CERN and the Large Hadron Collider
The Big Bang Machine

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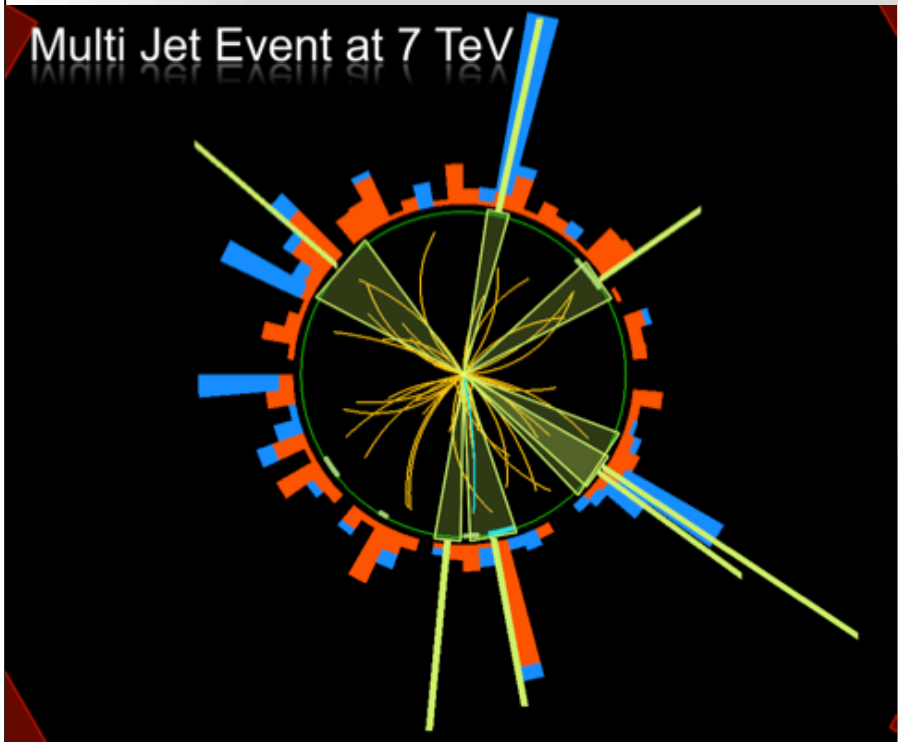
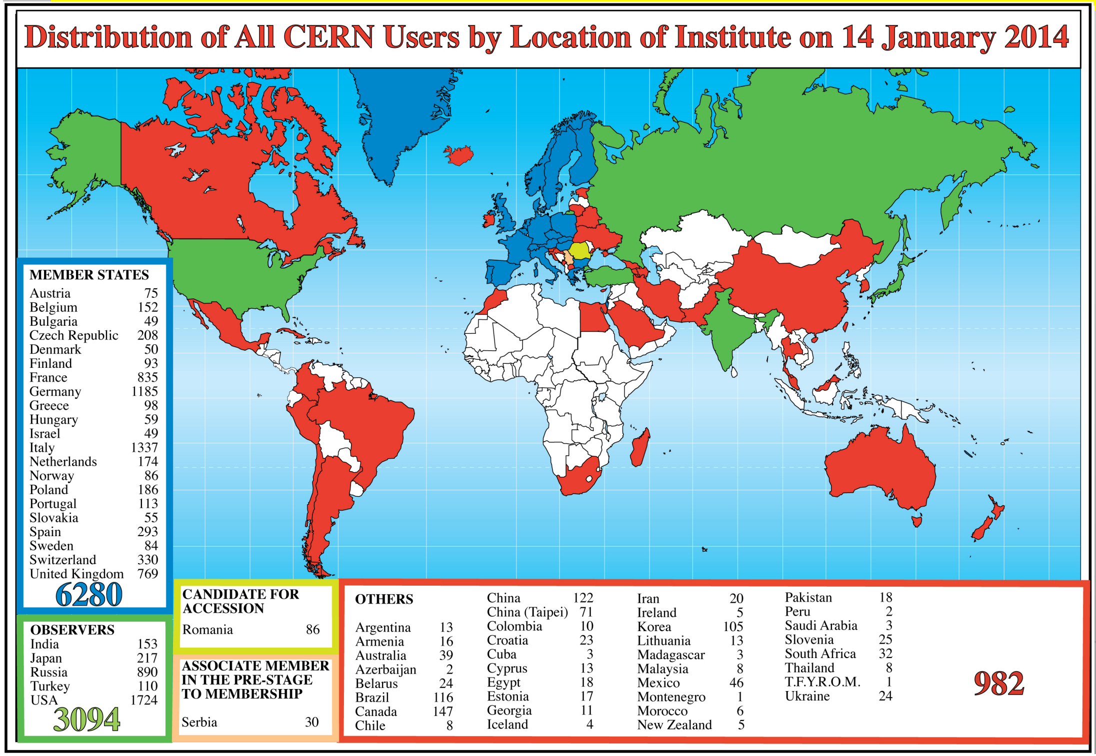


Outline

- Introduction
- The Physics program of the Large Hadron Collider
- Higgs Discovery
- Dark Matter & supersymmetry?
- Extra space dimensions?
- Matter versus anti-matter?
- Summary

CERN: The European Laboratory for Particle Physics

- CERN is the European Organization for Nuclear Research, the world's largest Particle Physics Centre, near Geneva, Switzerland
- It is now commonly referred to as European Laboratory for Particle Physics
- It was founded in 1954 and has 21 member states + several observer states.
- CERN employes ~4000 people + hosts ~11000 visitors from >500 universities.
- Annual budget ~ 1000 MCHF/year (2014)



Where the World Wide Web was born...


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

Accelerators are Powerful Microscopes

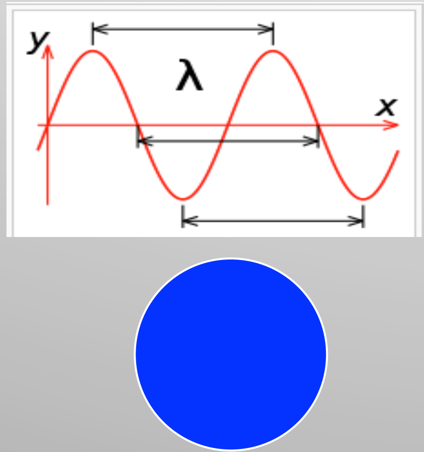
They make high energy particle beams that allow us to see small things.

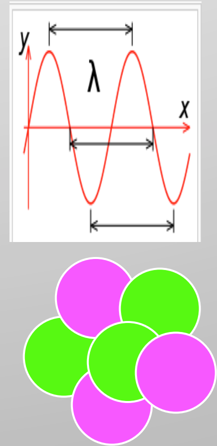
$$\lambda = \frac{h}{p}$$

Planck constant

wavelength

momentum ~ energy





seen by low energy beam of particles (poorer resolution)

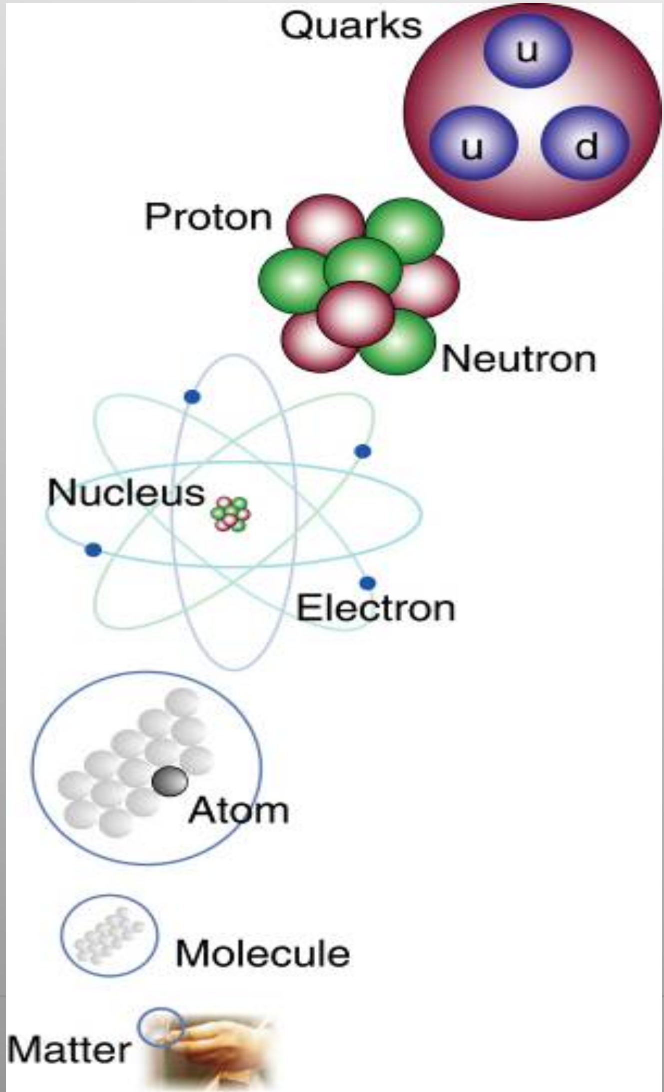
seen by high energy beam of particles (better resolution)

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?

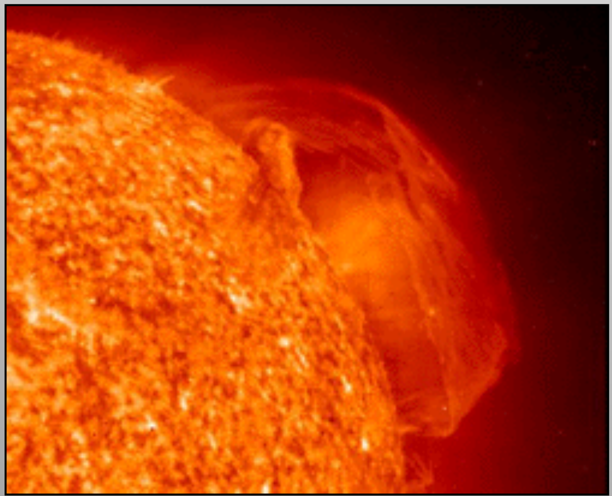
The Large Hadron Collider will address this question!

The Fundamental Forces of Nature

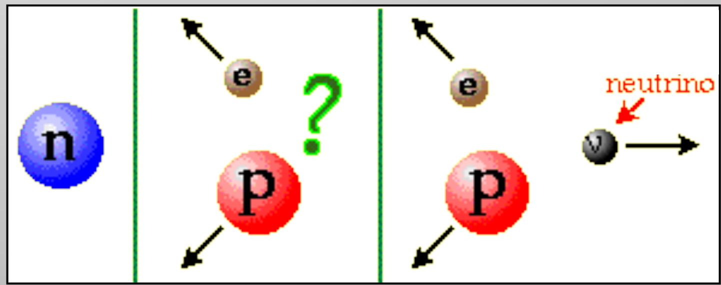
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity



together they make the Sun shine



Gravity: holds planets and stars together

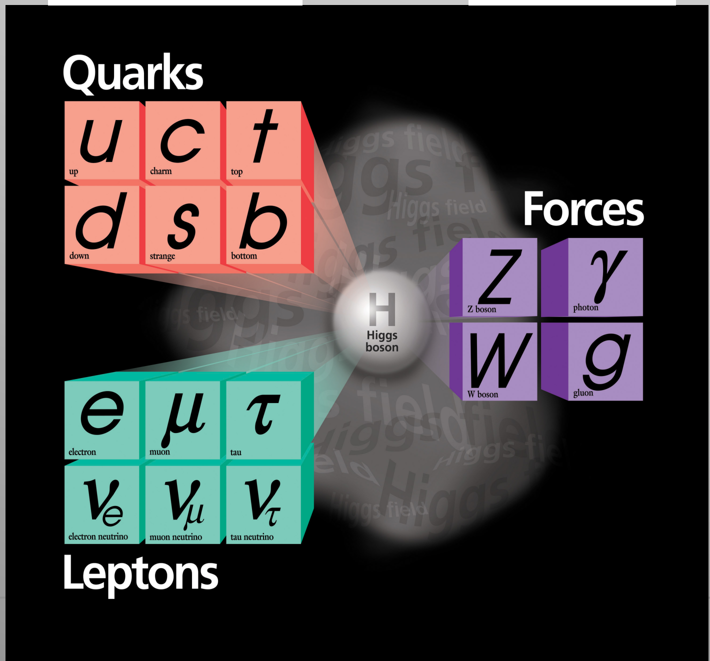
The “Standard Model”

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?

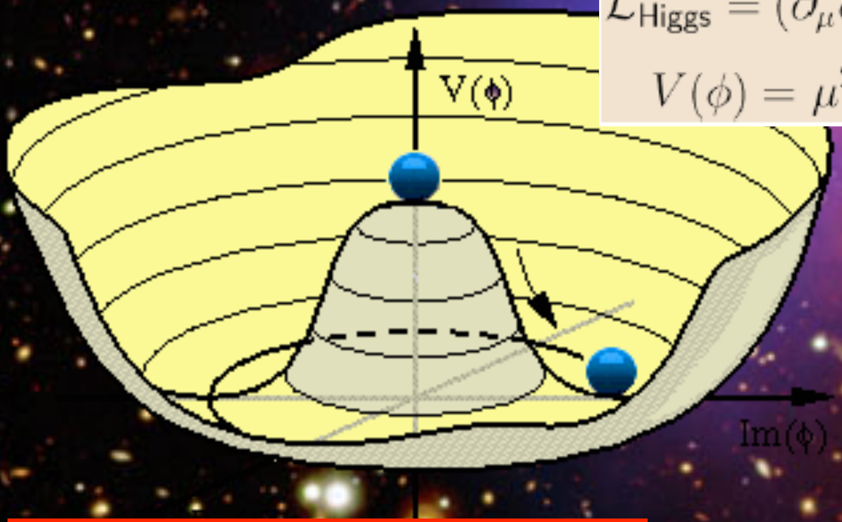
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

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

We do not know the mass of the Higgs Boson

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

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



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!!

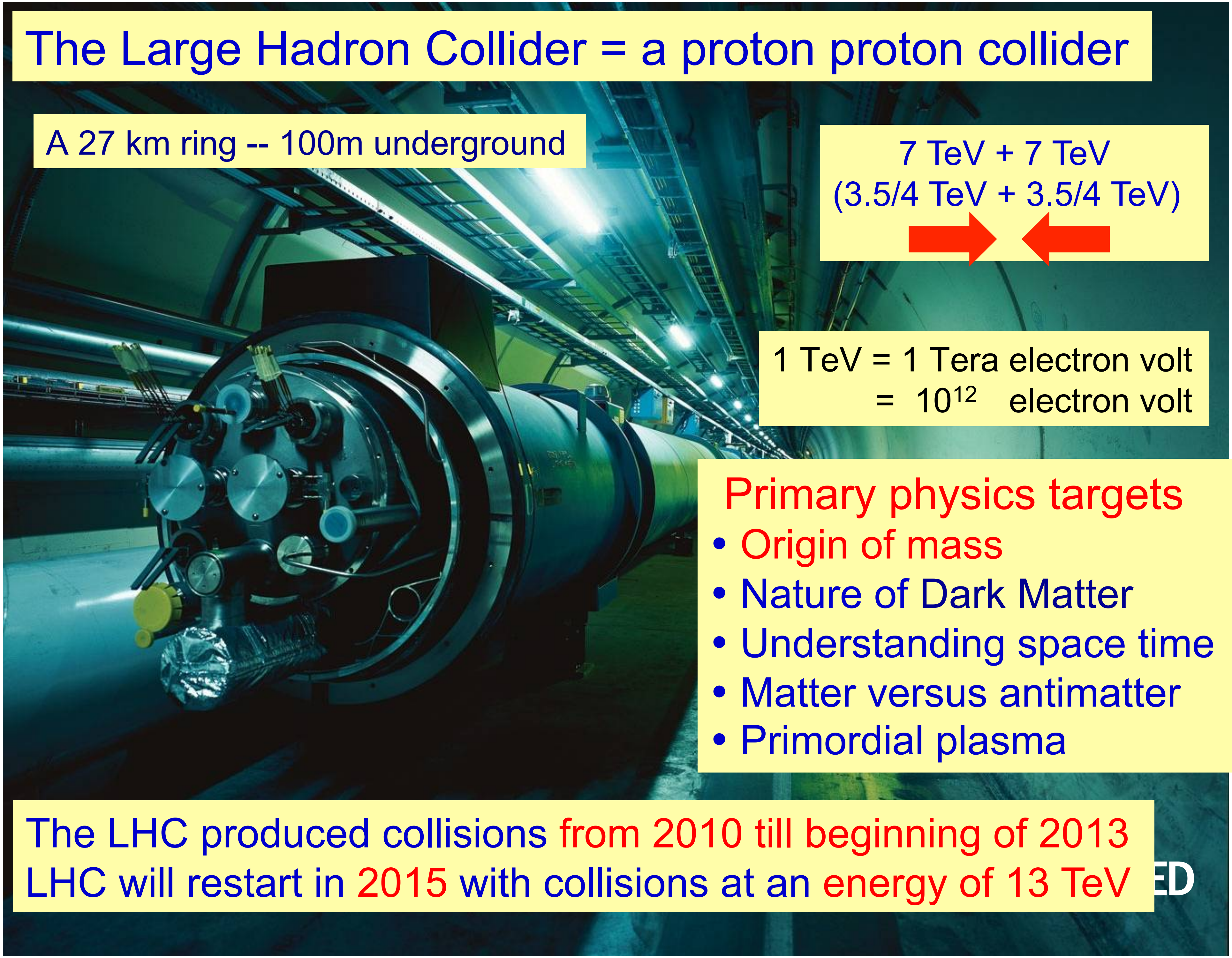
This Search Requires…….

1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".



The Large Hadron Collider = a proton proton collider
A 27 km ring -- 100m underground
7 TeV + 7 TeV
(3.5/4 TeV + 3.5/4 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 produced collisions from 2010 till beginning of 2013
LHC will restart in 2015 with collisions at an energy of 13 TeV

The LHC is an Extraordinary Machine

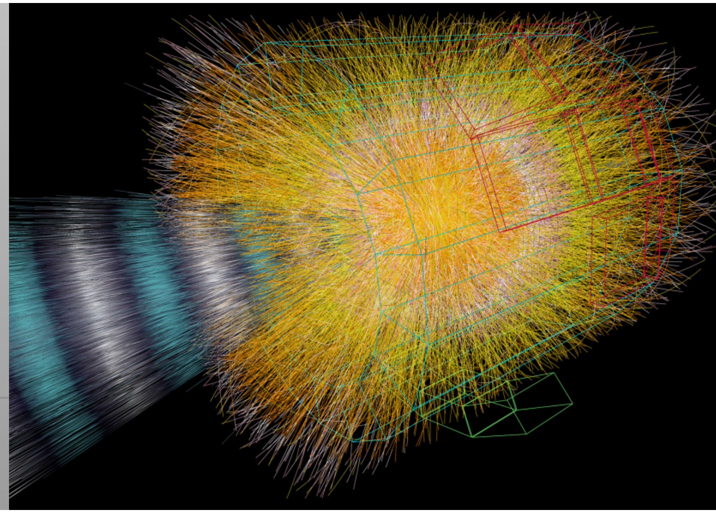
LHC facts

The LHC is …

Colder than the empty space in the Universe: 1.9K ie above absolute zero

The emptiest place in our solar system. The vacuum is better than on the moon

Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun



Experiments at the LHC

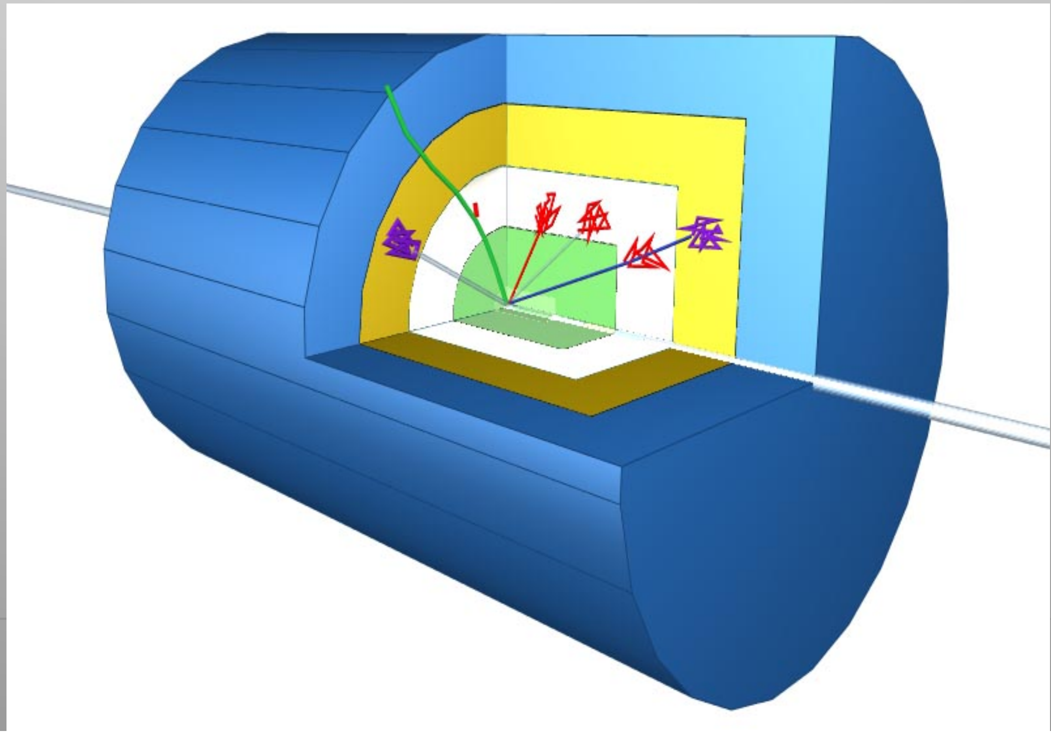
Schematic of a LHC Detector

Physics requirements drive the design!

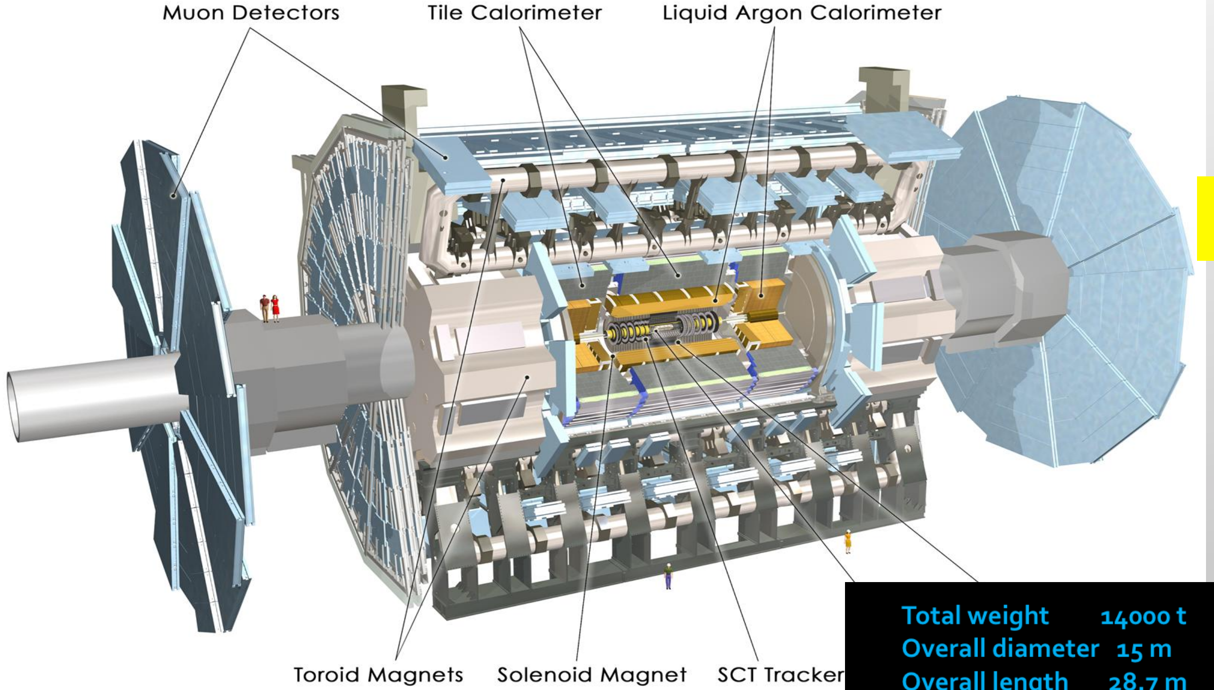
Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

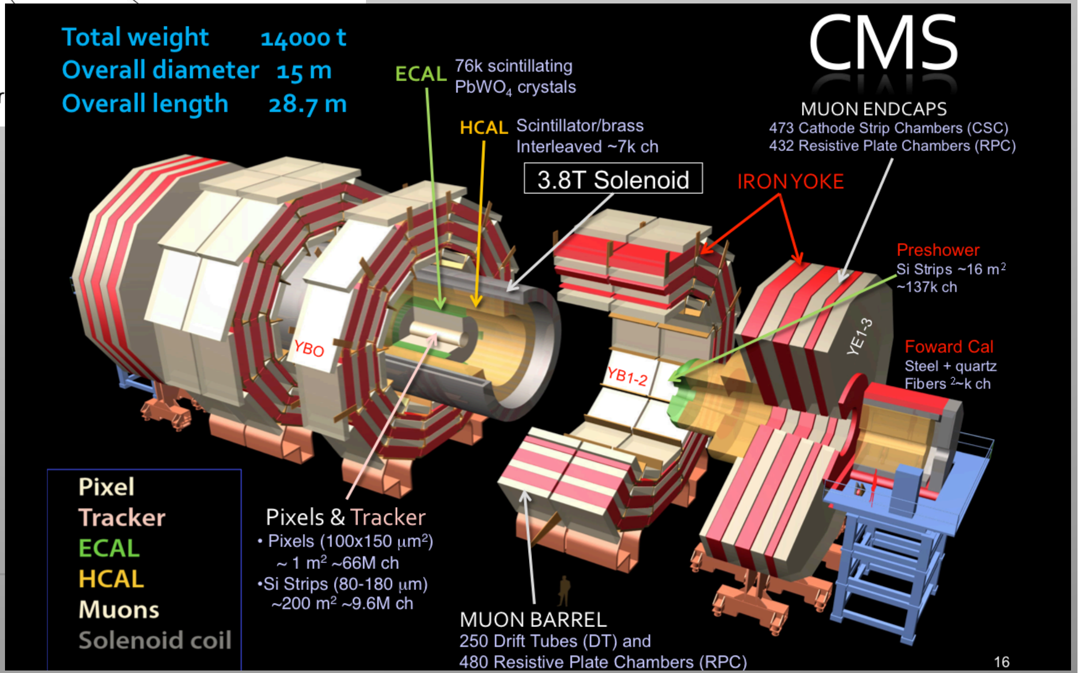
Such an experiment has ~ 100 Million read-out channels!!



The Higgs Hunters @ the LHC



The ATLAS experiment

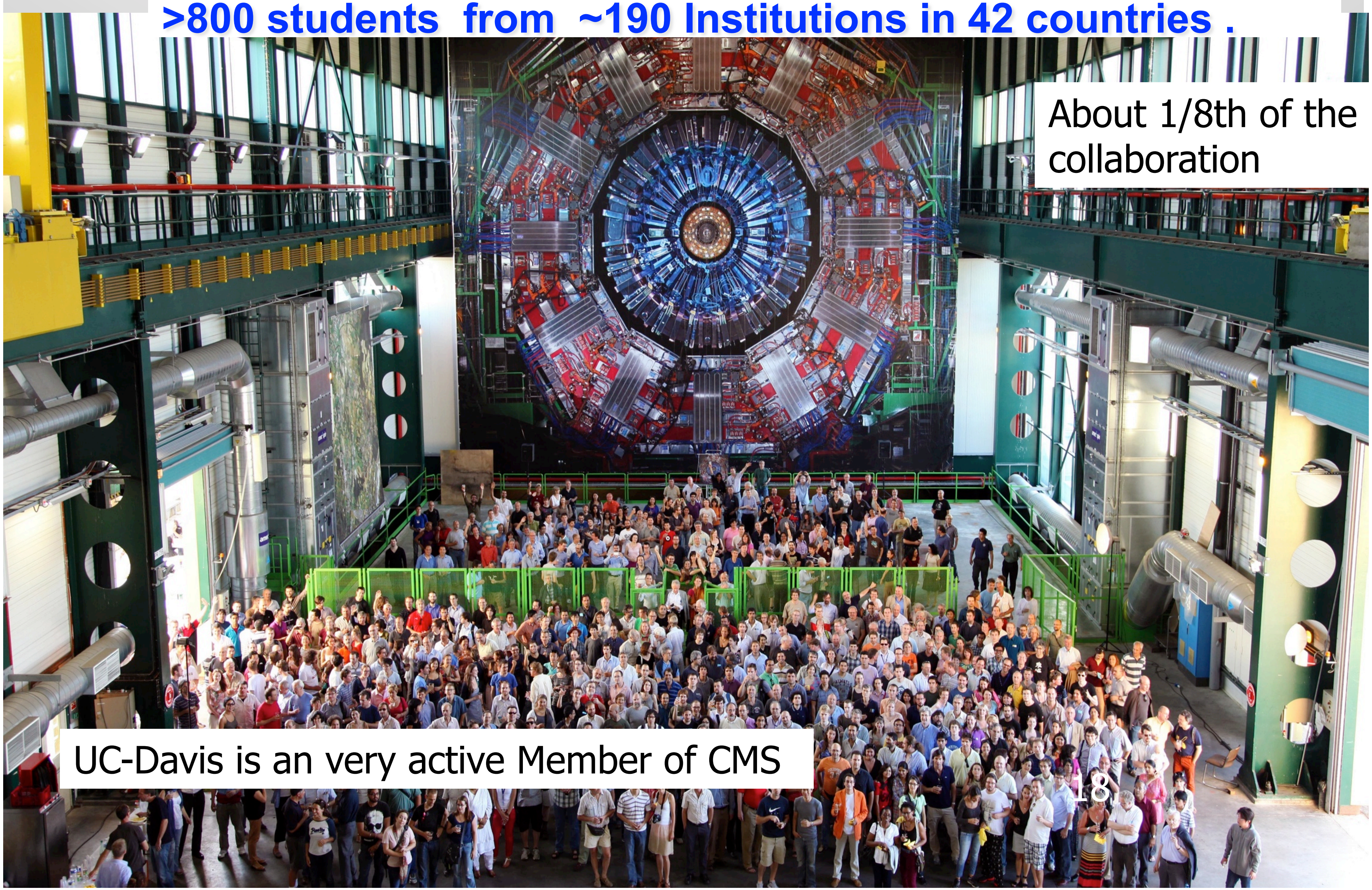


The CMS experiment

These experiments use different technologies for their detector components

CMS Collaboration June 27, 2012

The CMS Collaboration: >3200 scientists and engineers, >800 students from ~190 Institutions in 42 countries .



About 1/8th of the collaboration

UC-Davis is an very active Member of CMS


CMS before closure
HE-RBX 03
HE-RBX 02
HE-RBX 01
ME-1/1/06
ME-1/1/05
ME-1/1/04
ME-1/1/03
ME-1/1/02
ME-1/1/01
ME-1/1/36
ME-1/1/35
LIFTLUX

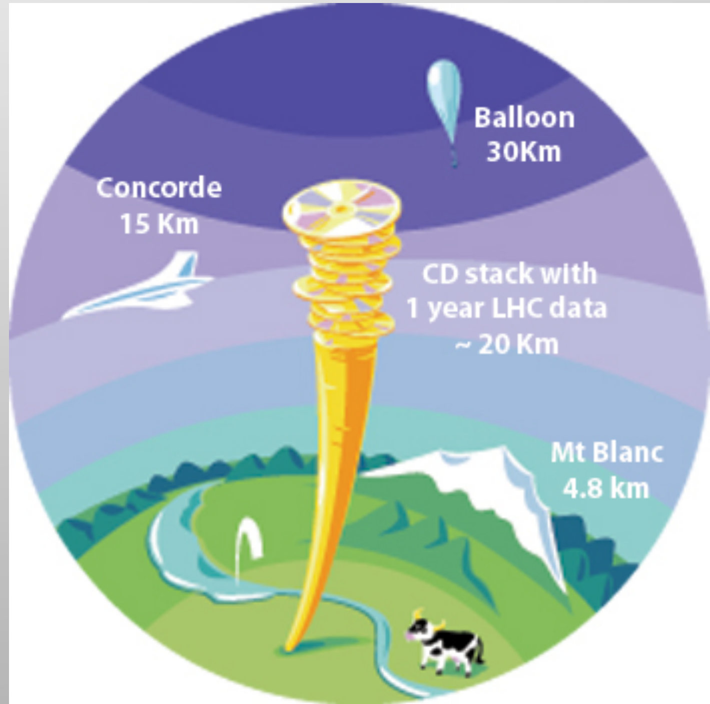
The LHC Data Challenges

Experiments were anticipated to produce about **15 Million Gigabytes** of data each year (~20 million CDs!)

