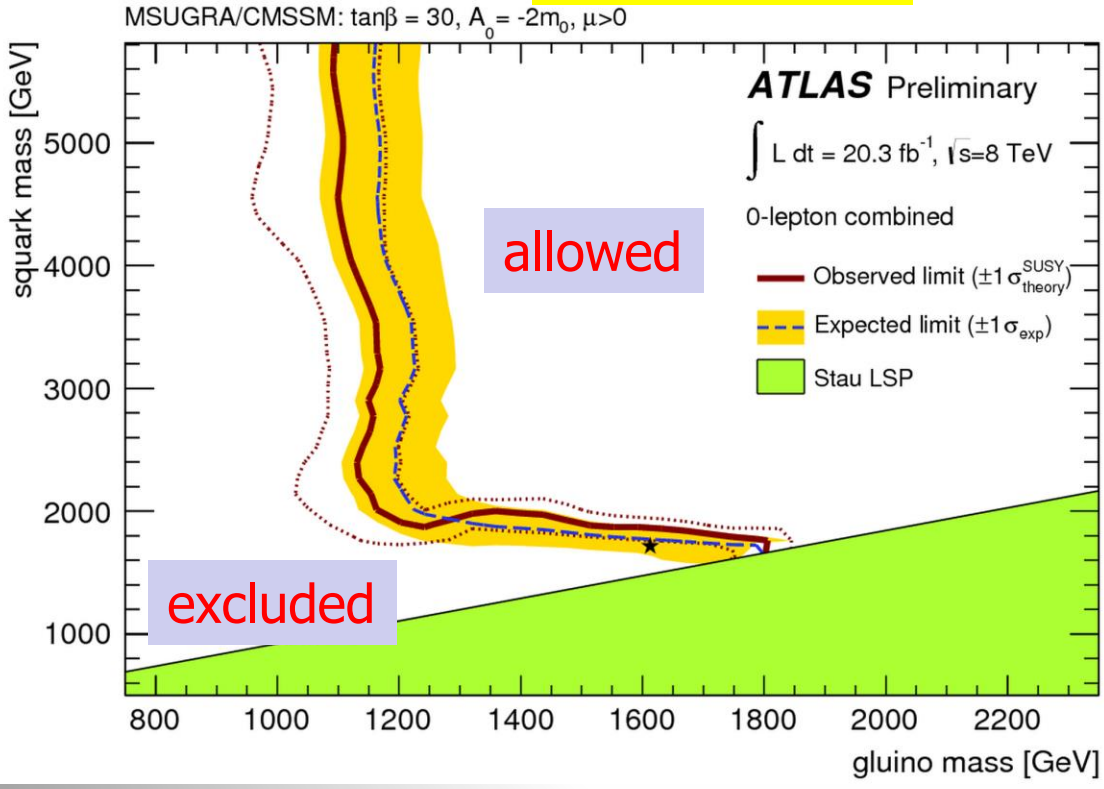




- Events with five jets of particles and large missing energy which could come from a possible dark matter particle
- But a few events is not enough too prove we have something new
  No visible excess has been building up with time…

SUSY Searches: No signal yet to date…

Status in 2013



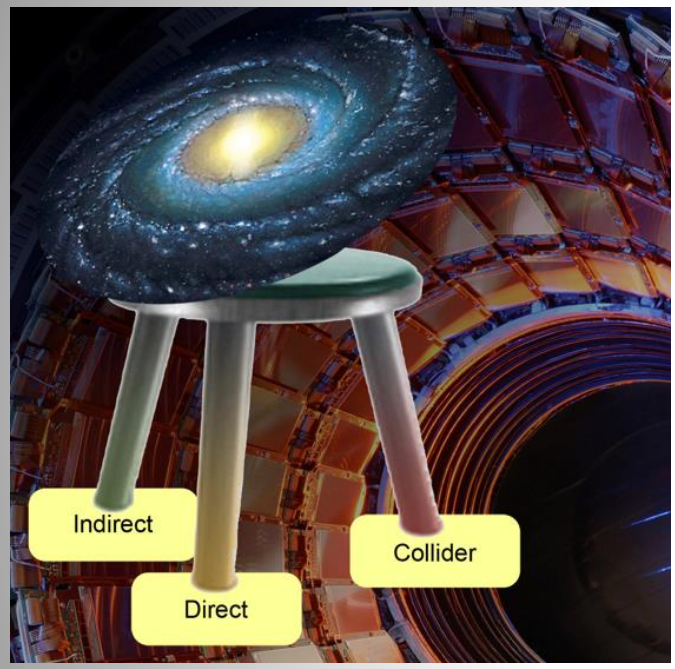
- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

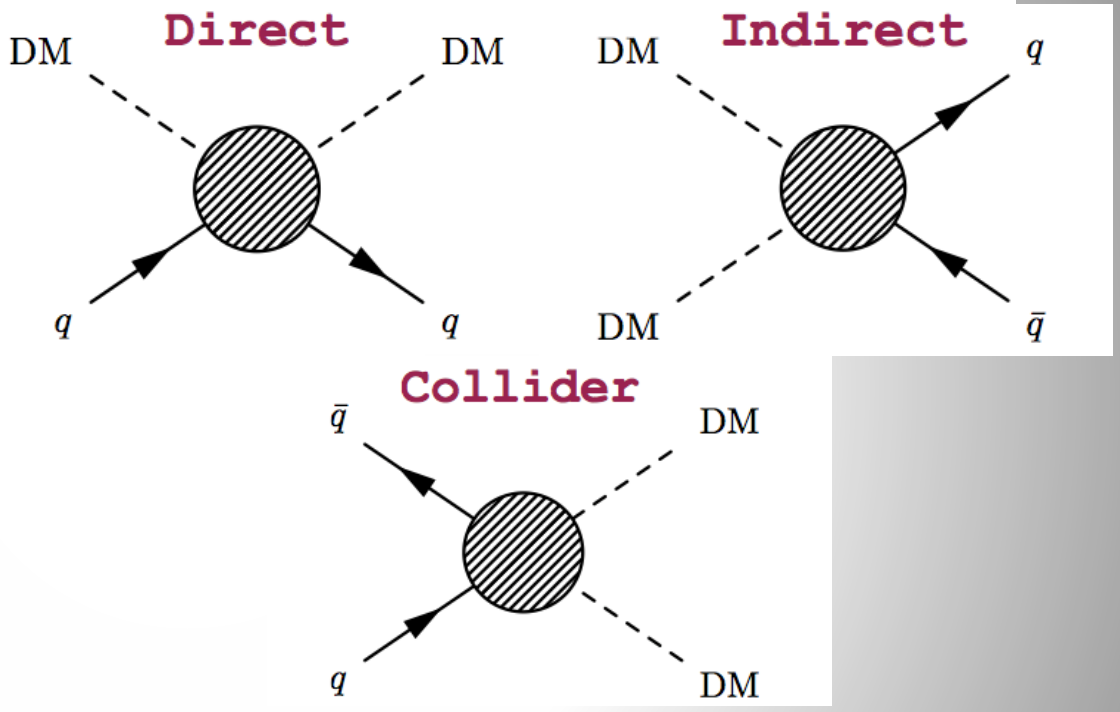
Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy

Also special searches for contrived model regions

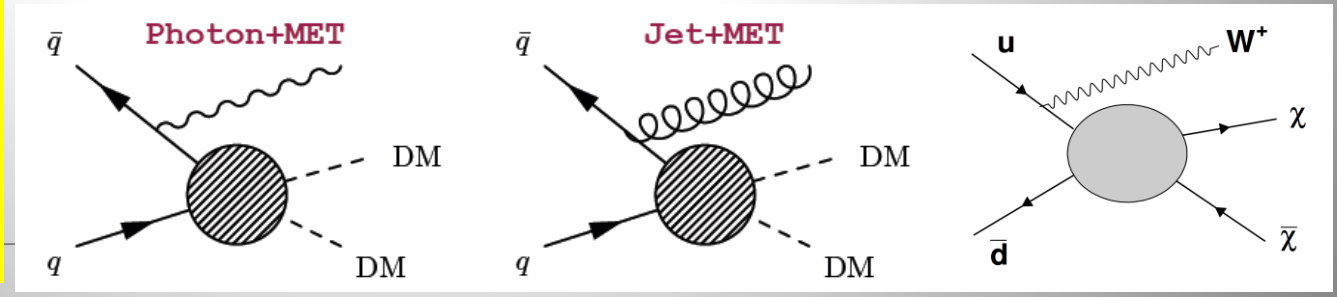
The Generic Dark Matter Connection

Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)





