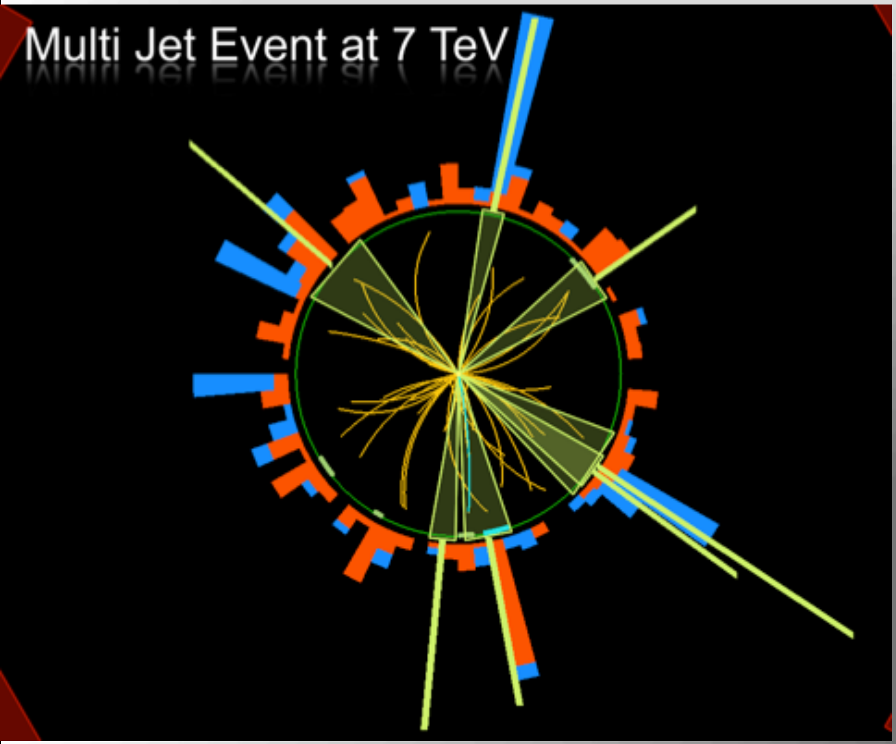


Outline

- Introduction
- The LHC & Experiments
- Higgs Discovery
- Studies of Higgs properties
- LHC & Dark Matter
- Summary

The Hunt for the Higgs

Where do the masses of elementary particles come from?

The key question: Where is the Higgs?

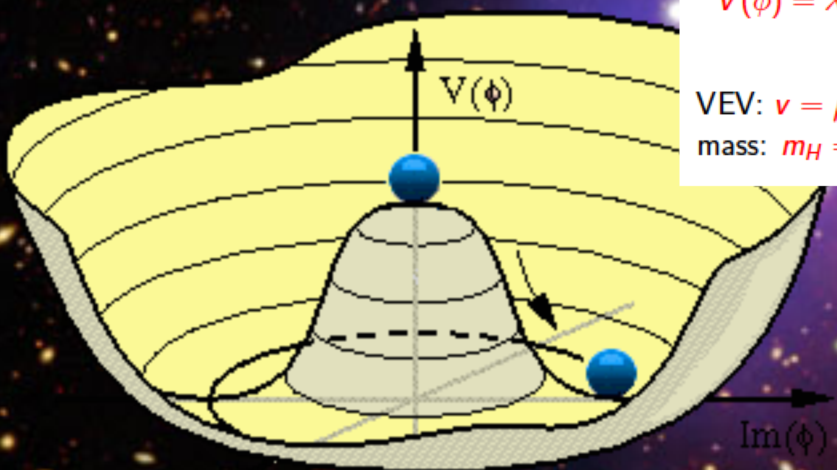
Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

$$V(\phi) = \lambda \left(\phi^\dagger \phi\right)^2 - \mu^2 \left(\phi^\dagger \phi\right)$$

VEV: $v = \mu/\sqrt{\lambda} = 2m_W/g$

mass: $m_H = \sqrt{2} \cdot \mu$

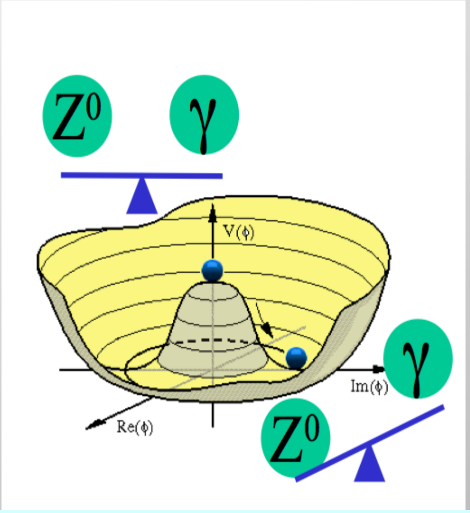


Scalar field with at least one scalar particle

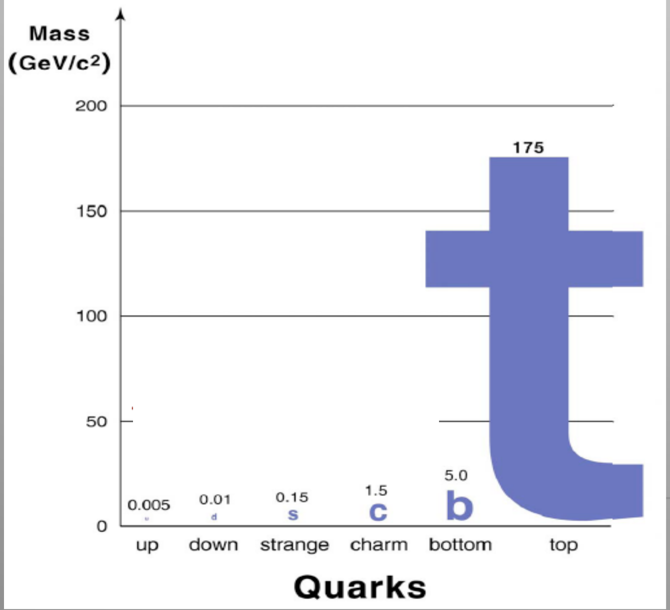
It could be anywhere from 114 to 700 GeV