The total volume in eg ATLAS is 5 billion detector events and several billion Monte Carlo events amounting to 100 Million Gigabytes of data in 3 years

LHC data analysis requires a computing power equivalent to **~100,000 of today's fastest PC processors**

=> Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity



GRID Computing

The Science Questions…

The Higgs Particle

Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem

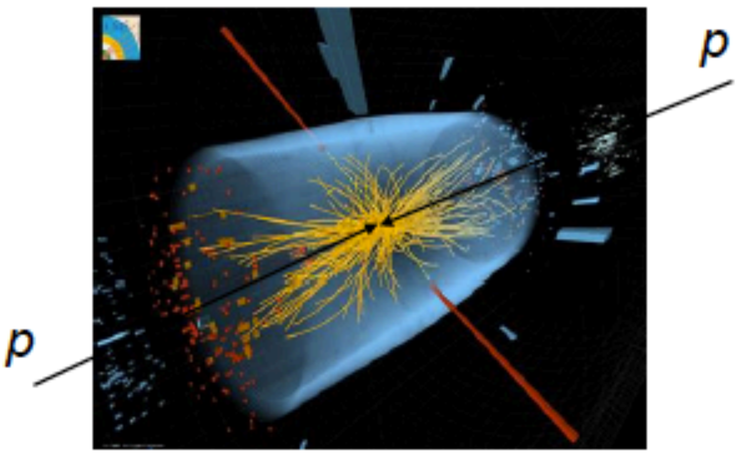
- need high energy:

  $E = mc^2$

- need lots of data

non-deterministic and very rare

order 1 in 10^{10}



* for us finding the Higgs it was 48 years = 1,513,728,000 sec

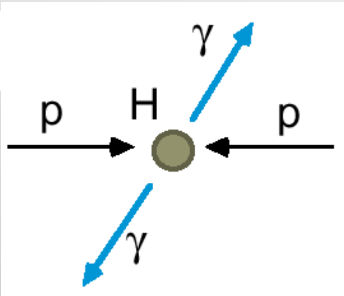
Higgs Boson Searches (simulation)

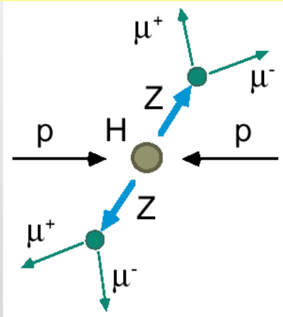
Low M_H < 140 GeV/c²

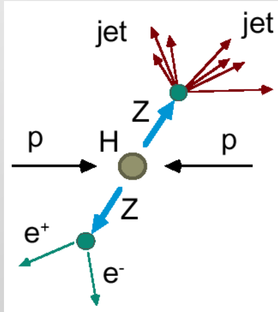
Medium 130<M_H<500 GeV/c²

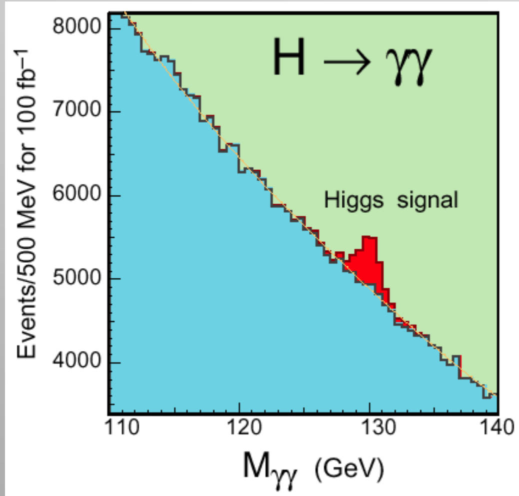
High M_H > 500 GeV/c²

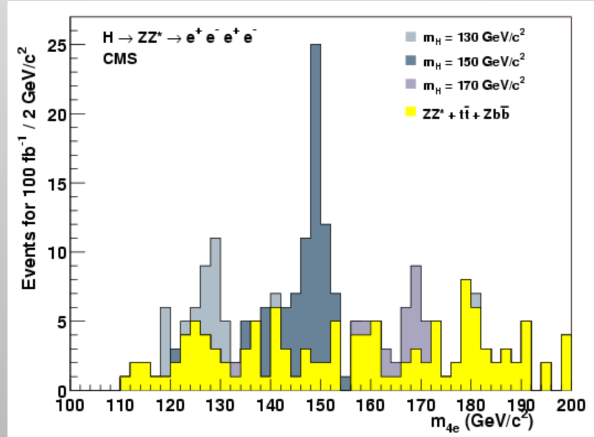
simulation

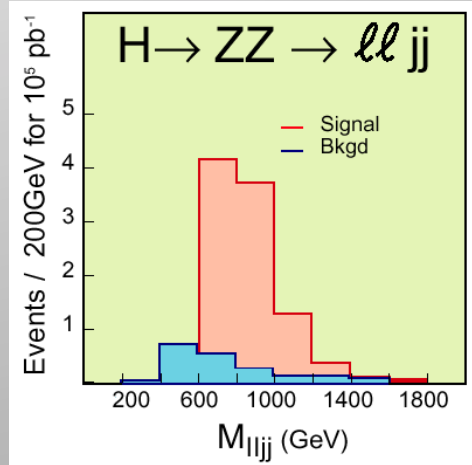


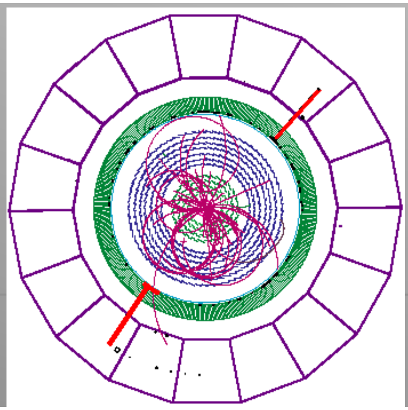


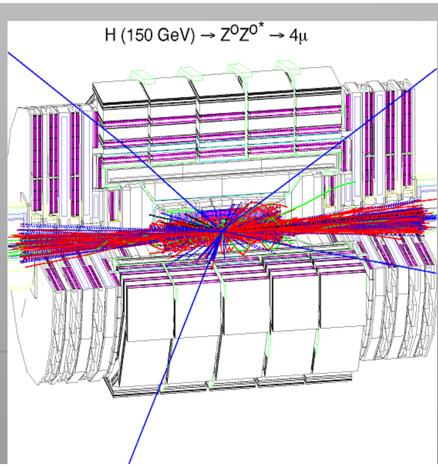


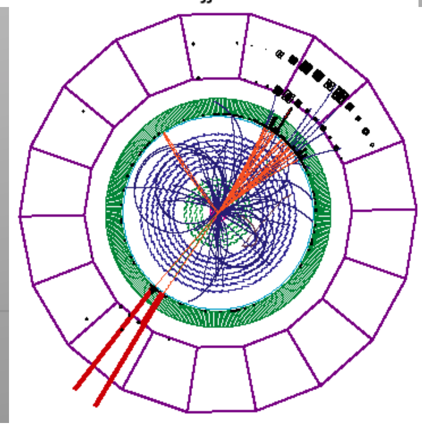




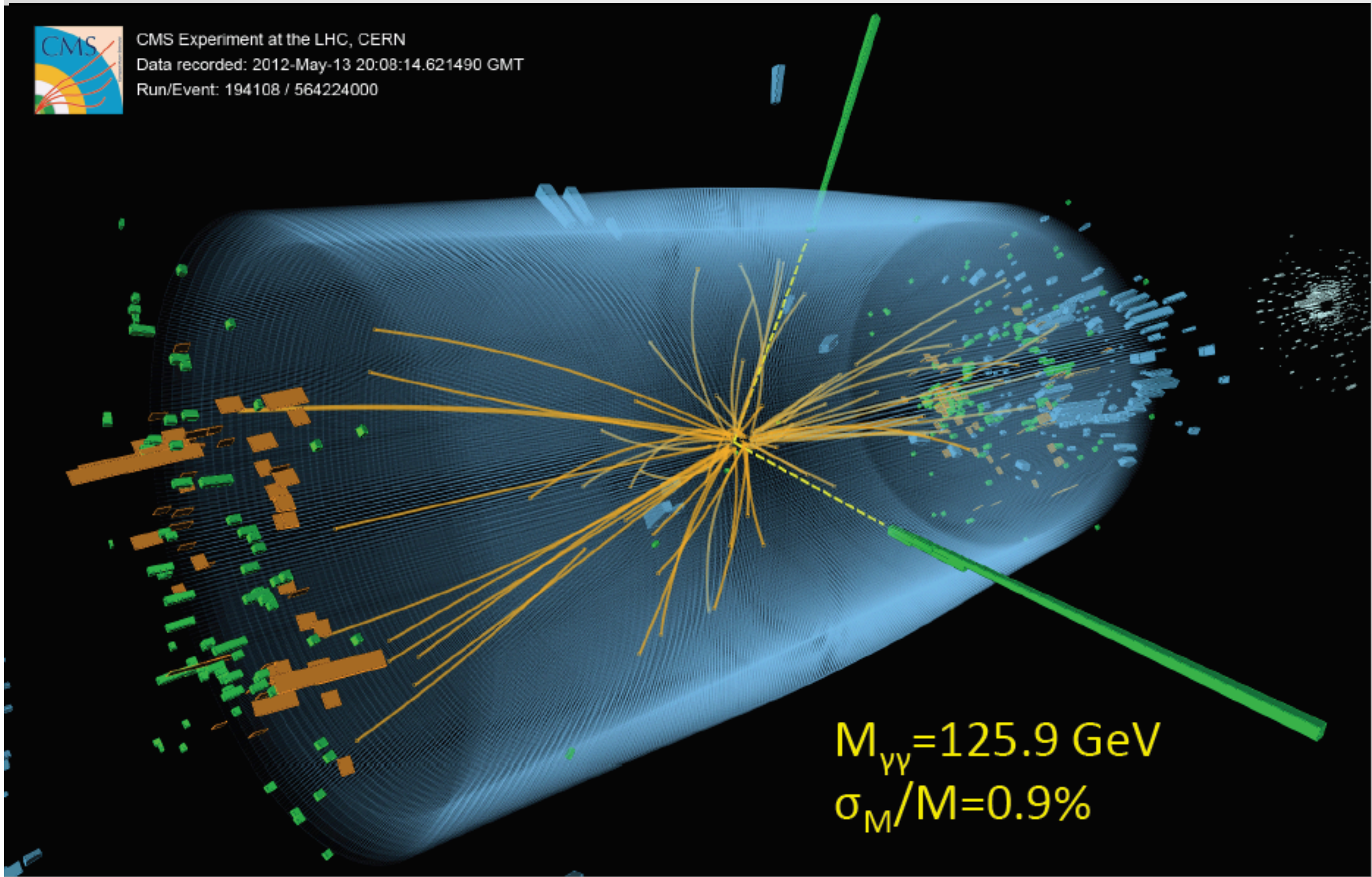


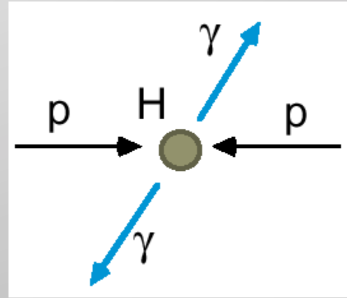






A Collision with two Photons

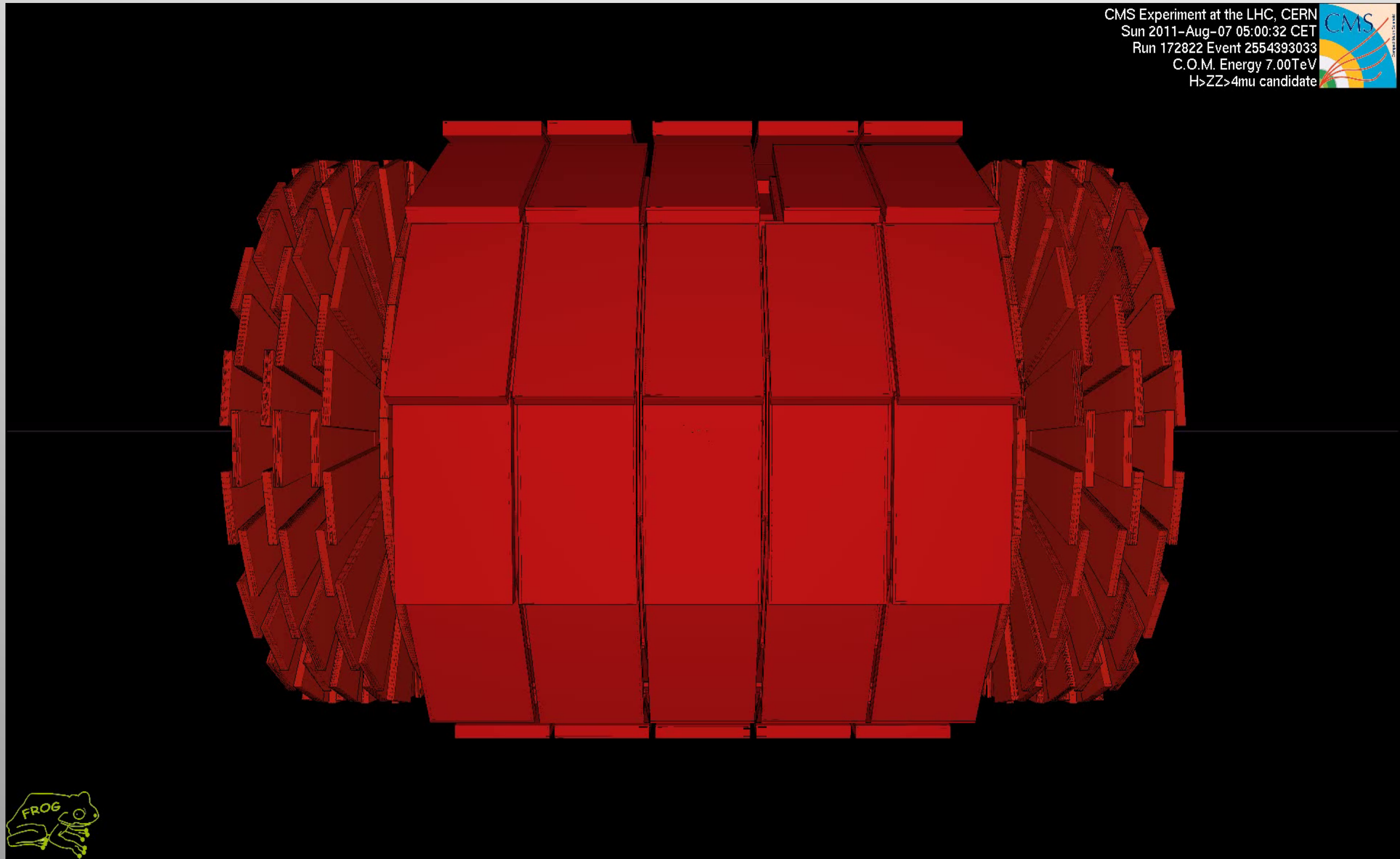


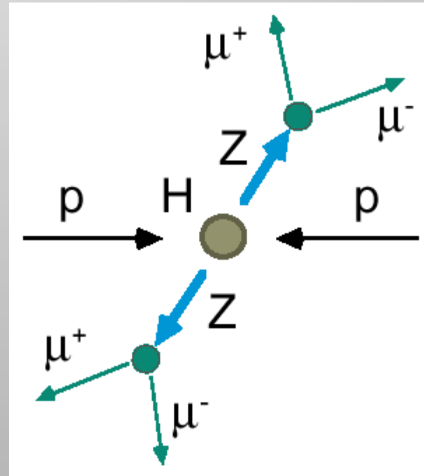


A Higgs or
a 'background' process without a Higgs?

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

A real collisions: ZZ-> 4 muons





The Higgs Boson

The Washington Post
NATIONAL

Spring 2012

Physicists hope to find the Higgs boson, key to unified field theory, this year

Fabrice Coffrini/Agence France-Presse via Getty Images - A superconducting solenoid magnet, the largest of its kind, is part of the Large Hadron Collider, which is searching for the Higgs boson.

The suspense was building up…

July 4th 2012

- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

CERN

Followed live around the world…

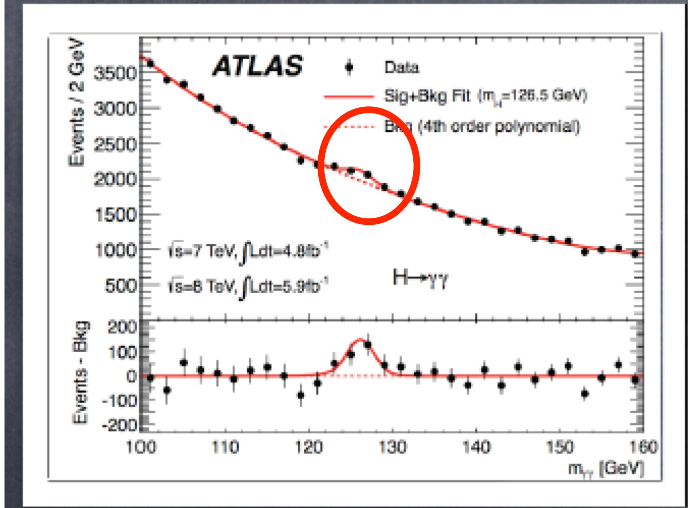
Melbourne

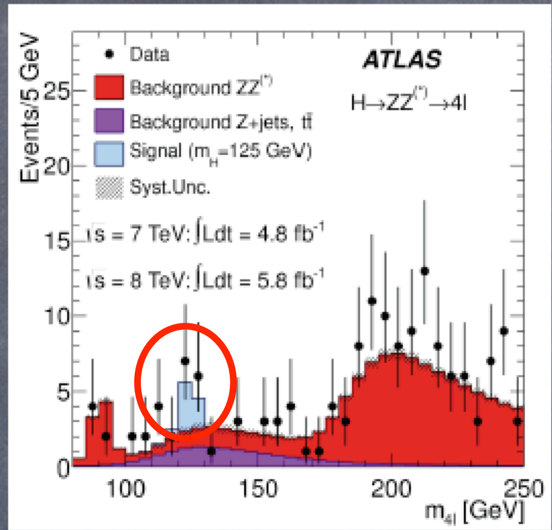
July 2012: Results

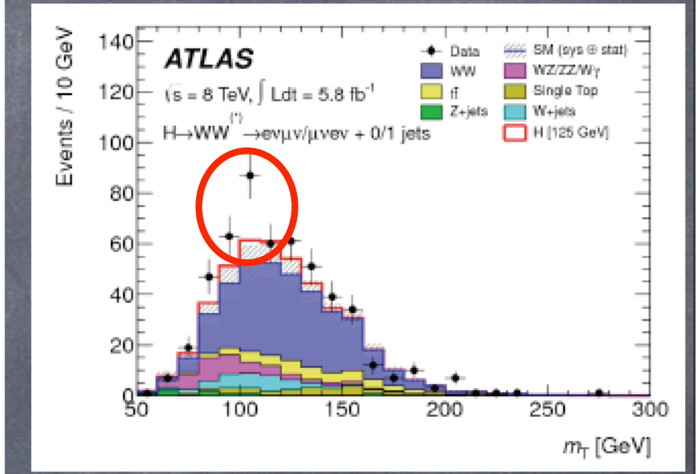
Higgs → 2 photons!!

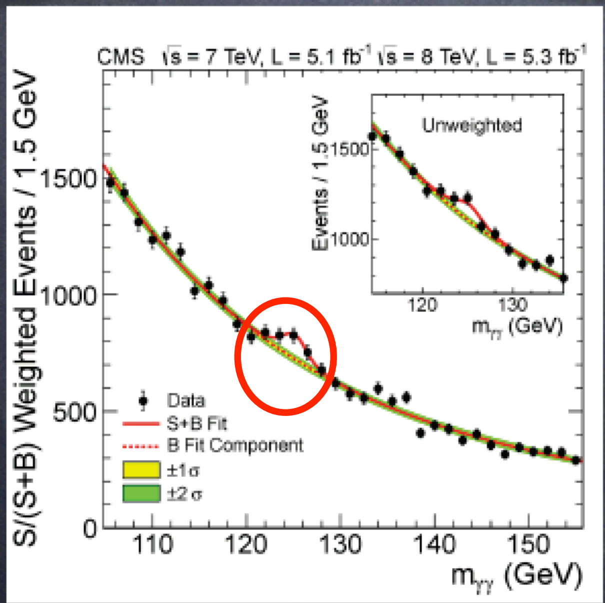
Higgs → 2Z →4 leptons!!

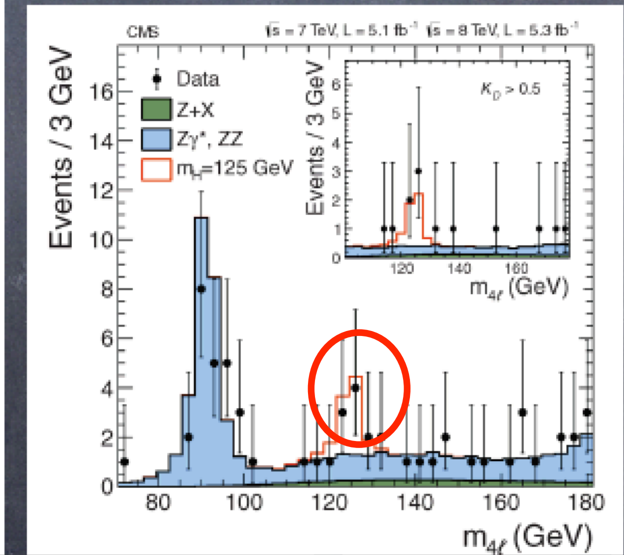
Higgs → 2W →2l2ν!!

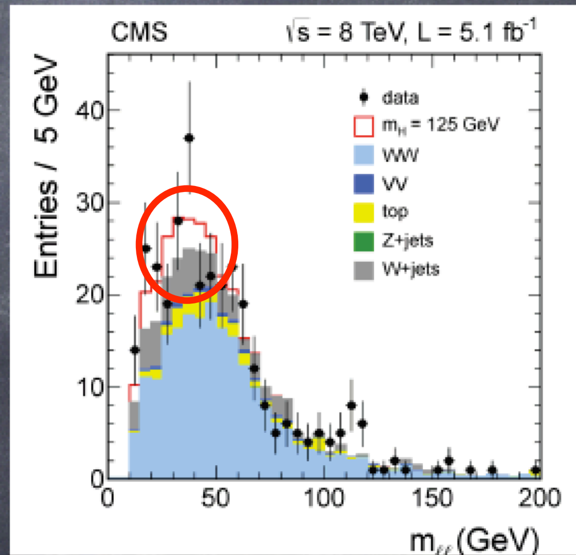












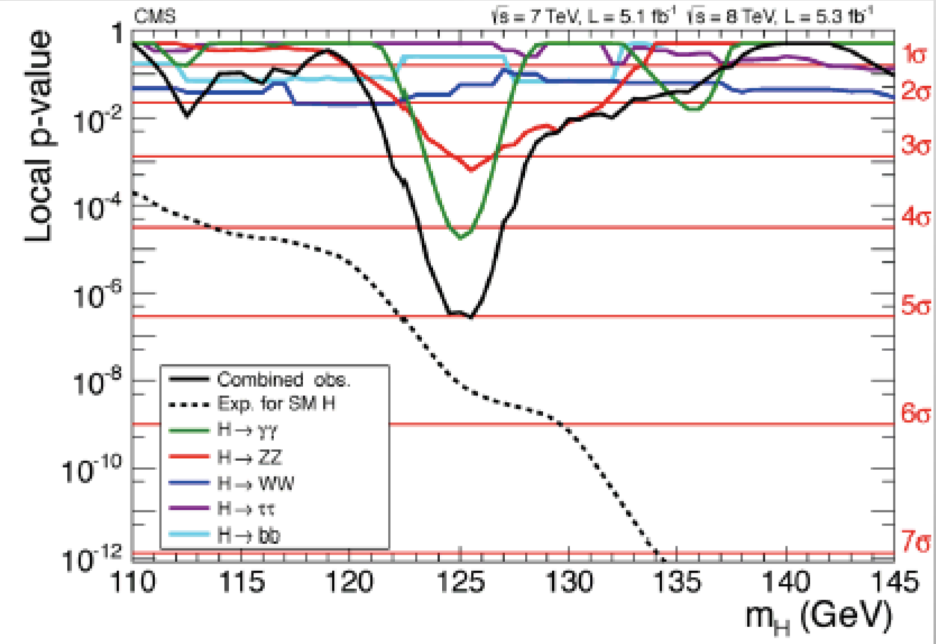
July 4th 2012

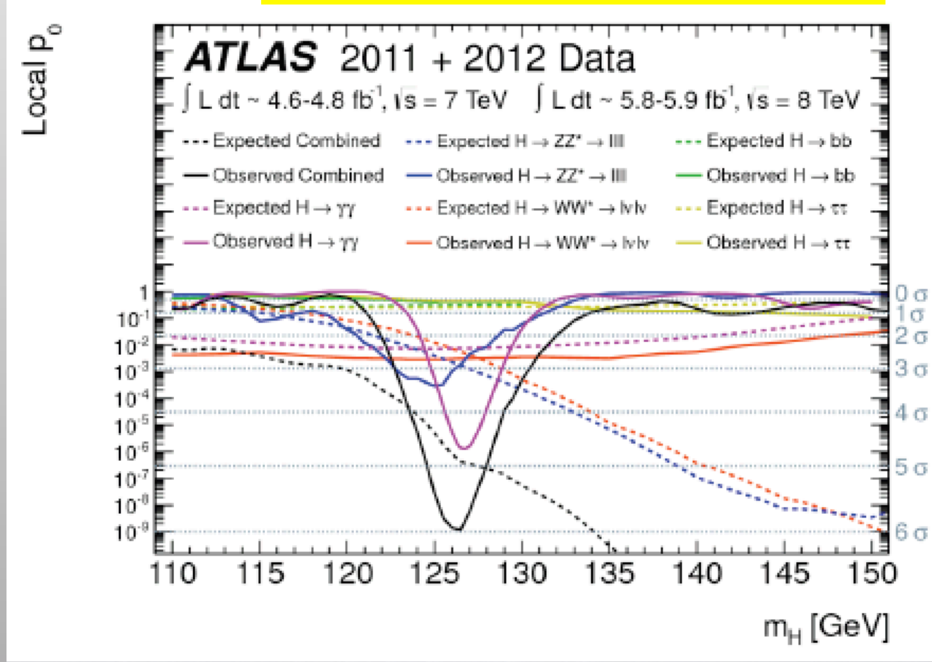
The discovery of a new particle

July 2012: Results

Both experiments see an excess ~125 GeV in the γγ, ZZ and WW channel
→Final result by adding up al the channels
Shown is the compatibility with a 'background only hypothesis"

5 fb-1/2011 and 5 fb-1/2012

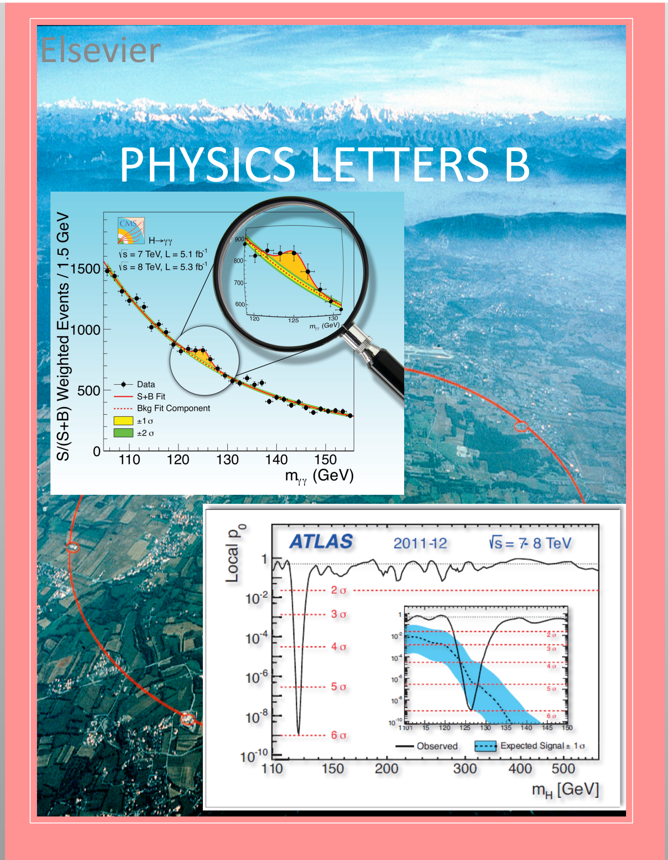




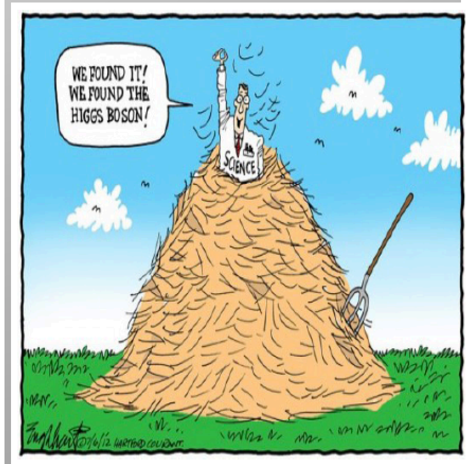
CMS and ATLAS observe a new boson with a significance of about 5 sigma (1 chance in 3 million to be wrong!!!)

Higgs Publications...

Special Physics Letters B edition with the ATLAS and CMS papers

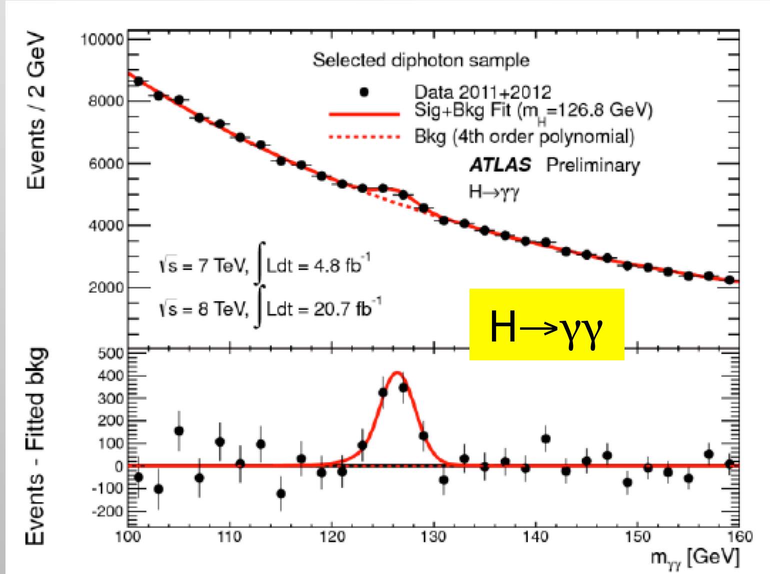


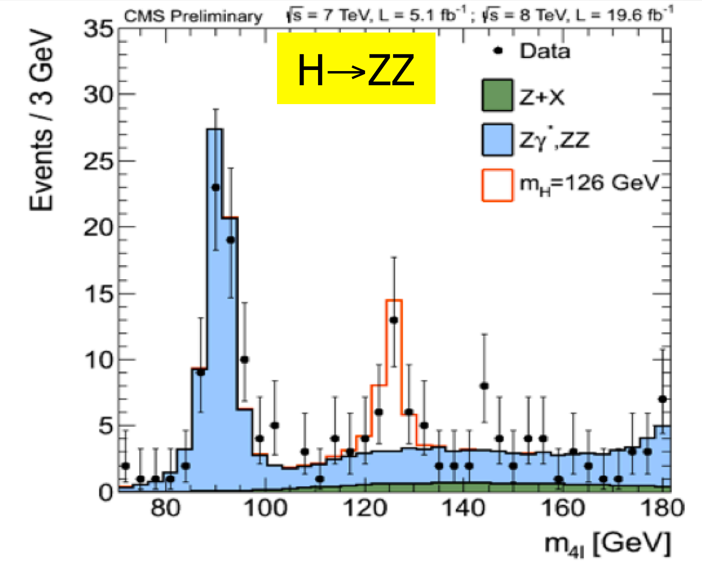
Also...

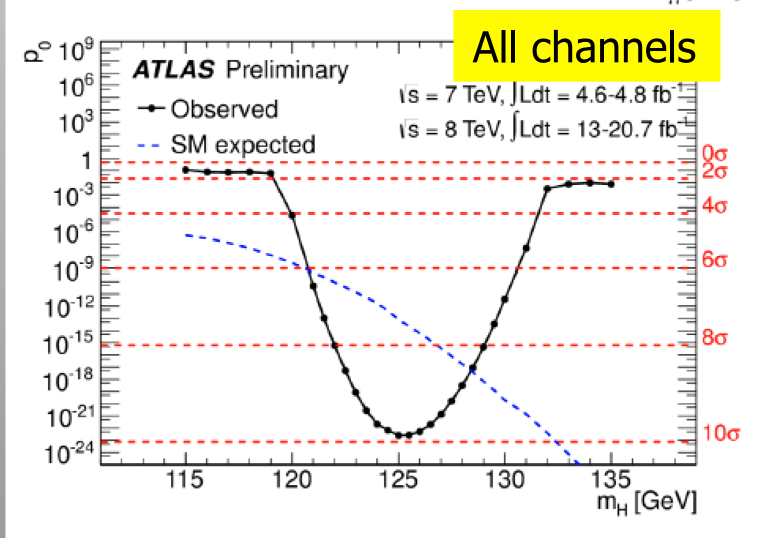


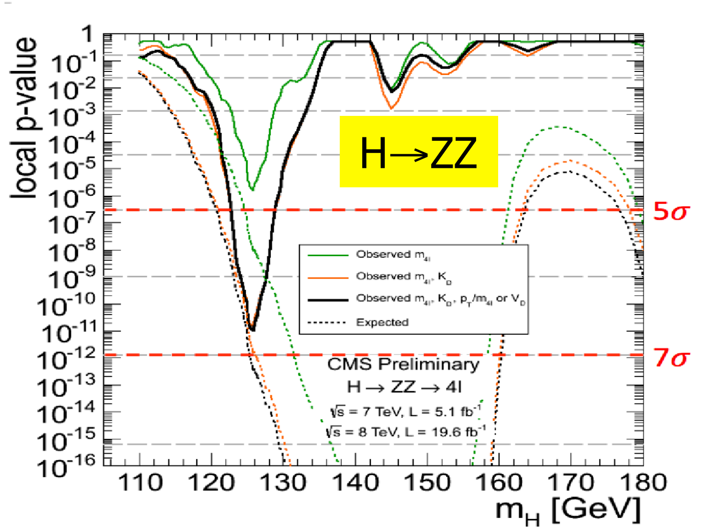
We called the new particle a “higgs-like” particle

Update with the Full 2012 Data Sample







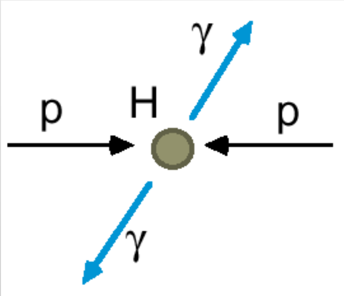


Increased data sample with a factor of ~3

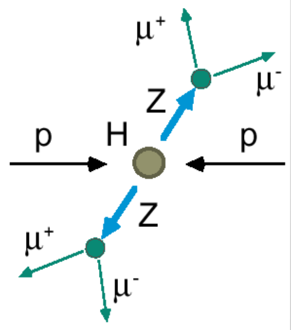
The particle is clearly still with us, now with a significance of >10σ !!

We now enter the phase of measuring the properties of the new particle

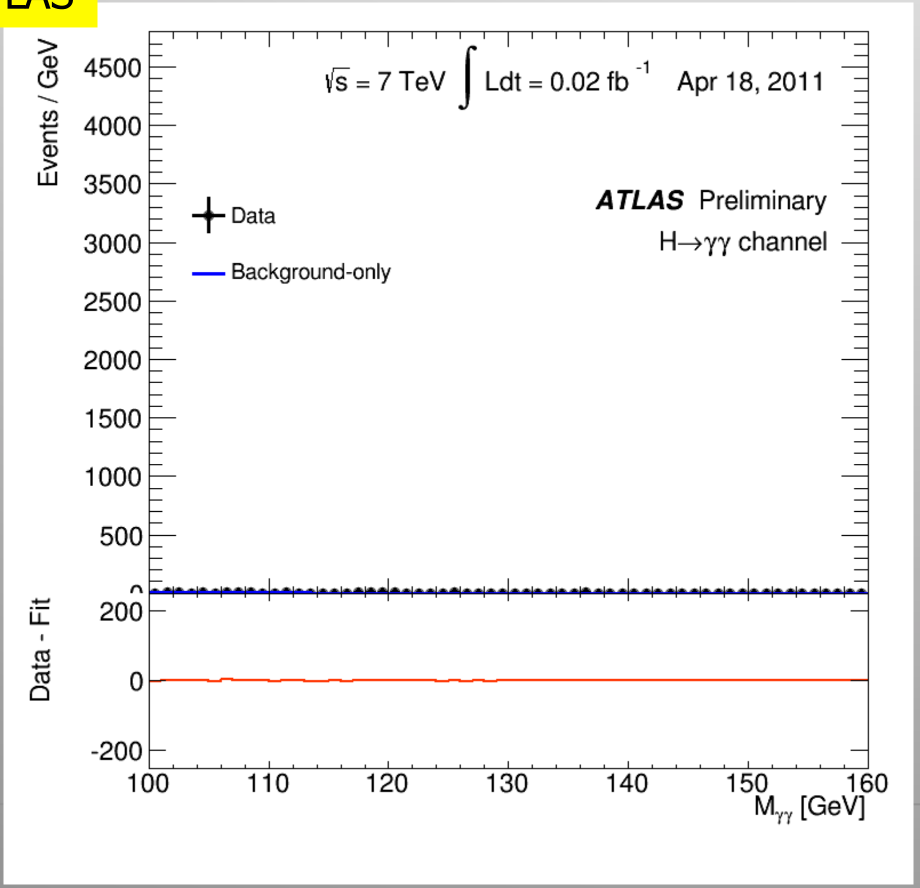
The Birth of a Particle



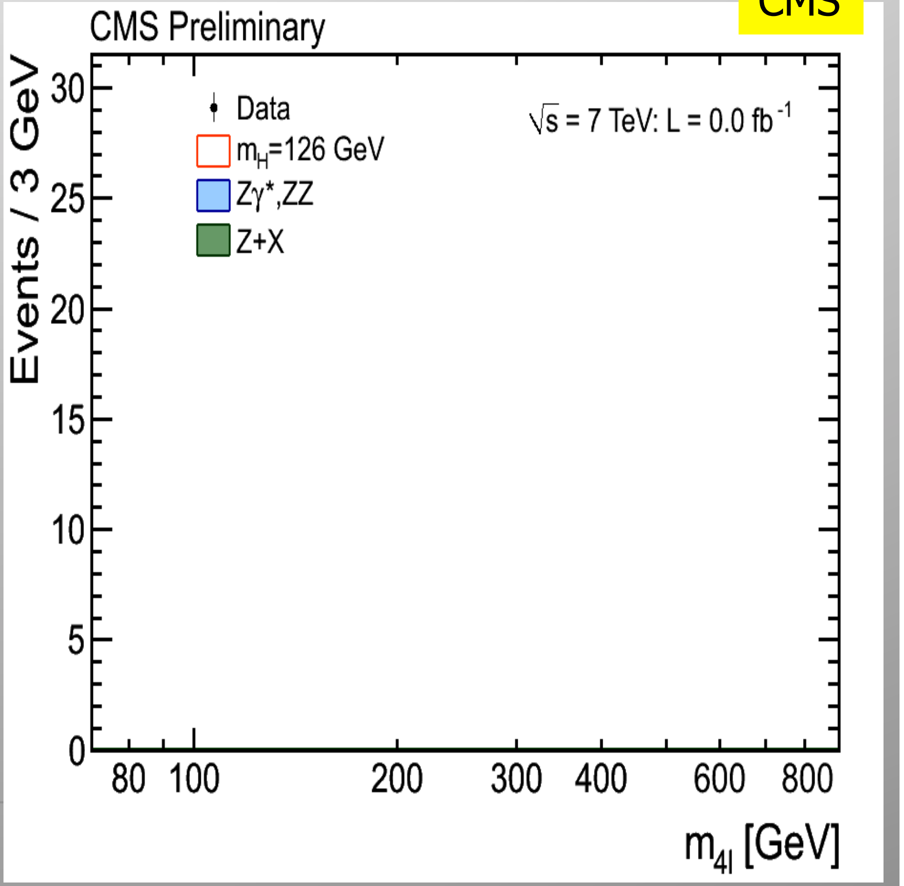
"History" of the data accumulation during the last two years



ATLAS



CMS



The News Since July 2012

- The discovery of the new particle has been confirmed with more added collisions in 2012.
- Signals in the fermion-channels start building up
- We tested the spin: it is compatible with a 0^+ state and not with a 0^- or spin 2 states
- The mass is measured better with time, now in the range125-126 GeV. A naïve average gives 125.6 GeV
- The couplings to Bosons and Fermions are consistent with the SM predictions (but these are not very precise yet; Surprises possible…)

March 2013: We call it now “a Higgs particle”

Tuesday 8 October 2013

Francois Englert

Peter Higgs

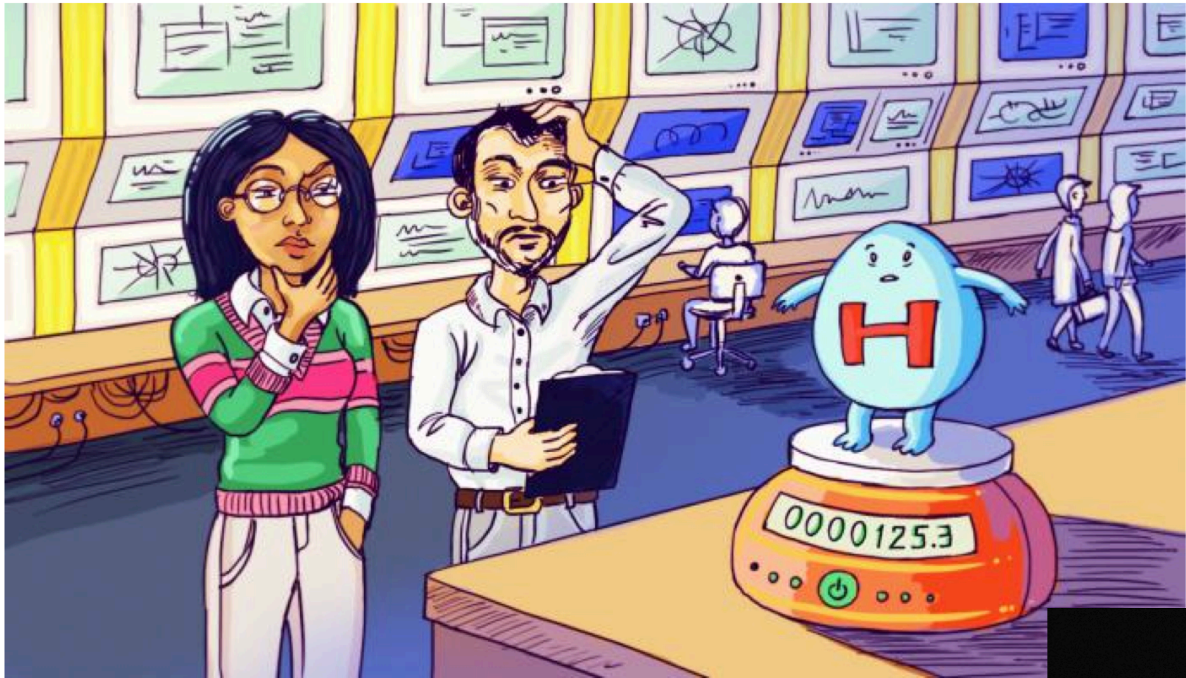
Congratulations!!!!