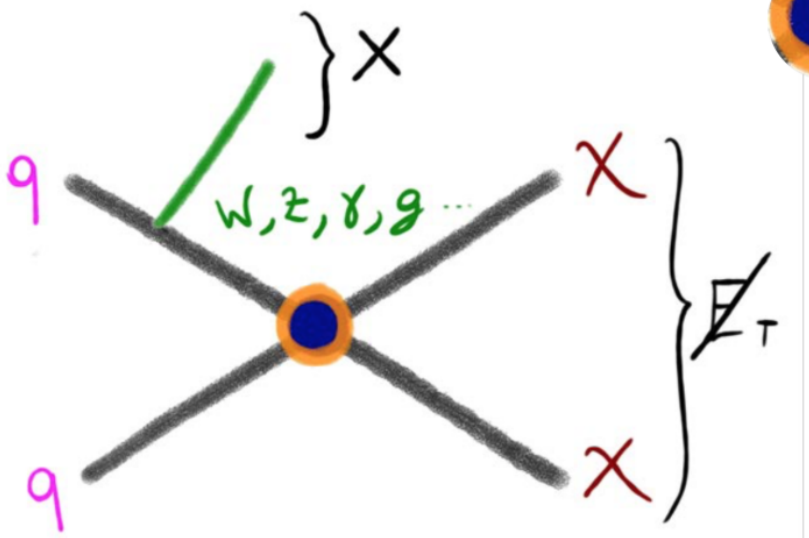
Use effective theory or simplified models to relate measurements to Dark Matter studies



Dark Matter at Colliders

Invisible DM particles **escape detection:**

LHC experiment strategy: tag events using **recoiling** object(s), measure **missing transverse momentum (Missing E_T)**



arxiv:1008.1783

= **EFT Operators** representing types of DM-SM interactions with DM particles

Advantages:

Limited number of degrees of freedom: scale of interaction (M* or Λ), DM mass

Disadvantages:

Only applicable at **low momentum transfer**

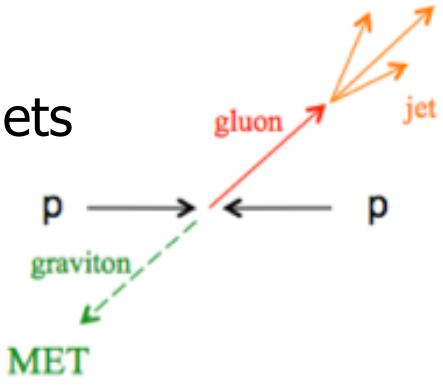
Searching at the LHC for WIMPs
Weakly Interacting Massiver Particles

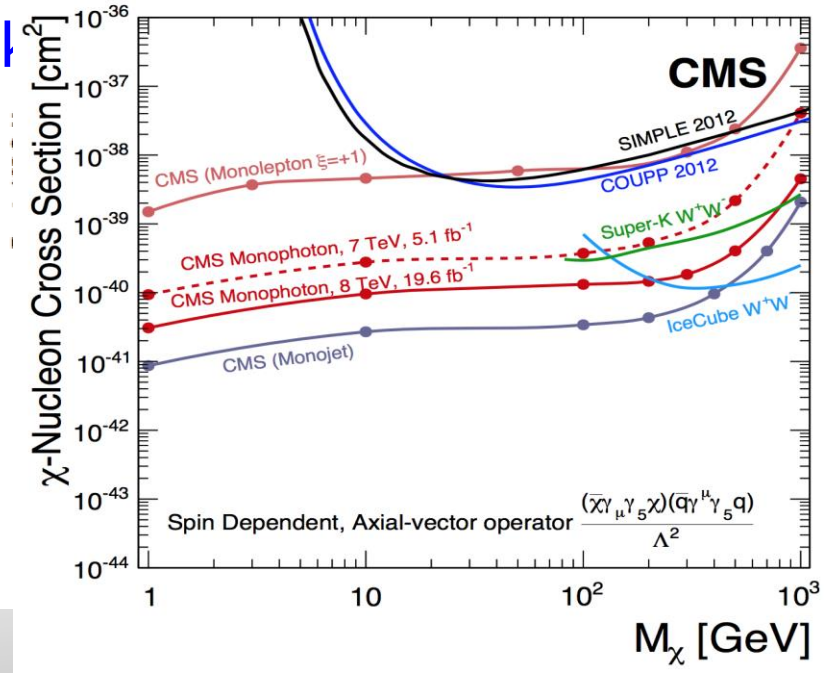
Mono-object Searches in CMS

- Mono-jets: Generally the most powerful
- Monophotons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs portal of dark

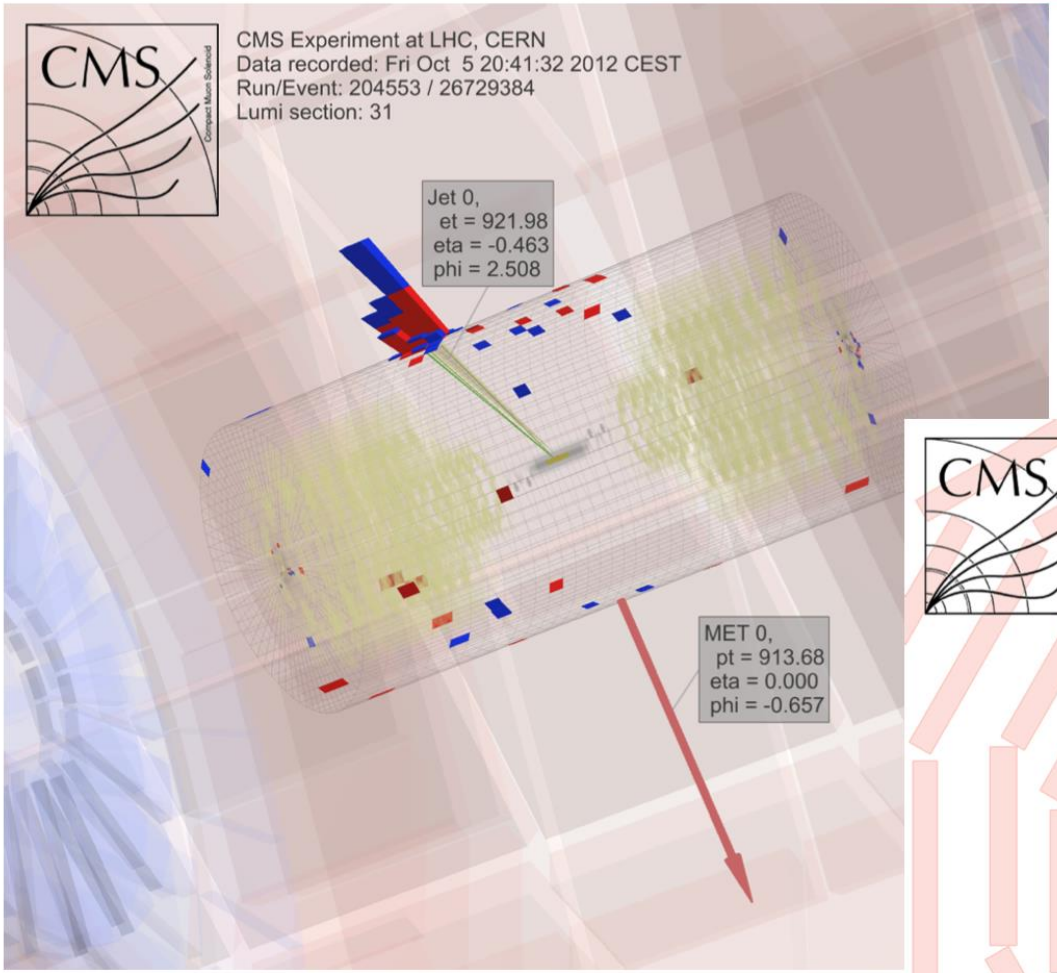
Effective Field Theories for DM interpretation are under scrutiny!
Alternatives such as SMS proposed…