The Origin of Particle Masses

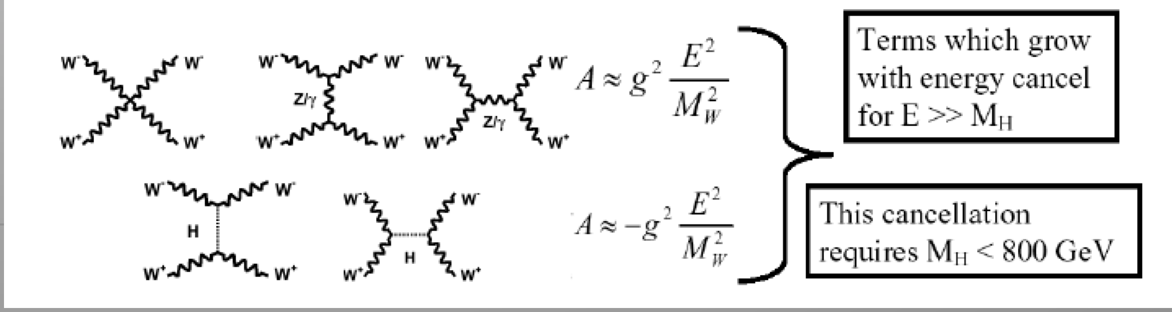
- At ‘low’ energy the Weak force is very different from the Electromagnetic force: Electroweak Symmetry Breaking
- The W an Z bosons are very massive (~ 100 proton masses) while the photon is massless.
- The proposed mechanism in 1964 by P. Higgs, R. Brout and F. Englert, and Kibble, Hagen and Guralnik gives mass to W and Z bosons and predicts the existence of a new elementary particle, the‘Higgs’ particle. This mechanism is further extended to give mass to the Fermions via Yukawa couplings.



The Higgs (H) particle has been searched for since decades at accelerators, LEP (CERN), Tevatron (Fermilab, Chicago) and the large hadron collider @ CERN



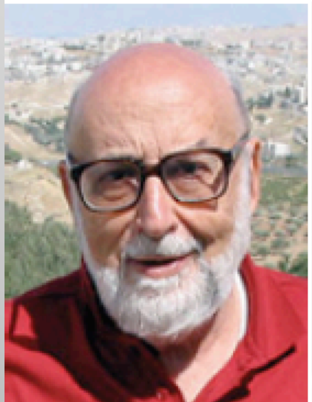
Also: WW scattering at High Energies:

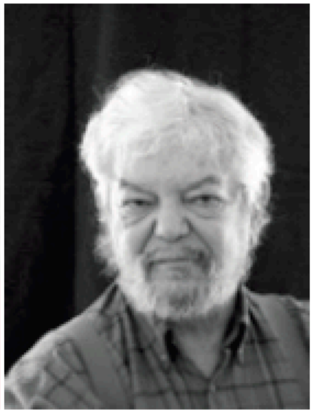


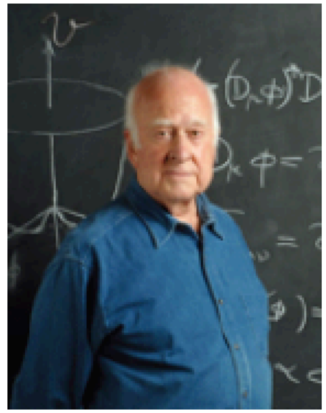
ESB Heroics

The year is 1964

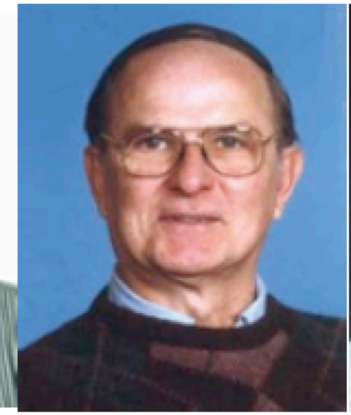
Electroweak Symmetry Breaking


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

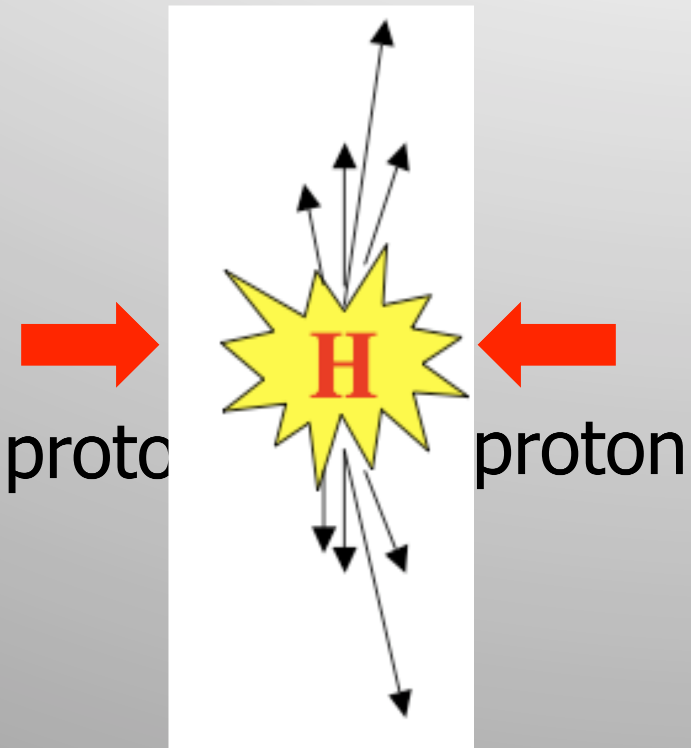
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