...and December 2013

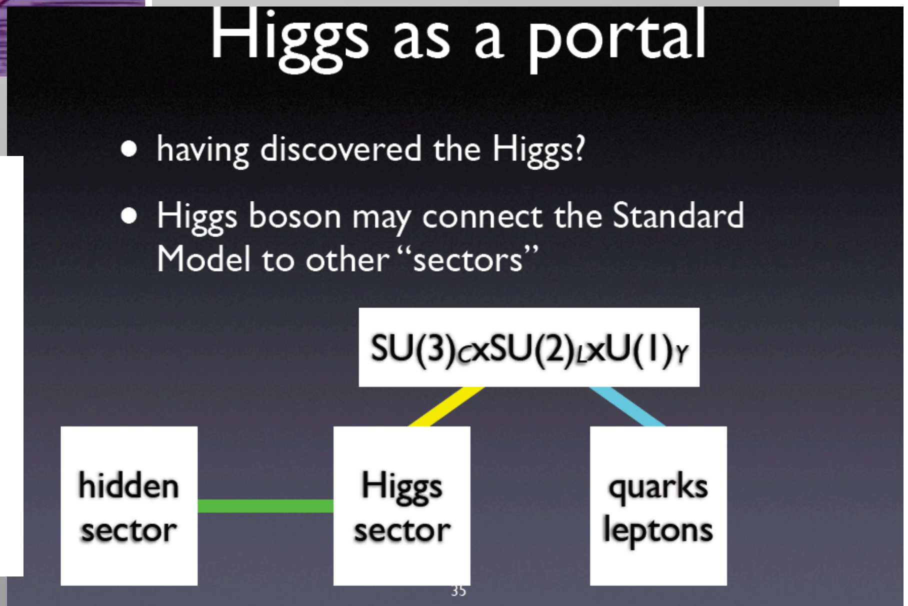
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental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

UC-Davis is a member of CMS

The Future: Studying the Higgs…



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?
- …

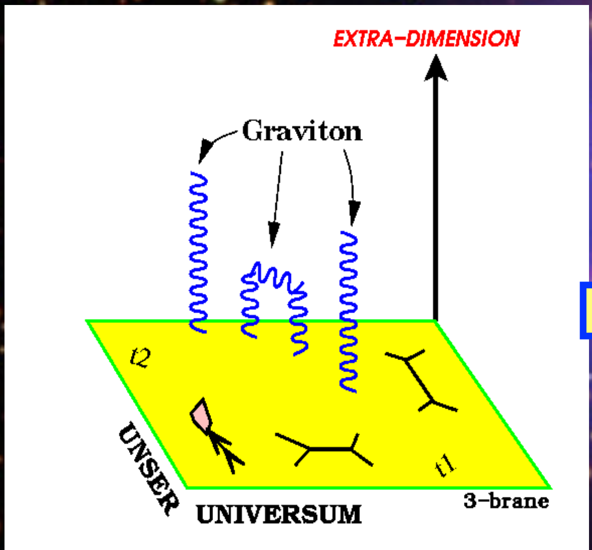
Other Questions…

Are there Extra Space Dimensions?

Or Micro Black Holes?

Extra Space Dimensions

Problem: $m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\ \mathrm{GeV}$ ⇔ $M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}\ \mathrm{GeV}$



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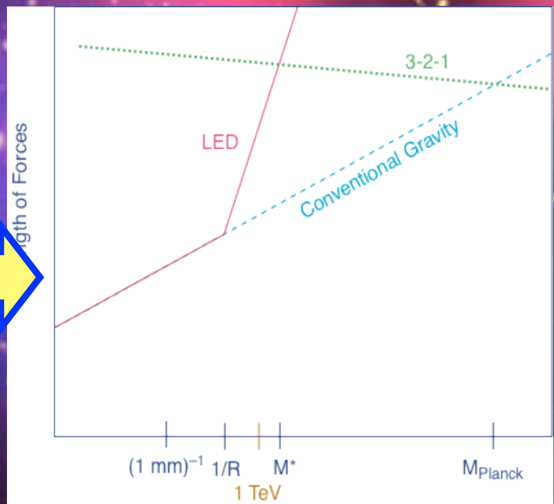

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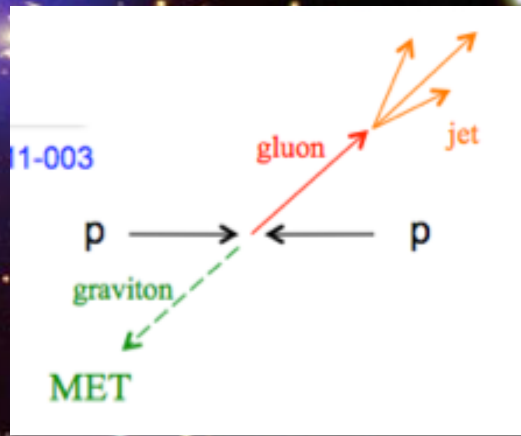
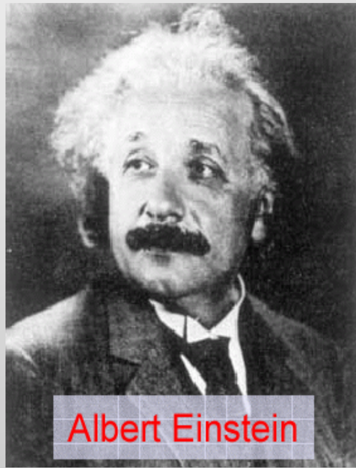


The Gravitational force becomes strong!

No signal found yet
New Planck scale is larger than 3 TeV

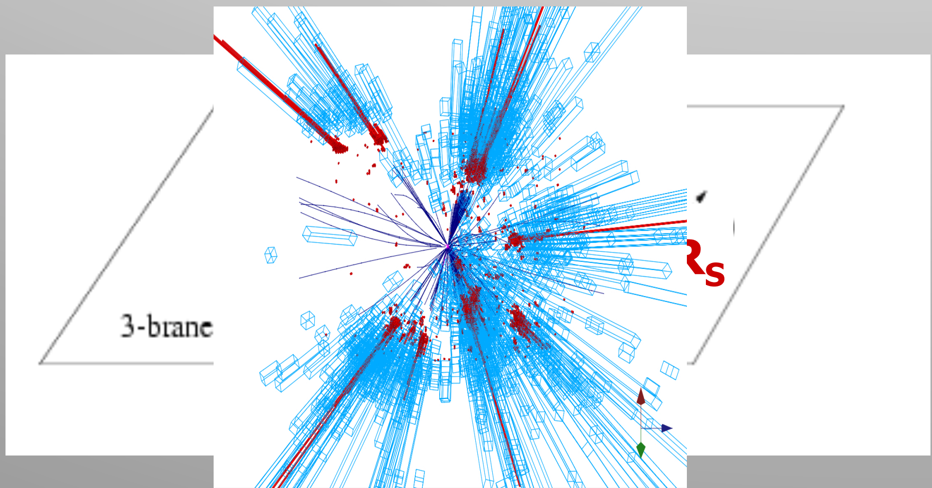
Quantum Black Holes at the LHC?

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

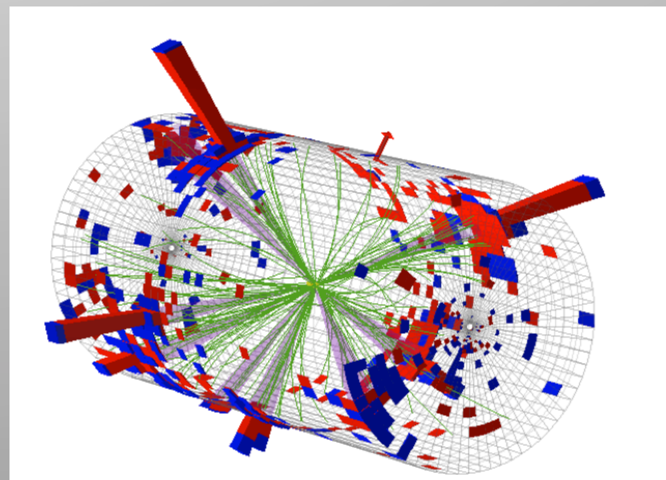


If the Planck scale is in ~TeV region:
can expect Quantum Black Hole production

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



Simulation of a Quantum Black Hole event



Black holes with mass of up to 5 TeV are excluded


Black Holes
Hunters
at the LHC…

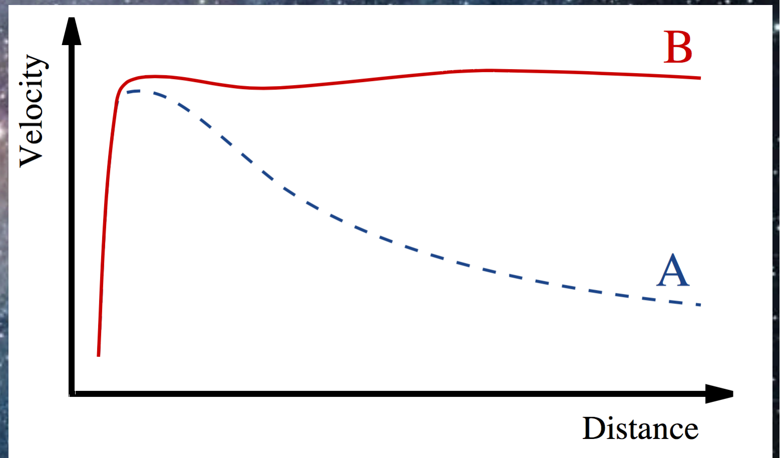
Other Questions…

Dark Matter at the LHC?

Are we supersymmetric?

Dark Matter in the Universe

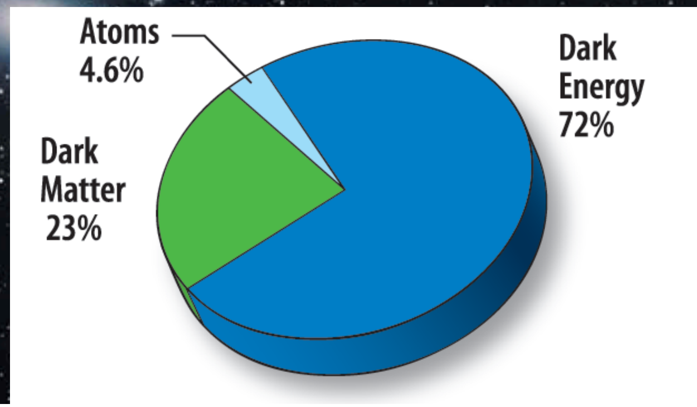
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



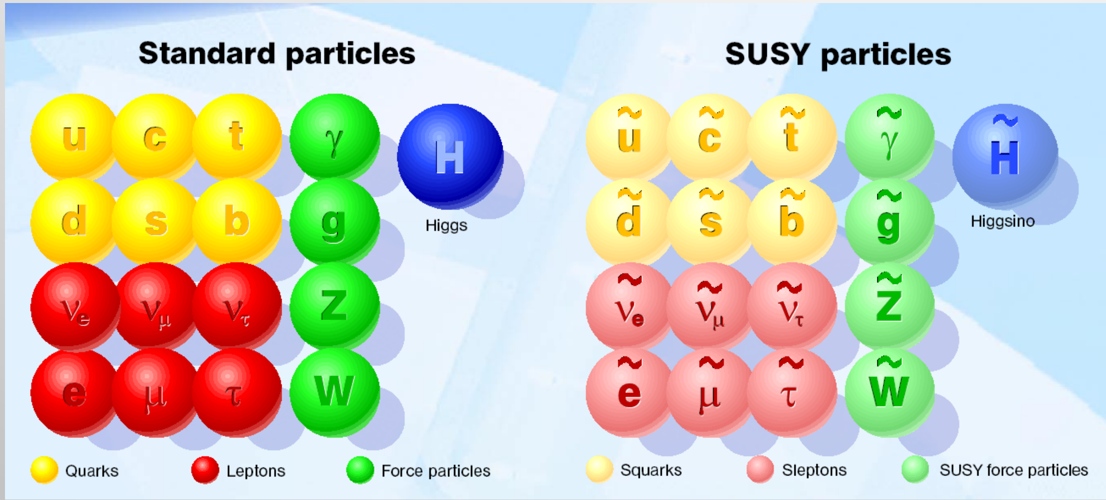
'Supersymmetric' particles ?

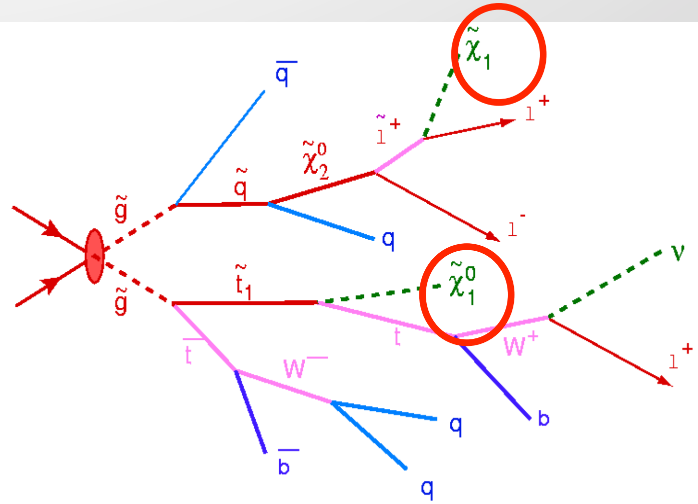
F. Zwicky 1898-1974

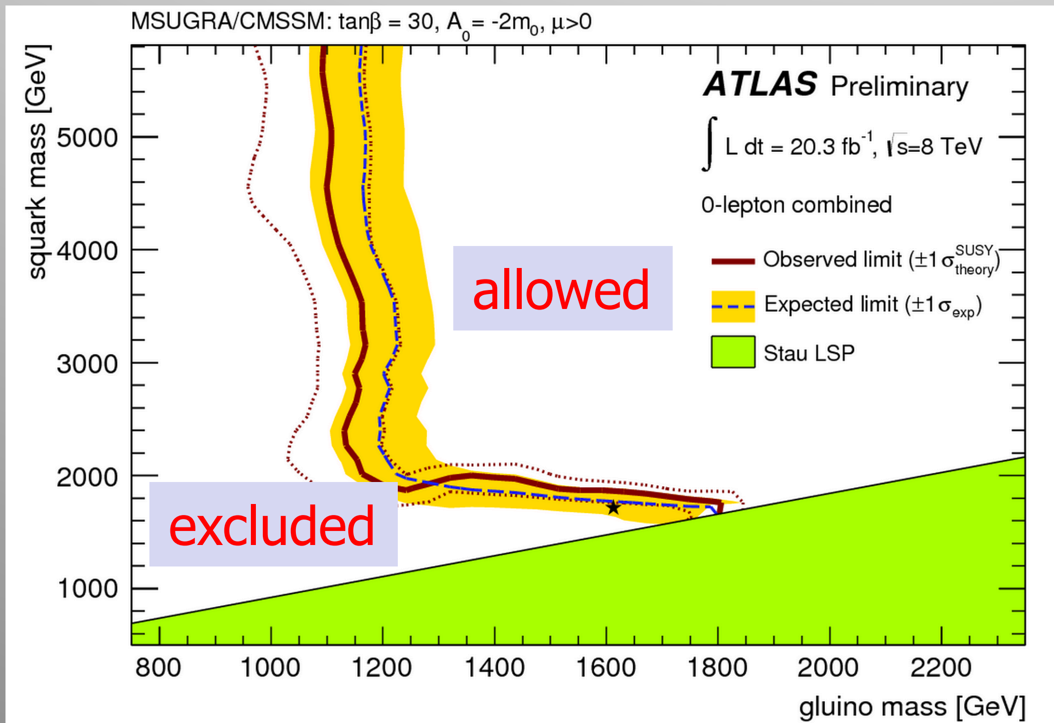
Vera Rubin ~ 1970



SUSY Searches: No signal yet to date…



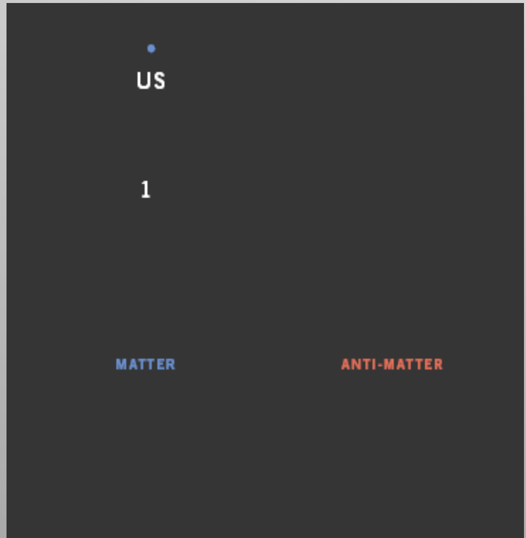


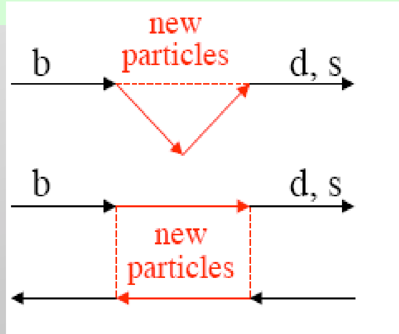


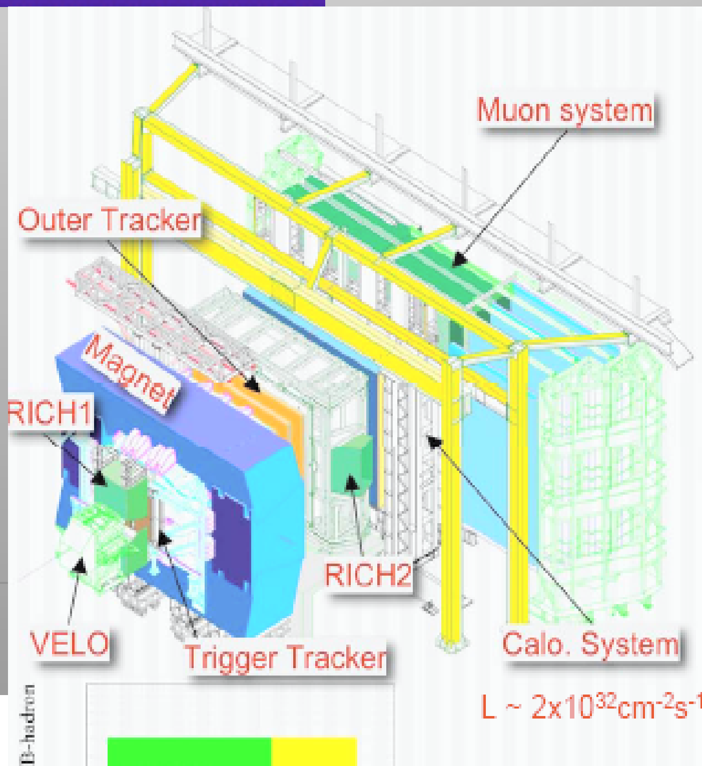
- So far NO clear signal of supersymmetric particles has been found so far
  SUSY particles must be heavier than 1000 GeV
- We can exclude regions where the new particles could exist.
- Searches will continue for the next years

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



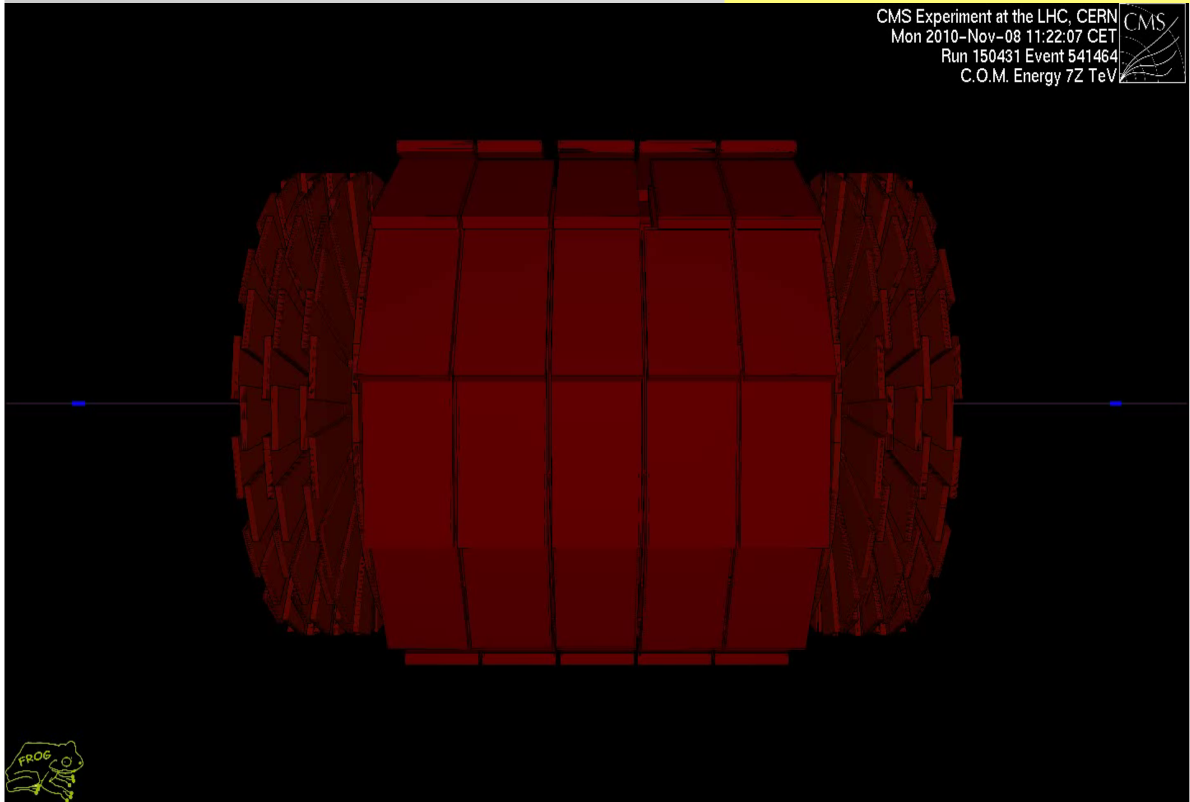




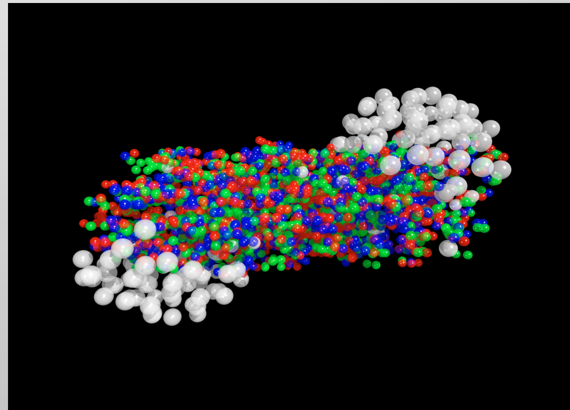
Primordial Plasma

Lead-lead collisions at the LHC to study the primordial plasma, a state of matter in the early moments of the Universe

Hundreds of particles in the detector



A recorded lead lead collision in the CMS detector



Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today

The Physics Program at LHC

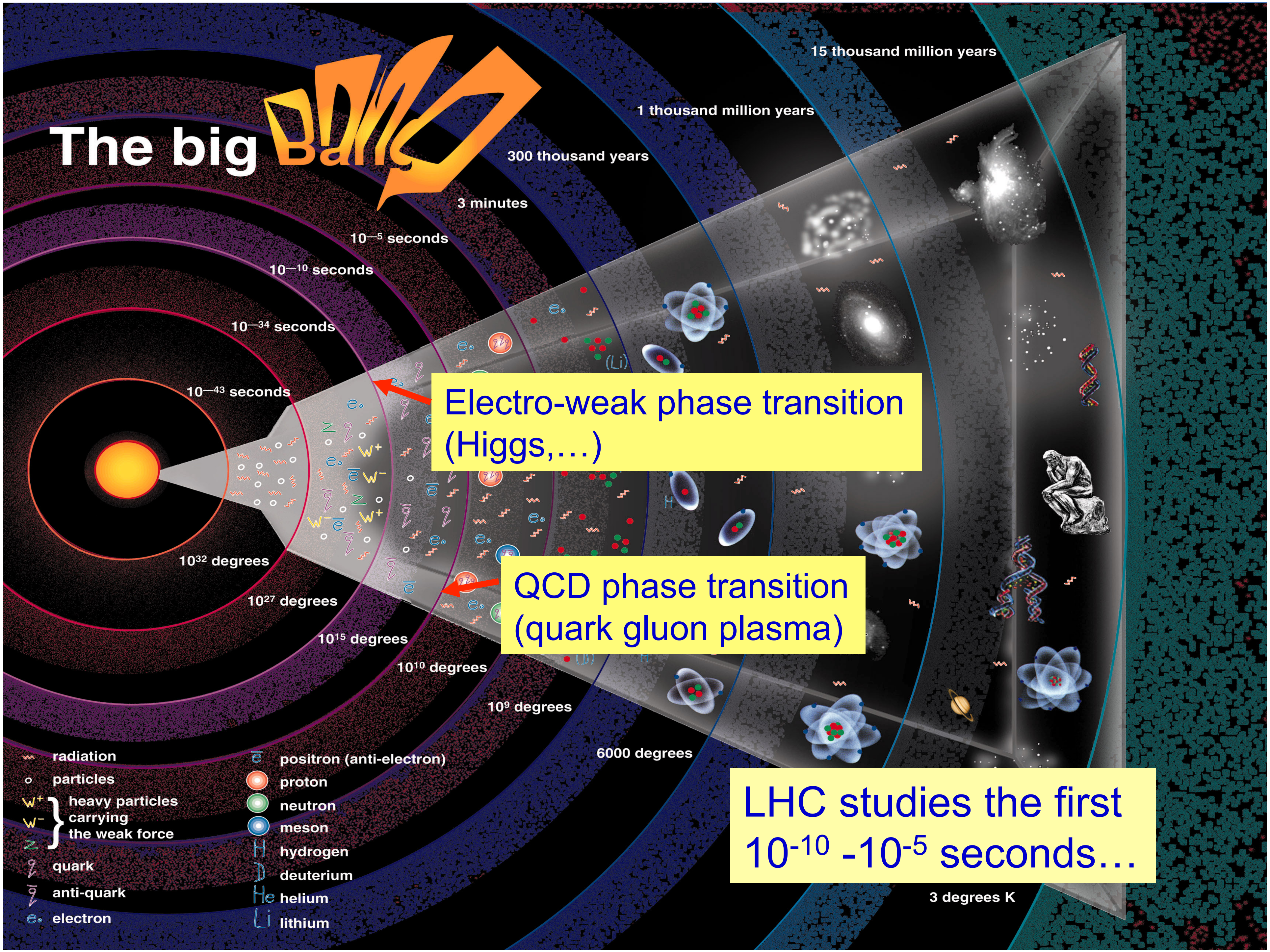
Data taking started in 2010

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!!



Electro-weak phase transition (Higgs,…)

QCD phase transition (quark gluon plasma)

LHC studies the first 10^{-10} - 10^{-5} seconds…

Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought fundamental scalar boson, postulated in 1964.

March 2013: The full statistics of 2011+2012 (about a factor 3 more data) confirms the existence of the new particle.

The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it now "a Higgs particle". This is a brand new fundamental particle, as we never seen before.

This Higgs boson is 'very light' which suggest new physics Beyond the Standard Model will be needed. Supersymmetry? Extra Dimensions? Other? The next years @ the LHC will tell…

We are on the verge of a revolution in our understanding of the Universe and our place within it. UC-Davis and many other US-scientist participate!!

This is only the beginning!!!

The Physics Program at LHC

Data taking started in 2010

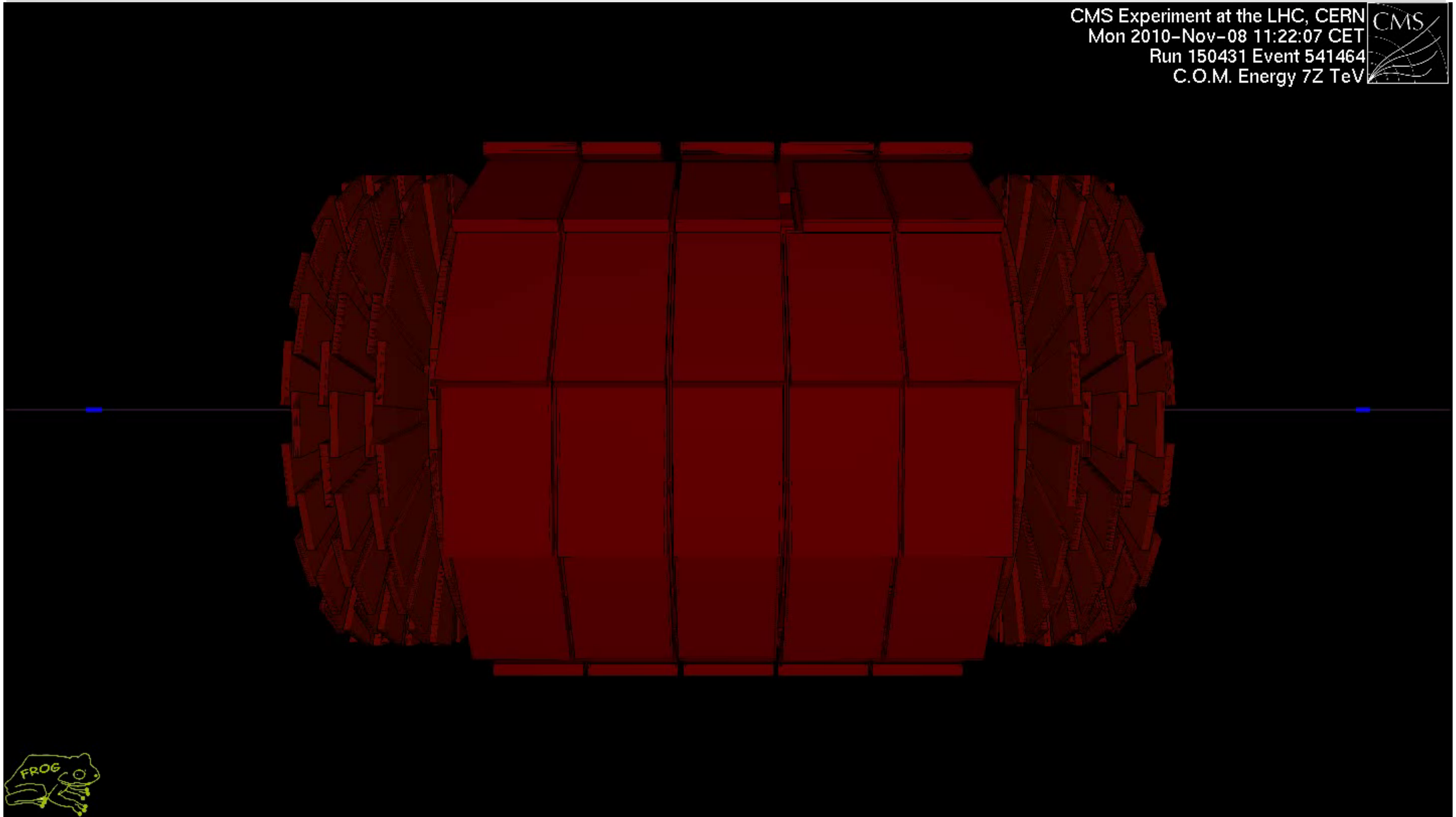
Now we have more than 300 reviewed scientific papers per experiment!

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

- **-Are quarks the elementary particles?**
- **-Do we see supersymmetric particles/Dark Matter?**
- **-Do we see extra space dimensions?**
- **-Do we see micro-black holes?**

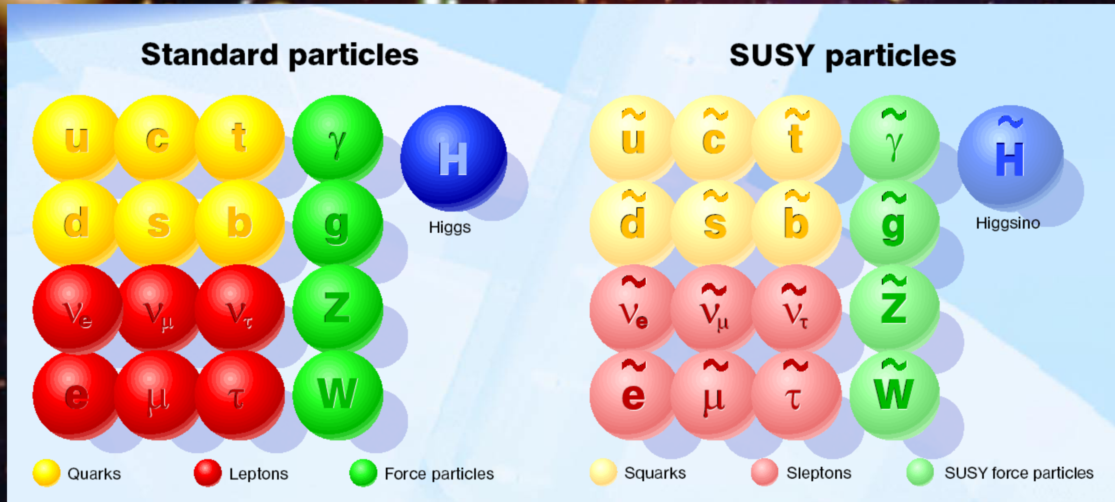
->The Discovery of a Higgs-like particle!!

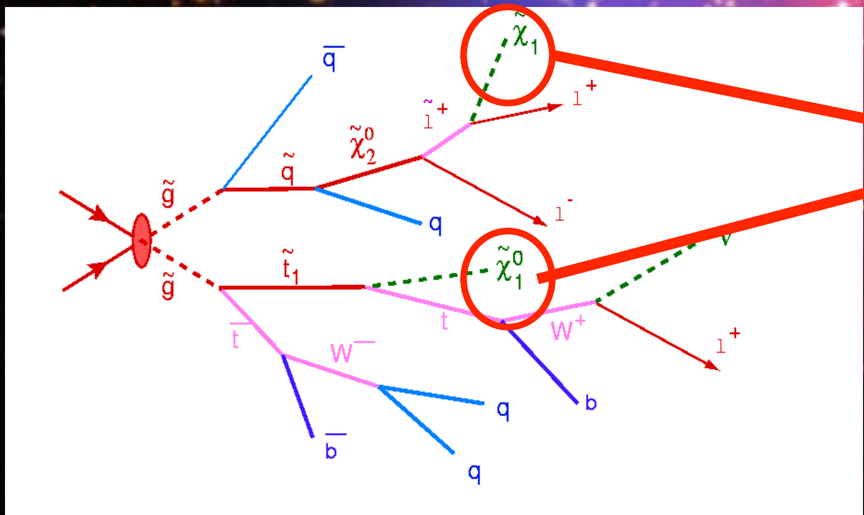
A Recorded Heavy Ion Collision



Are Quarks Elementary Particles?

Supersymmetry: a new symmetry in Nature?





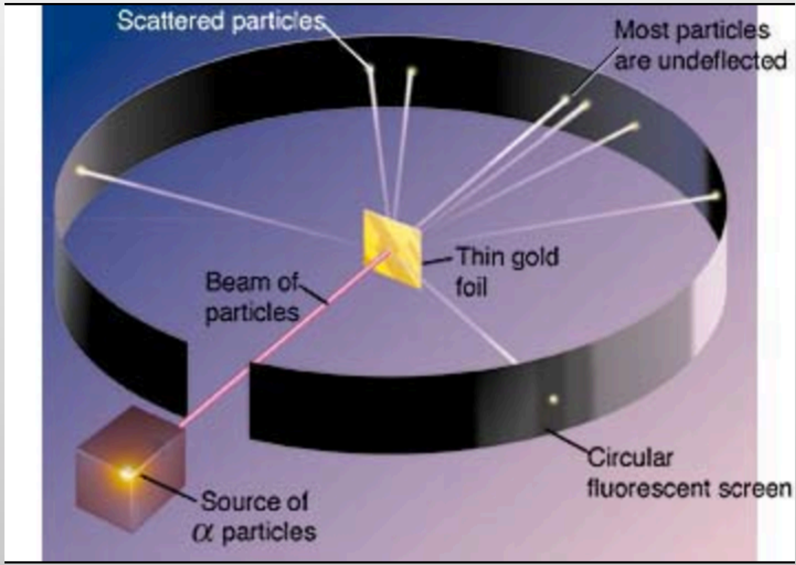
SUSY particle production at the LHC

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

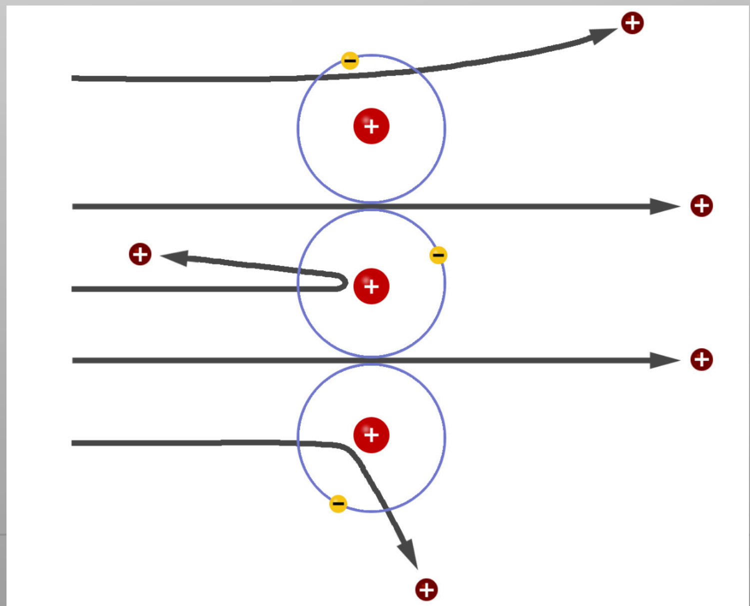
Picture from Marusa Bradac

+ 4 jets

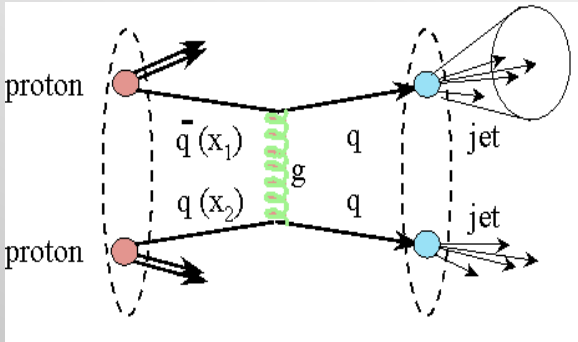
Are Quarks Elementary Particles?