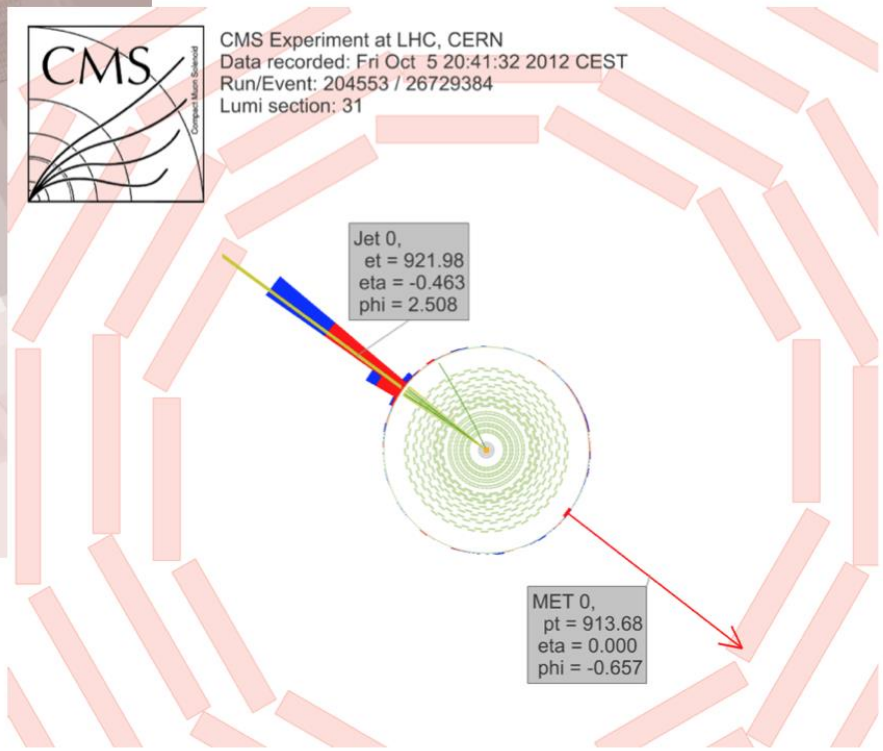
Example Monojets



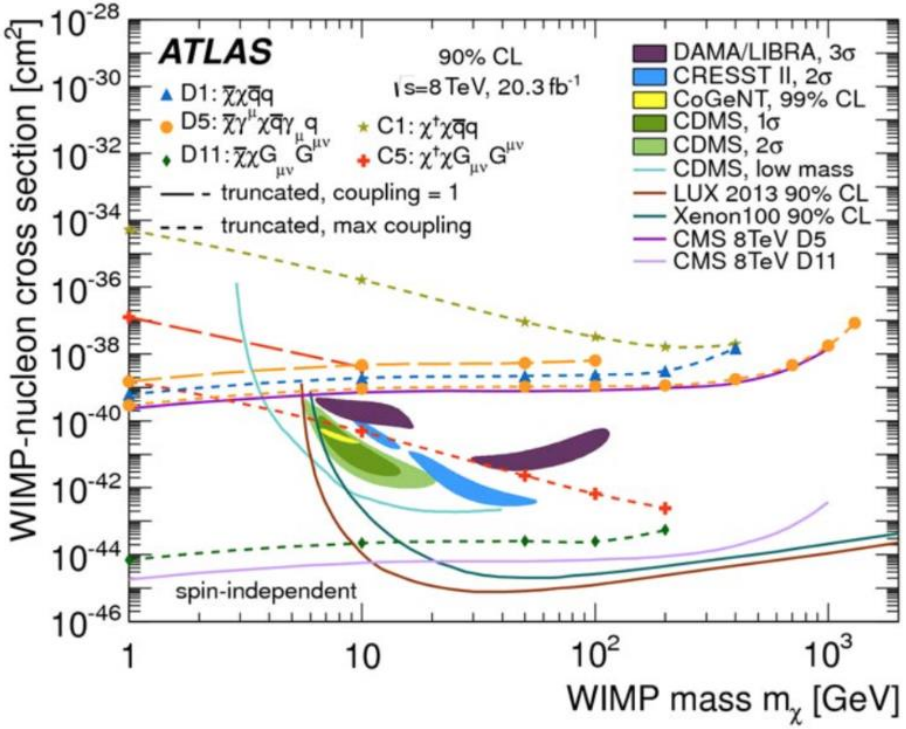


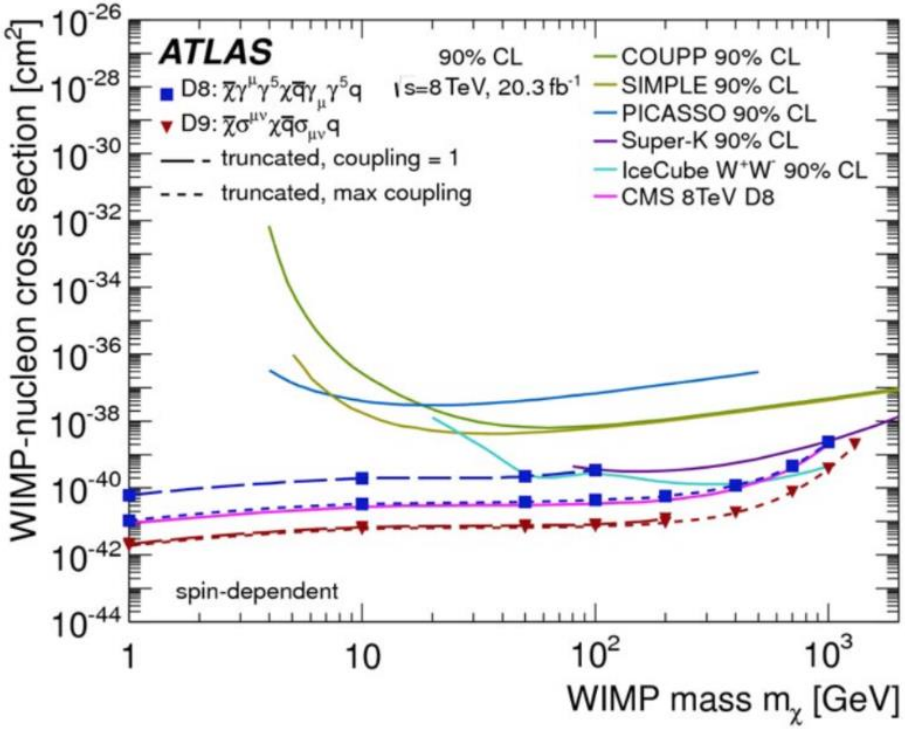
Mono-Jet Event





Mono-Jet Studies: Latest Results





Model-dependent comparison

Needs **agreement** on benchmarks and assumptions

→ e.g. **truncation** procedure to ensure **EFT validity**

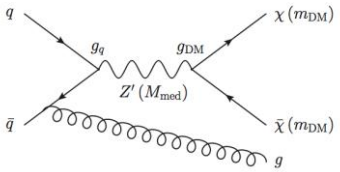
Complementarity of direct/indirect detection and colliders:

outlines strengths of each of the experiments

Mono-object Searches in CMS

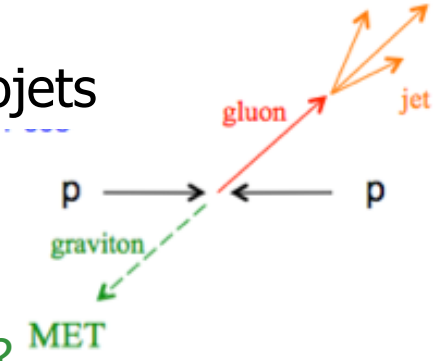
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Effective Field Theories for DM interpretation are under scrutiny!
Alternatives such as SMS proposed

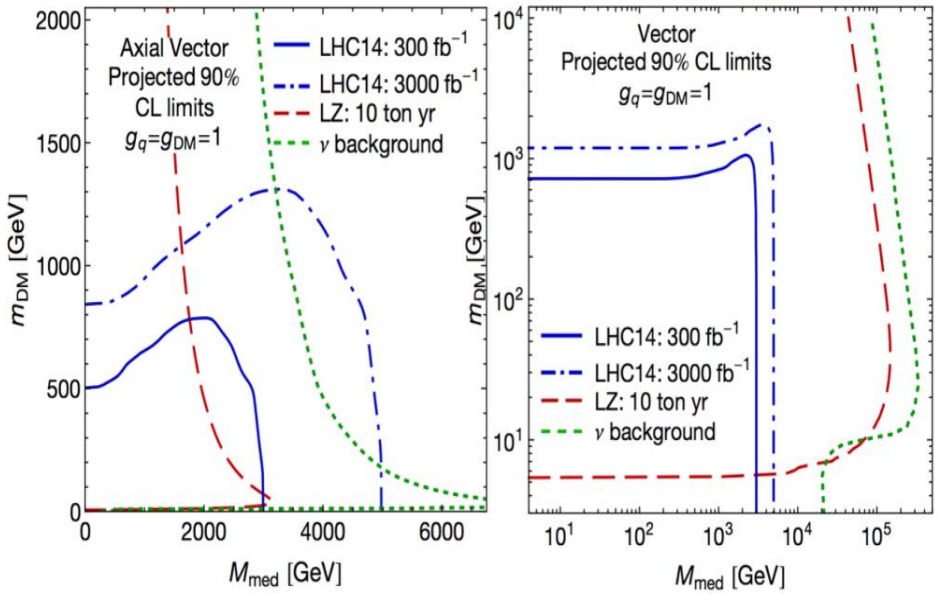


arXiv:1407.8257
arXiv:1411.0535

Example Monojets



Dark Matter?