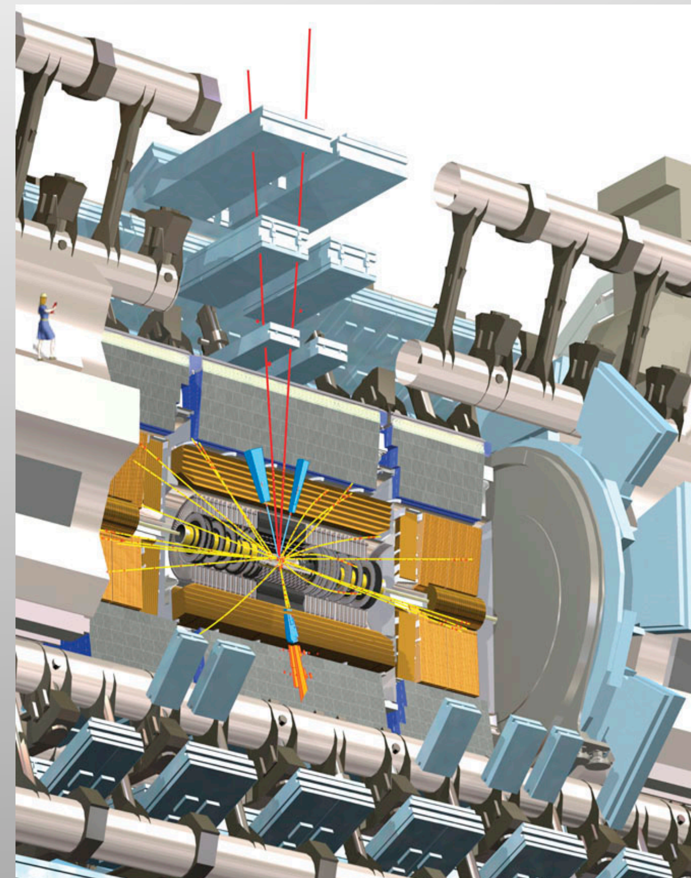
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

+ others could be mentioned that have inspired the above

The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders





The Higgs particle is the last missing particle in the Standard Model
It could also give us the first window "Beyond the Standard Model"

This Search Requires…….

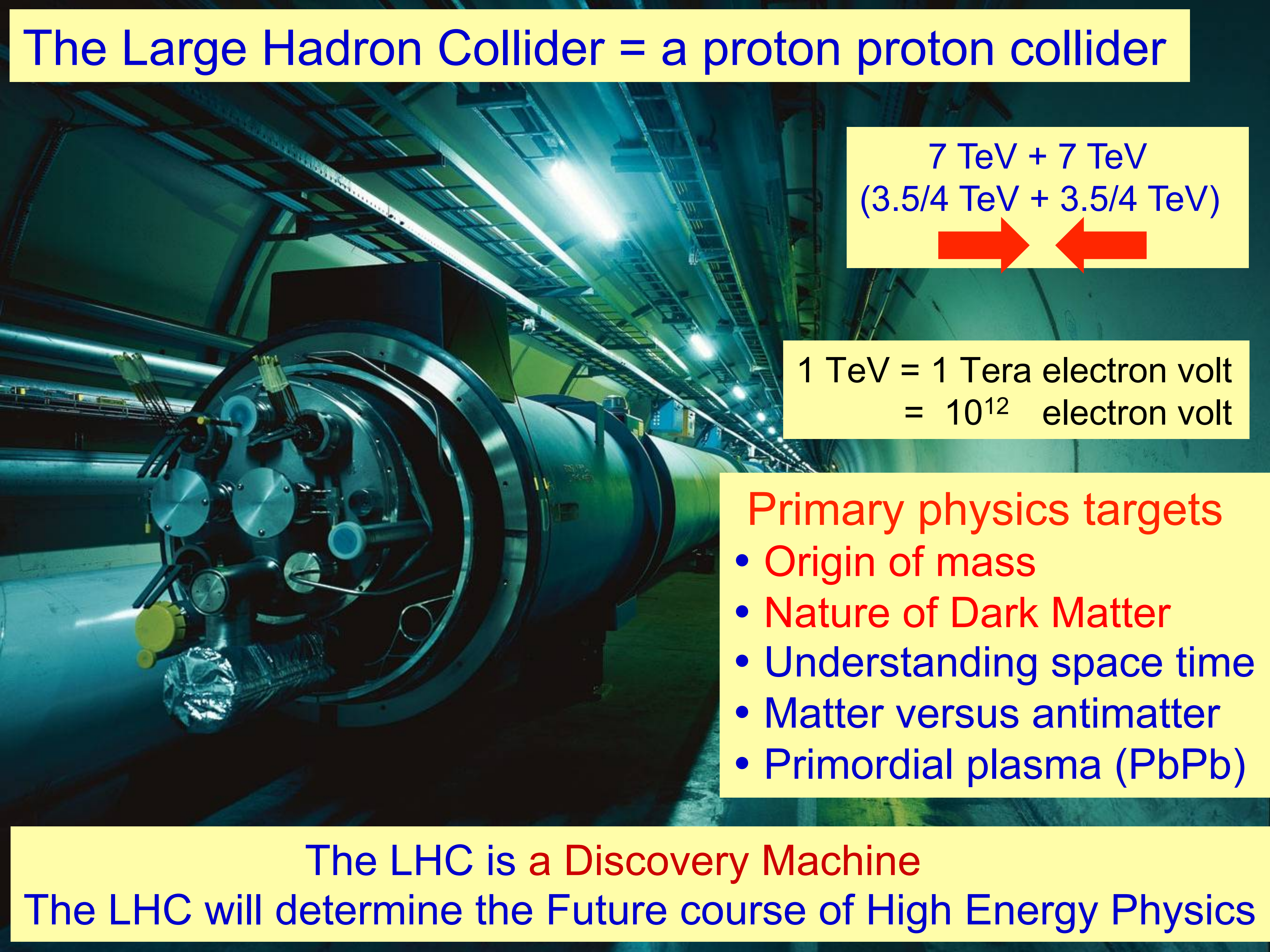
1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