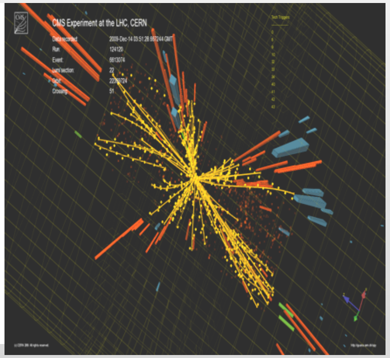


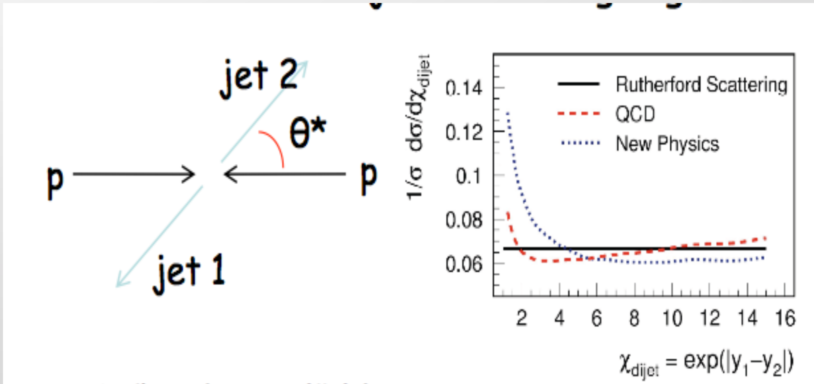
Rutherford experiment:
Unexpected backscattering of α-particles:
Evidence for the structure of atoms !! (1911)



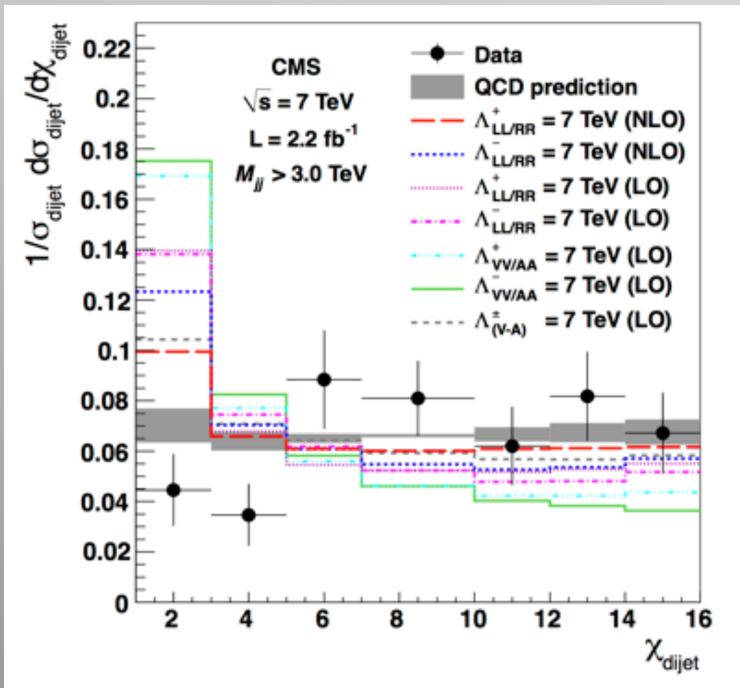
Are Quarks Elementary Particles?

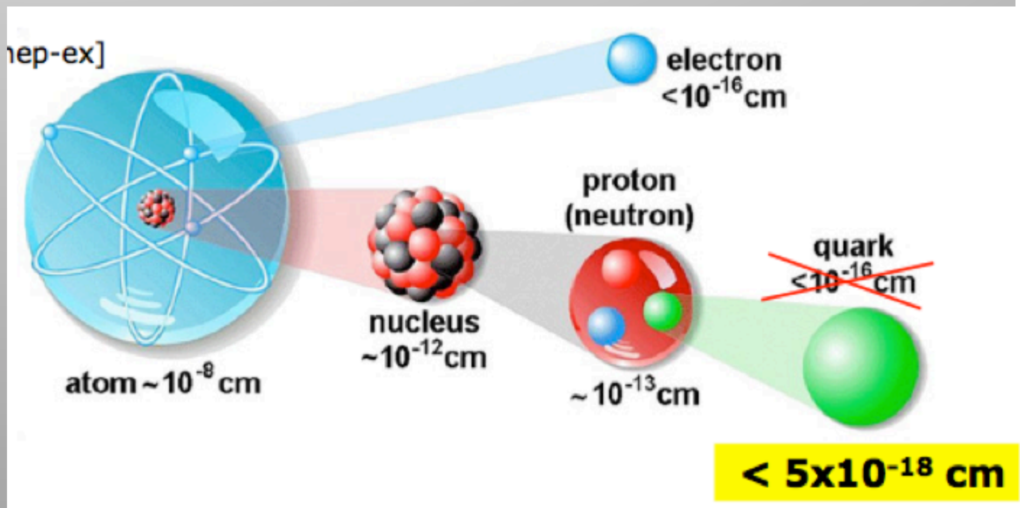






Measurement of the production angle of the jet with respect to the beam
-> High Energy Rutherford Experiment





Quarks remain elementary particles after these first results

The Press… (5th July 2012)

The discovery of the Higgs made the headlines worldwide

Hawking lost $100 bet over Higgs boson

What Comes After Higgs Boson?

Atlantic wire what matters now

'God Particle' 'Discovered': European Researchers Claim Discovery of Higgs Boson-Like Particle

HOW THE HIGGS COULD BECOME ANNOYING

Yes, the discovery of the Higgs boson is thrilling and game-changing. But it could also introduce some aggravating situations.

Хиггс увидит бозон

В CERN открыли бозон Хиггса

Текст

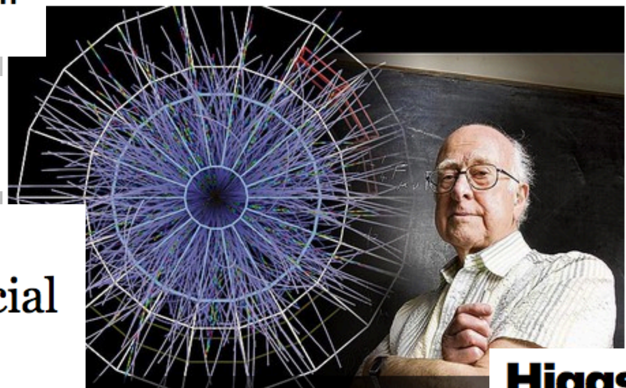
— 3.07.12 15:13 —

ТЕКСТ: АЛЕКСАНДРА БОРИСОВА

D: SCIENCEUNSEEN.COM

Discovery of Higgs Boson Bittersweet News in Texas

Scientists Set The Higgs Boson To Music



Знаменитый физик Питер Хиггс

3 Ways the Higgs Boson Discovery Will Impact Financial Services

Higgs boson discovery could make science fiction a reality

Discovery of the 'God particle' could make science fiction a reality, and answer one of the most basic questions of our universe: How did light become matter — and us?

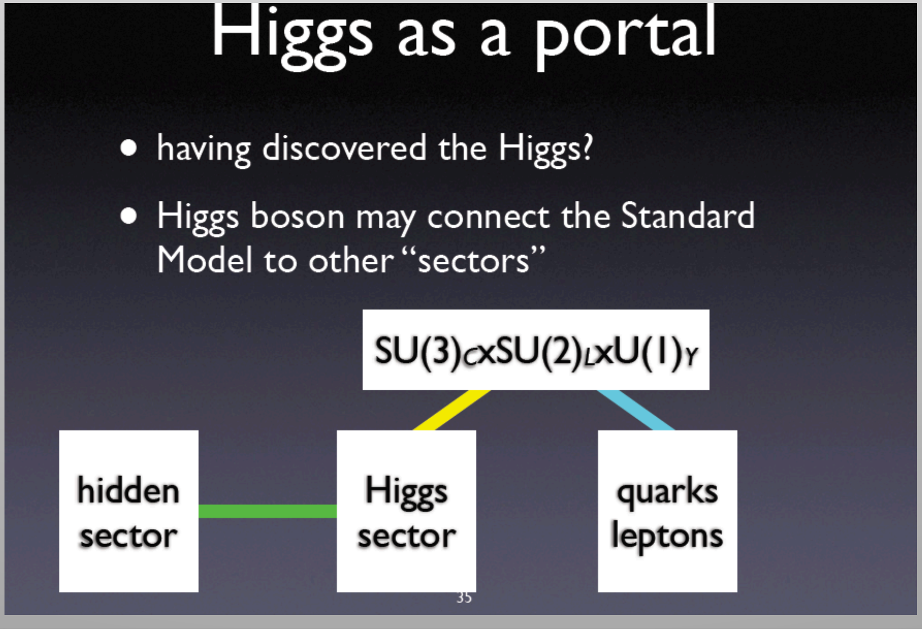
Higgs boson researchers consider move to Cloud computing

"Within another decade the Cloud will be where grid computing is now"

What is Next?

The work is not over yet: Many questions still remain unanswered:

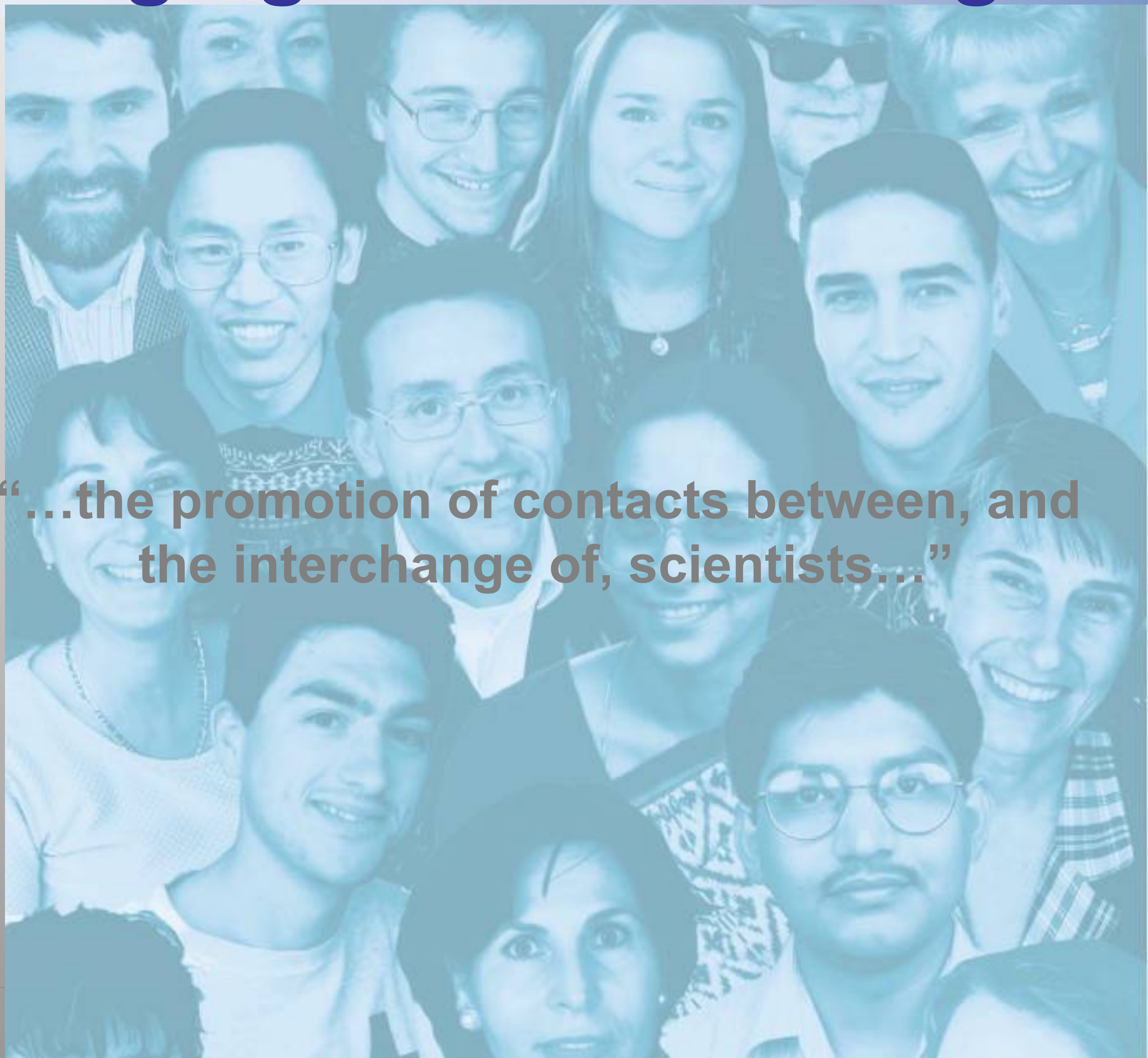
- Is it THE Standard Model Higgs boson or a messenger of New Physics ?
- How can we explain a Higgs mass ~ 126 GeV? What stabelizes the mass?
- What explains the mass pattern of the particles that we observe?
- What is Dark Matter and Dark energy? Supersymmetry at higher masses??
- Where is the antimatter in the Universe? How did it dissapear??



Need for precision measurements with ~100x the present statistics

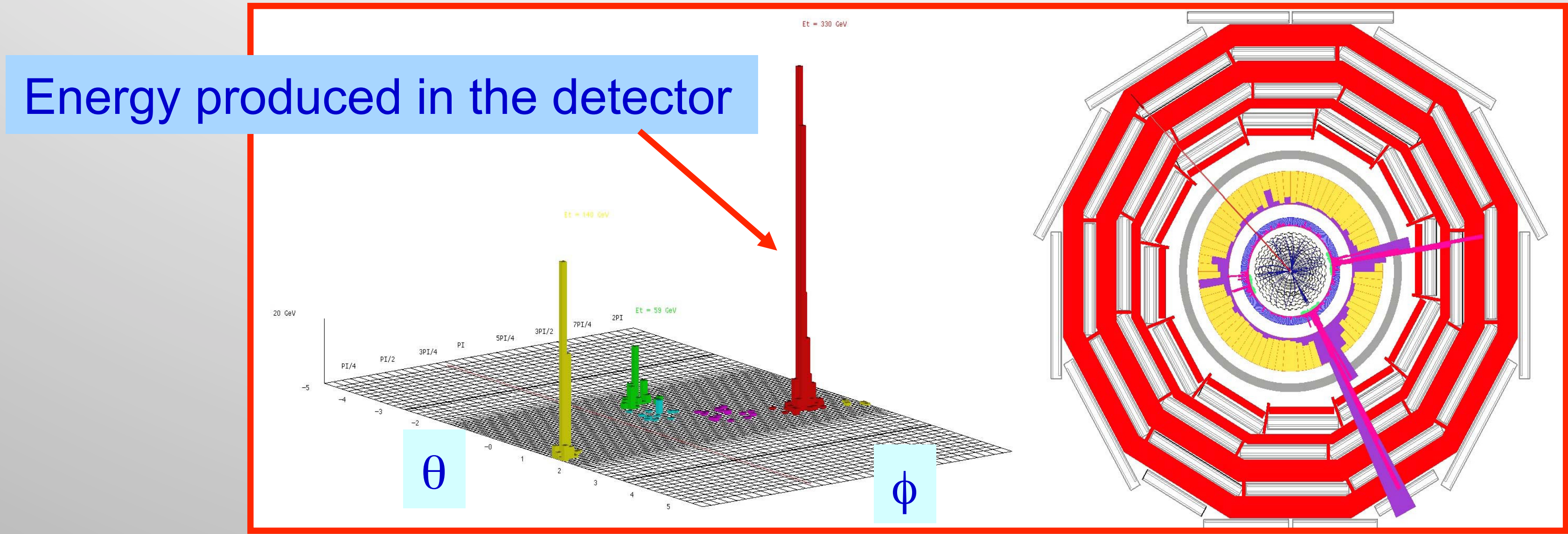
LHC upgrade ! Experiment upgrades!! (Other machines?)

Bringing the Nations Together



"…the promotion of contacts between, and the interchange of, scientists…"

Detecting Supersymmetric Particles



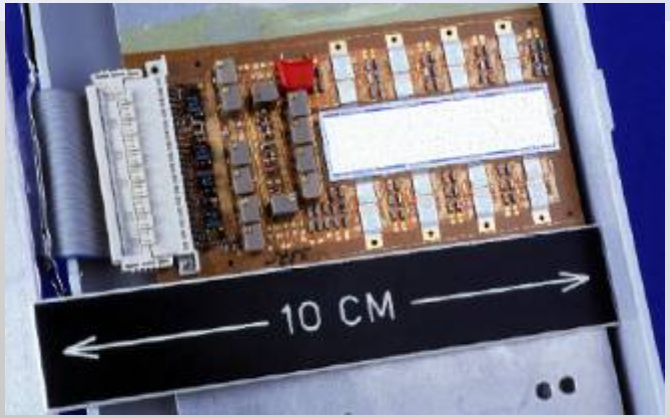
Supersymmetric particles decay and produce a cascade of jets, leptons and missing (transverse) energy due to escaping 'dark matter' particles

➡ Very clear signatures in CMS and ATLAS

LHC can discover supersymmetric partners of the quarks and gluons as heavy as 2 to 3 TeV

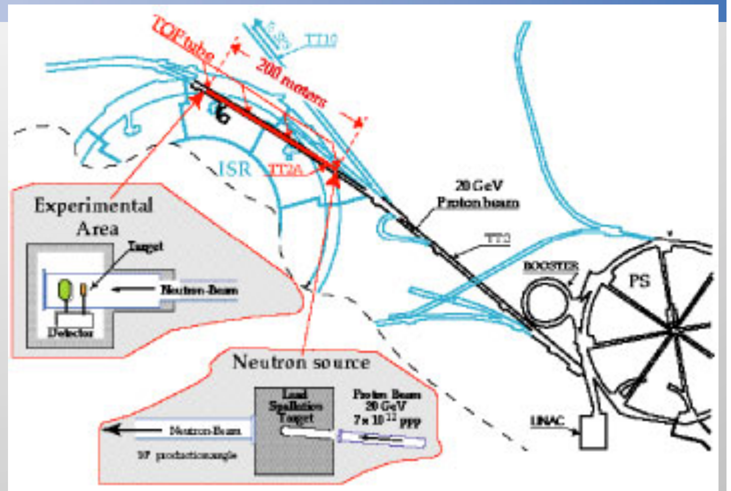
The expected cross sections are huge!! ⇒ ~10,000 particles per year

CERN is also: Technology Transfer

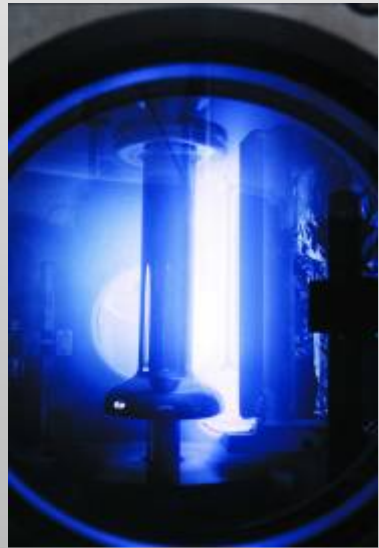


Silicon detector for a Compton camera in nuclear medical imaging

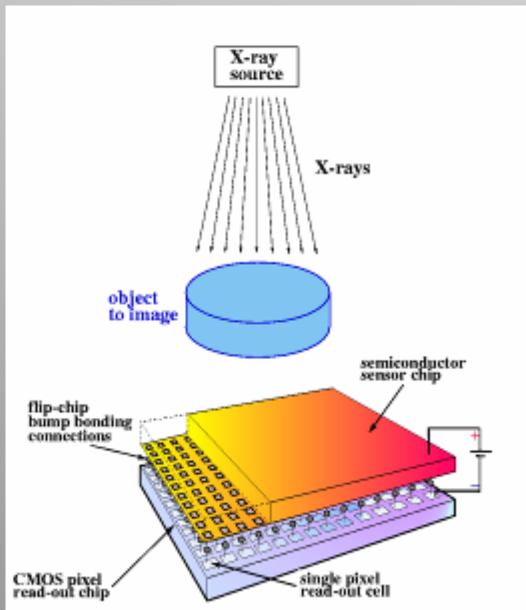
GRID Computing!



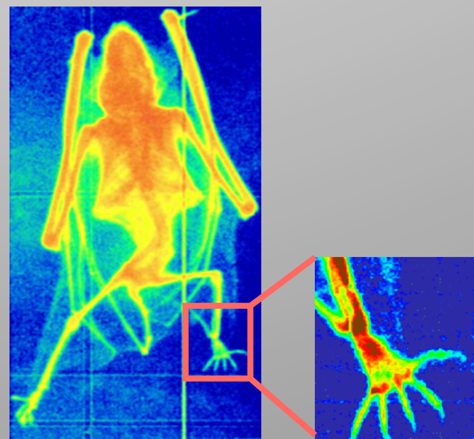
Radio-isotope production for medical applications



Thin films by sputtering or evaporation



Medipix: Medical X-ray diagnosis with contrast enhancement and dose reduction

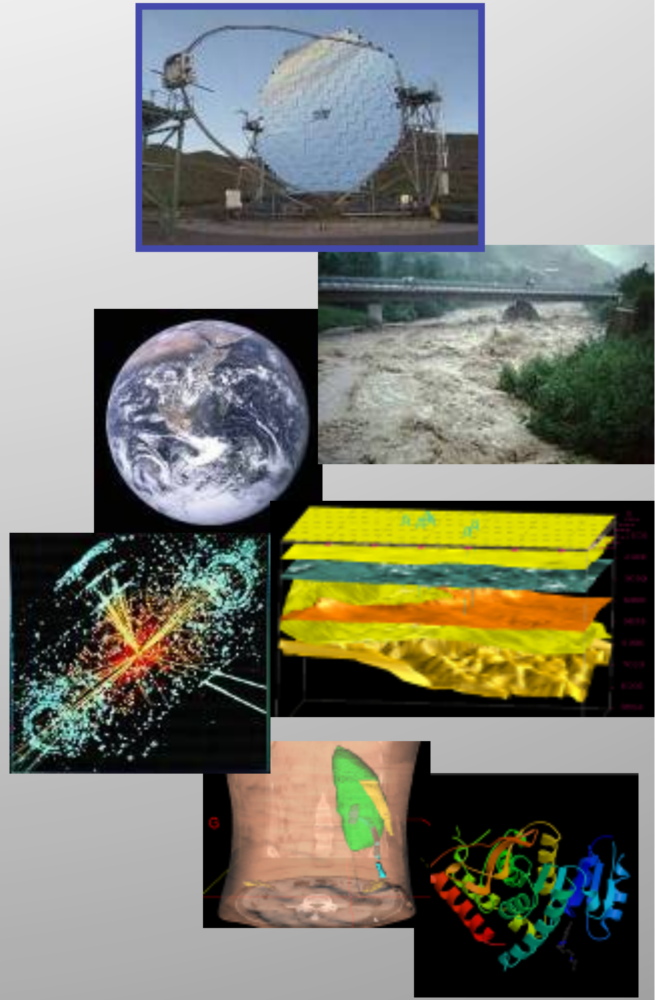


Radiography of a bat, recorded with a GEM detector

Applications of Grid Computing

Multitude of applications from a growing number of domains

- Archeology
- Astronomy & Astrophysics
- Civil Protection
- Computational Chemistry
- Earth Sciences
- Financial Simulation
- Fusion
- Geophysics
- High Energy Physics
- Life Sciences
- Multimedia
- Material Sciences
- …



Infrastructure used by >10000 researchers

CERN as an Educator

Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought Higgs boson, postulated in 1964.

March 2013: The full statistics of 2011+2012 (about a factor 3 more data) confirms the existence of the new particle.

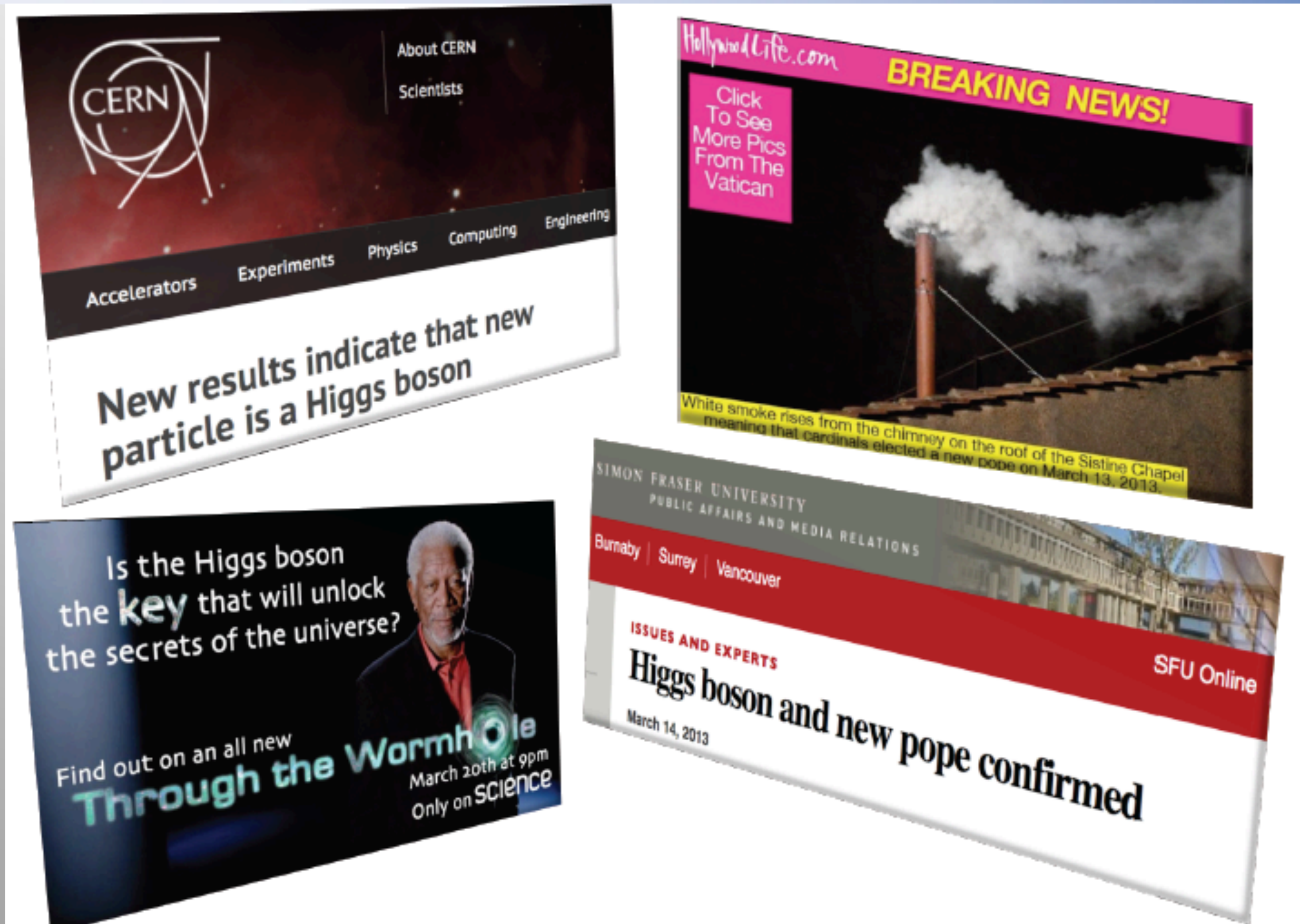
The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it from now onwards "a Higgs particle". This is a brand new particle, as we never seen before.

This Higgs boson is likely to carry the 'genetic code' for the physics Beyond the Standard Model. Present studies do not yet reveal any BSM signatures but have only a ~20% precision.

We are on the verge of a revolution in our understanding of the Universe and our place within it. We expect more discoveries at the LHC (Supersymmetry, Extra dimensions, other?)

This is only the beginning!!!

March 2013 News



Following the data released by ATLAS and by CMS last March, we now call it a Higgs boson (instead of a Higgs-like boson)

The LHC is an Extraordinary Machine

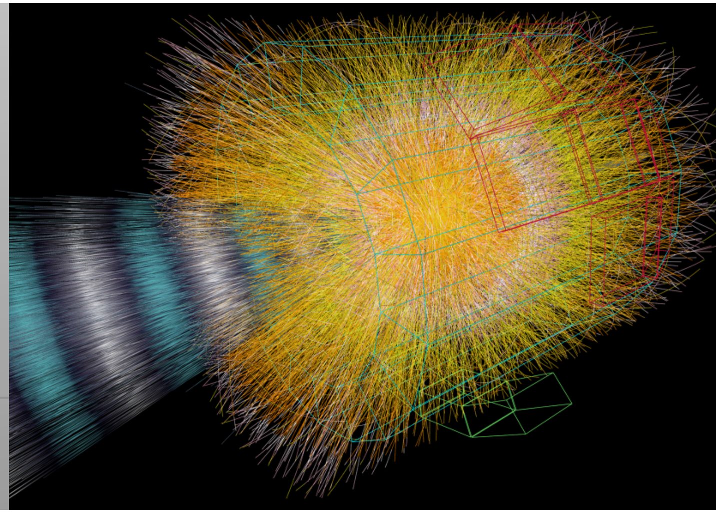
LHC facts

The LHC is …

Colder than the empty space in the Universe: 1.9K ie above absolute zero

The emptiest place in our solar system. The vacuum is better than on the moon

Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun



The Higgs Boson

The Washington Post
NATIONAL

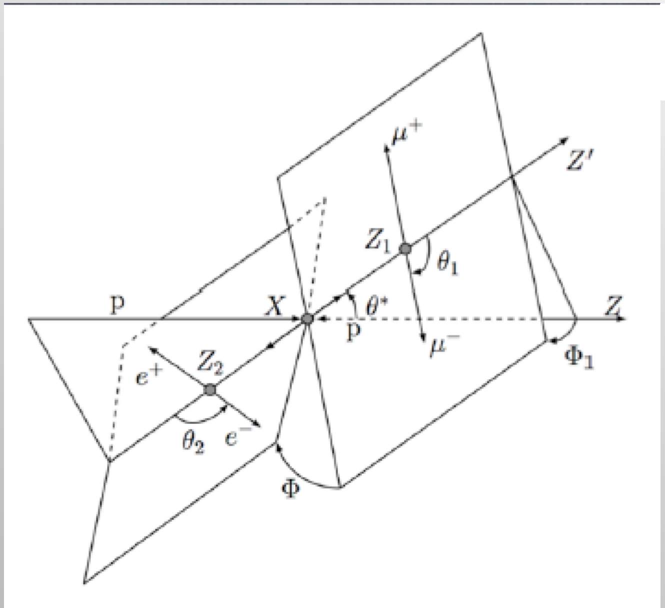
Spring 2012

Physicists hope to find the Higgs boson, key to unified field theory, this year

Fabrice Coffrini/Agence France-Presse via Getty Images - A superconducting solenoid magnet, the largest of its kind, is part of the Large Hadron Collider, which is searching for the Higgs boson.

The suspense was building up…

The Spin of the New Particle

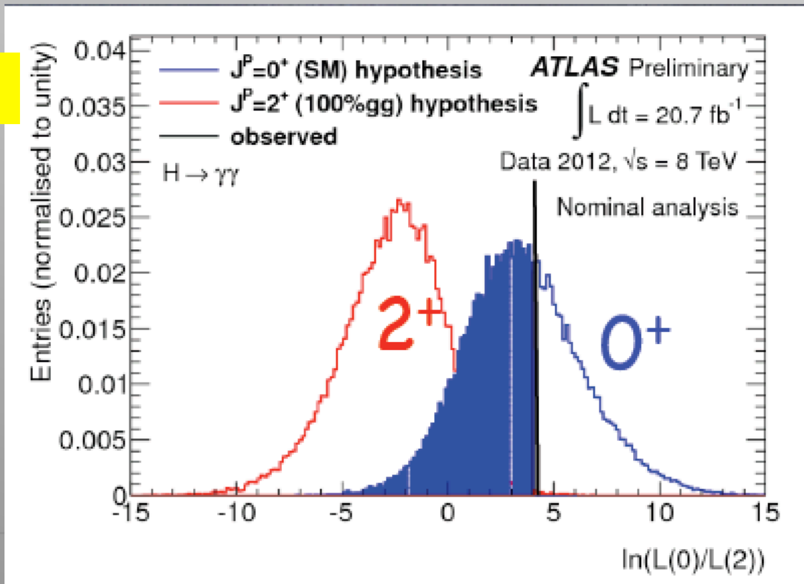


A Higgs particle should be a spin 0^+ state

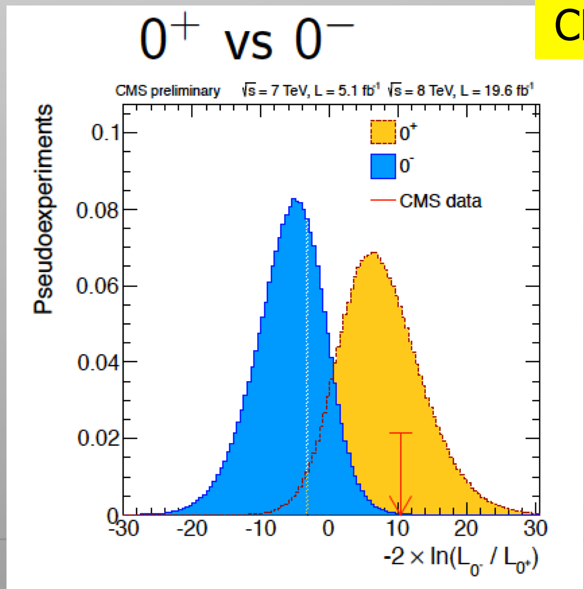
- Study angular correlations in the decays of the particle; build likelihoods and test spin- and parity hypotheses
- Use the ZZ, 2-photon and WW final states

=> Particle is consistent with a 0^+ state!!