New Questions…

Are there Extra Space Dimensions?

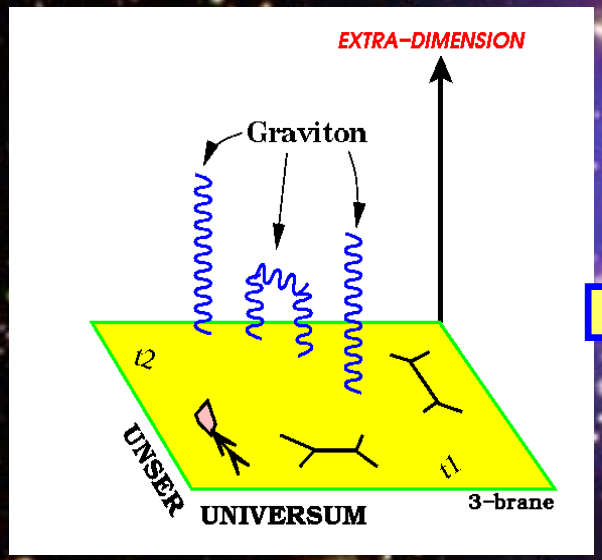
Or Micro Black Holes?

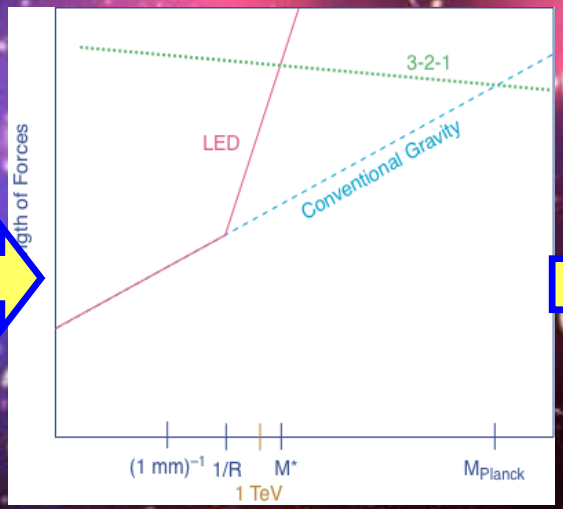
Extra Space Dimensions

Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\ \text{GeV}$$

$$M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}\ \text{GeV}$$



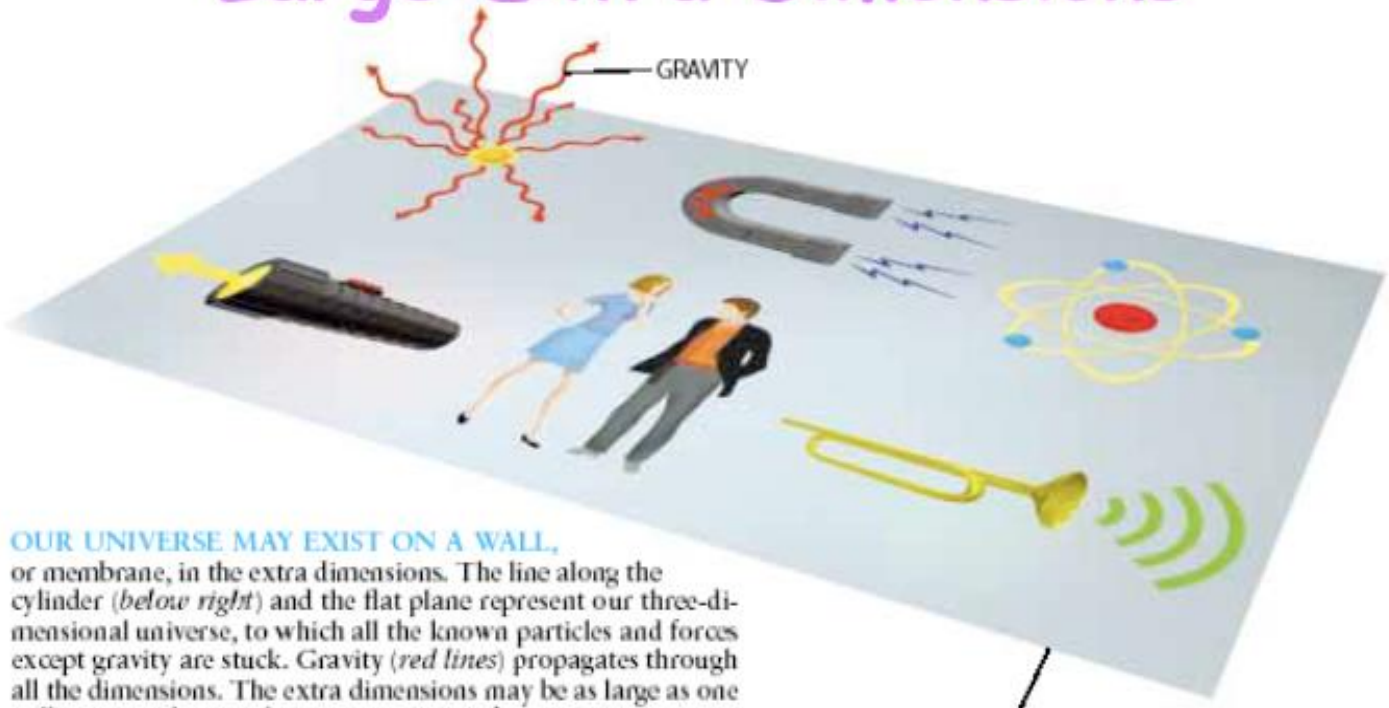


The Gravitational force becomes strong!

New Planck scale is larger than 3 TeV

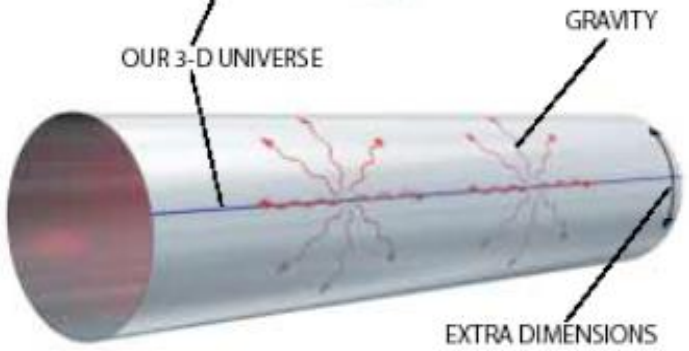
Large Extra Dimensions

Large Extra Dimensions



OUR UNIVERSE MAY EXIST ON A WALL, or membrane, in the extra dimensions. The line along the cylinder (*below right*) and the flat plane represent our three-dimensional universe, to which all the known particles and forces except gravity are stuck. Gravity (*red lines*) propagates through all the dimensions. The extra dimensions may be as large as one millimeter without violating any existing observations.

Model of Arkani-Hamed, Dvali, Dimopoulos: Standard Model particles are localized on a 3-D brane. Gravity propagates inside the bulk (a more dimensional space)

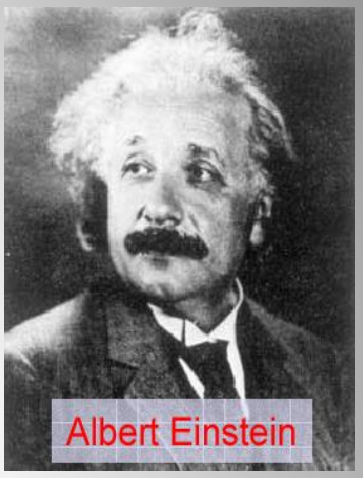


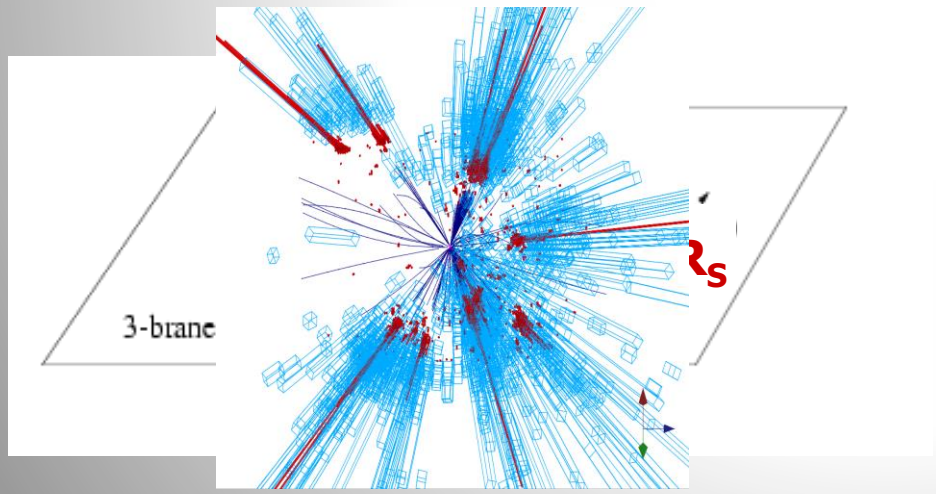
Quantum Black Holes at the LHC?