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



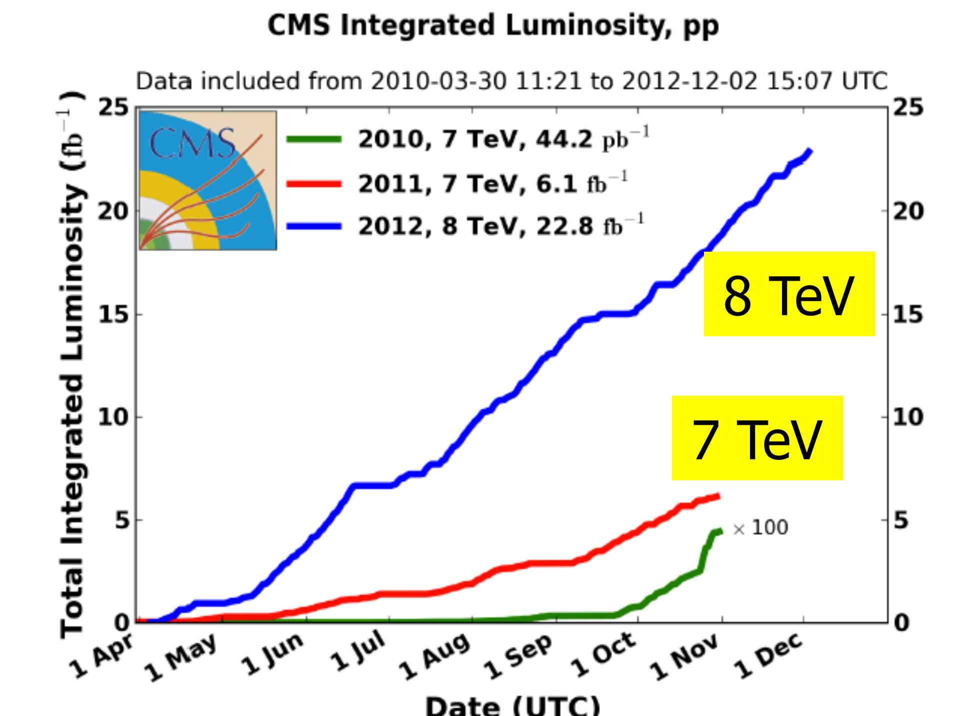
7 TeV + 7 TeV
(3.5/4 TeV + 3.5/4 TeV)

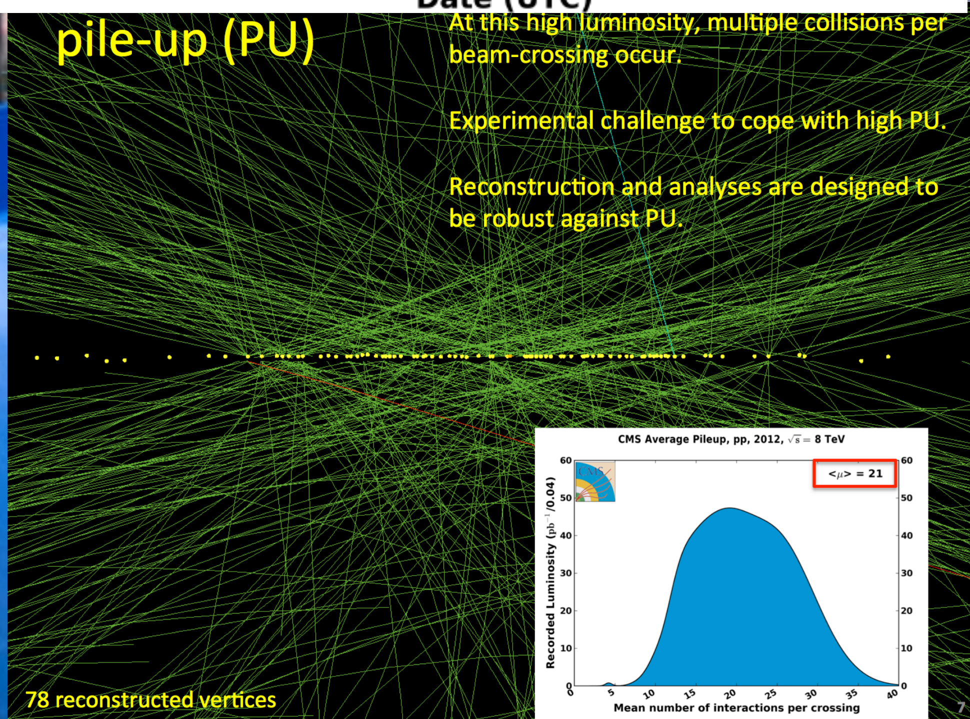
1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

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

The LHC is a Discovery Machine
The LHC will determine the Future course of High Energy Physics