ATLAS

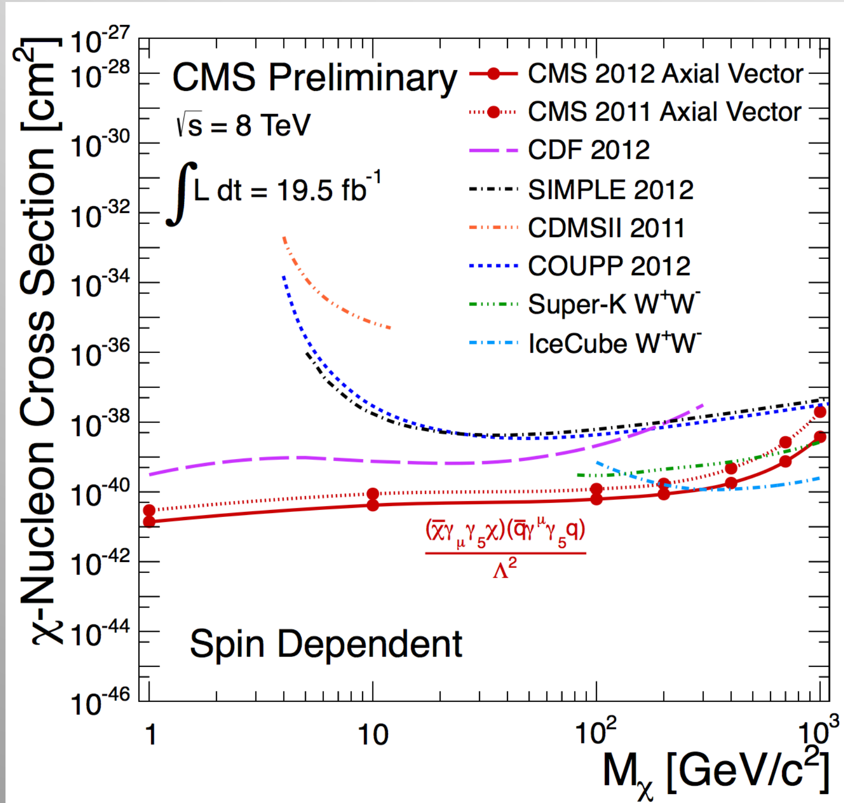


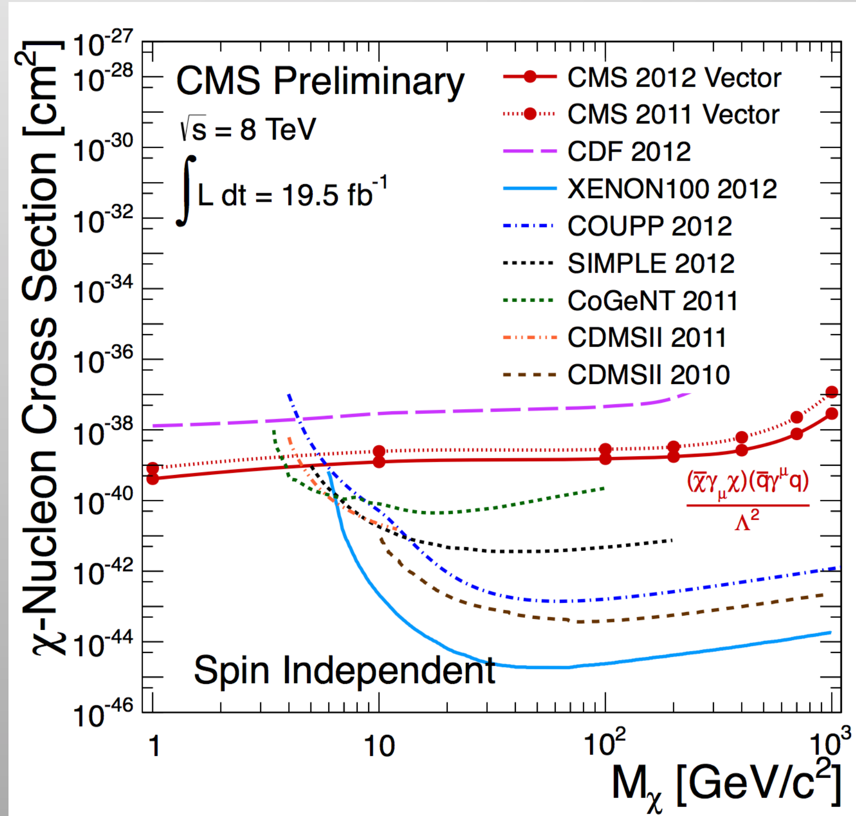
CMS



The Dark Matter Connection

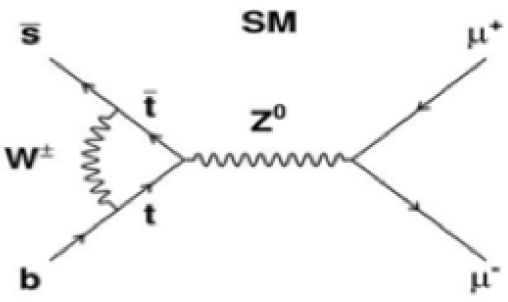
Results for direct searches and collider searches for Dark Matter
-> Spin dependent and spin independent cross sections of Dark Matter with ordinary matter (monojets searches)





Competitive limits with direct searches (under the effective theory assumptions)

Rare Decays: B_s to μμ Decays

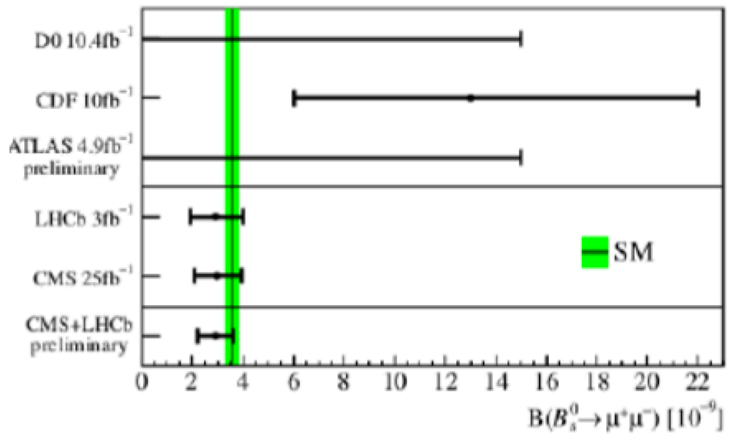


- A B_s particle is a particle consisting of a beauty-quark and strangeness-quark, with a mass of ~ 10 GeV
- Three B_s particles in a million will decay into two muons. This decay has been chased since 25 years.
- New physics modifies these Standard Models predictions

$$\text{BR}(B_s \to \mu^+\mu^-) = 3.56 \pm 0.29 \times 10^{-9}$$

Observation:

$$\text{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$



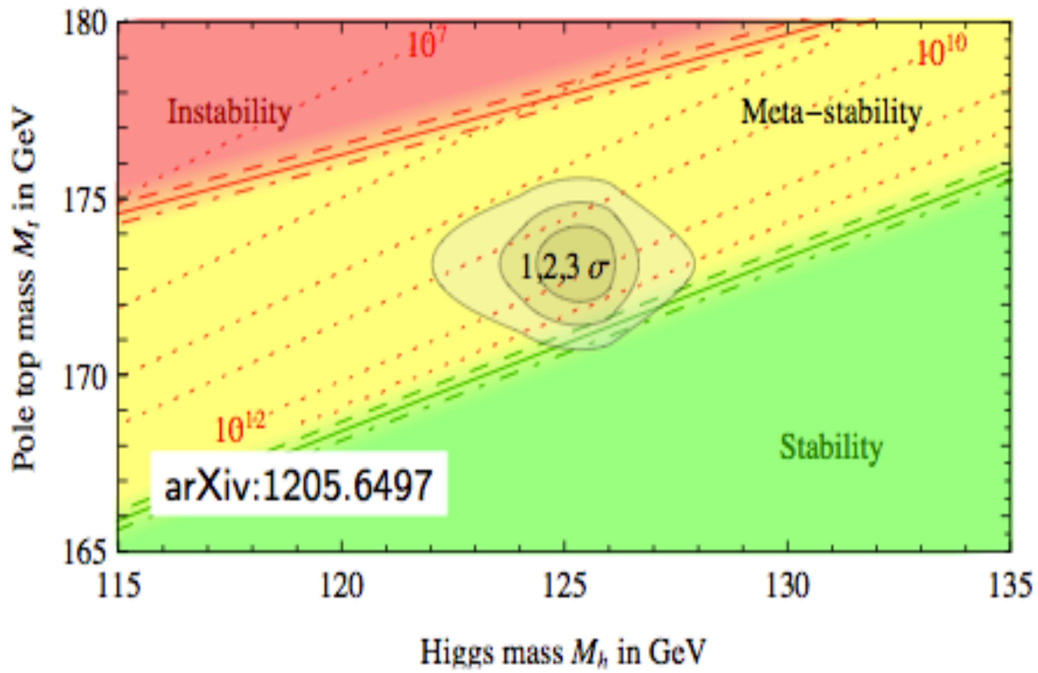
Results from LHCb +CMS experiment combined

And it continues…

- European physics society prize in July for the ATLAS and CMS experiments…
- Prestigious Prince of Asturias Award two weeks ago for CERN and Englert & Higgs…

Consequences for our Universe?

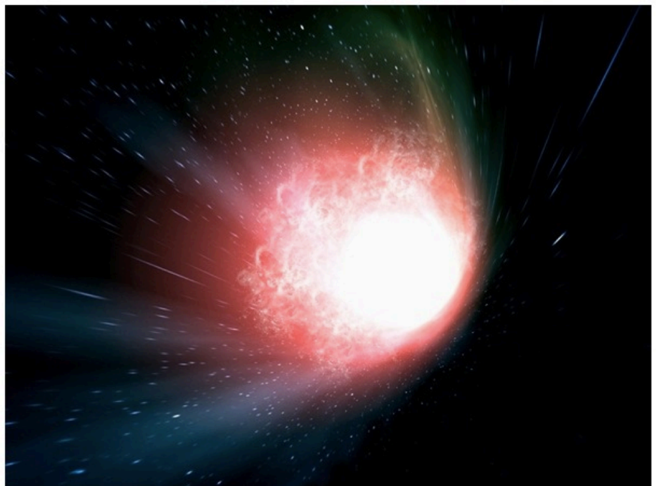
Important SM parameter → stability of EW vacuum



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

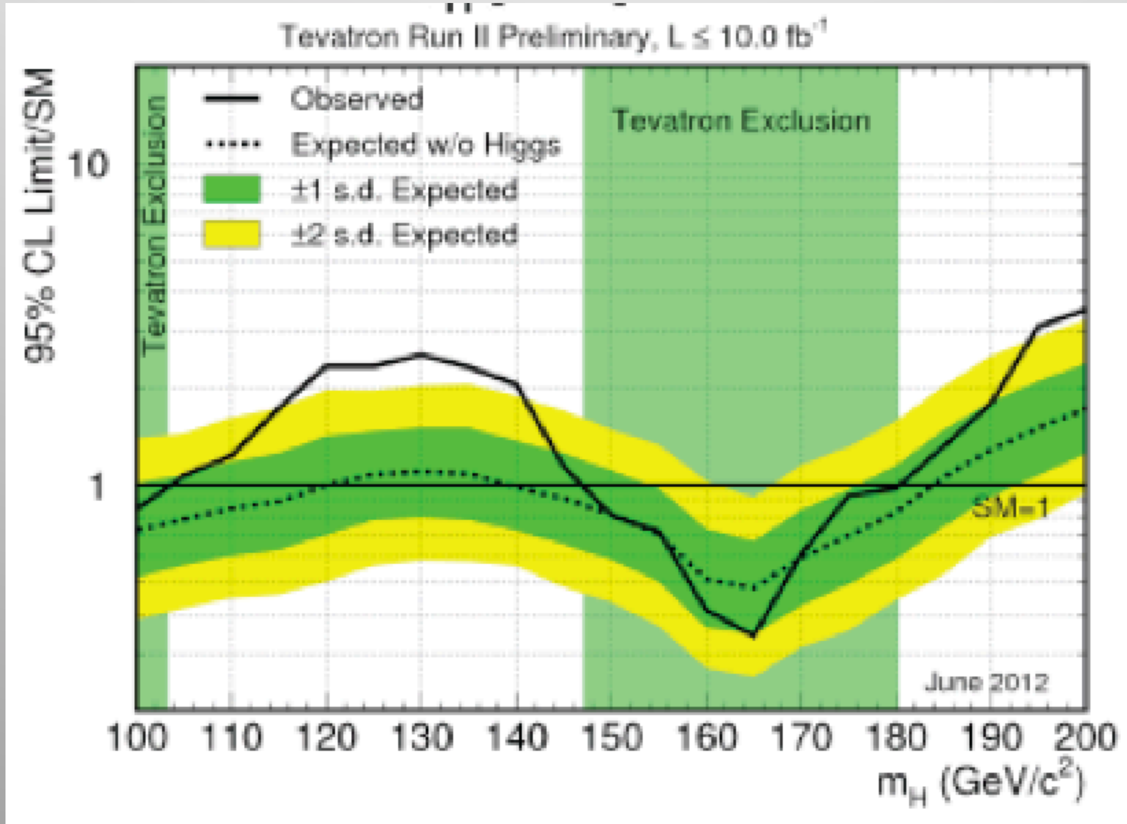
Our Universe meta-stable ? Will the Universe disappear in a Big Slurp? (NBCNEWS.com)

Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



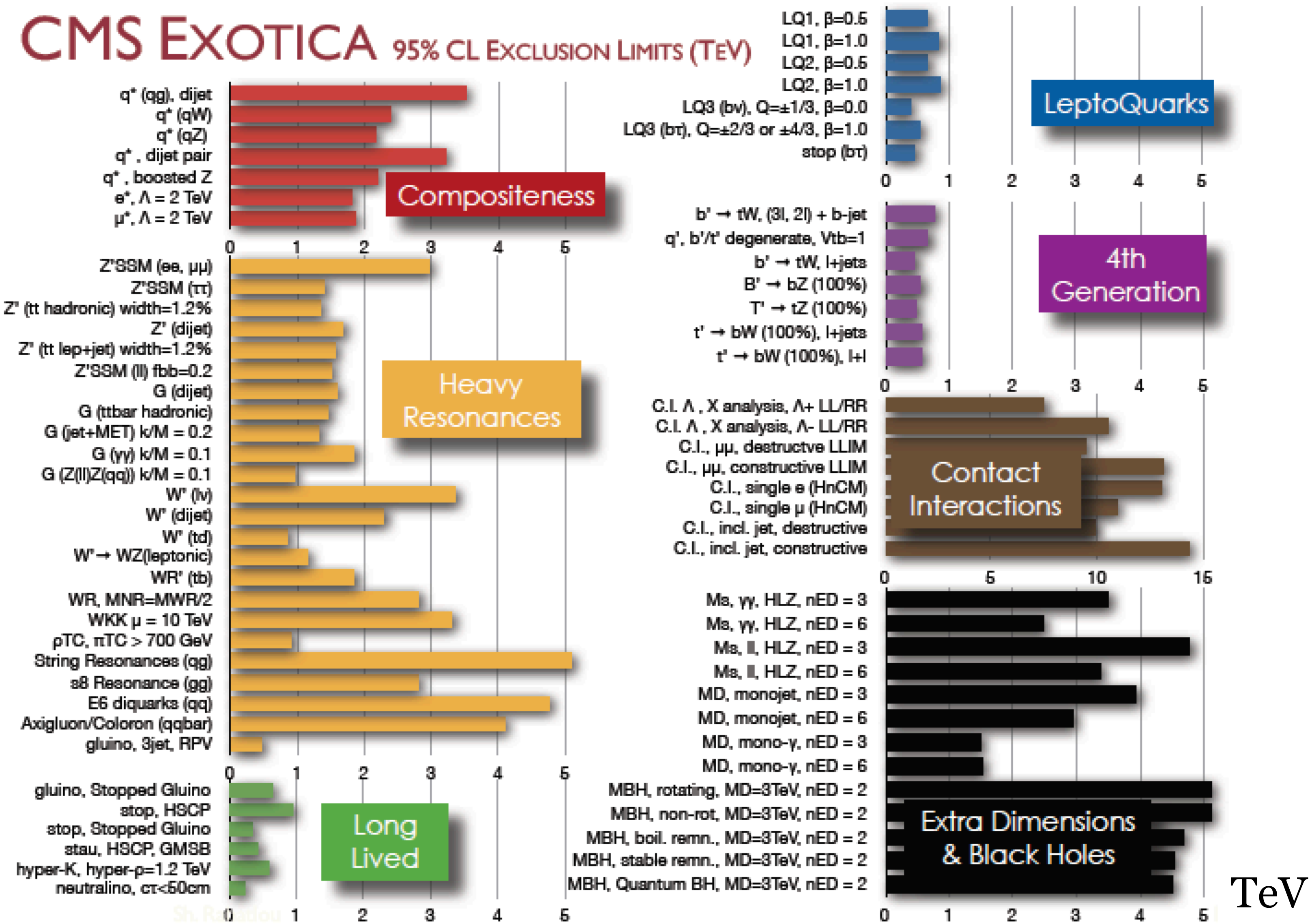
Searches at the Tevatron

In the last 10 years most information came from the Tevatron
This will be discussed in a separate lecture



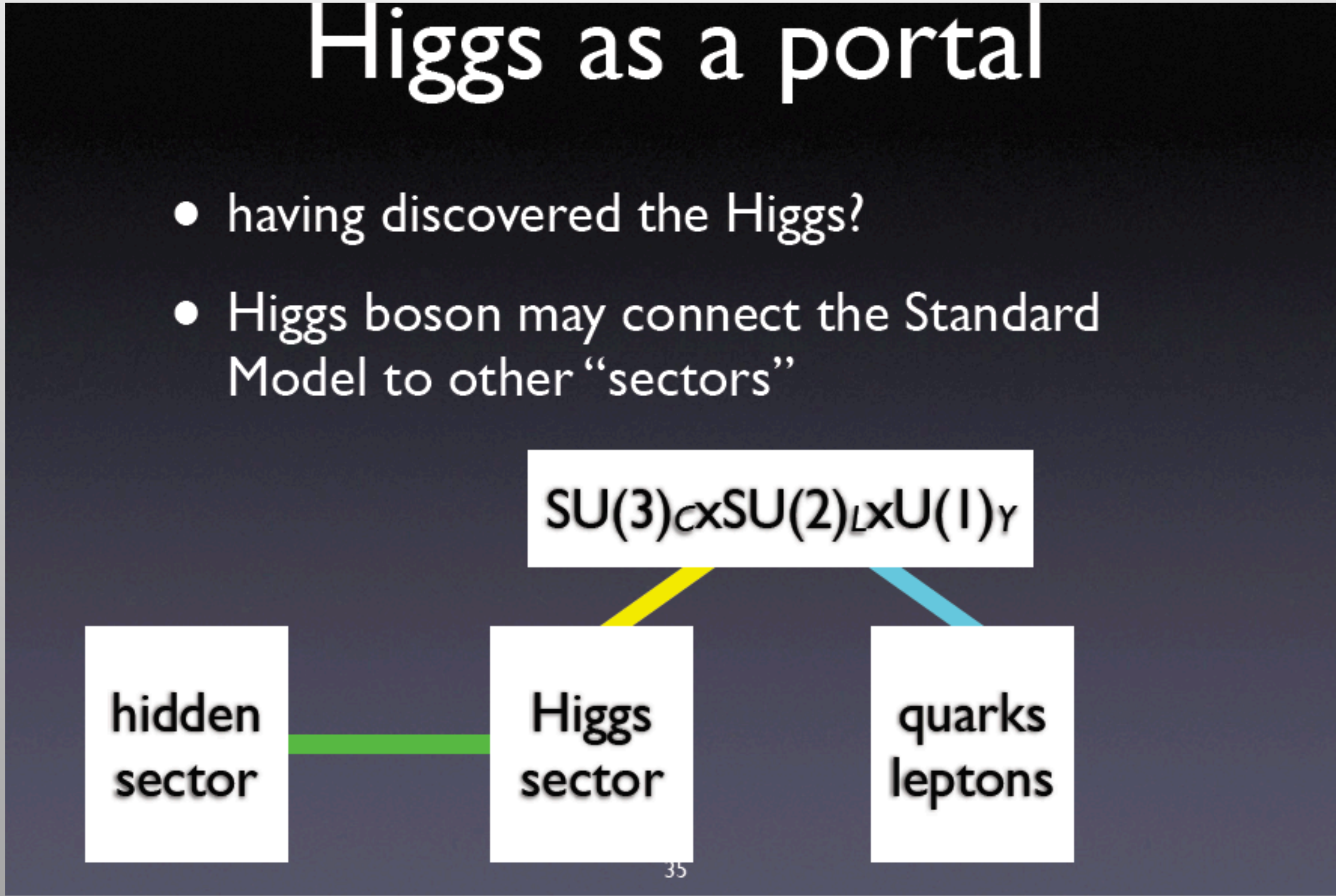
....An excess at M_H ~ 120-135 GeV !

Searches for Exotica



*similar results obtained by ATLAS

What is Next?



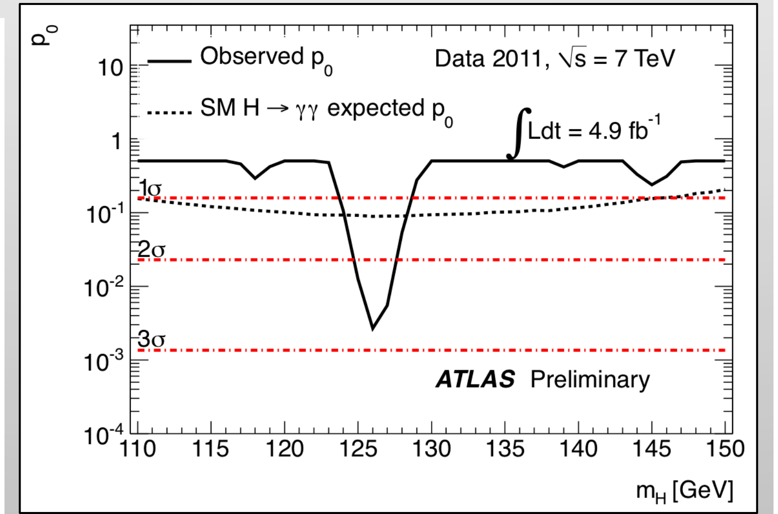
Need for precision measurements with ~100x the present statistics

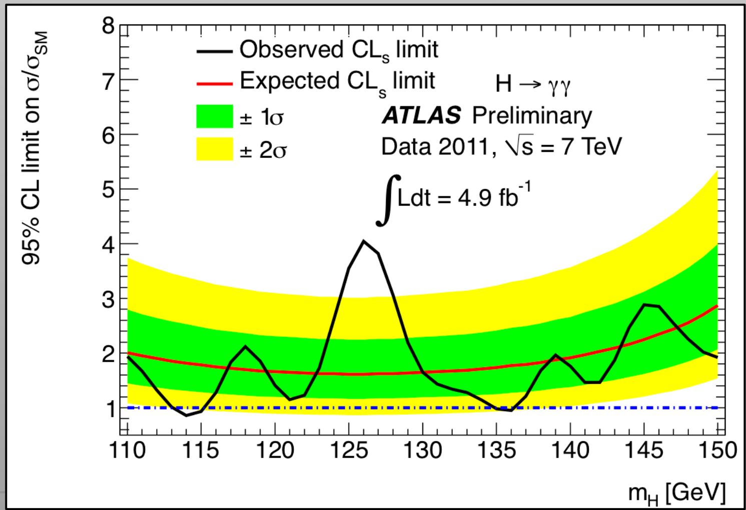
LHC upgrade ! Experiment upgrades!! (Other machines?)

Aside :Profile likelihood Ratio, p_0 and CL_s

- Local significance p_0 to test background hypothesis

- $CL_s = CL_{s+b}/CL_b$ (log-likelihood ratio) to test signal hypothesis





3 sigma= "Evidence"

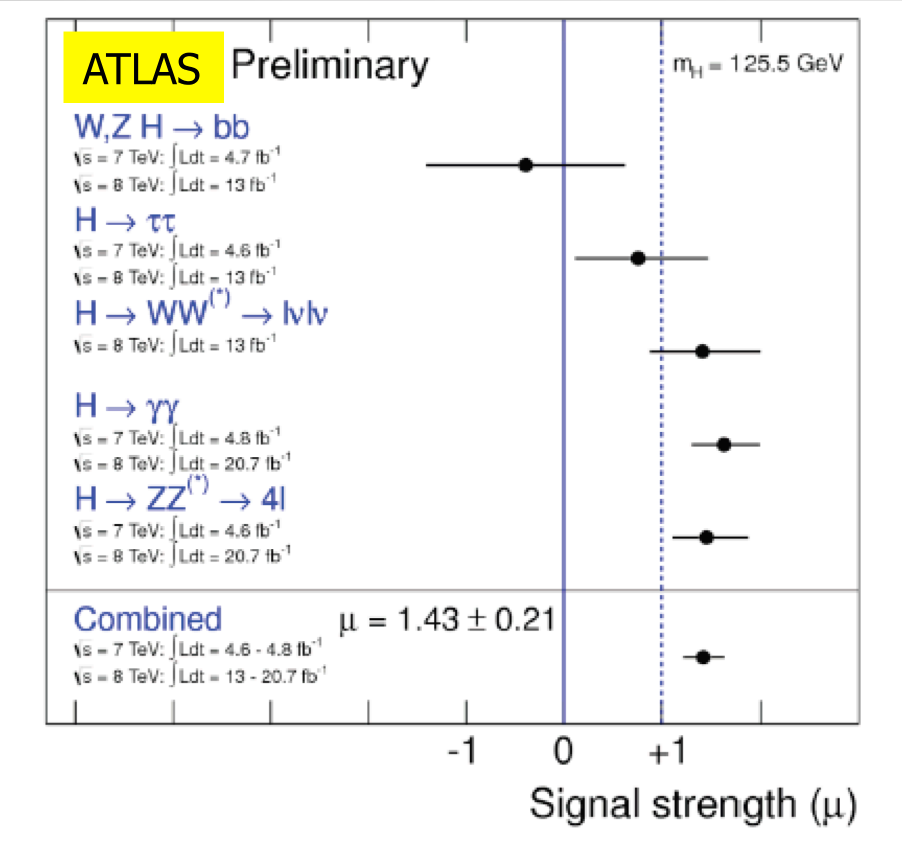
1 chance in 1000 to be wrong!

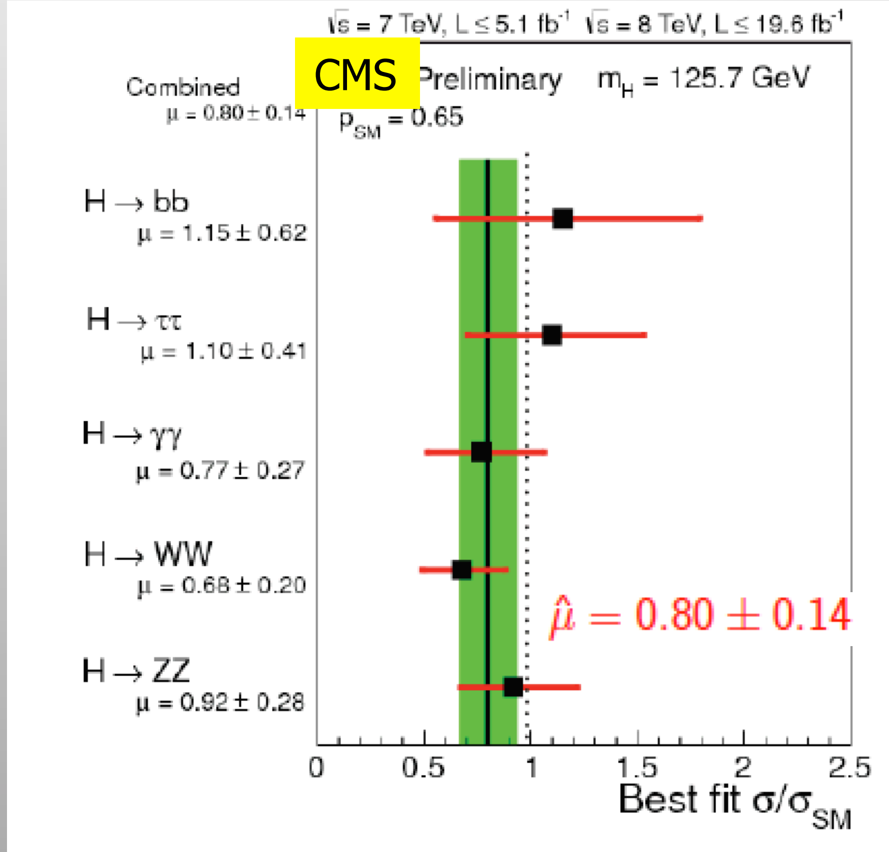
5 sigma="Discovery"

1 chance in 3 million To be wrong!!!

Signal Strength

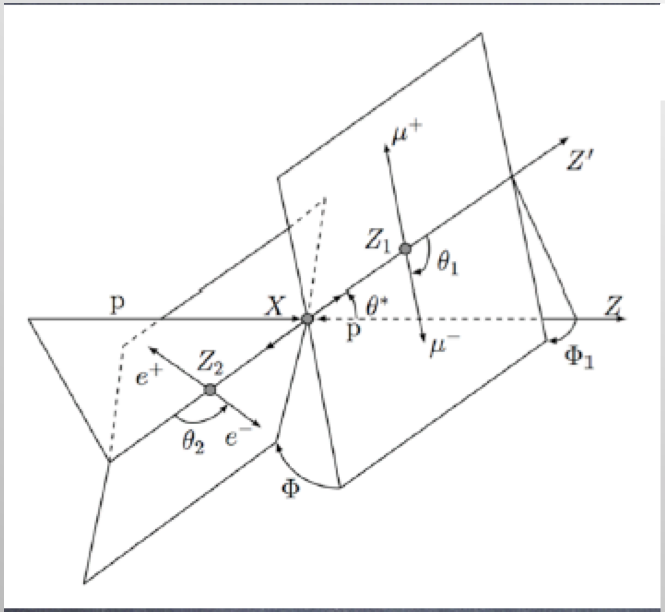
•Signal strength μ is the observed over Standard Model expected cross section
•For μ=1 the production rate is compatible with Standard Model expectation





ATLAS a bit above and CMS a bit below μ=1…

The Spin of the New Particle

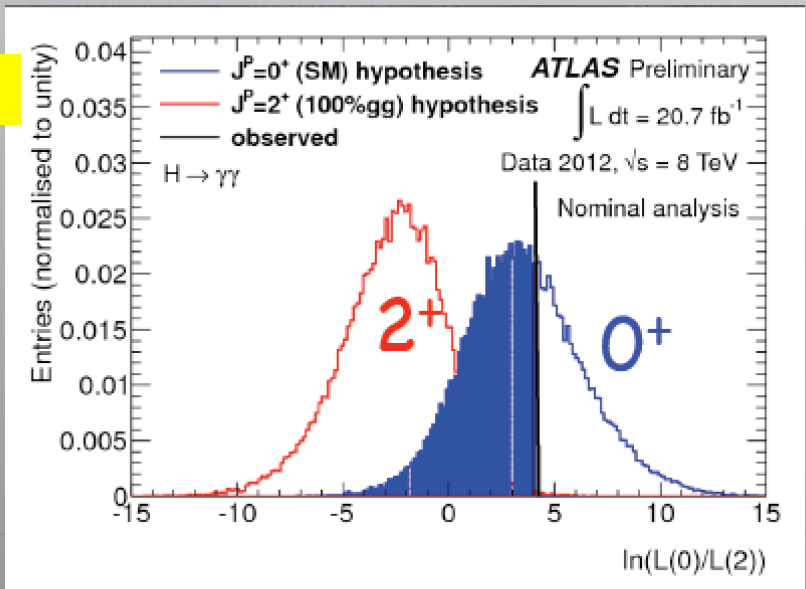


A Higgs particle should be a spin 0^+ state

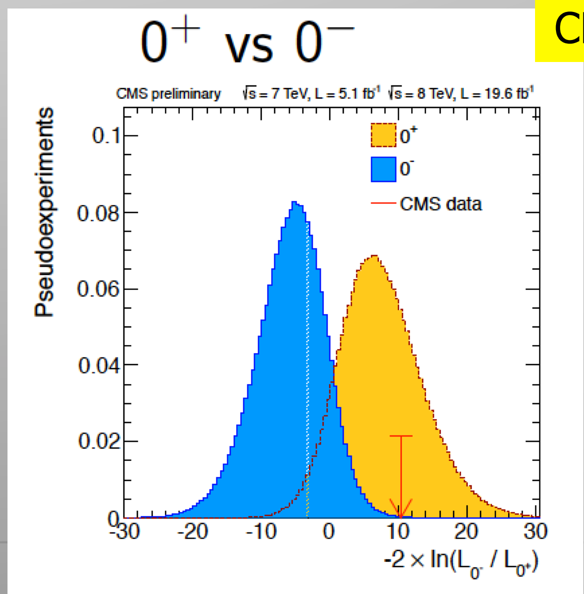
- Study angular correlations in the decays of the particle; build likelihoods and test spin- and parity hypotheses
- Use the ZZ, 2-photon and WW final states

=> Particle is consistent with a 0^+ state!!

ATLAS

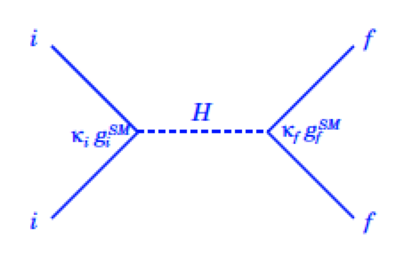


CMS

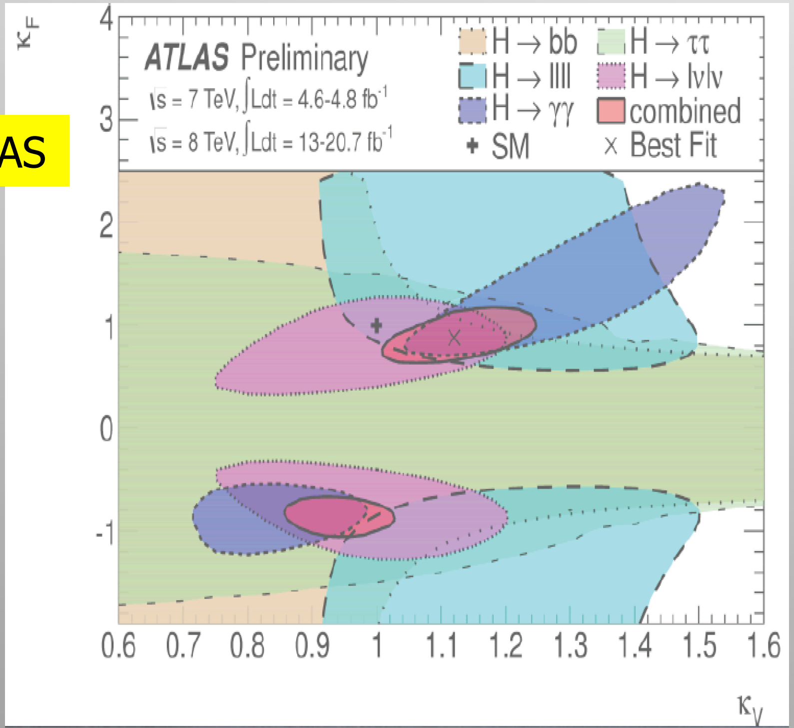


Couplings to the New Particle

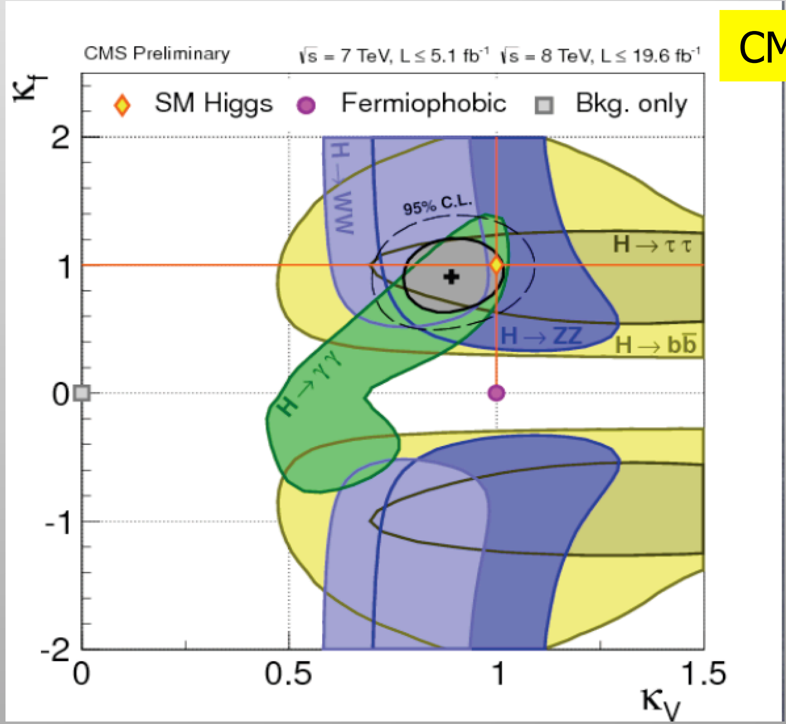
- Use information of all production and decay channels
- κ_f and κ_V are scale factors w.r.t. the Standard Model values for fermions and vector bosons



ATLAS



CMS



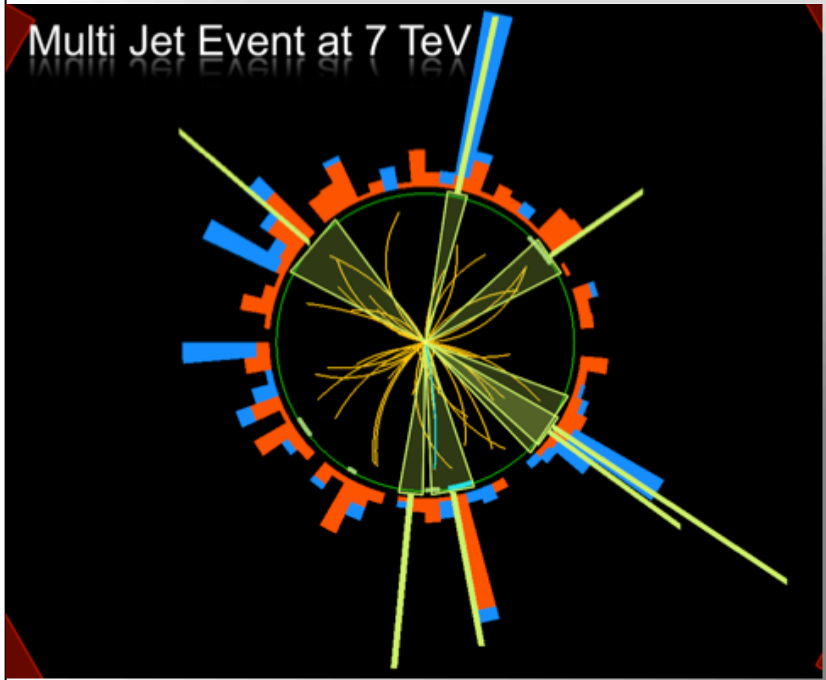
⇒ Couplings compatible Standard Model values, but large uncertainties

…Future data will decide…

A Timely Lecture

2013 Nobel Prize in Physics

- 8 October 2013: Prof. François Englert and Prof. Peter W. Higgs were jointly awarded the Nobel Prize in Physics "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”
- This seminar will discuss the discovery of the particle…



Outline

- Introduction: The LHC and the boson Hunter experiments
- The birth of a new particle: The discovery of a new kind of fundamental particle:

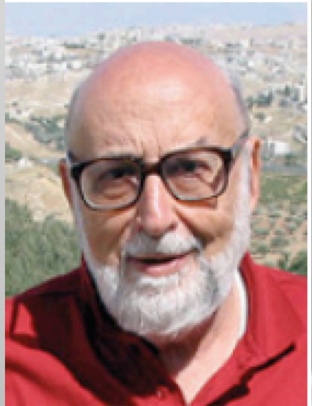
  A Higgs Boson
- Studies of its properties
- What is next?
- Summary

(*) I will mostly use that name throughout.