Black Holes are a direct prediction of Einstein's general theory on relativity

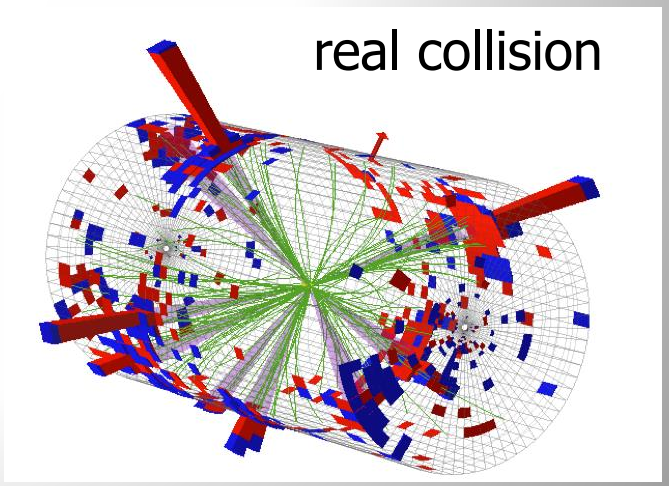
If the Planck scale is in ~TeV region:
can expect Quantum Black Hole production

Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds $\Rightarrow$ SAFE!





Simulation of a Quantum Black Hole event

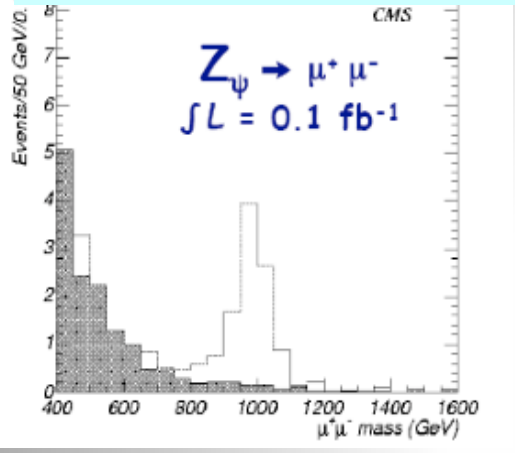


Black holes with mass below 6 TeV are excluded

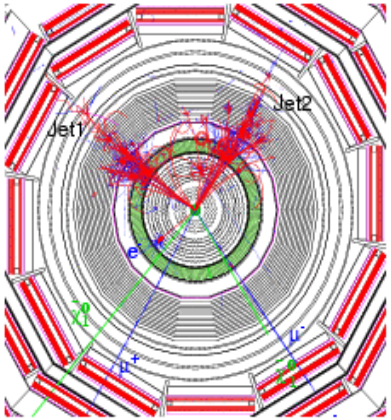

Black Holes
Hunters
at the LHC…

New Physics?

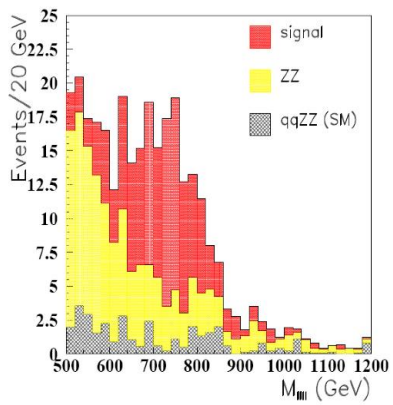
New Gauge Bosons?



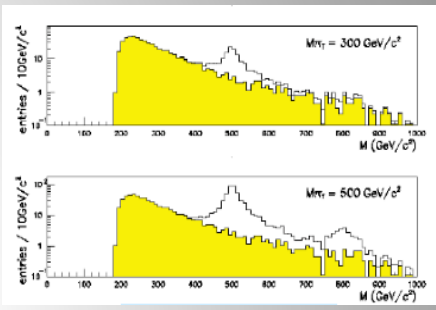
Supersymmetry



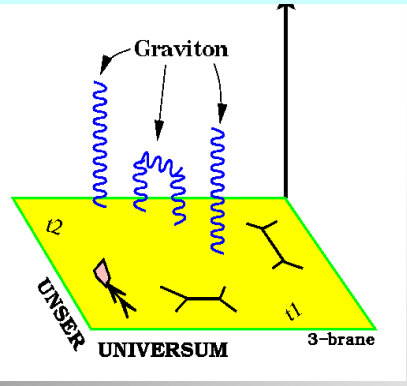
ZZ/WW resonances?



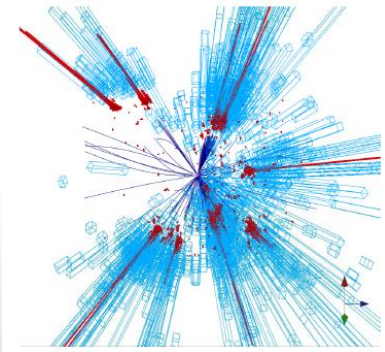
Technicolor?



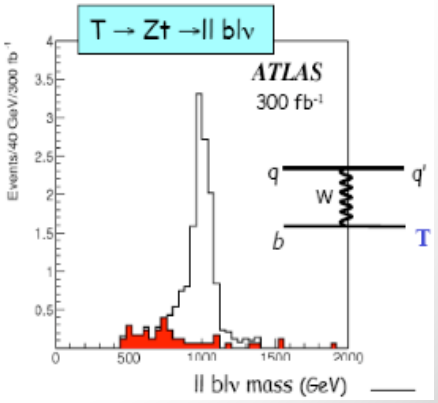
Extra Dimensions?



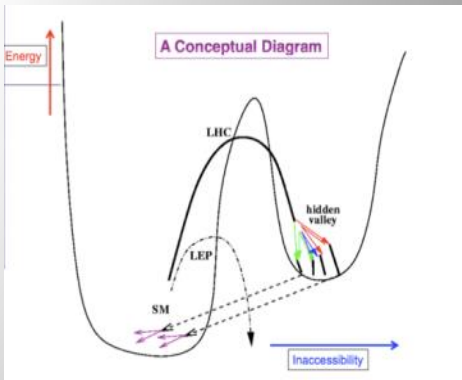
Black Holes???



Little Higgs?



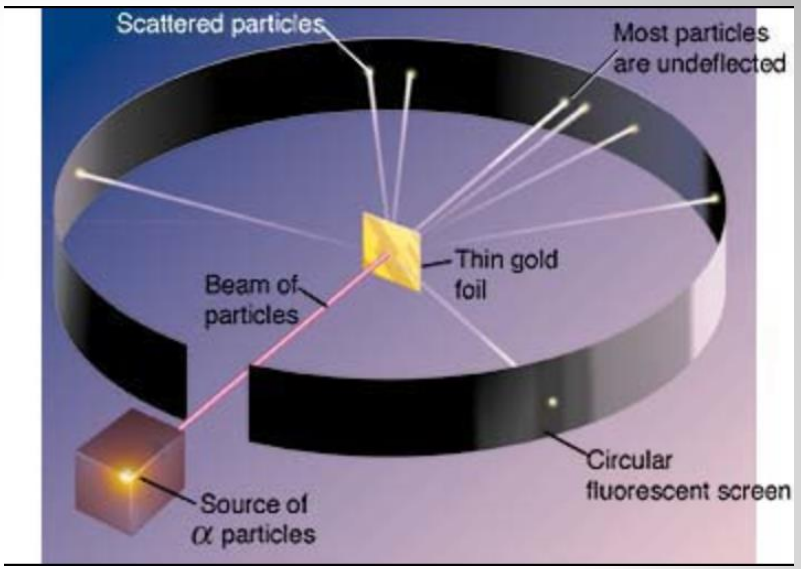
Hidden Valleys?