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

27 km ring
100 meter underground

The LHC is an Extraordinary Machine

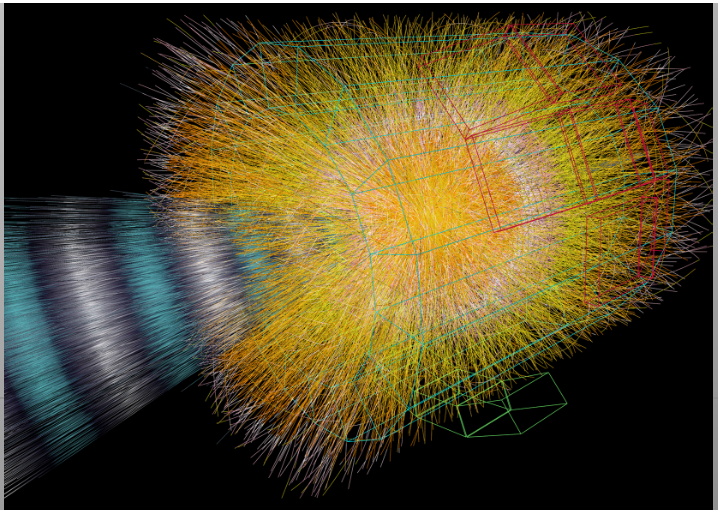
LHC facts

The LHC is …

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

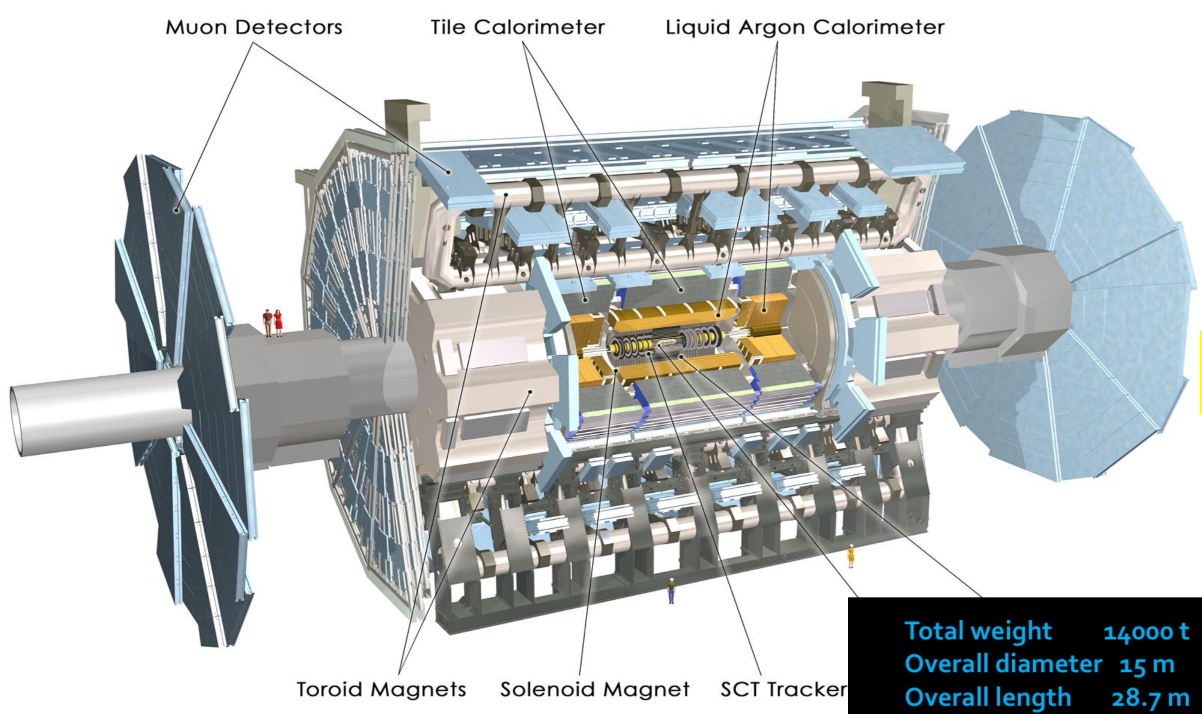
The emptiest place in our solar system. The vacuum is better than on the moon