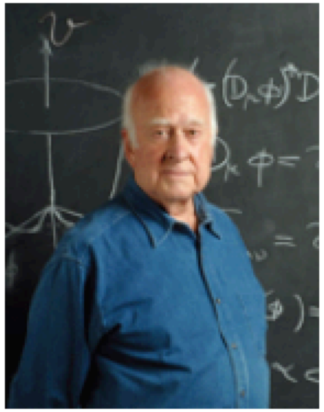
EWSB Heroics

The year is 1964

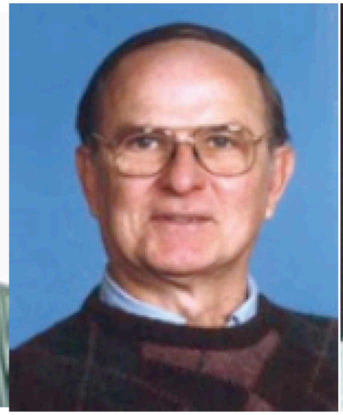
Electroweak Symmetry Breaking


François Englert


Robert Brout


Peter Higgs


Gerald Guralnik


Carl Hagen


Tom Kibble

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

+ others could be mentioned, that have inspired those above

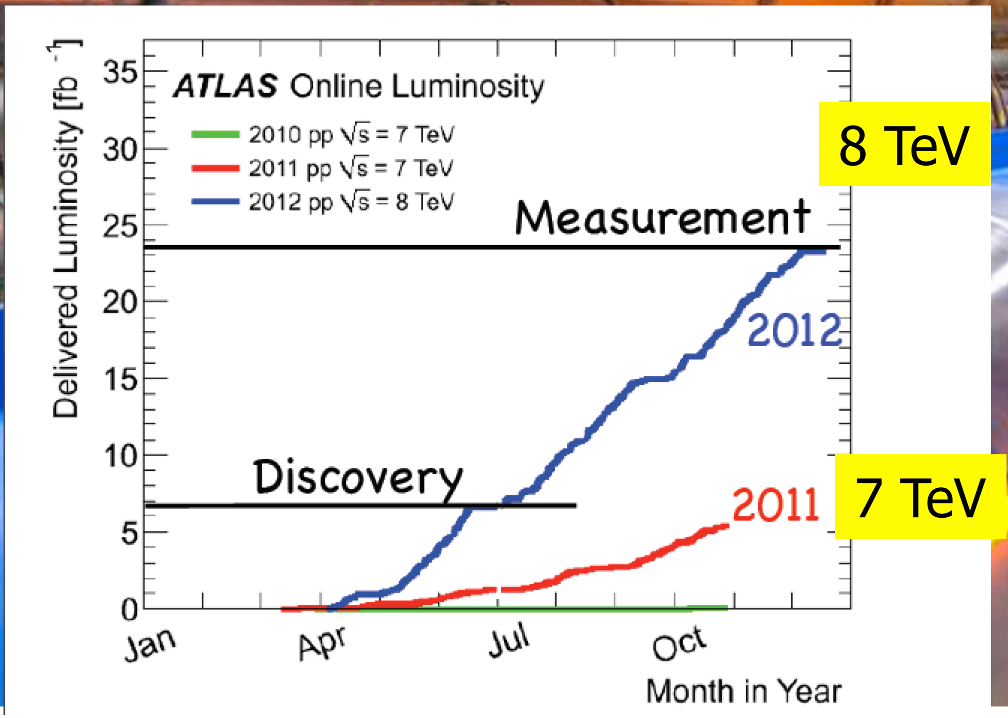
A Propos: What is in a Name?

- In 1964 Peter Higgs, and Francois Englert & Robert Brout introduce scalar fields as a solution to EWSB. Peter Higgs mentions as a side-remark that there should be a particle associated with these fields in his second paper.
- Steve Weinberg picks up the idea for the Standard Model formulation at the end of the 60's. Benjamin Lee coins at ICHEP 1972 the particle as 'Higgs' particle. The name stuck…
- In recent years some new proposals have been tried such as:
  - The Brout-Englert-Higgs particle (BEH particle)
  - The Electro-weak fundamental scalar
  - The Standard Model Boson (SMS)

  None really got stuck so far: the Particle Data Group & community is used to 40 years of then name "Higgs particle"
- We do call it the "Brout-Englert-Higgs Mechanism"

See eg. "The Particle at the End of the Universe" by Sean Carroll

- Several thousand billion protons
- Each with the energy of a fly
- 99.9999991% of light speed
- They orbit a 27km ring 11 000 times/second
- A billion collisions a second in the experiments



Luminosity = # events/cross section/time

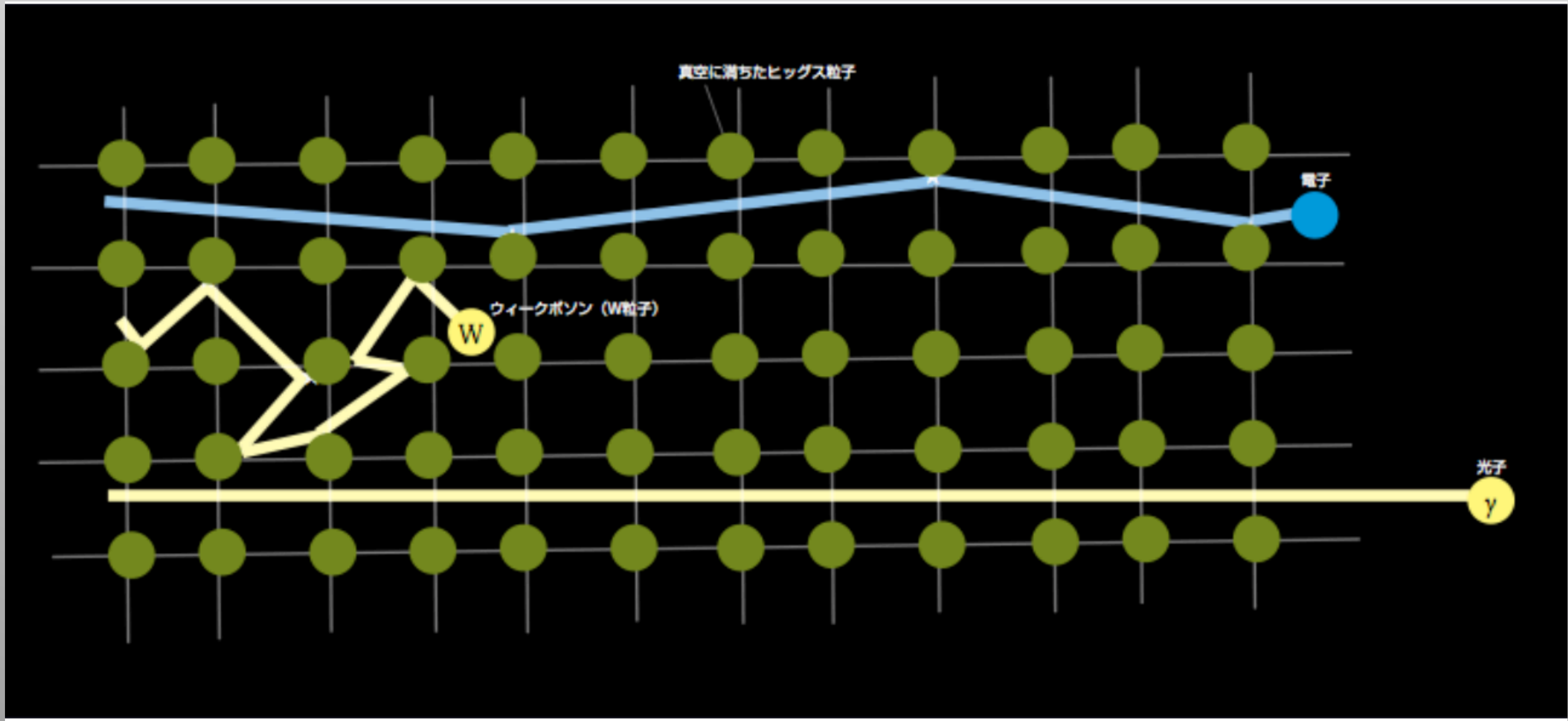
LHC operation is now stopped for 2 years, and the machine is being prepared for running at 13-14 TeV from 2015 onwards

100 meter underground


Power consumption ~ 100 MW
= 60% of one Aswan Turbine
Aswan can power 20 LHCs

The Higgs Field

Another view of the Higgs field



Electron
light

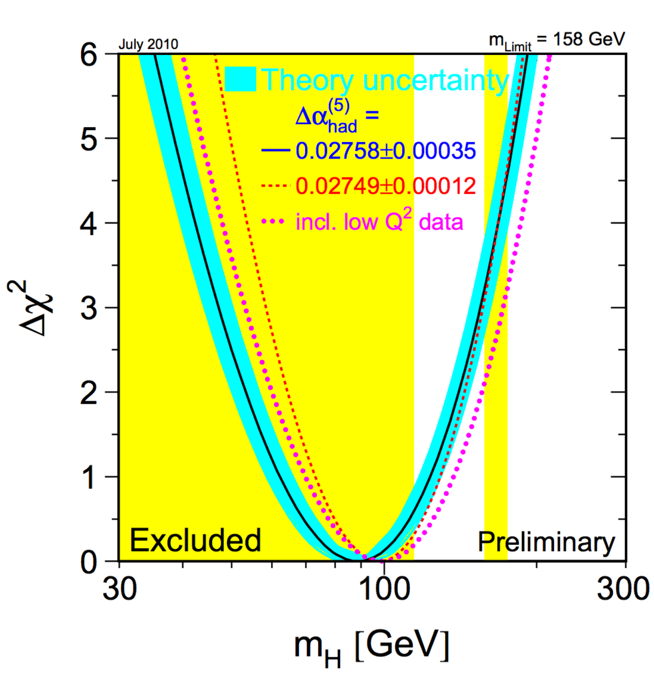
W-boson
Heavy

Photon
no mass

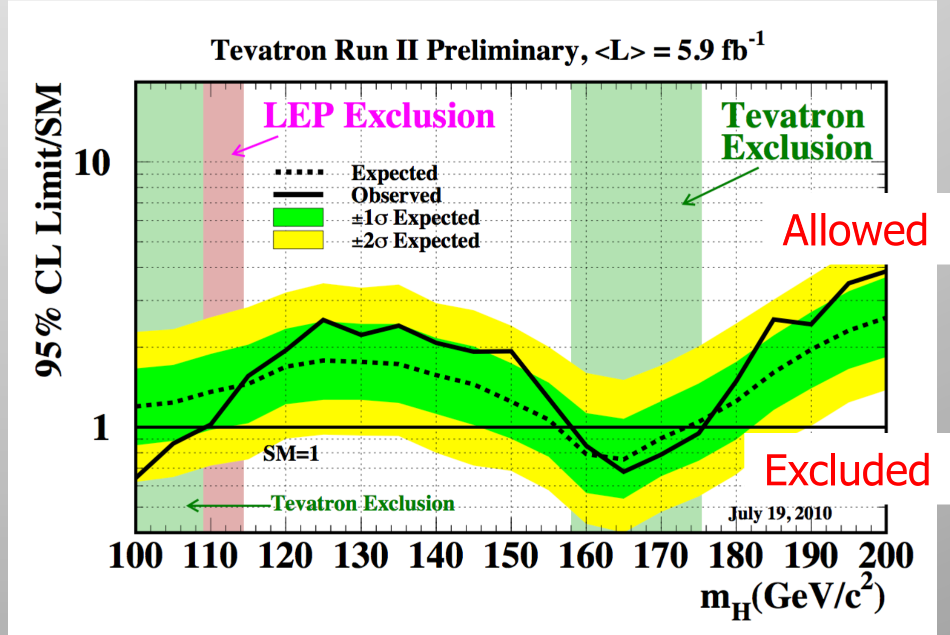
Pre-LHC: Higgs Searches in 2010

- •Searches for the Higgs particle started end of the '70's and 80's
- •Stringent results came in the '90's from the LEP and Tevatron accelerators

Precision Measurements (LEP…)



Tevatron p anti-p collisions at 1.96 TeV



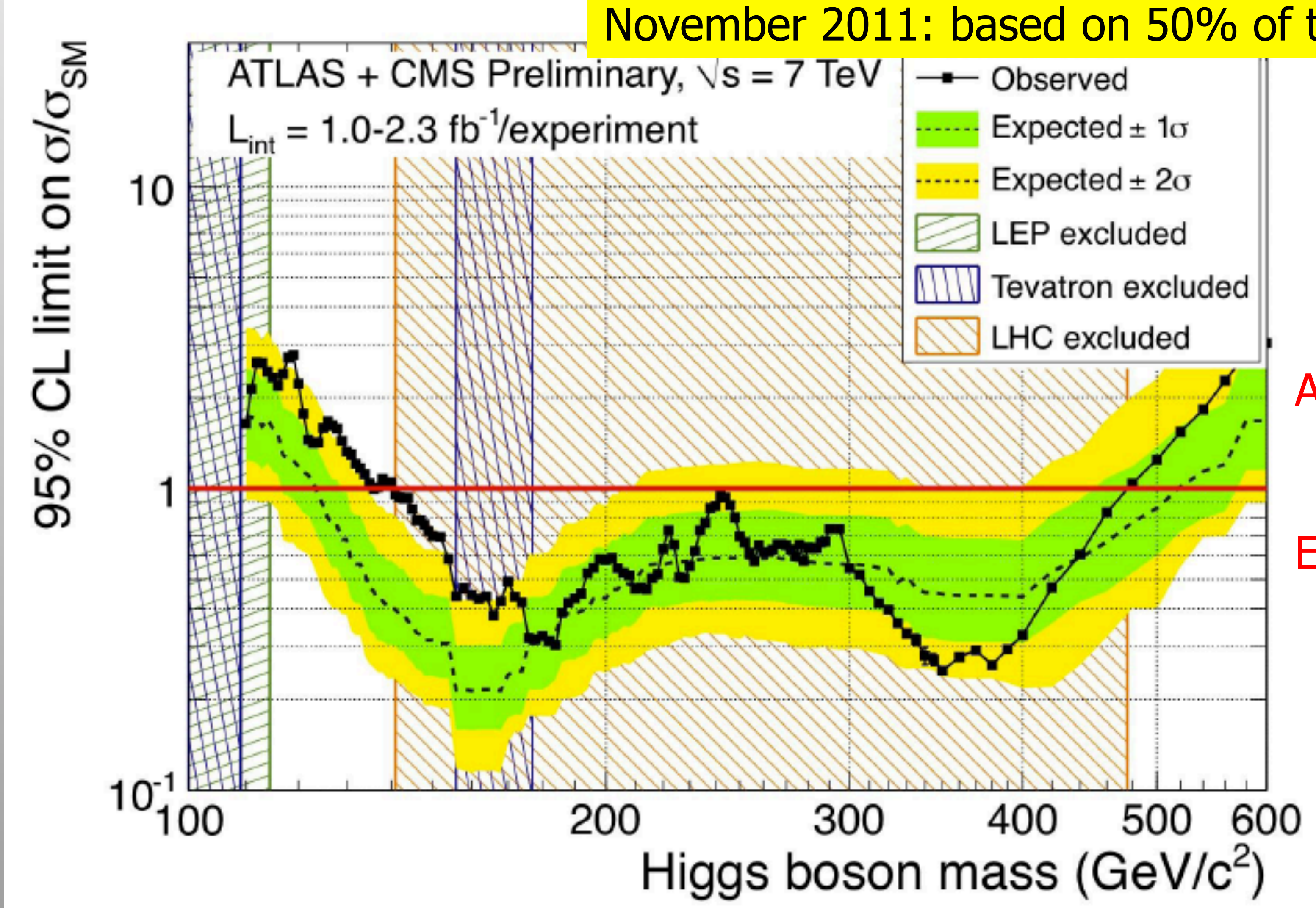
- •Direct exclusion M_H< 114 GeV
- •Results from quantum corrections: favorite mass M_H= 92+/-34 GeV

- •Direct exclusion: M_H = 158-176 GeV

….Enter the LHC !

Higgs Search in 2011

November 2011: based on 50% of the data



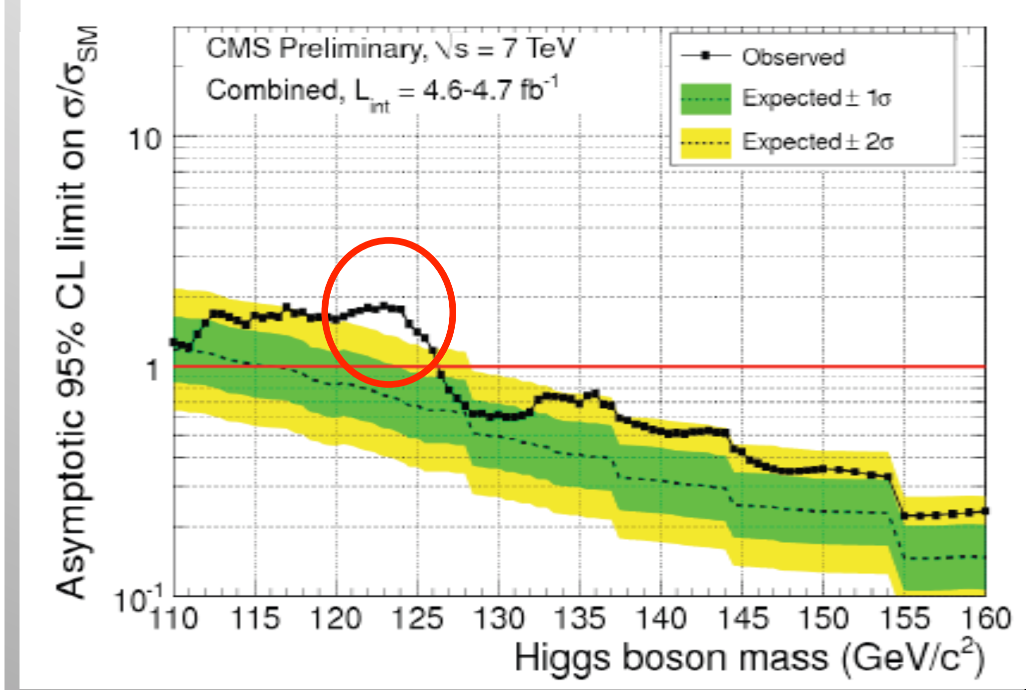
Allowed

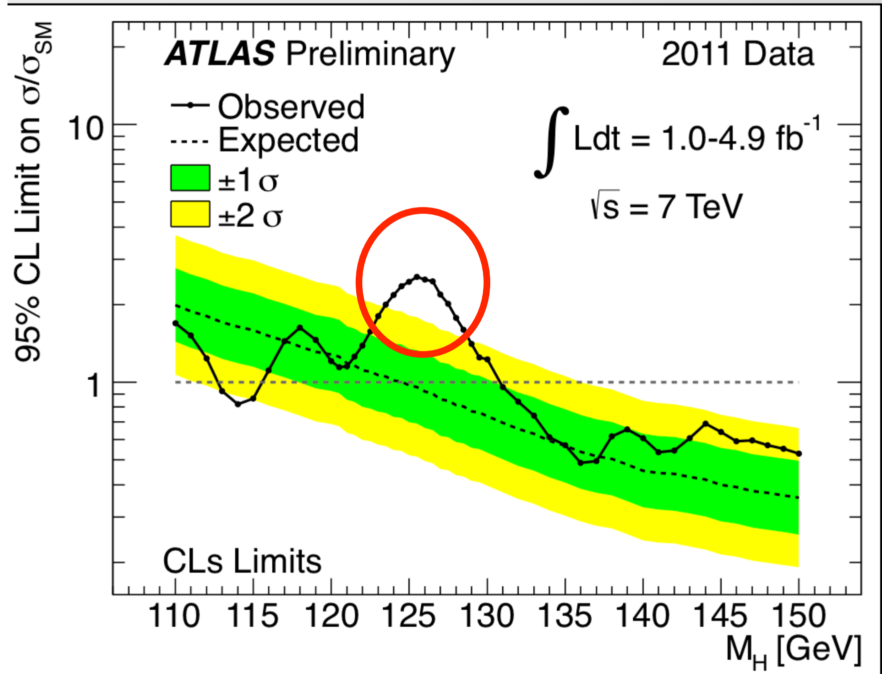
Excluded

No sign of a new particle yet, but mass limited to 114.4 -141 GeV or >476 GeV

The Higgs Search by December 2011

December 2011: based on 100% of the data





All the data from 2011 was now analysed and the combination the decay channels showed the following:

-We see – for the first time-- an excess of events building up in a region over expectation from pure background. Cool!

Is this the first sign of the ‘growing Higgs signal?

Higgs Phenomenology Starting 1975

- Neutral currents (1973)
- Charm (1974)
- Heavy lepton τ (1975)
- Attention to search for $W^{\pm}$, Z^0
- **For us, the Big Issue: is there a Higgs boson?**
- Previously ~ 10 papers on Higgs bosons
- M_H > 18 MeV
- We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

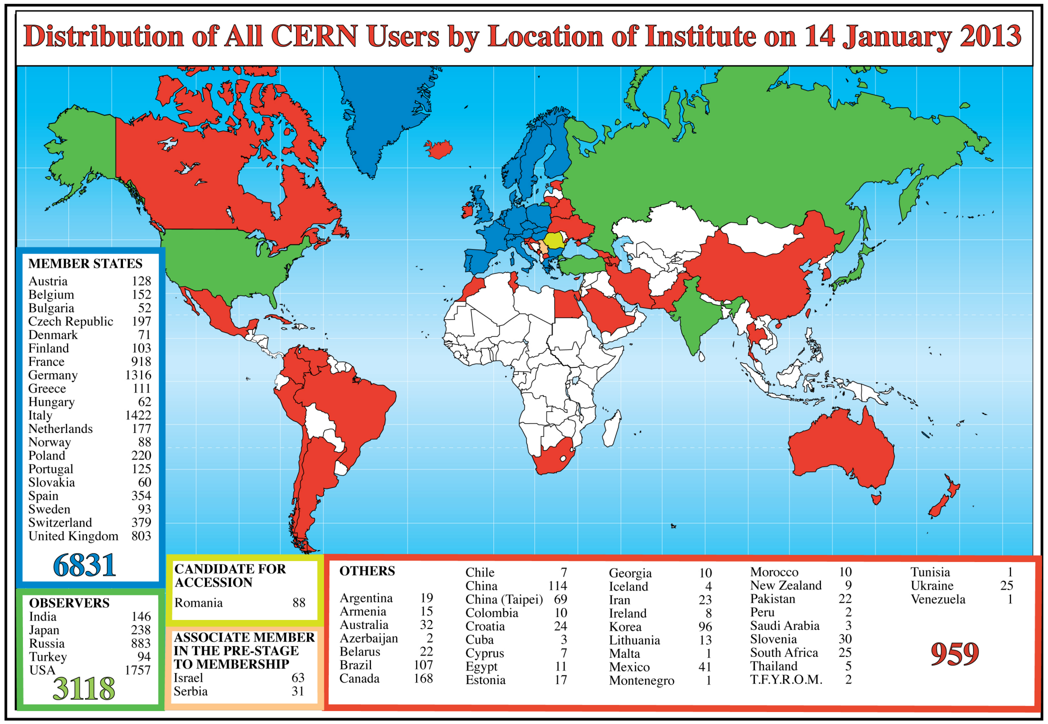
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

CERN: The European Laboratory for Particle Physics

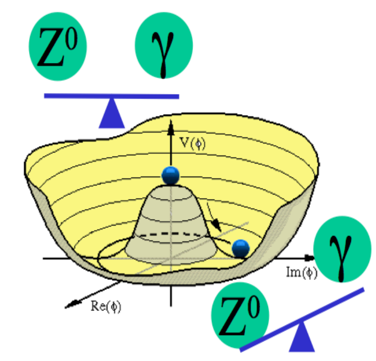
- CERN is the European Organization for Nuclear Research, the world's largest Particle Physics Centre, near Geneva, Switzerland
- It is now commonly referred to as European Laboratory for Particle Physics
- It was founded in 1954 and has 20 member states + several observer states
- CERN employes >3000 people + hosts ~11000 visitors from >500 universities.
- Annual budget ~ 1200 MCHF/year (2013)



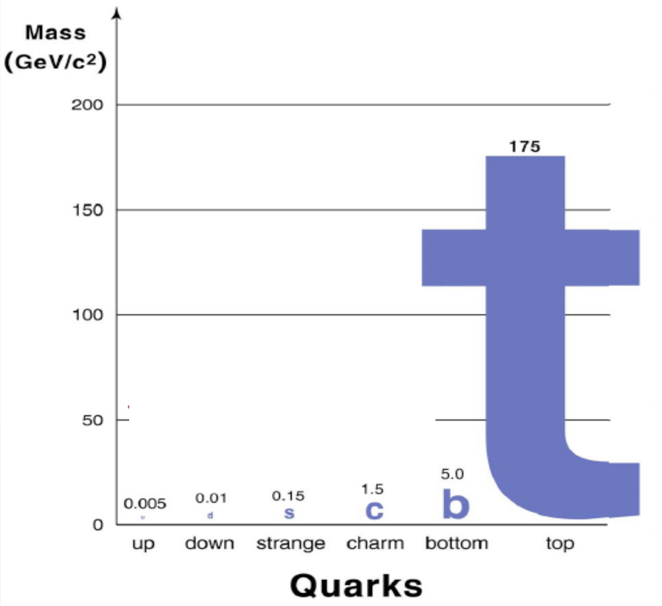
Where the World Wide Web was born...

The Origin of Particle Masses

- At 'low' energy the Weak force is much weaker than the Electromagnetic force: Electroweak Symmetry Breaking: EWSB
- The W an Z bosons are very massive (~ 100 proton masses) while the photon is massless.
- The proposed mechanism(*) in 1964 gives mass to W and Z bosons and predicts the existence of a new elementary 'Higgs' particle,. Extend the mechanism to give mass to the Fermions via Yukawa couplings.



(*) Brout , Englert, Higgs, Kibble, Hagen and Guralnik, …



The Higgs (H) boson is the quantum of the new postulated field and has been searched for since decades at other particle colliders such as LEP and the Tevatron, and now at the Large Hadron Collider @ CERN

Blinding the Data

Not to have a bias in the analysis we decided to analyse the 2012 data blinded
The unblinding in CMS was on June 15th 2012
About 900 participants (400 persons in a room for 250 people, rest by video)

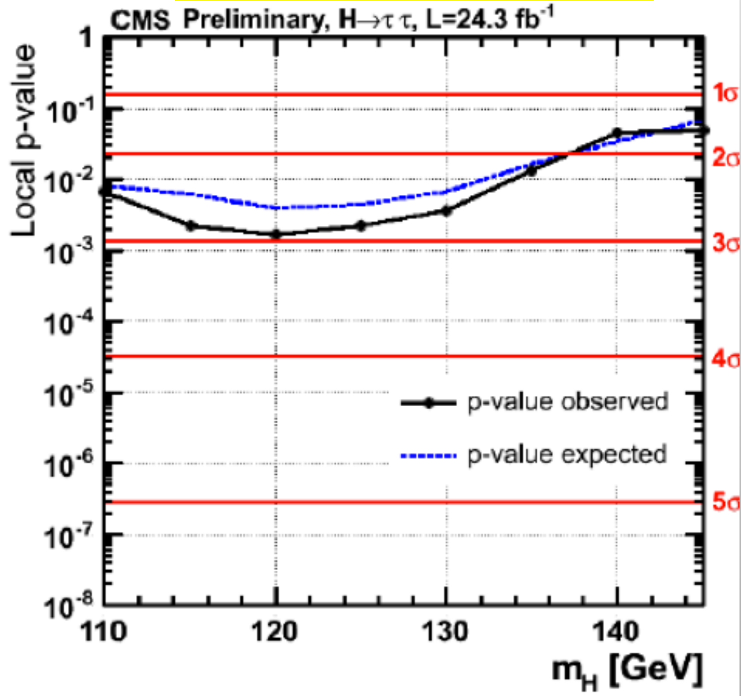
That day CMS knew whether they had a discovery or not…

Does this Particle Decay into Fermions?

- The BEH Mechanism was proposed in 1964 to give mass to the W and Z boson
- Does it also give mass to the fermions? Does the particle couple to fermions?

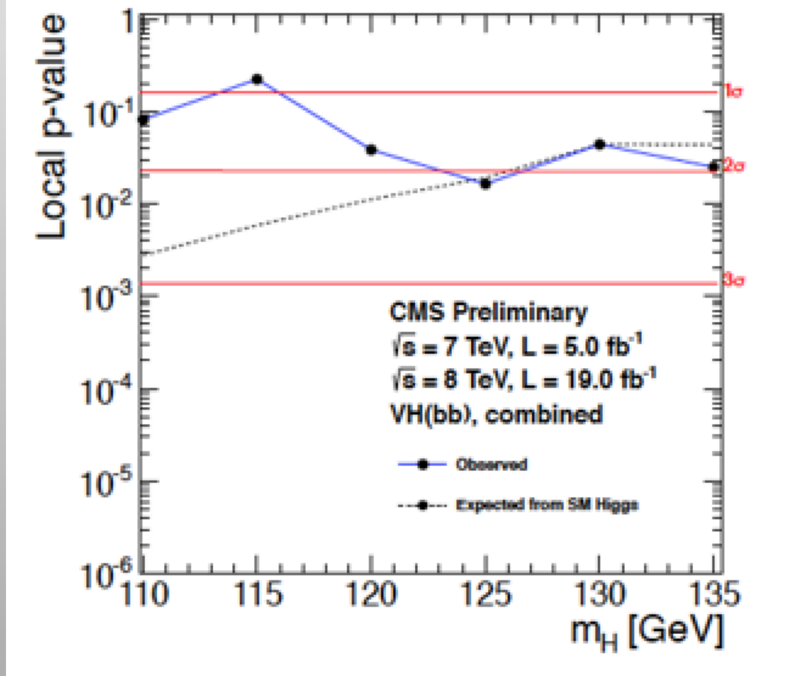
  ⇒ Direct test: check for the decays H→ tau tau and H → b quark pairs

Higgs →ττ leptons



Significance 2.85σ at 125 GeV

Higgs → b-quark pairs



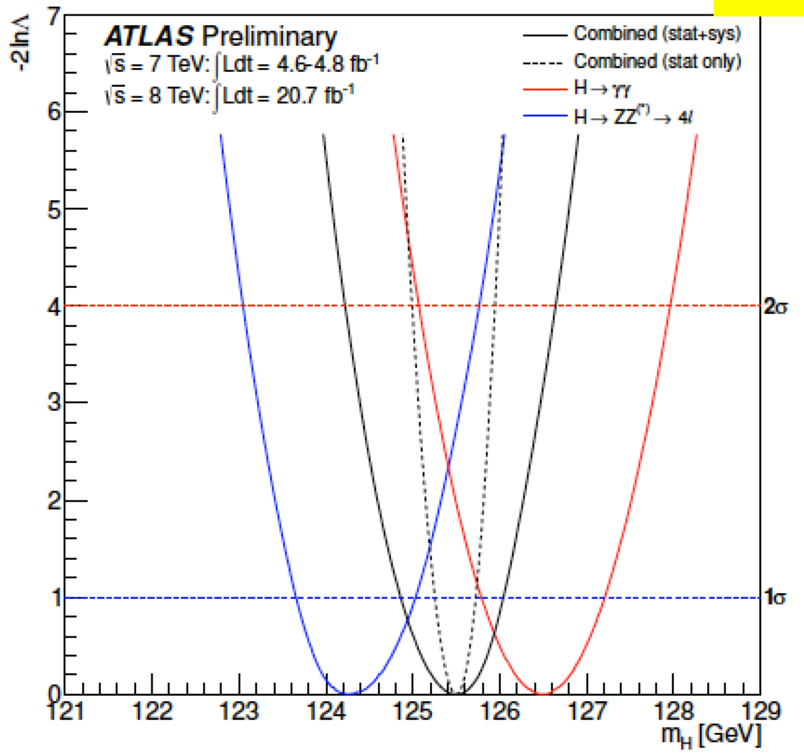
Significance 2.1σ at 125 GeV

Yes: A mild excess is building up also for these channels!!

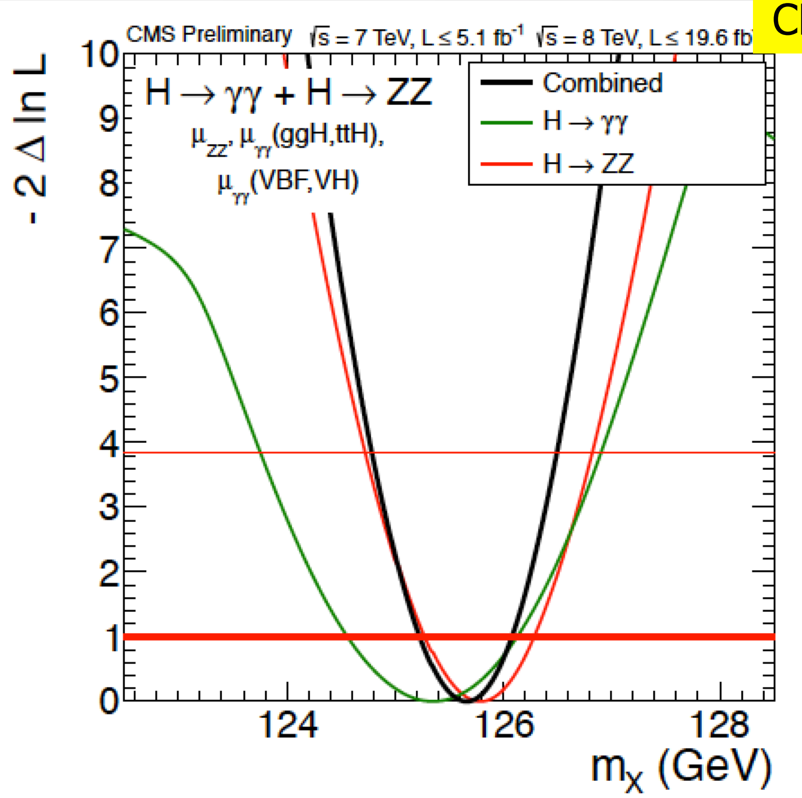
The Mass of the Particle

Determine the mass from ZZ and 2-photon channels which show a peak!