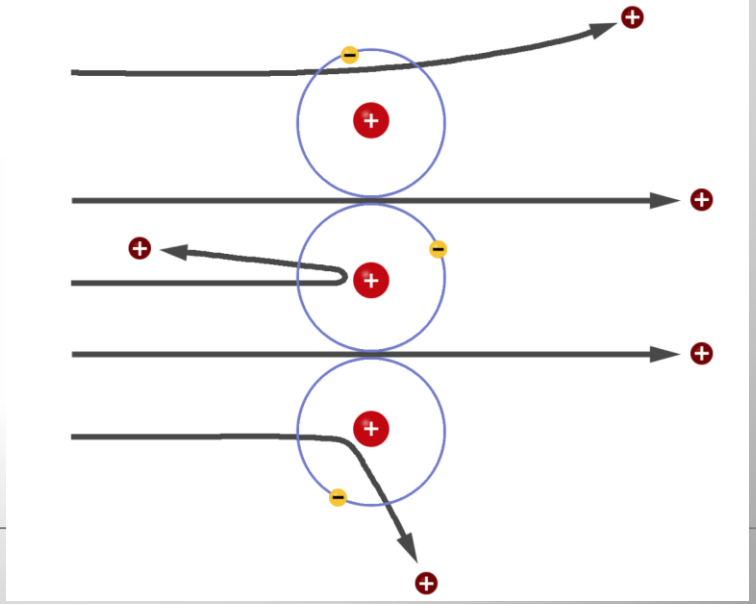
What stabelizes the Higgs Mass? Many ideas, not all viable any more

A large variety of possible signals. We have to be ready for that

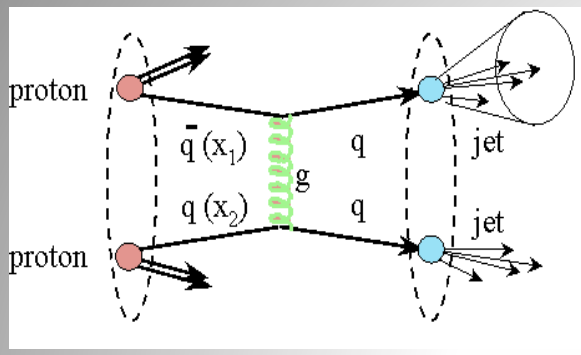
Are Quarks Elementary Particles?

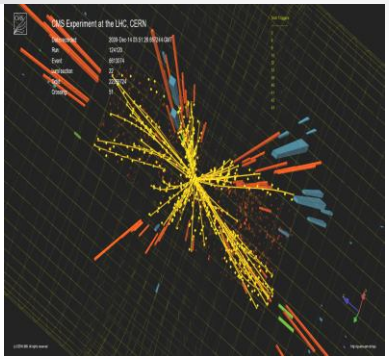


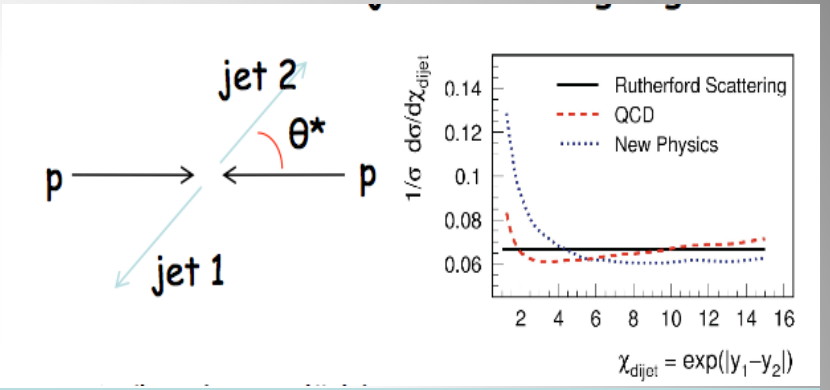
Rutherford experiment:
Unexpected backscattering of α-particles:
Evidence for the structure of atoms !! (1911)

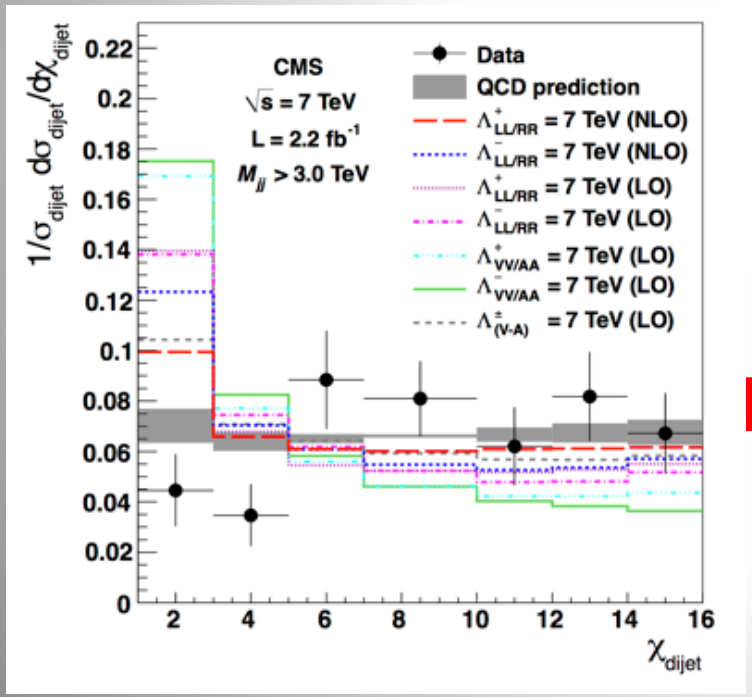


Are Quarks Elementary Particles?