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

The Higgs Hunters @ the LHC

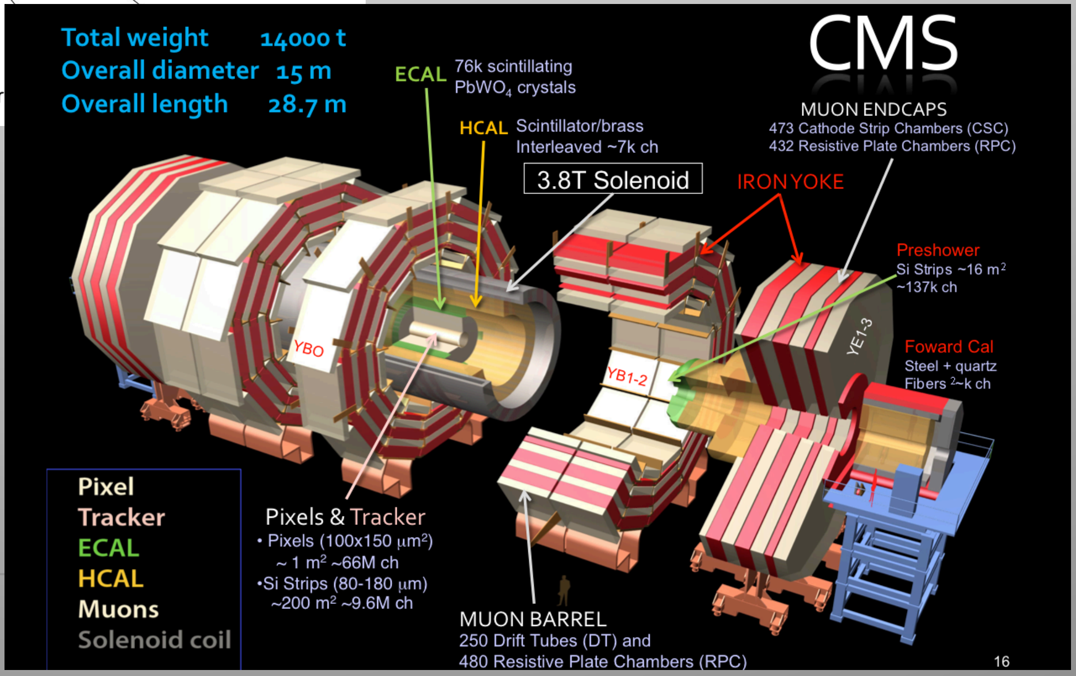


LHC: pp collisions at 7/8 TeV

The ATLAS experiment

The CMS experiment

These experiments use different technologies for their detector components

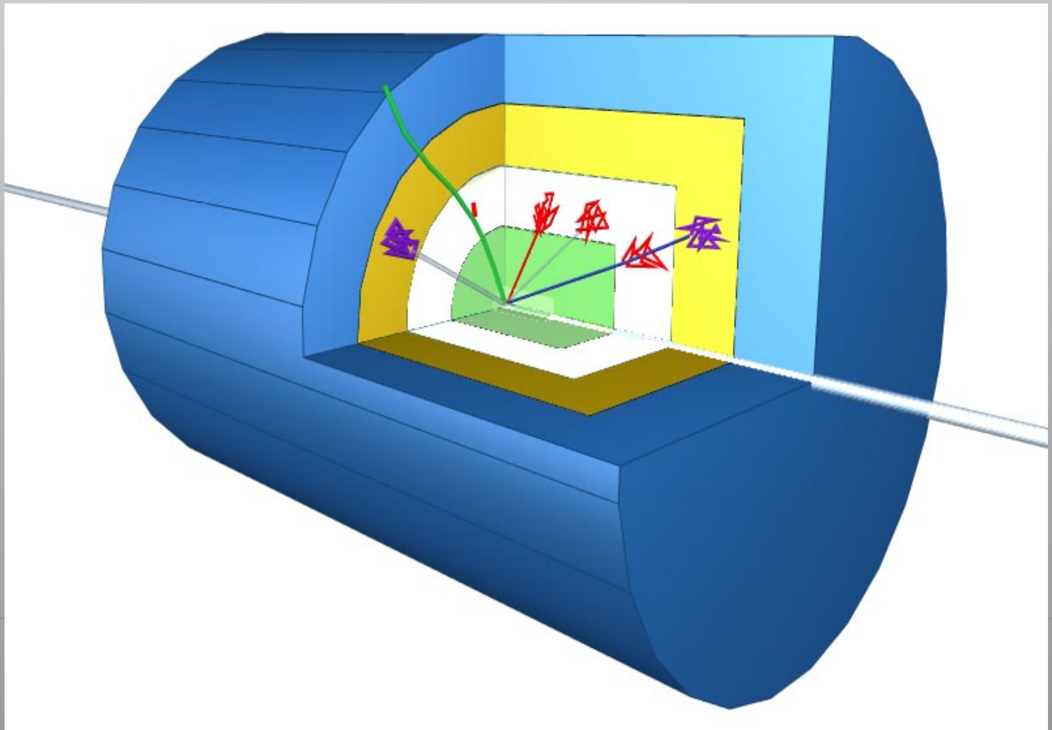


Schematic of a LHC Detector

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.



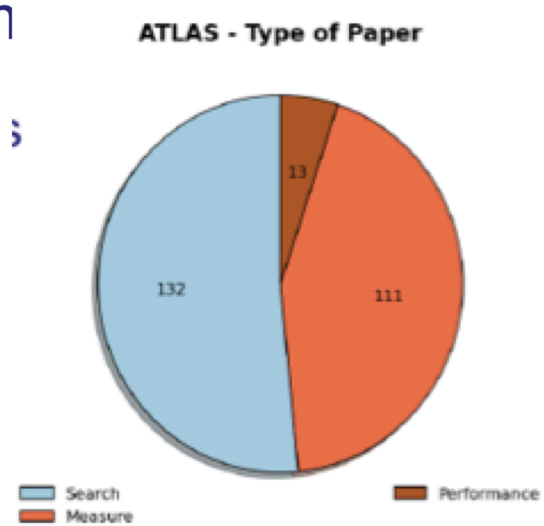
Such an experiment has ~ 100 Million read-out channels!!

Data Taking Challenges

- Collider: 20M bunch crossings per second
- ~ 20-30 events per bunch crossing: pile-up
- Trigger on 400 events/sec (+ another 400-600 Hz of parked data in CMS): keep the interesting, incl. unknown physics
- Total data volume in eg ATLAS: 5 billion detector events, 120 PB of data (simulation and data). Several billion Monte Carlo events (produce ~ 10^9 events/2 m
- ATLAS+CMS > 500 papers so far

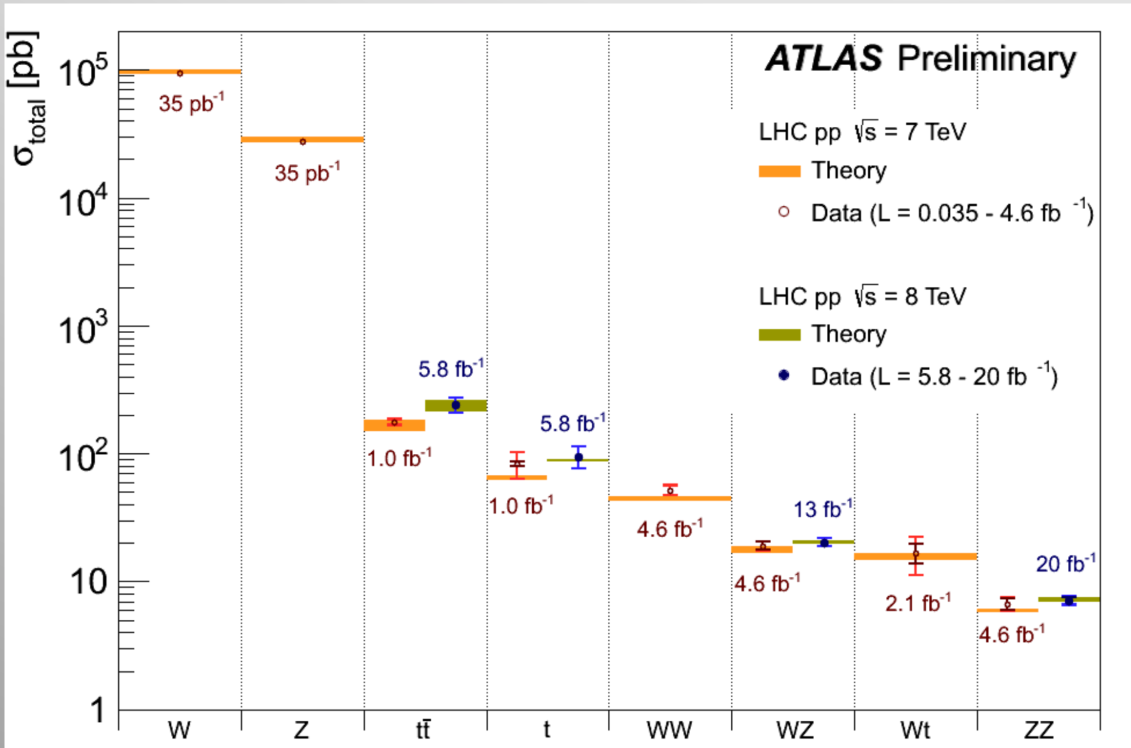
  > ~600 papers for all experiments

Searches for Higgs and New Physics but also studies of QCD, EWK interactions, top quark, heavy flavor physics, heavy ions…