ATLAS



CMS



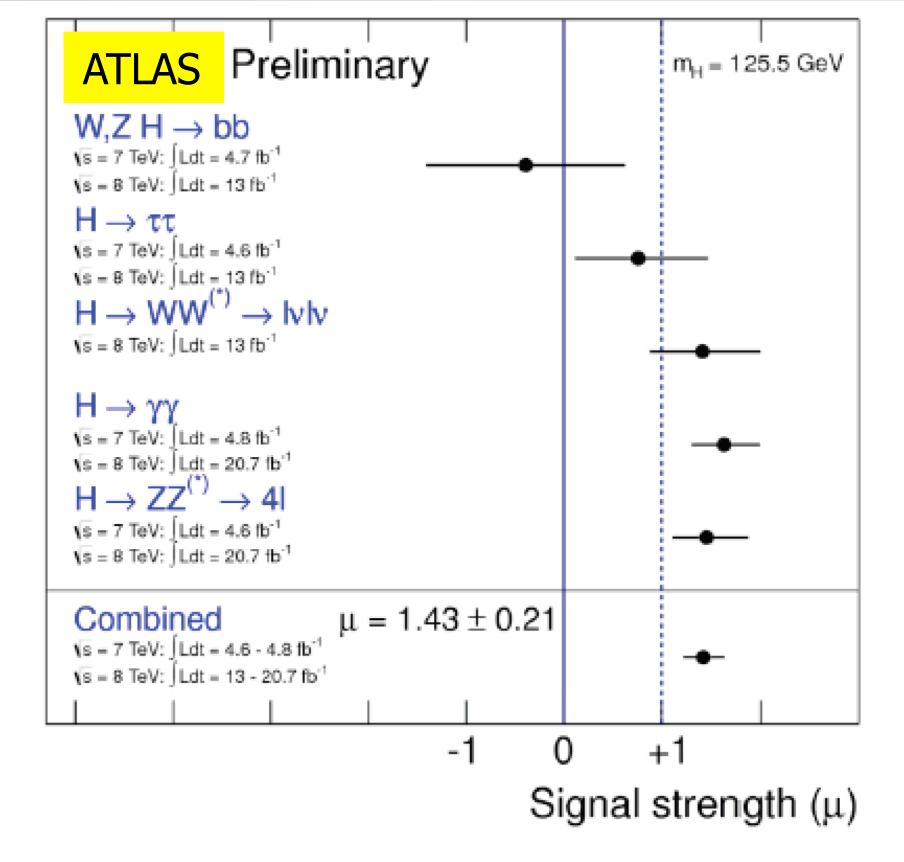
$\hat{m}_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)\ \mathrm{GeV}$

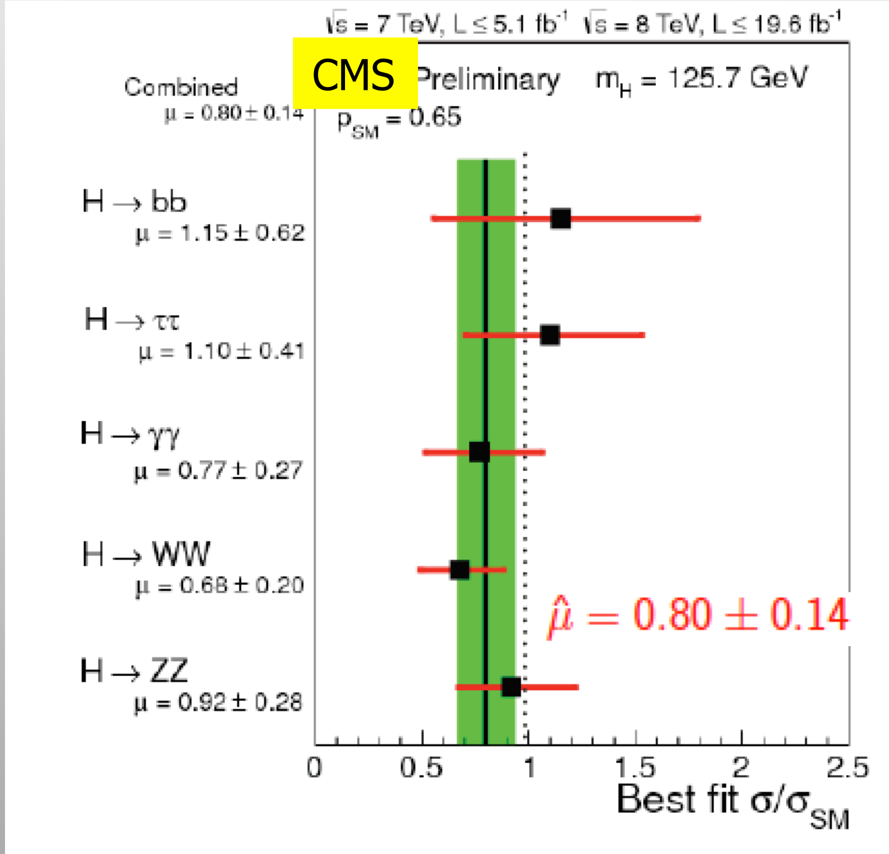
$\hat{m}_H = 125.7 \pm 0.3(stat) \pm 0.3(syst)\ \mathrm{GeV}$

ATLAS and CMS observe the same particle!! ☺

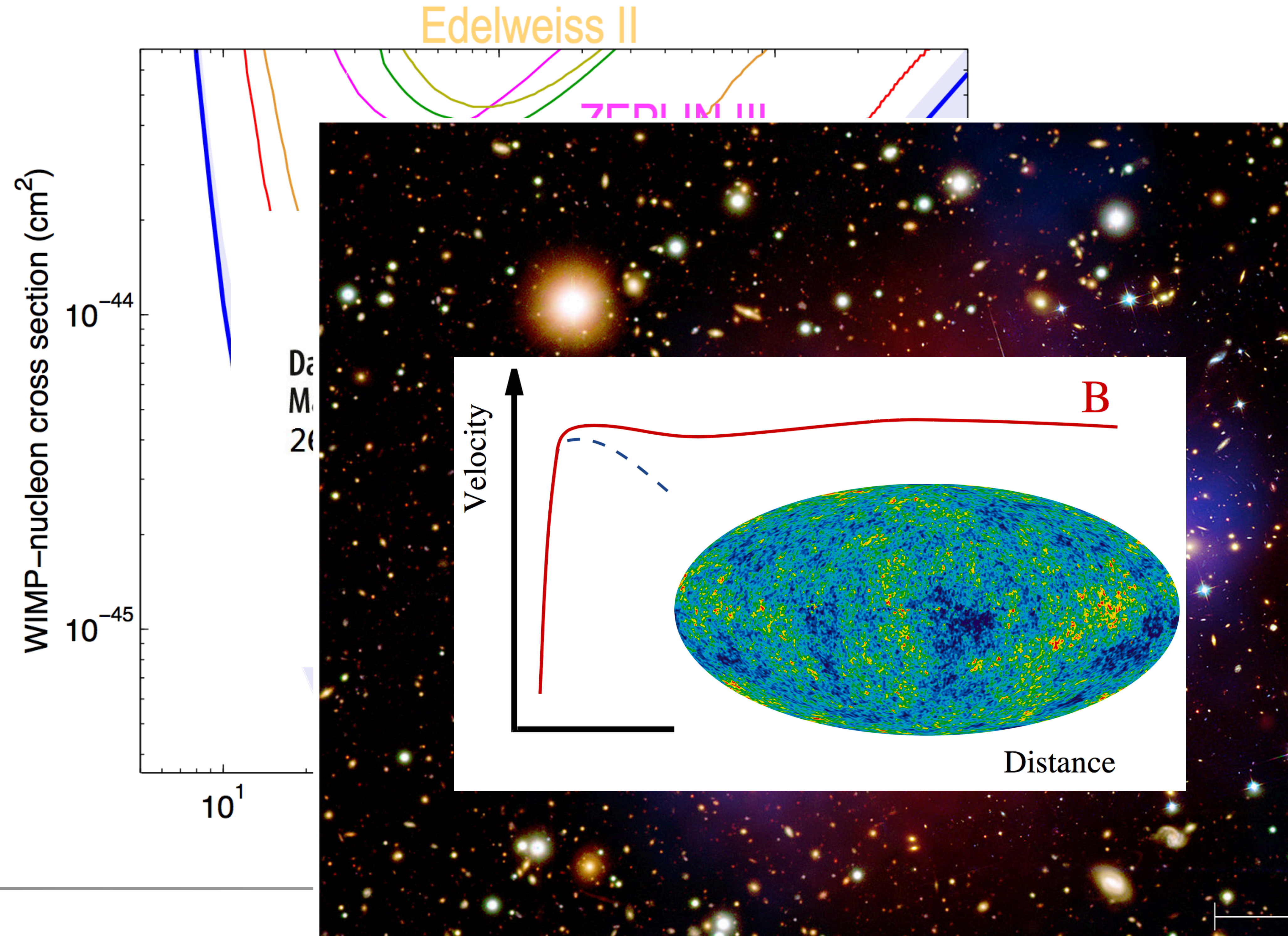
Signal Strength

- Signal strength μ is the observed over Standard Model expected cross section
- For μ=1 the production rate is compatible with Standard Model expectation





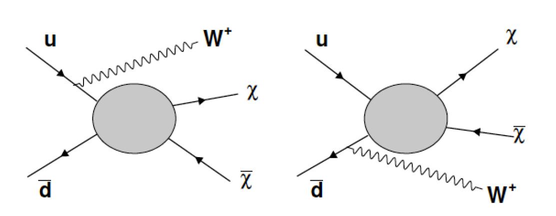
ATLAS a bit above and CMS a bit below μ=1…

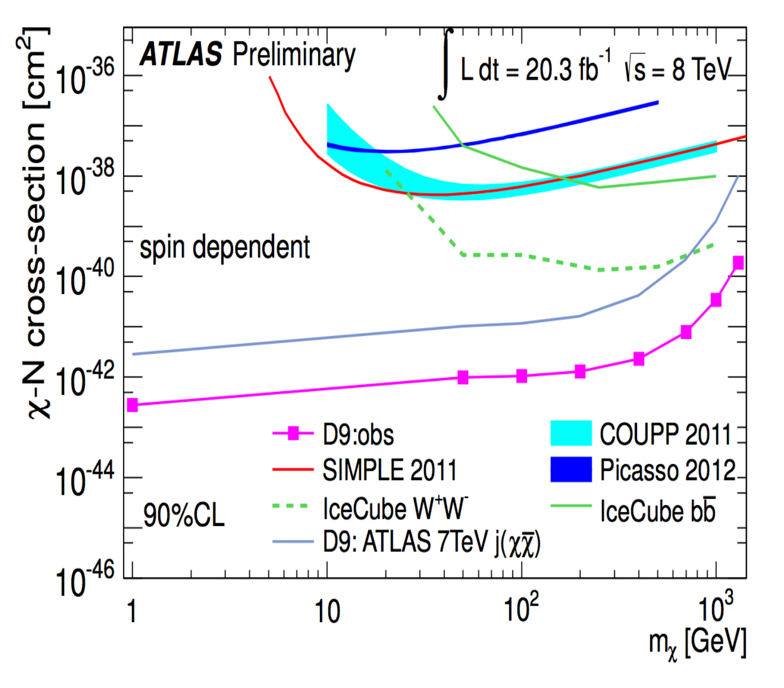


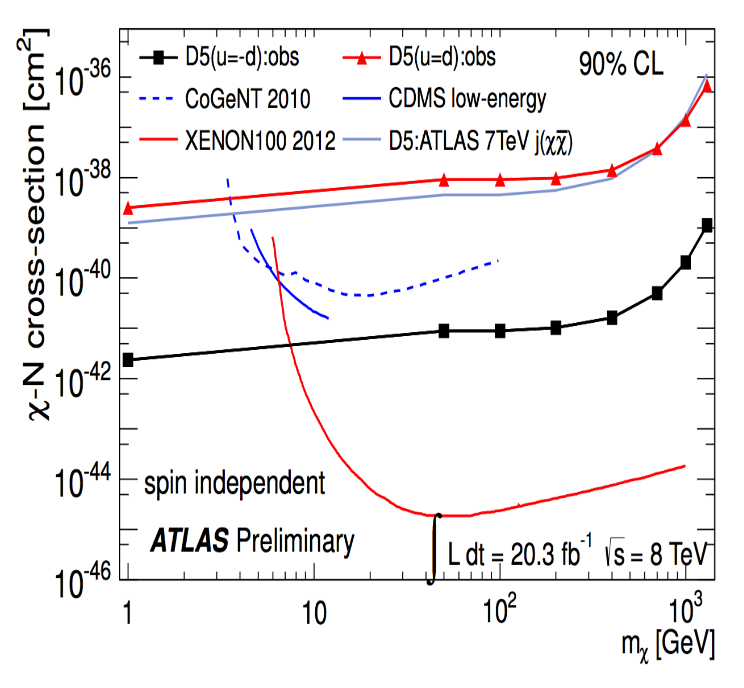
Edelweiss II
WIMP–nucleon cross section (cm2)
10−44
10−45
101
B
Velocity
Distance

The Dark Matter Connection

Results for direct searches and collider searches for Dark Matter
-> Spin dependent and spin independent cross sections of Dark Matter with ordinary matter (W/Z + MET searches)





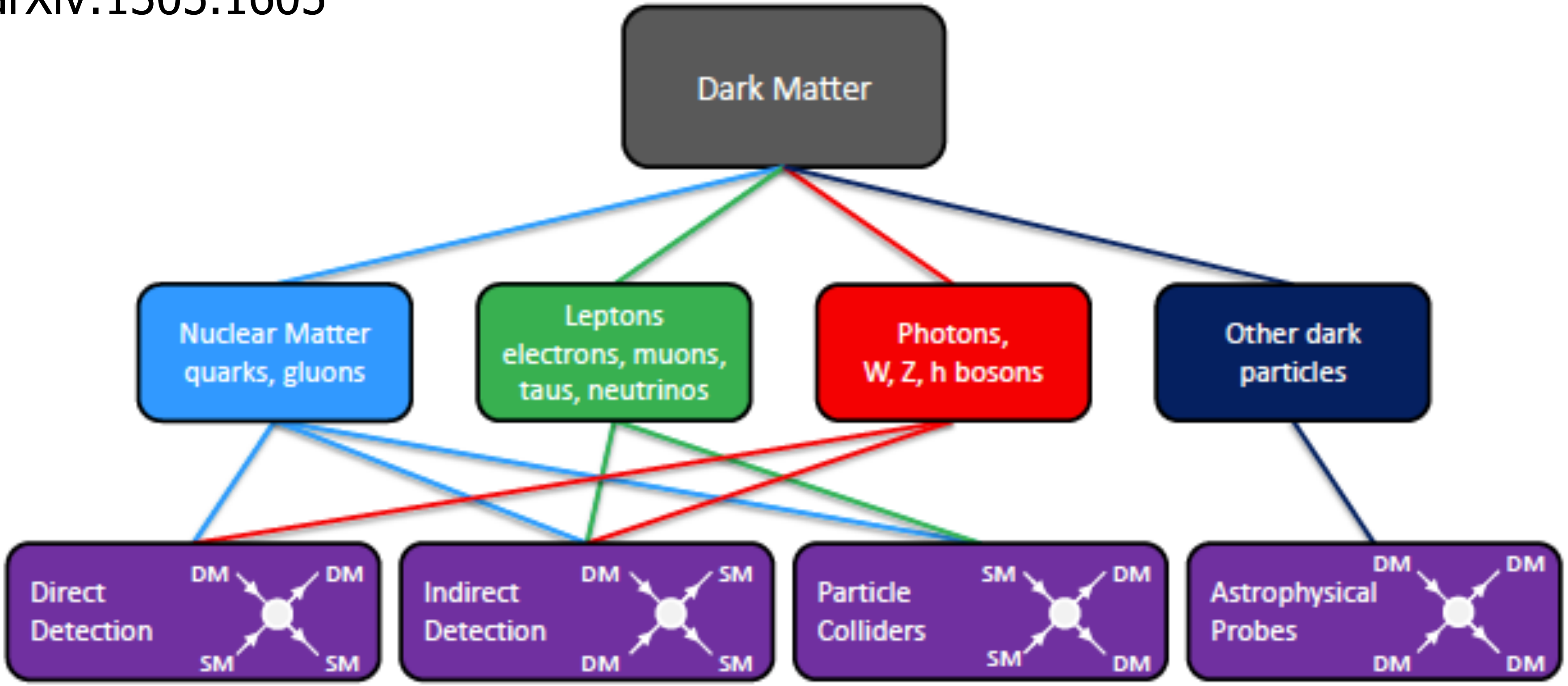


Competitive if DM-u quark coupling different from DM-d quark coupling

Dark Matter @ LHC?

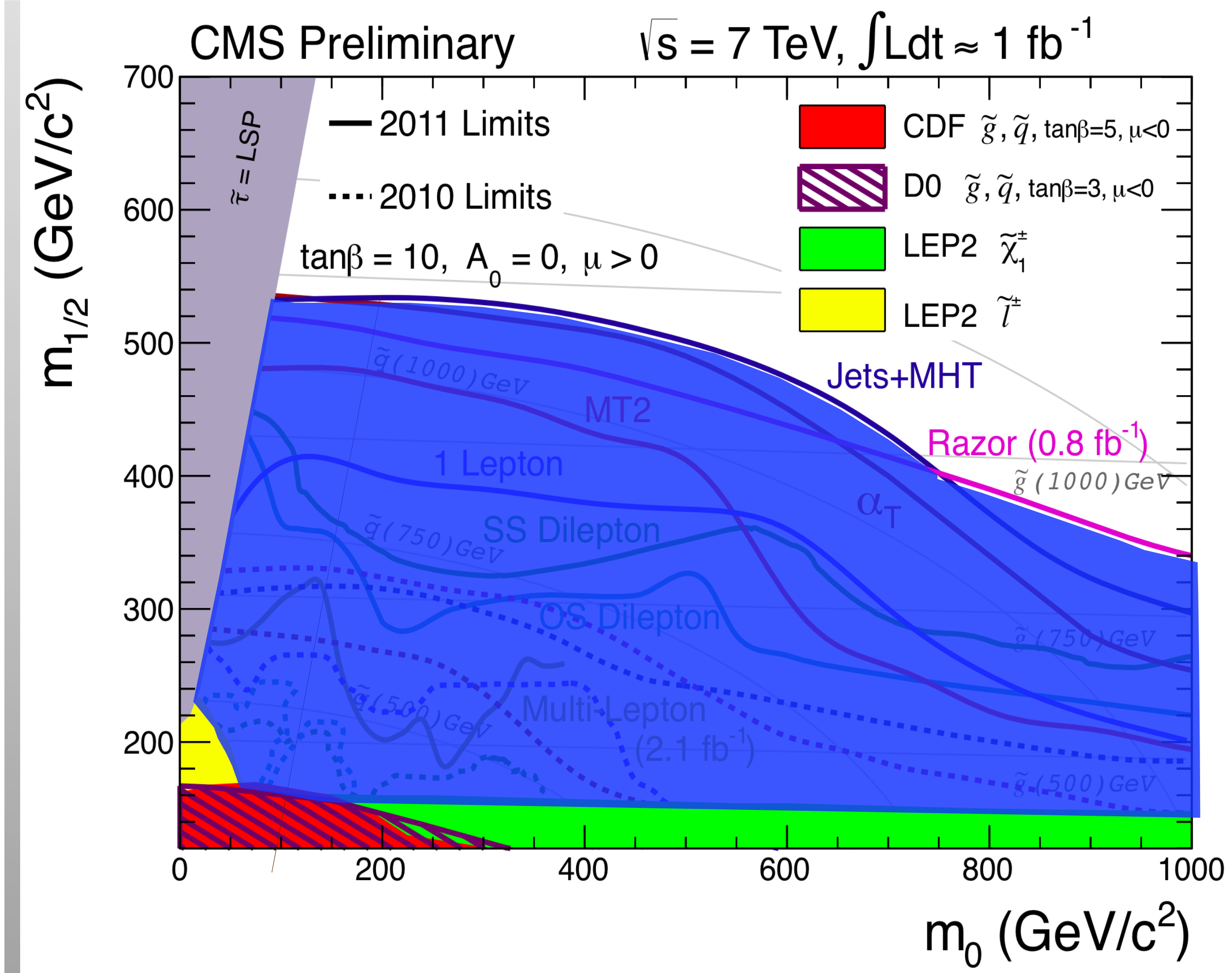
Search for Weakly Interacting Massive Particle (WIMPs) candidates in events with Missing Transverse Momentum
EG: SUSY searches, monojet and mono-photon Searches, W' searches…

arXiv:1305.1605



+ CAST experiment, searching for axion DM

Do we see Supersymmetric Particles?



- 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 next years

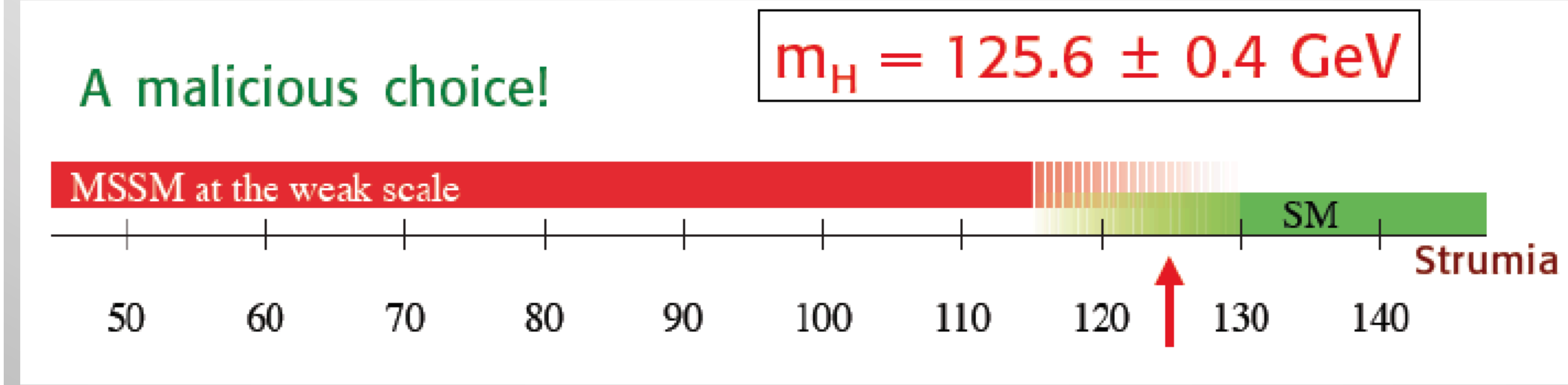
m_0 and $m_{1/2}$ are SUSY parameters

Masses of SUSY particles are larger than 1000 GeV!!!

So these particles are heavier than 1000 times the proton

Explore other than the simplest/constrained SUSY models

A Higgs…



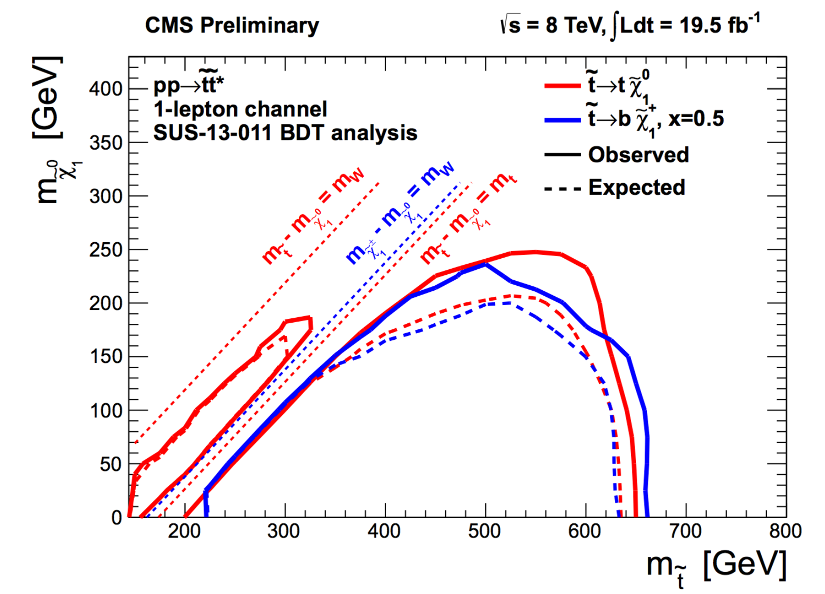
The Higgs:
so simple yet so unnatural

Guido Altarelli

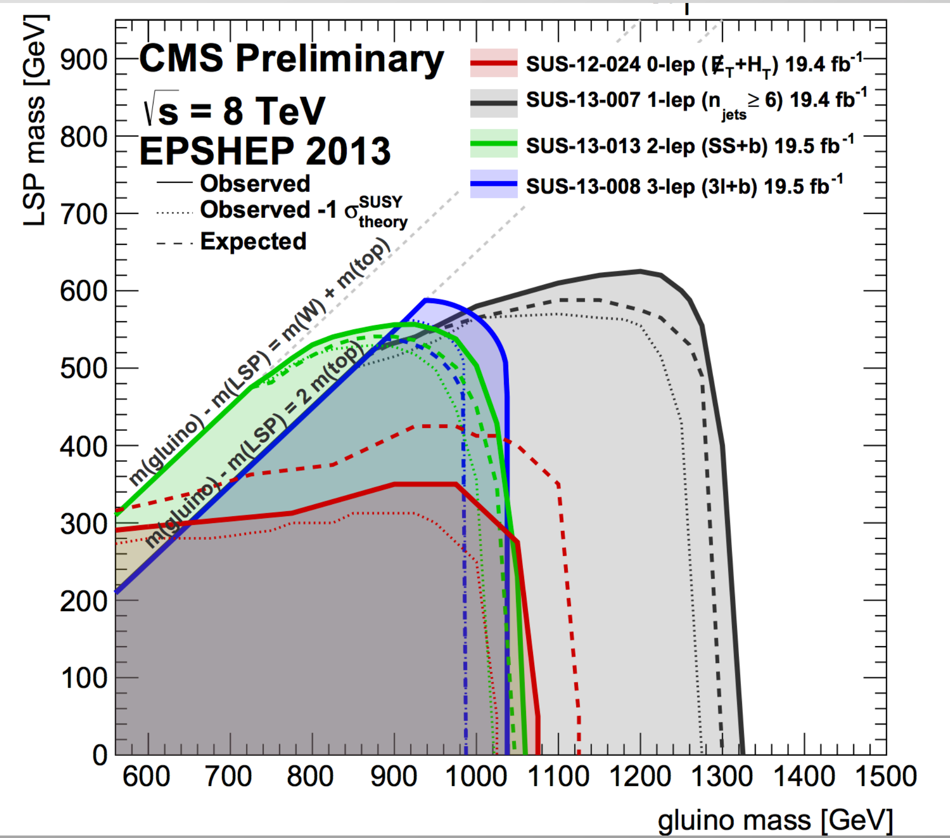
Stockholm Nobel Symposium
May 2013

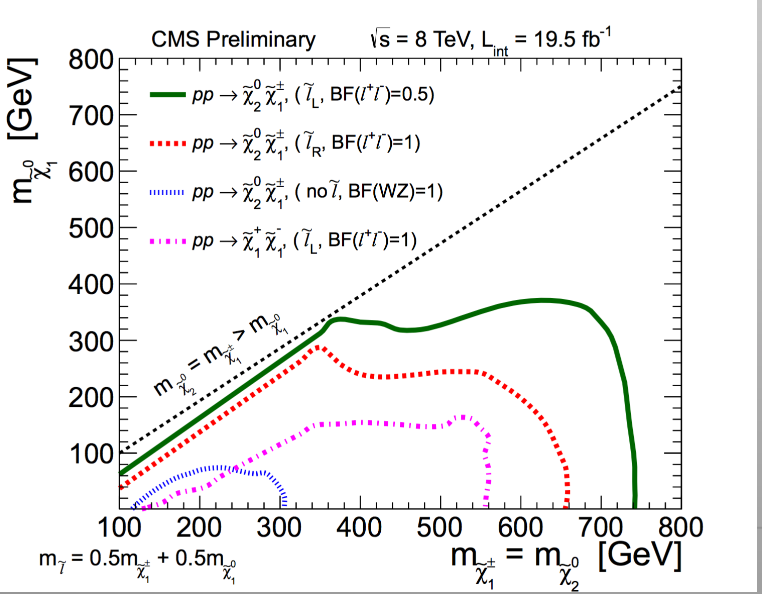
Naturalness: Requires Top squarks < ~1 TeV, gluino < ~1.5 TeV…
So far no evidence found…

SUSY Searches: LSP limits…



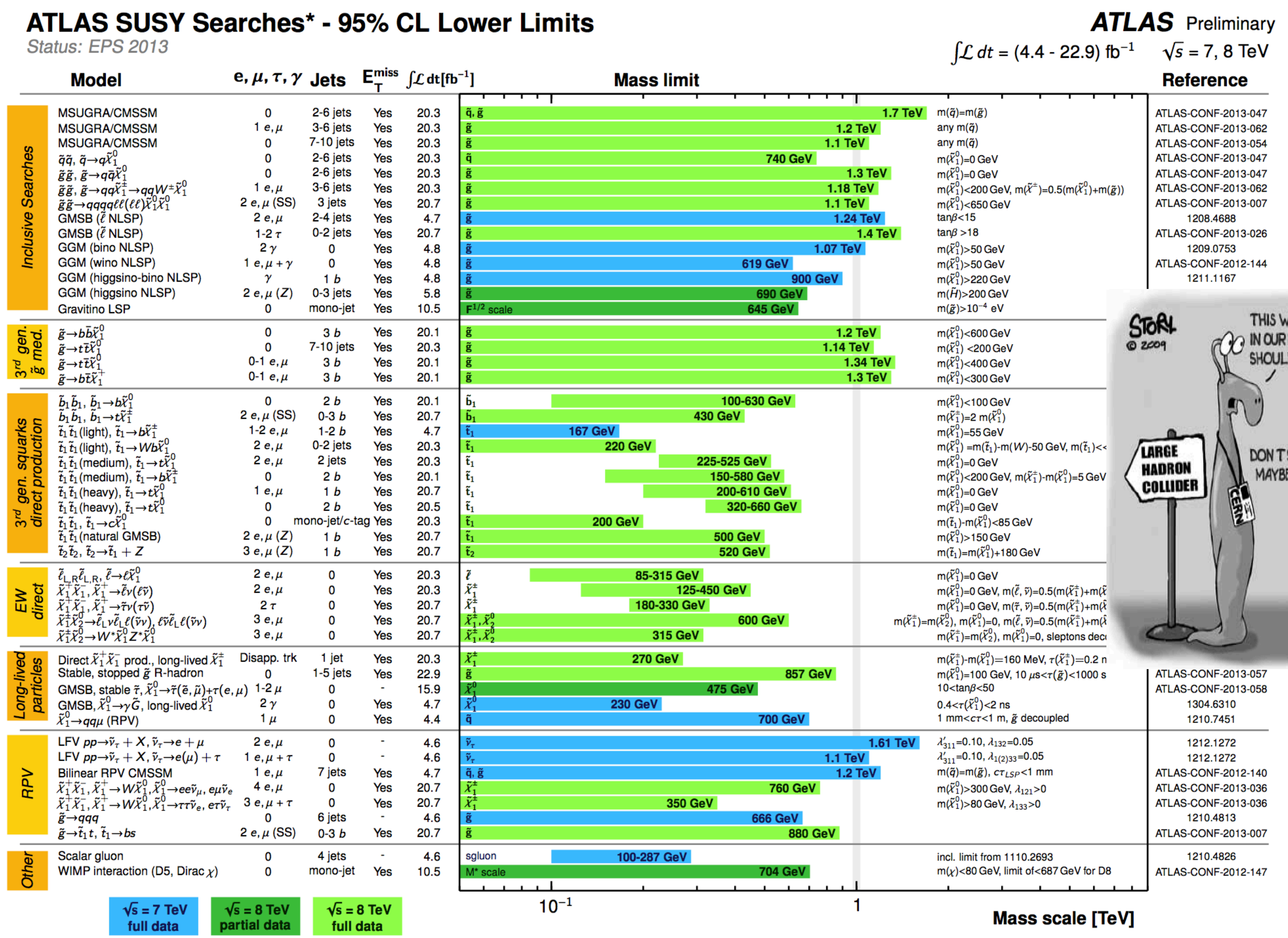
Various limits on sparticles:
No 'light' Lightest SUSY Particle (LSP) so far





But could hide in contrived scenarios

Searches for SUSY



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

$\int \mathcal{L} dt = (4.4 - 22.9)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

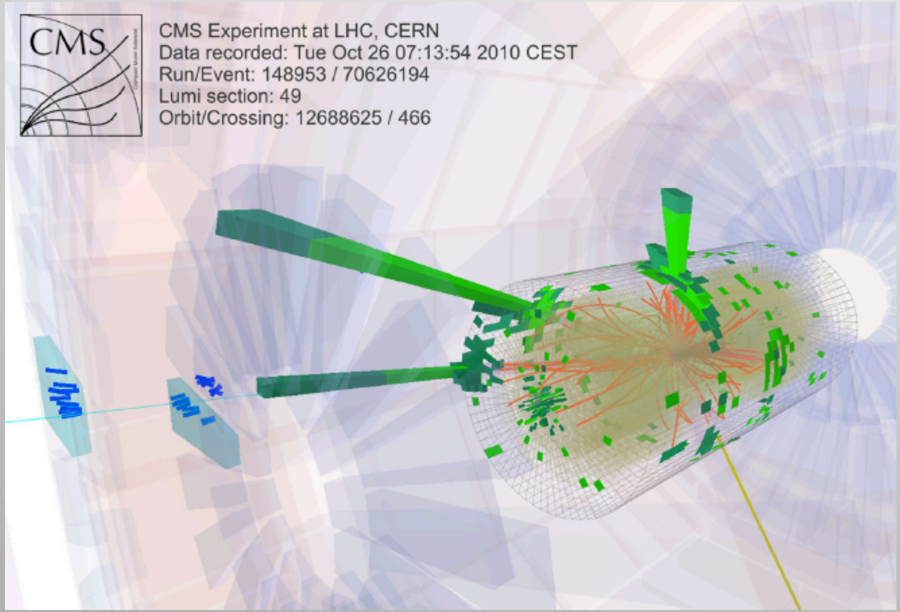
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm \to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	$m(\tilde{\chi}_1^0)$ <200 GeV	
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<	
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 200 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	$m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV	
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}$	
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}$	
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}$	
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0 Z^*\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons deco	
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 n	
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 857 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	0	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

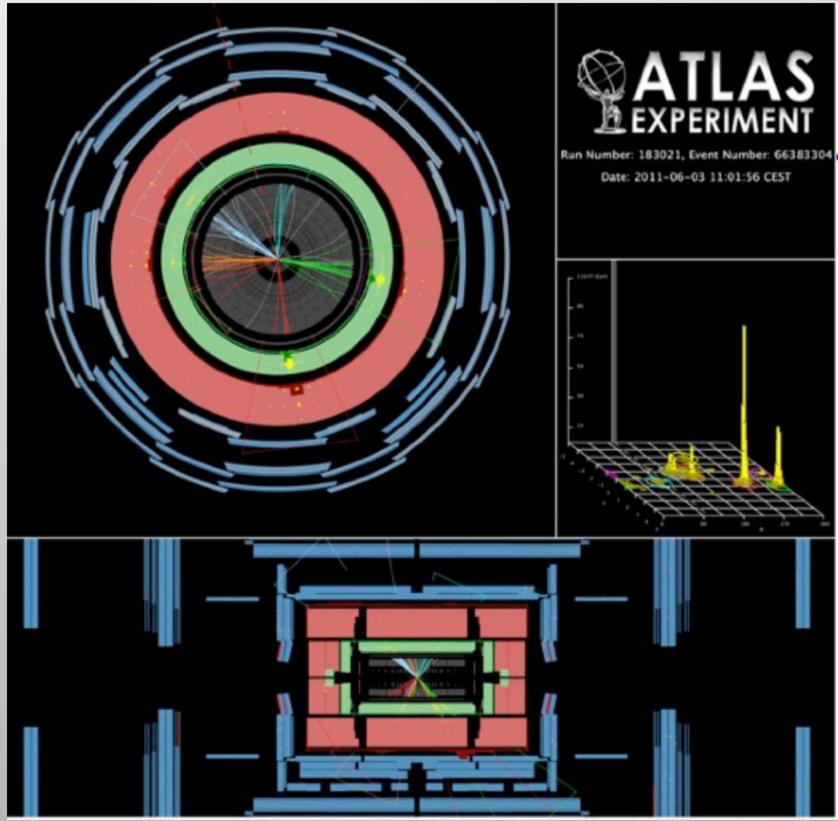
$\sqrt{s}$ = 7 TeV full data — $\sqrt{s}$ = 8 TeV partial data — $\sqrt{s}$ = 8 TeV full data

Mass scale [TeV] (10^{-1}, 1)

*similar results obtained by CMS

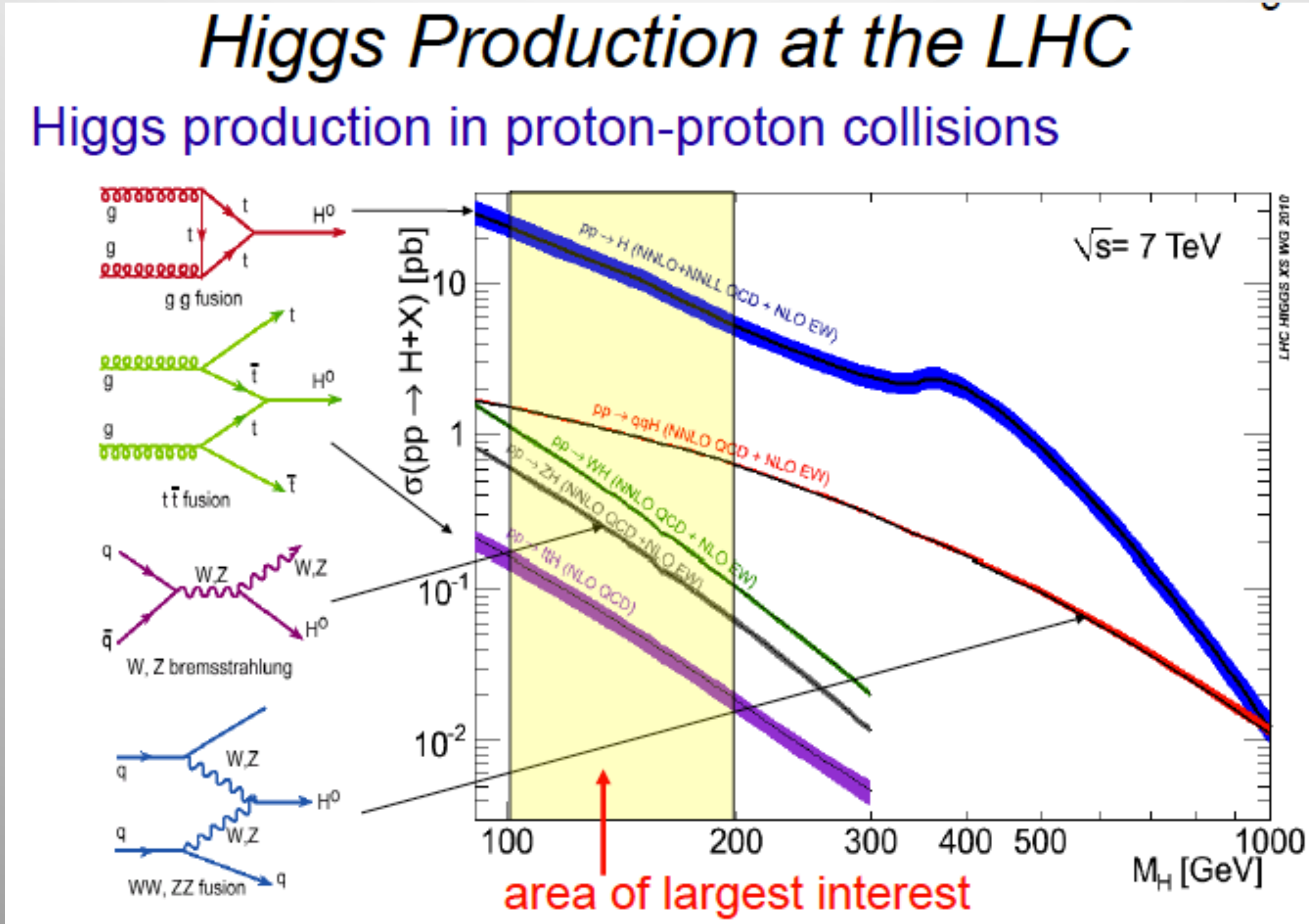
…Some Interesting Collisions…





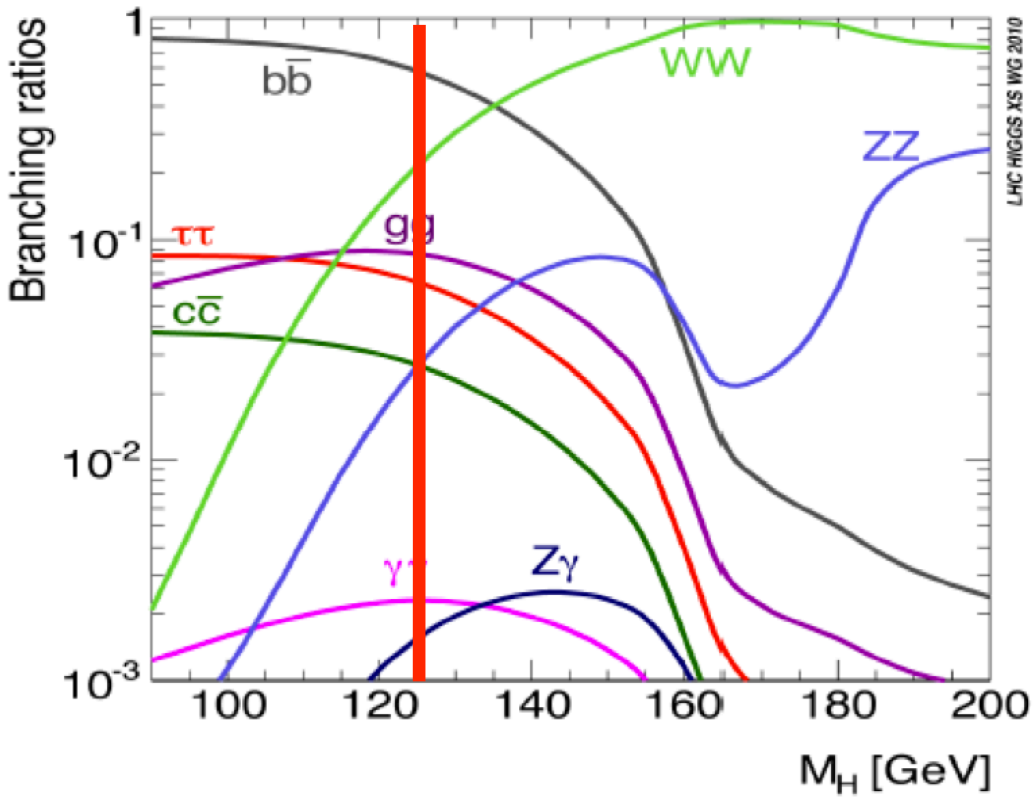
- Events with five jets of particles and large missing energy which could come from a possible dark matter particle
- But a few events is not enough too prove we have something new