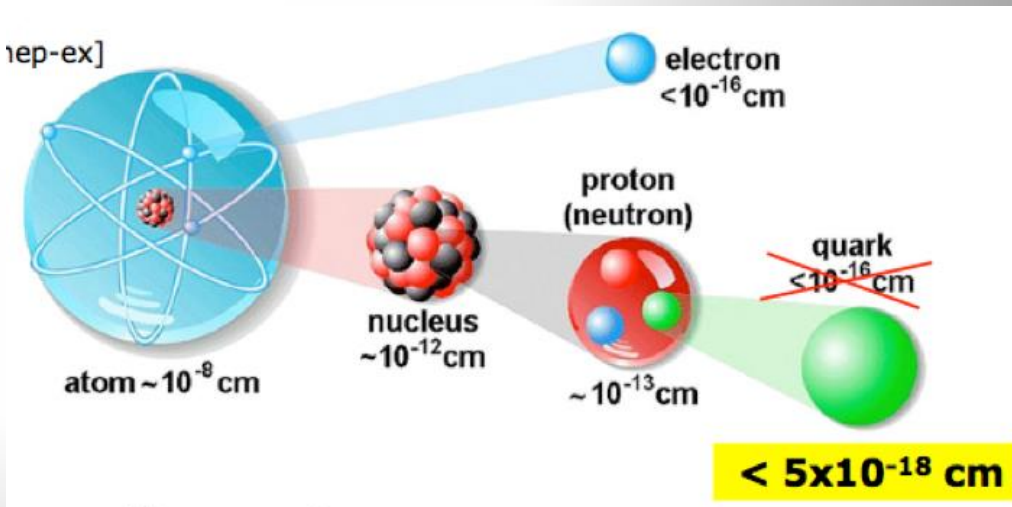






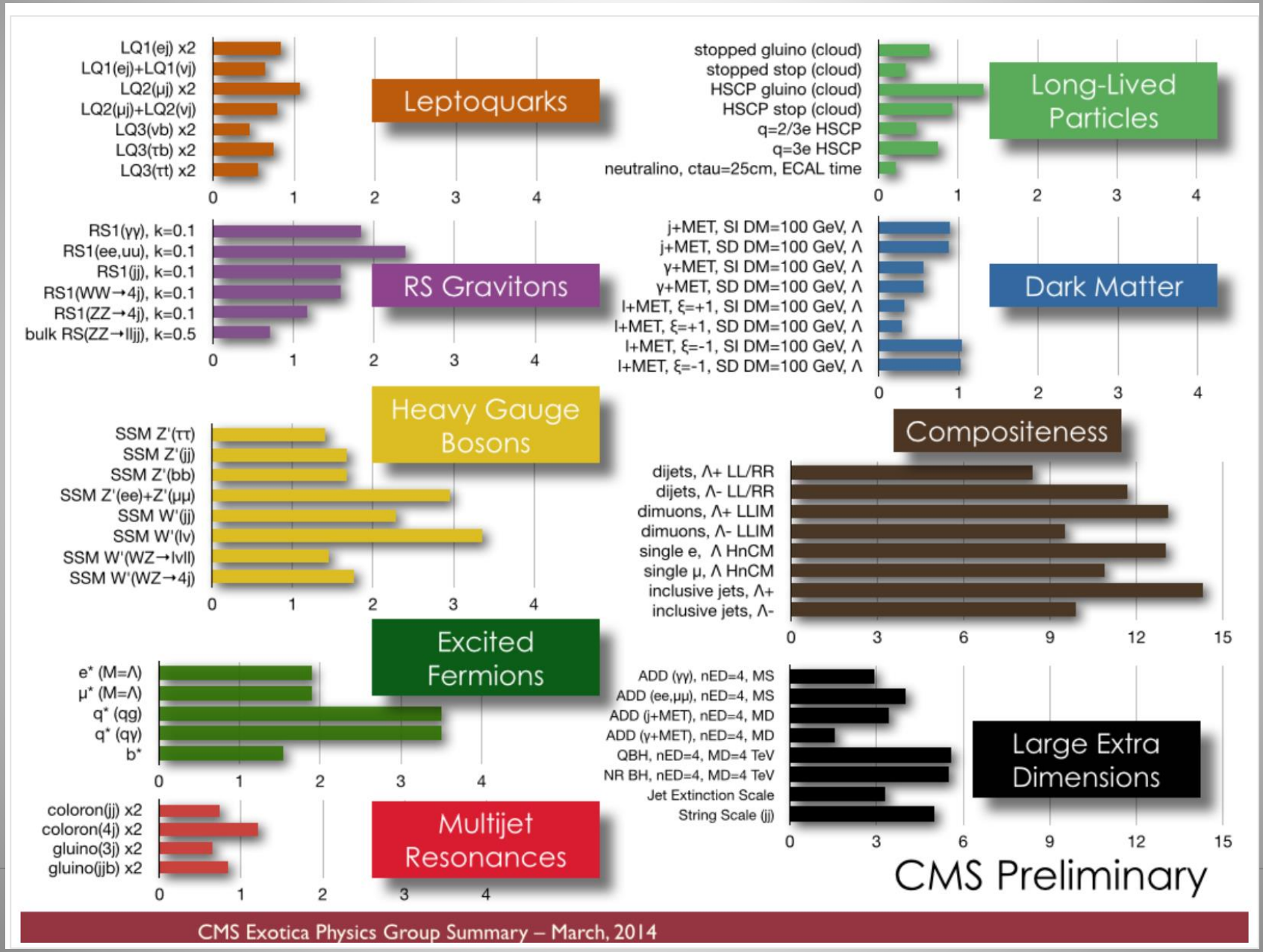


Measurement of the production angle of the jet with respect to the beam
-> High Energy Rutherford Experiment



Quarks remain elementary particles after these first results

Summary of Searches for Exotica



The Physics Program at LHC

Data taking started in 2010

Now we have more than 300 reviewed scientific papers per experiment!

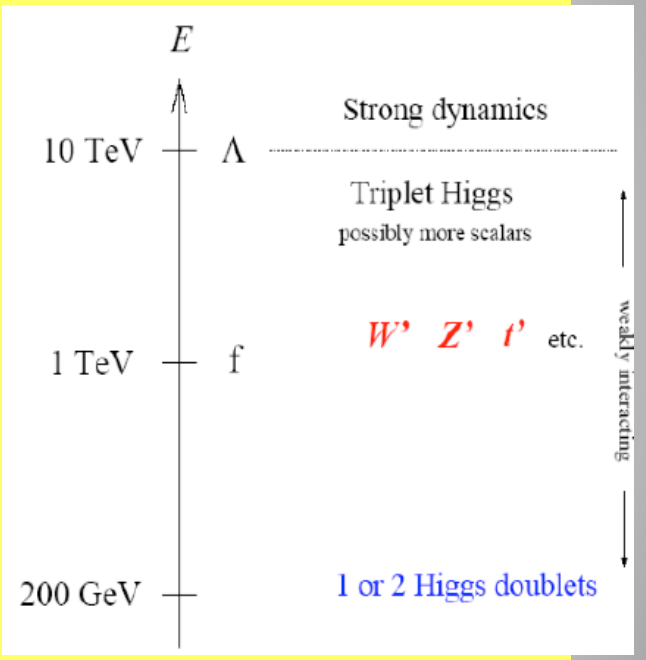
Mostly measurements of the strong and electroweak force at 7/8 TeV and Searches

-Are quarks the elementary particles?	So far yes
-Do we see supersymmetric particles?	Not yet
-Do we see extra space dimensions?	Not Yet
-Do we see micro-black holes?	No

->The Discovery of a Higgs-like particle!!

Many Other New Physics Ideas…

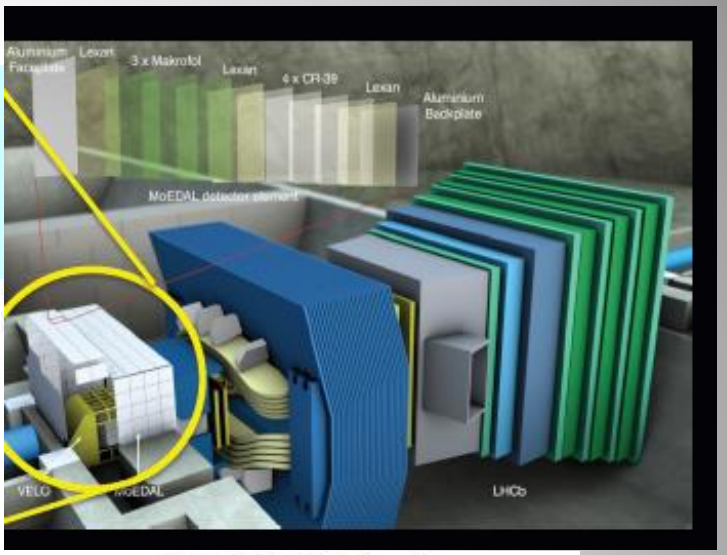
- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - leptoquarks
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Unparticles
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more….

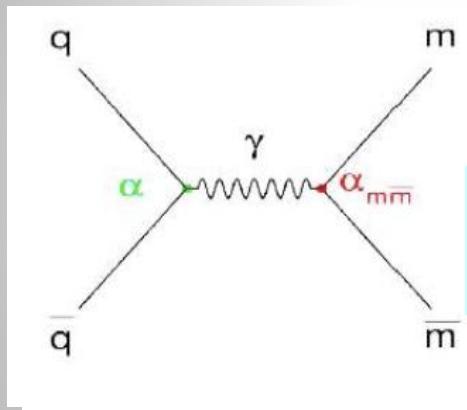


Have to keep our eyes open for all possibilities:
Food for many PhD theses!! And Discoveries!!!

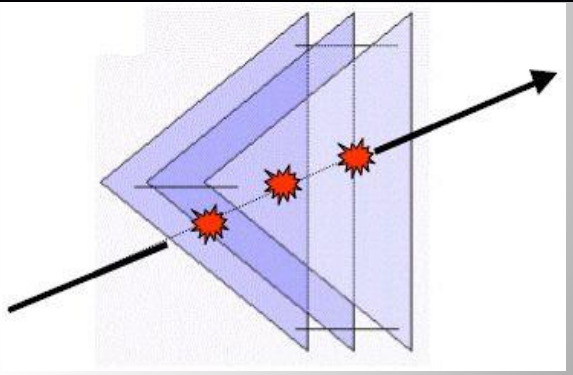
MoEDAL: Monopole and Exotics Detector at the LHC

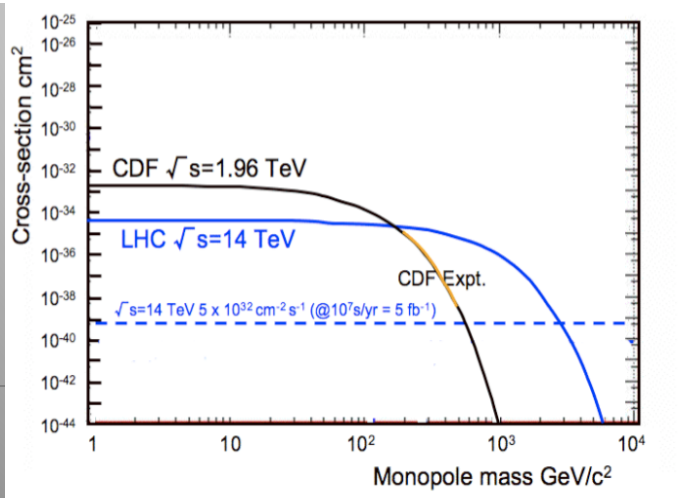
Heavy particles which carry “magnetic charge”
Could eg explain why particles have “integer electric charge”