Higgs Production Channels vs Mass



We now have data on all production channels…

Higgs Decay Channel vs. Mass



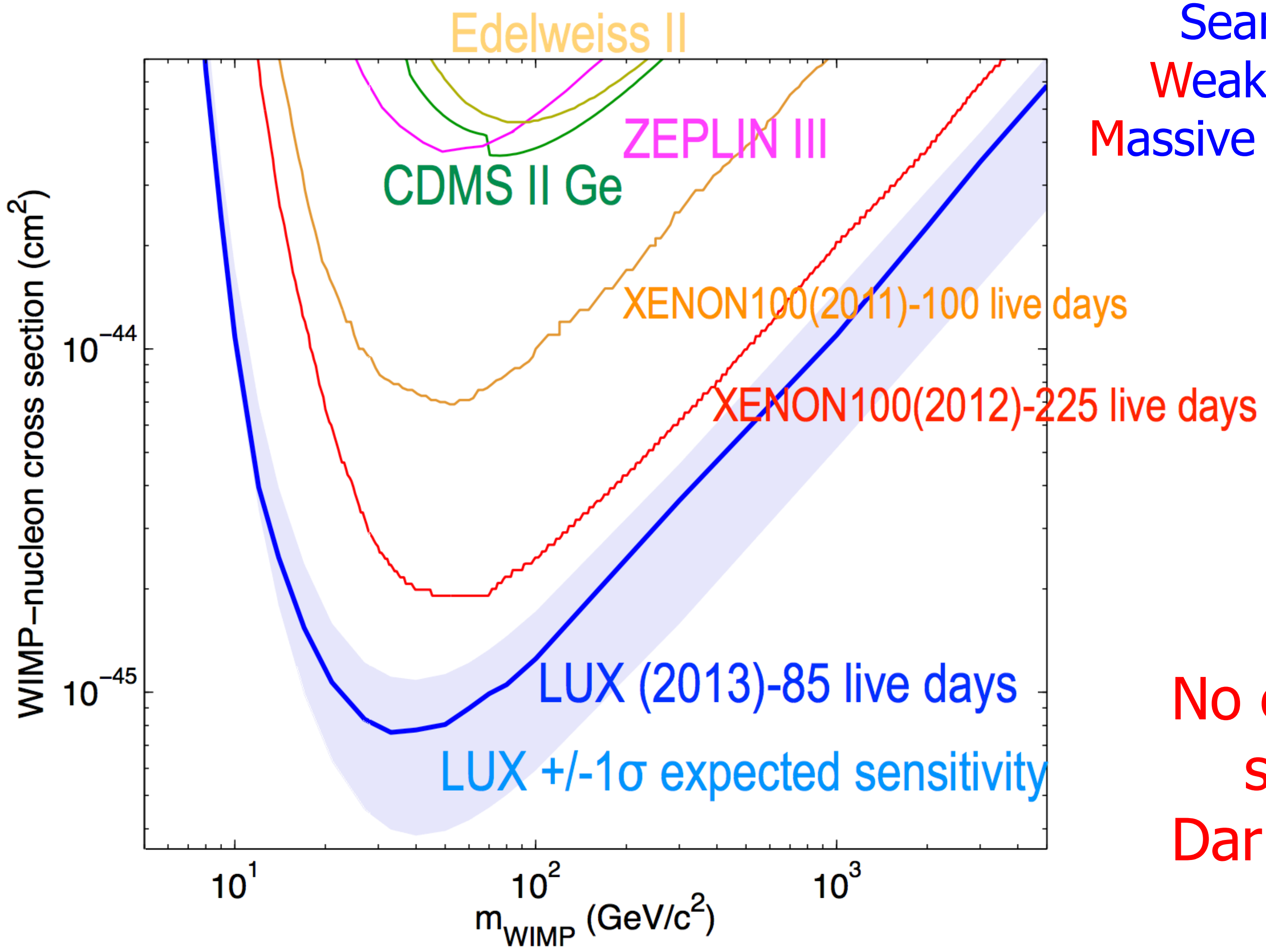
Higgs boson couples to mass

$\Gamma_{Hff} \sim m_f^2$

The five main decay channels:

Channel	m_H range (GeV/c^2)	Data used 7+8 TeV (fb^{-1})	m_H resolution
H -> γγ	110-150	5.1+19.6	1-2%
H -> tautau	110-145	4.9+19.6	15%
H -> bb	110-135	5.0+19.0	10%
H -> WW -> lnulnu	110-600	4.9+19.5	20%
H -> ZZ -> 4l	110-1000	5.1+19.6	1-2%

Dark Matter Search Experiments



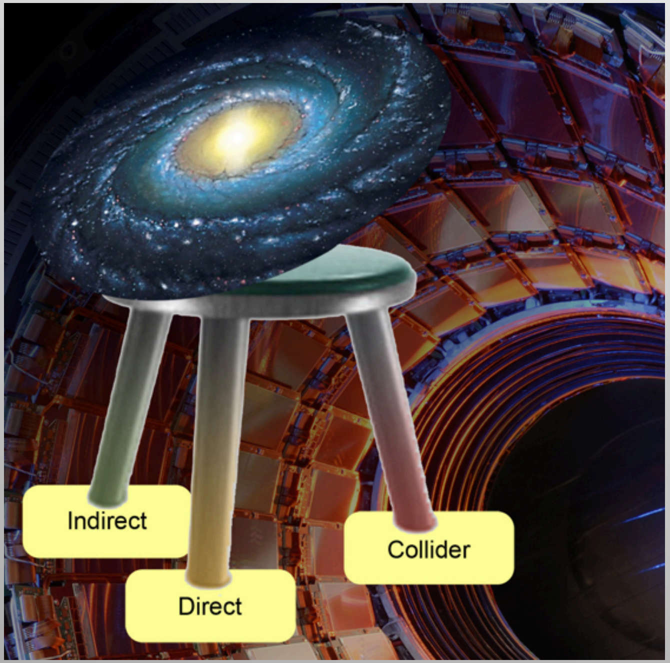
Search for Weakly Interacting Massive Particle (WIMPs)

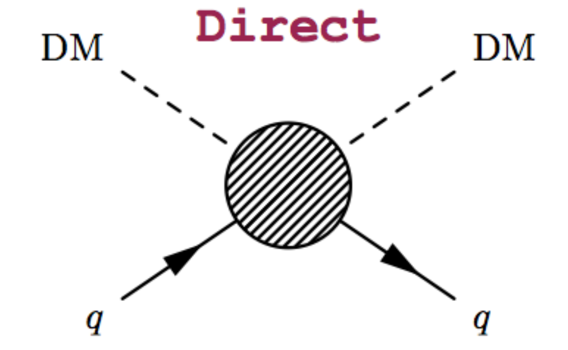
No established signal for Dark Matter yet

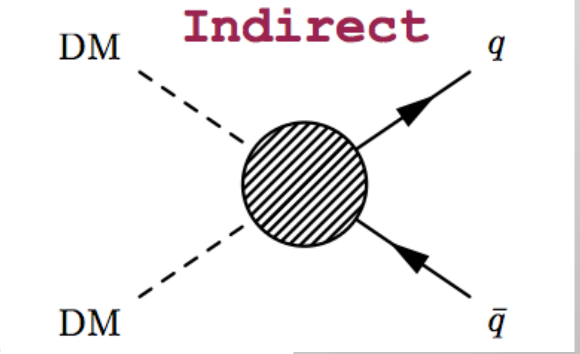
Dark Matter Experiments provide limits on cross section vs. WIMP mass

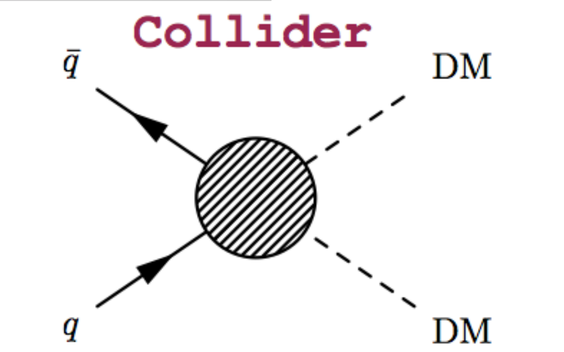
The Other Dark Matter Connection

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

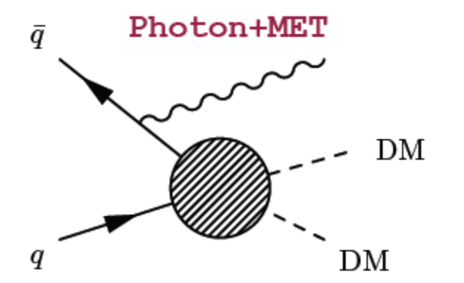


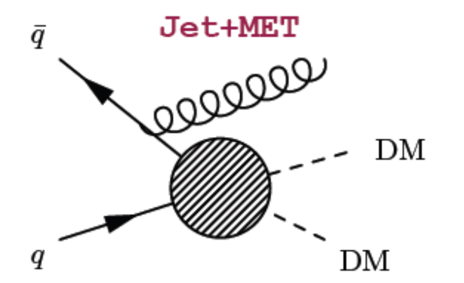


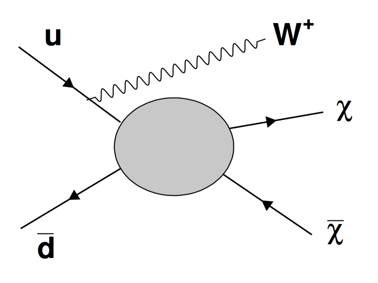




Use effective theory to relate measurements to Dark Matter studies

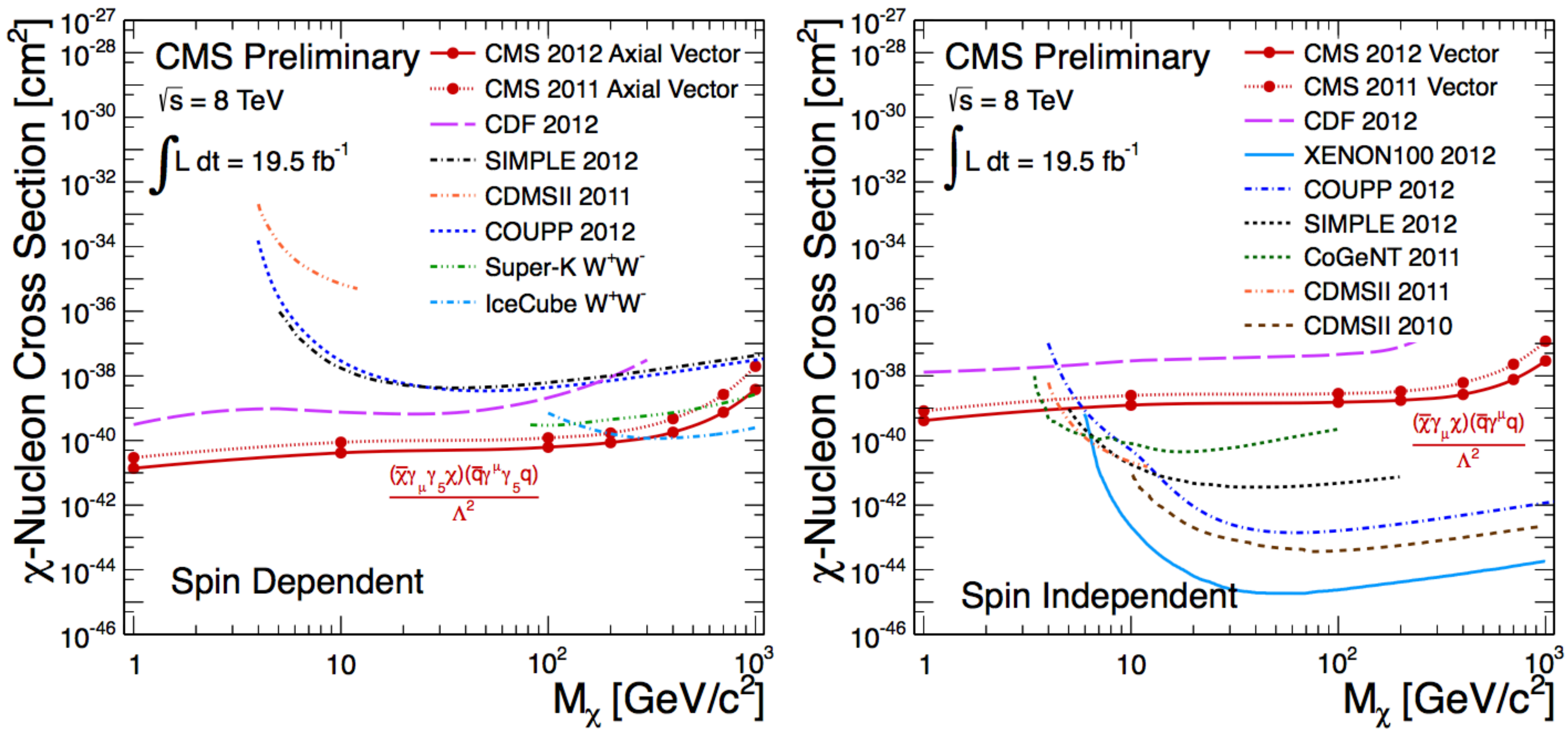






The Dark Matter Connection

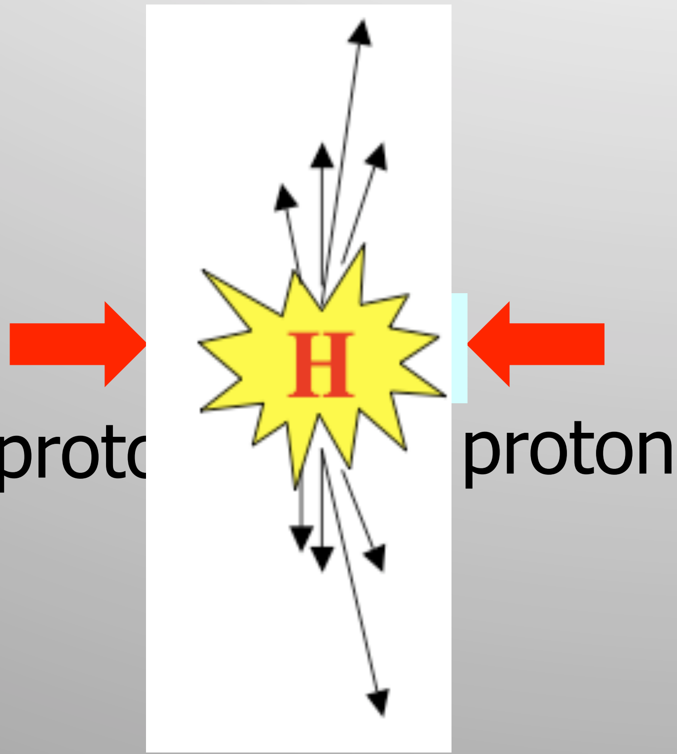
Results for direct searches and collider searches for Dark Matter
-> Spin dependent and spin independent cross sections of Dark Matter with ordinary matter (monojets searches)



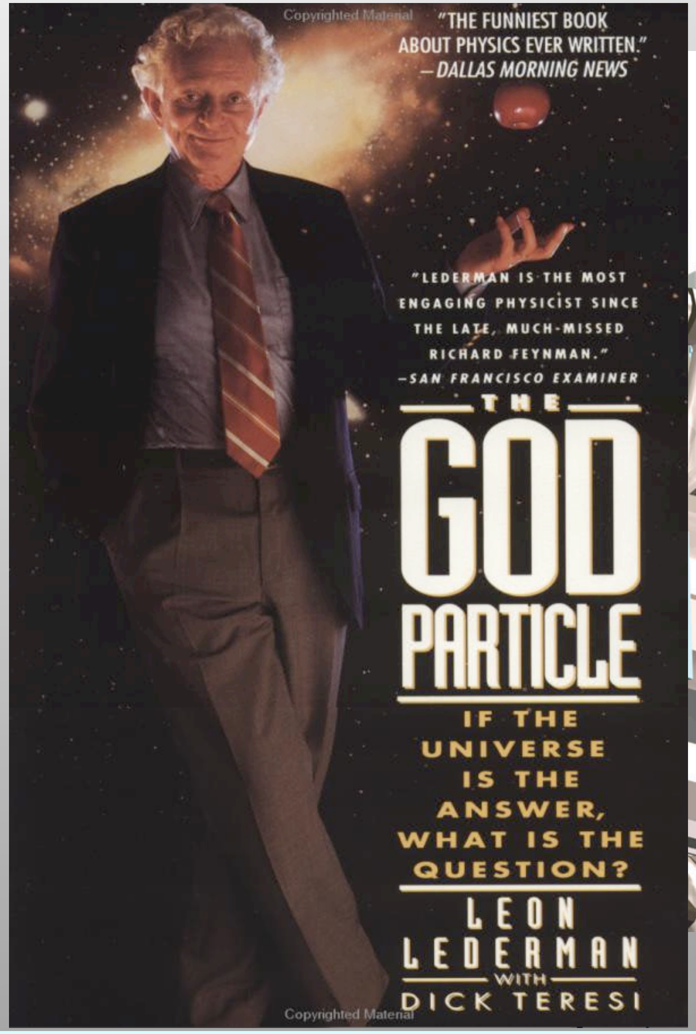
Competitive limits with direct searches (under the effective theory assumptions)

The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders



1993



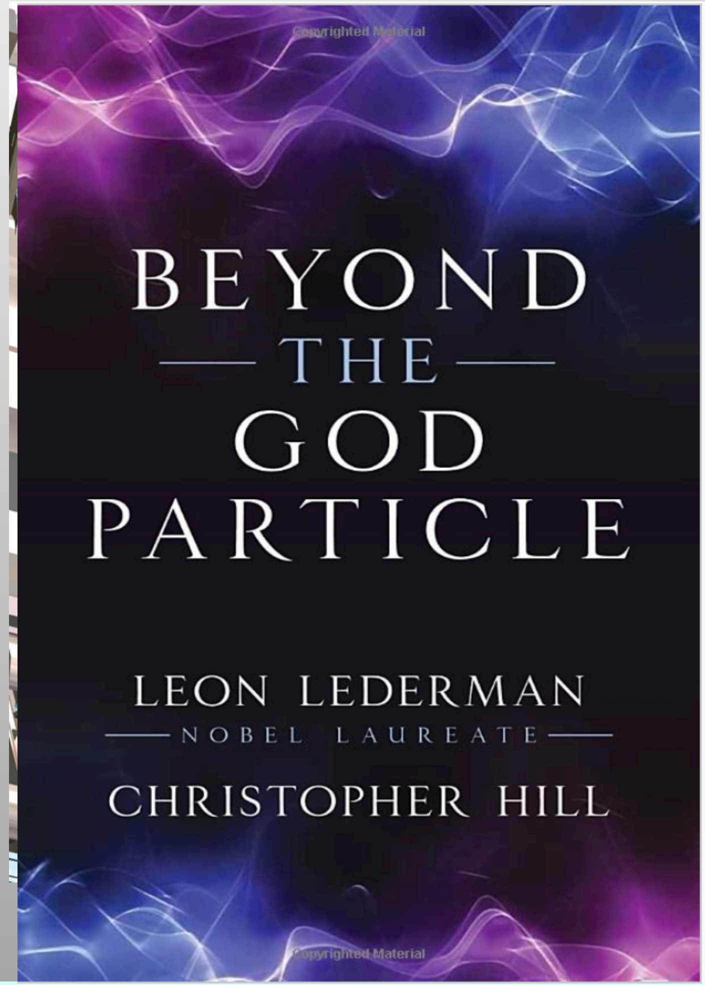
The Higgs particle is the last missing particle in the Standard Model

The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders

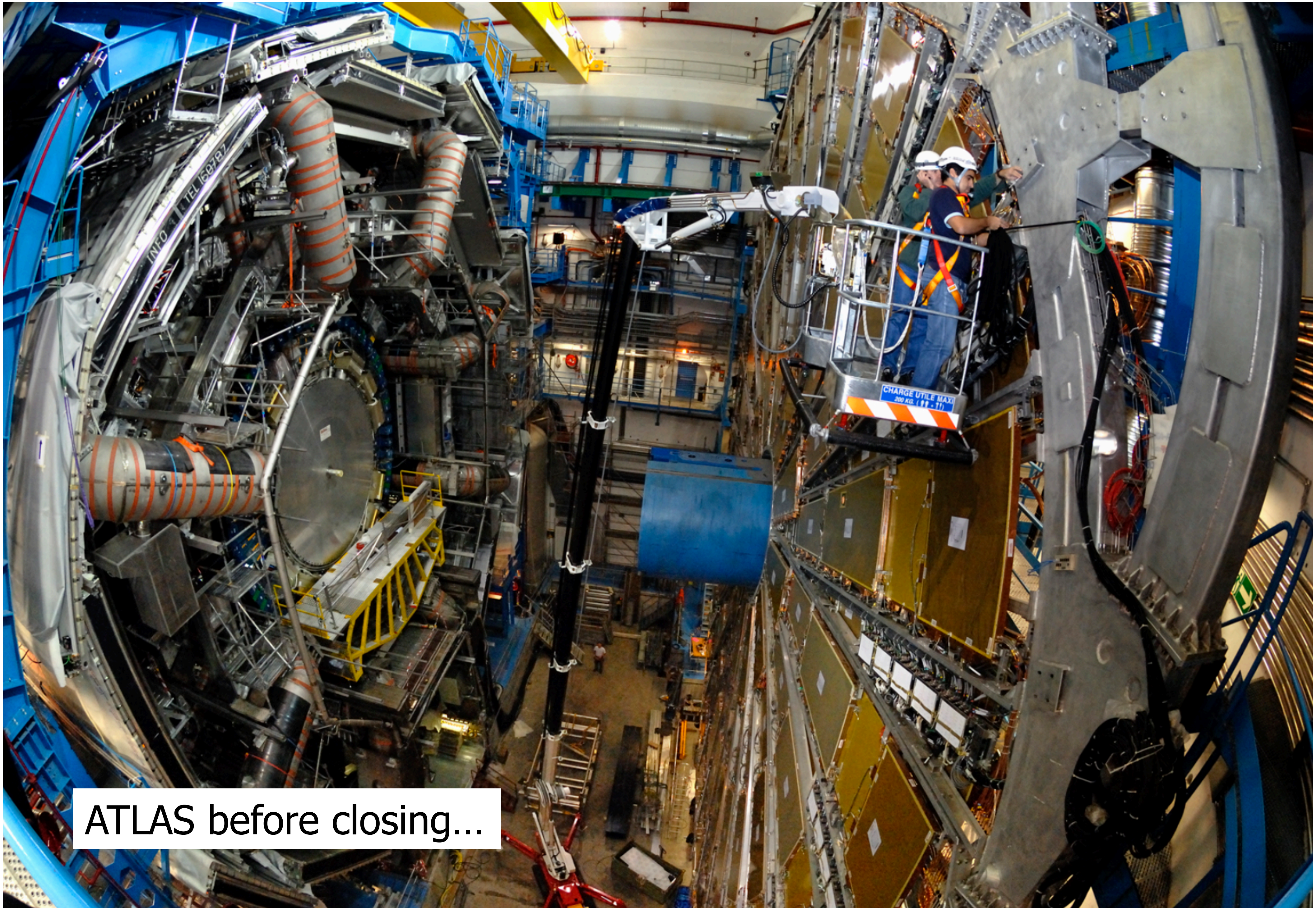
$E=mc^2$

proton proton



2013

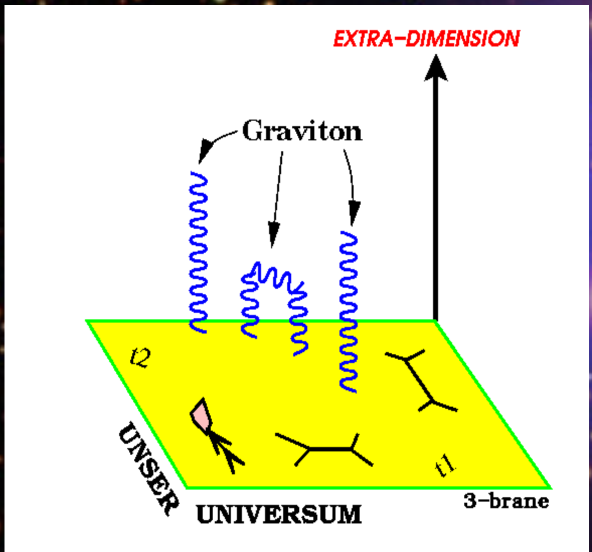
The Higgs particle is the last missing particle in the Standard Model

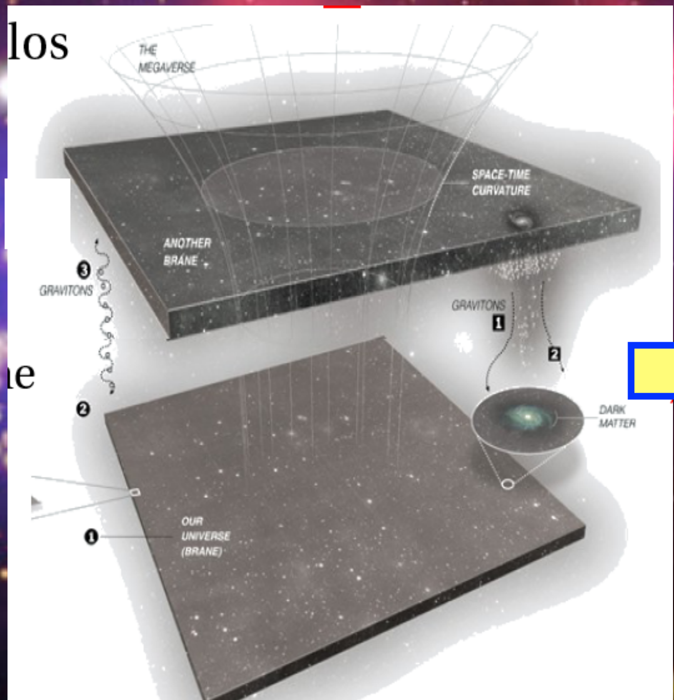


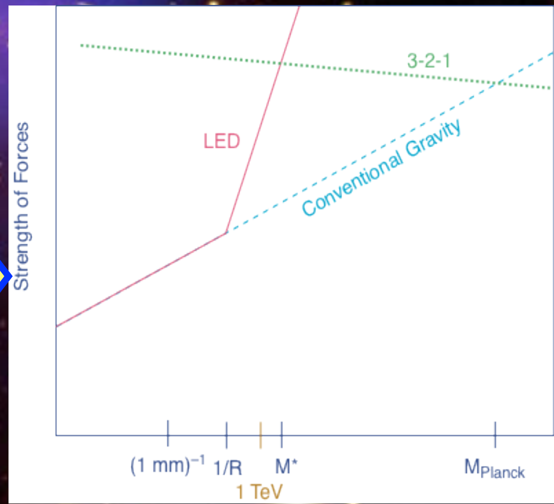
ATLAS before closing…

Extra Space Dimensions

Problem: $m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246$ GeV $\Leftrightarrow$ $M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}$ GeV





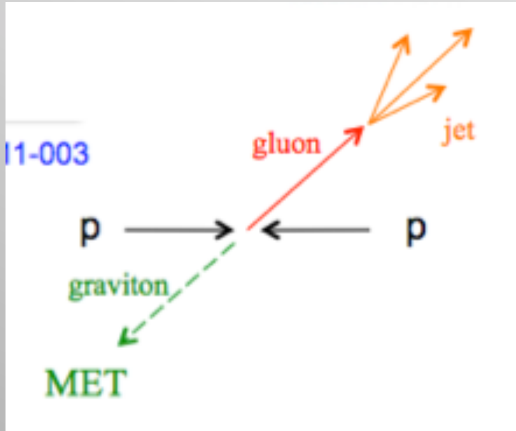


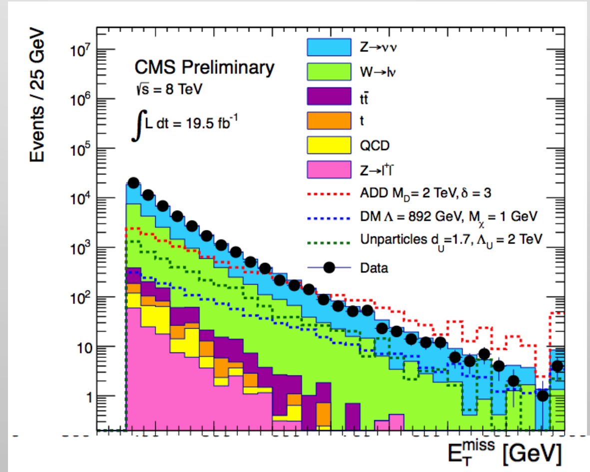
The Gravity force becomes strong!

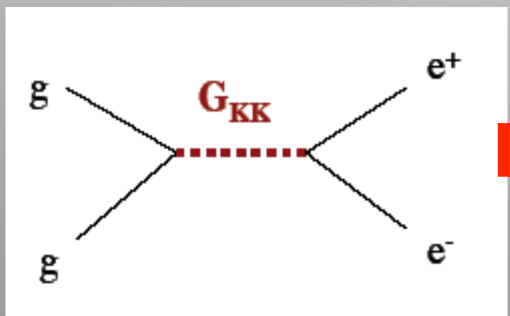
Extra Dimensions at the LHC

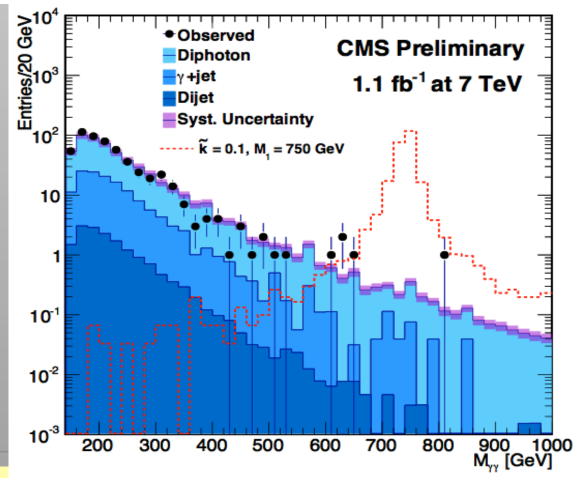
Main detection modes at the experiments

- Collisions with Large missing (transverse) energy
- Resonance production in two particle distributions





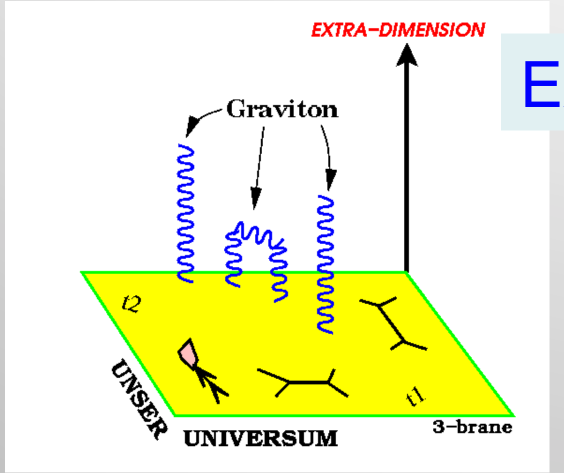




No signal yet
If extra dimensions exist then the Planck scale is larger than 2-3 TeV

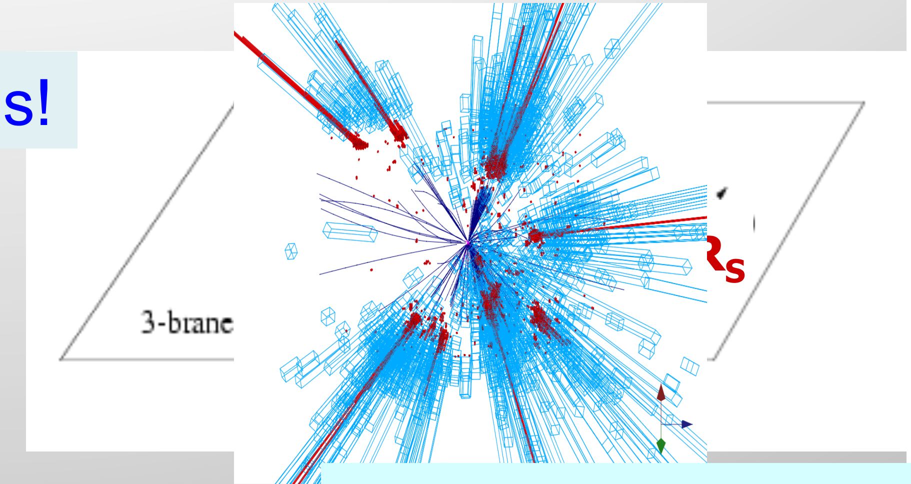
LHC can detect extra dimensions for scales up to 5 to 9 TeV

Search for Micro-black Holes



Extra Dimensions!

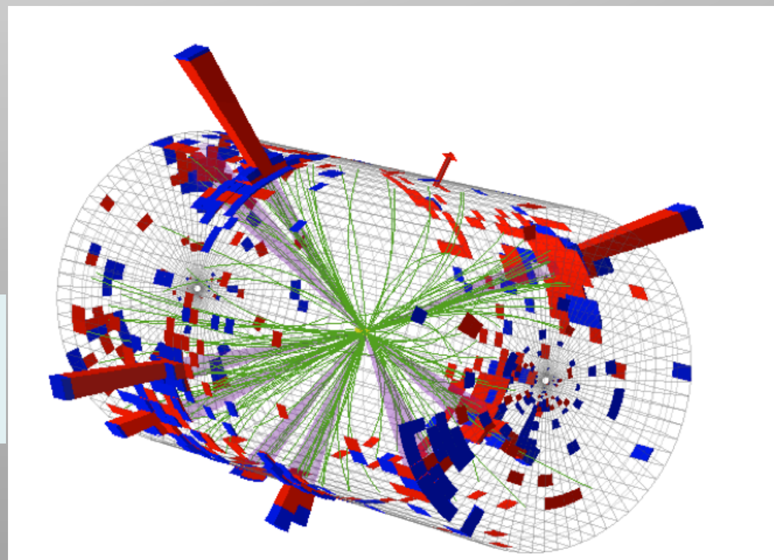
Planck scale a few TeV?



Evaporates in 10^{-27} sec

No evidence for micro black holes was found in the data so far

But some do see some interesting events
These could be background



Black holes with mass of up to 5 TeV are excluded (model dependent)

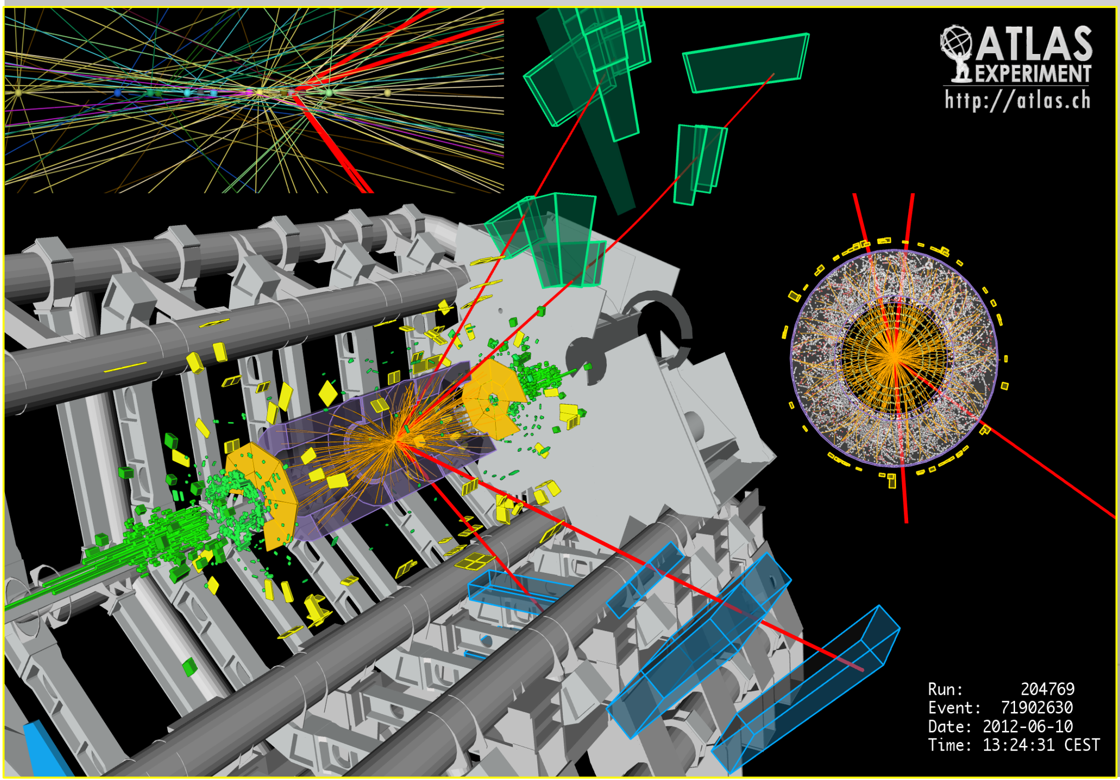
Searches for the Higgs Particle

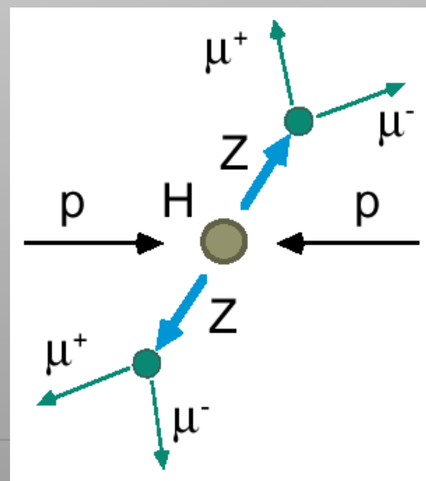
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

Example: Higgs(?) decays into ZZ and each Z boson decays into μμ

So we look for 4 muons in the detector

But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for on event by event (we can reconstruct the total mass with the 4 muons)





Is it really the Higgs Boson?

In summer 2012 we called it a "Higgs-like" particle

- Does this new particle have all the properties that we expect a Higgs Boson to have? (Summer 2012 5+5 fb^{-1})
  - So far it seems to couple as expected to photons, heavy Z and W bosons, but at the time of the discovery it was not seen that they also couple to quarks or leptons
- What are the quantum numbers of this new particle?
  - EG Spin and Parity: for the SM Higgs we expect it to have spin = 0 and parity = +.
- Is there more than one Higgs-like particle? Some theories beyond the Standard Model predict these…
- Does it have 'exotic' properties?

Still a lot of questions to be answered in summer 2012!!
Let's look at the new updates with full 2012 data (~ 25 fb^{-1})