Direct Monopole production



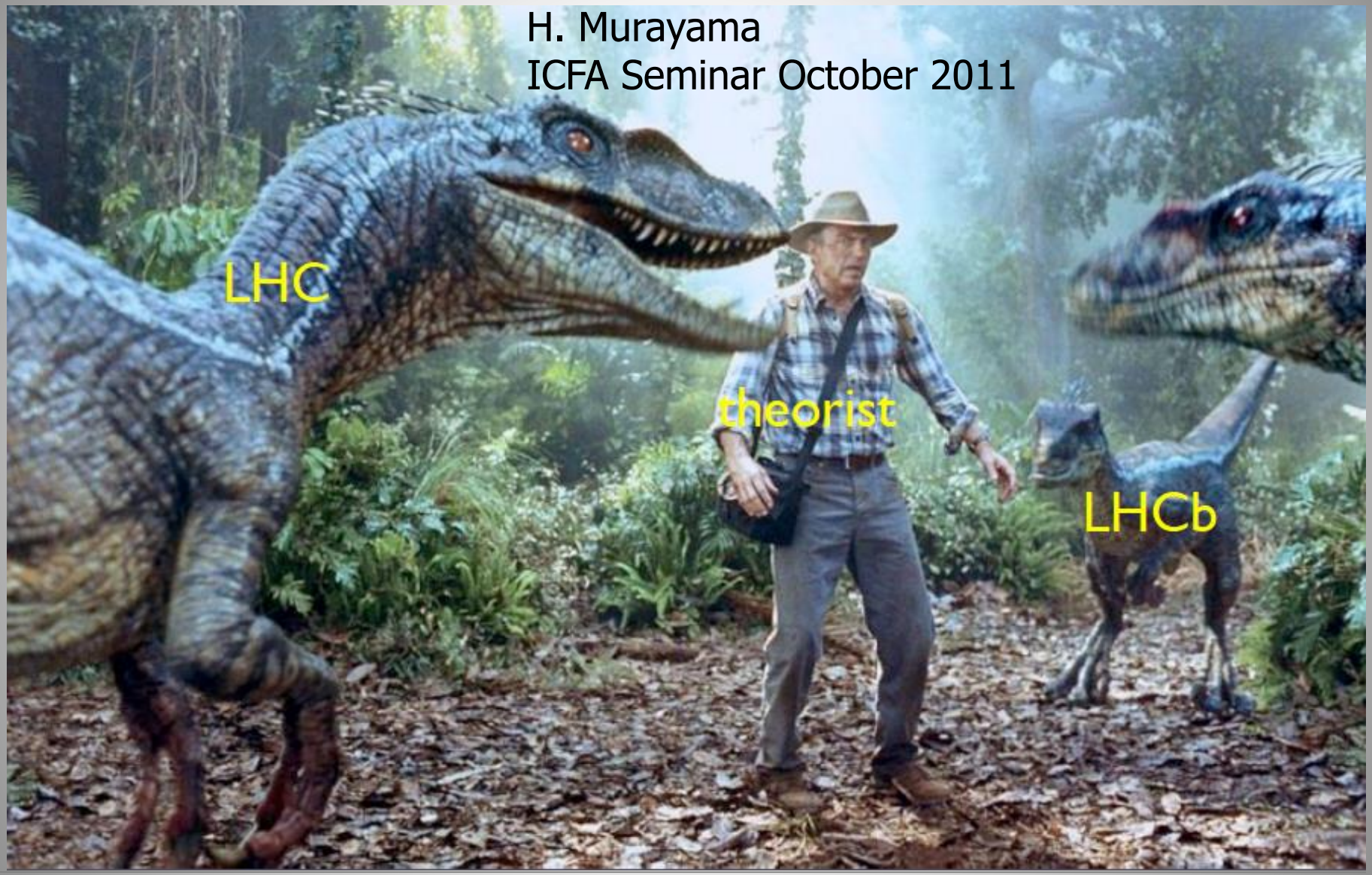


Remove the sheets after some running time and inspect for ‘holes’

LHC data and Theorists

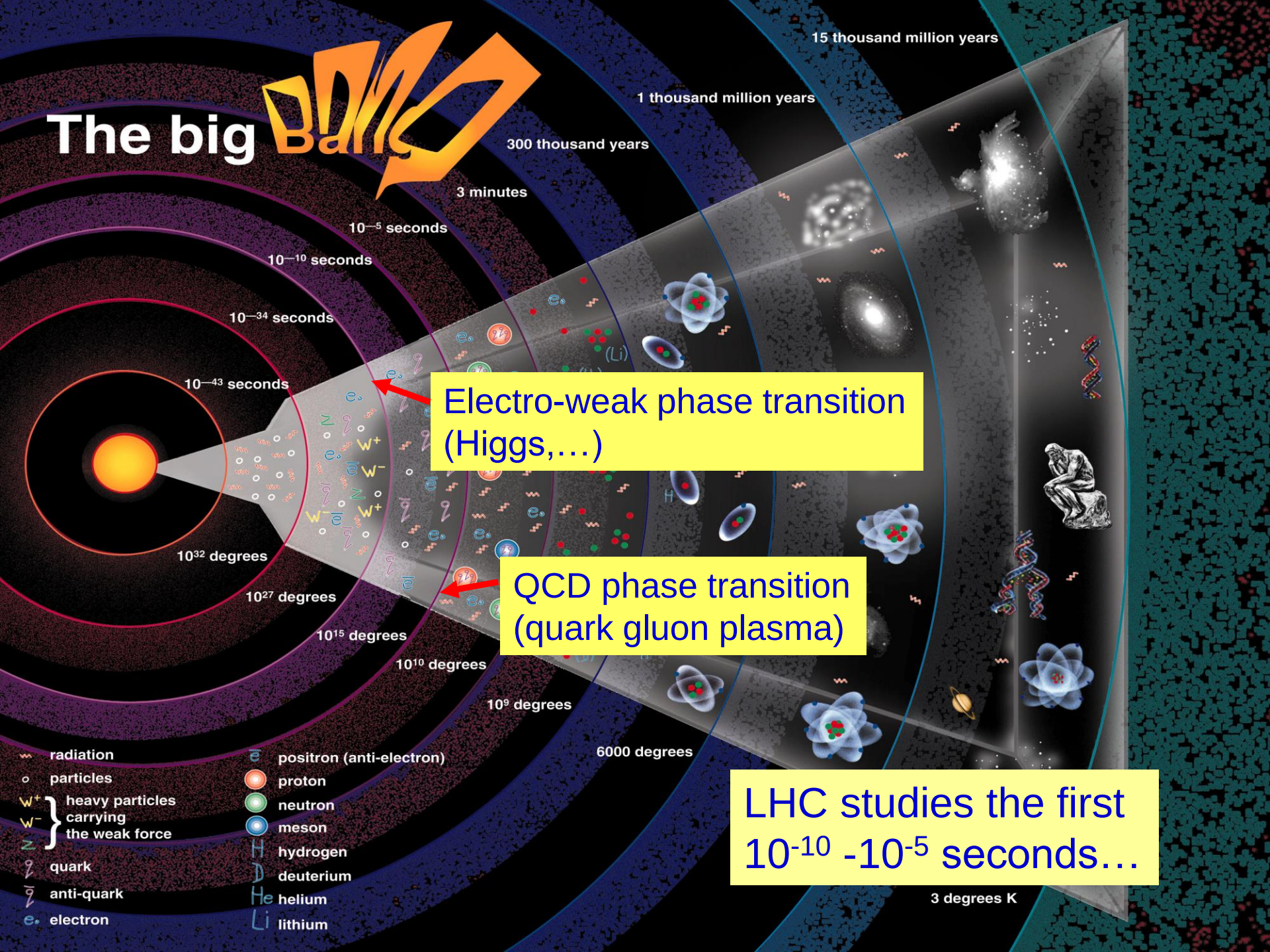
"Data are coming! Data are coming!"

How does it feel to be a (BSM) Theorist?



Summary: The Searches at the LHC!

- The LHC has entered a new territory. The ATLAS and CMS experiments are heavily engaged in searches for new physics. The most popular example is SUSY, but many other New Physics model searches are covered.
- No sign of new physics yet in the first 20 fb^{-1} at 8 TeV with the analyses reported in this lecture.. This starts to cut into the 'preferred regions' for a large number of models
- More exotic channels are now being covered: monopoles, fractional or multiple charged particles, long lived particles… Still many unexplored channels left to explore
- The LHC did its part so far with a great run in 2
  Collected about 20 fb^{-1}@ 8 TeV by end of 2012
- In 2015 the energy will be 13/14 TeV, excellent
- And maybe one day soon:


The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
3 degrees K
Electro-weak phase transition (Higgs,…)
QCD phase transition (quark gluon plasma)
LHC studies the first 10-10 -10-5 seconds…
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Matter-Antimatter

The properties and subtle differences of matter and anti-matter using mesons containing the beauty quark, will be studied further in the LHCb experiment