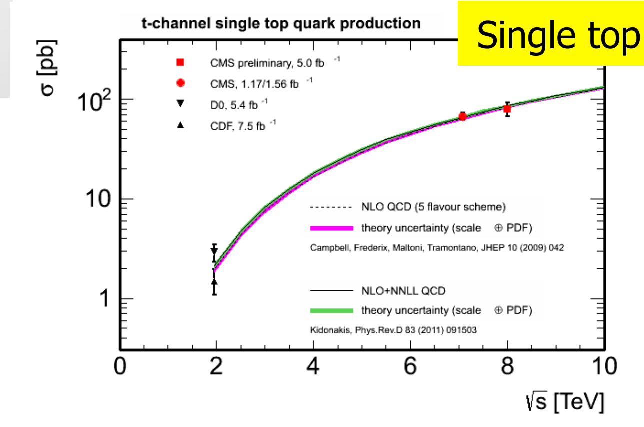


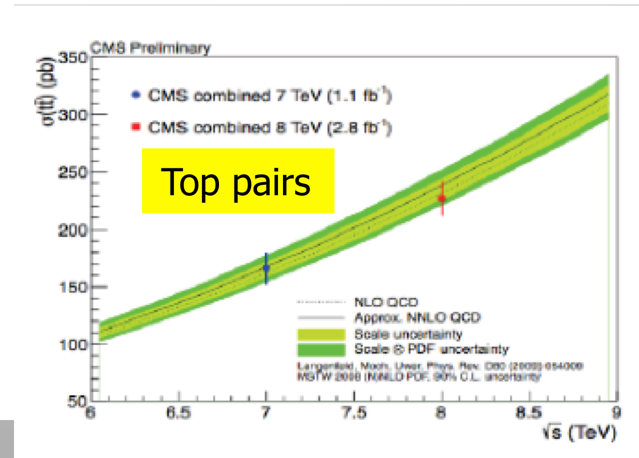
Standard Model Measurements

Electroweak Measurements



Top Quark Cross Sections





Good understanding of the detector + accurate theory predictions
→Precise measurements of the SM processes in a large range
→Good knowledge of the backgrounds to the Higgs analyses

Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem

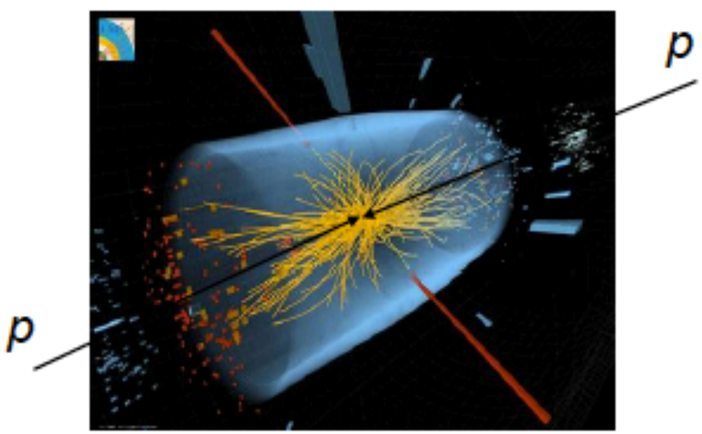
- need high energy:

  $E = mc^2$

- need lots of data

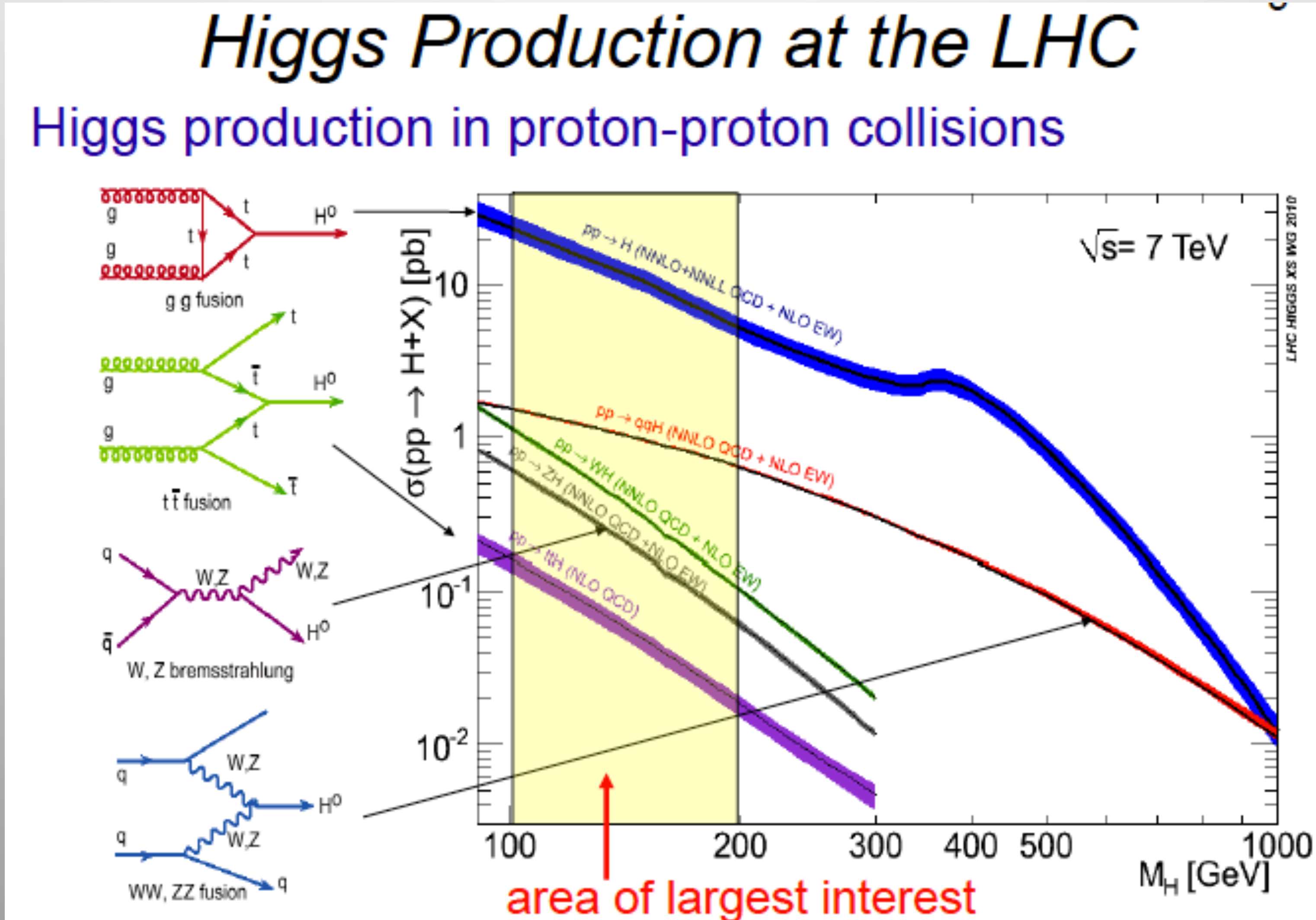
non-deterministic and very rare

order 1 in 10^{11}



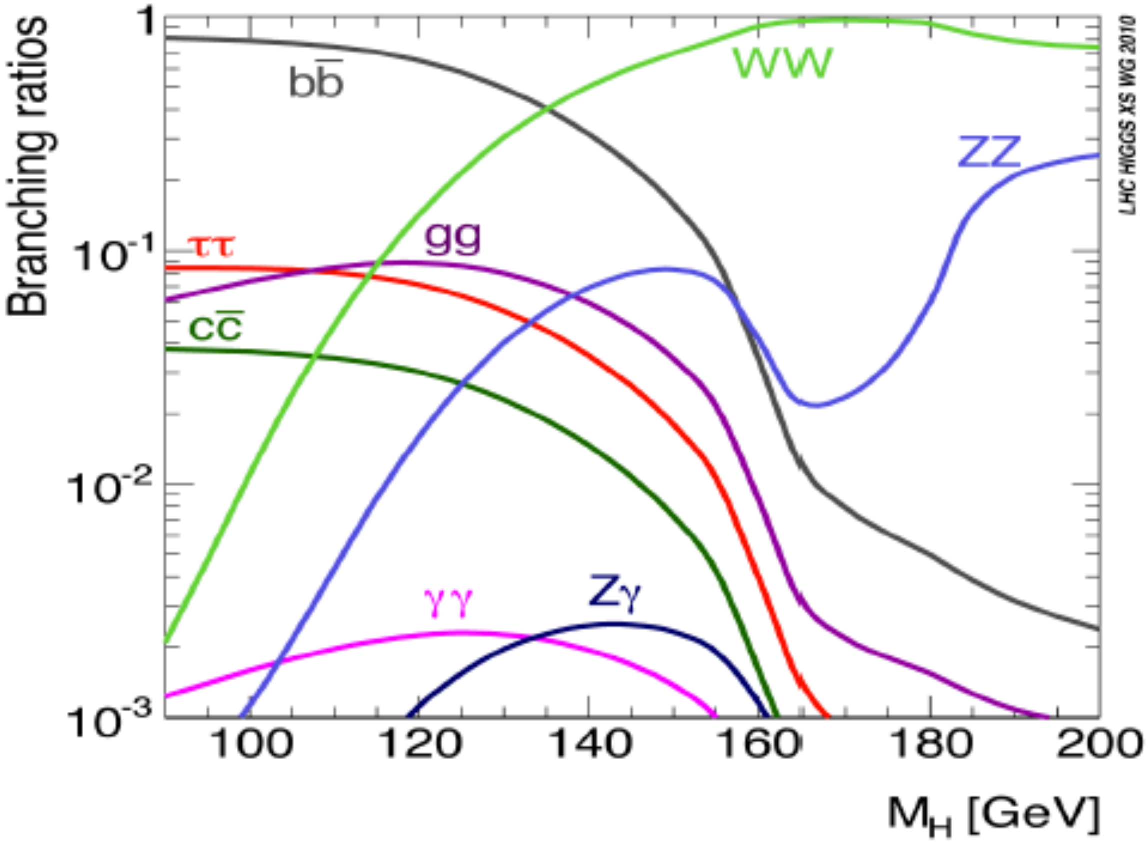
* for us finding the Higgs it was 48 years = 1,513,728,000 sec

Higgs Production Channels vs Mass



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

Higgs Decay Channel vs. Mass



Higgs boson couples to mass

- couplings to the electroweak gauge bosons:

$$gm_W \cdot (HWW^*) \quad + \quad \frac{gm_Z}{2\cos\theta_W} \cdot (HZZ)$$

- Yukawa couplings to all fermions

$$\frac{m_f}{v} \cdot (H\bar{f}f)$$

Messy: many channels, many subsequent decays *etc. etc.*

- common: leptons/photons essential for any search
- 5 channels are most promising

Higgs Hunting at the LHC

Overview – The big five

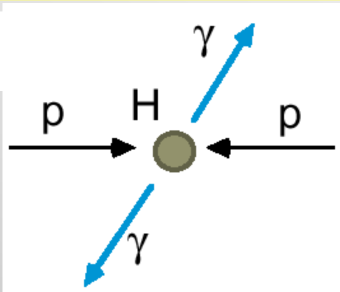
Channel	m_H range [GeV/c²]	data set [fb⁻¹]	Data used CMS [fb⁻¹]	m_H resolution
1) $H \rightarrow \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \rightarrow$ tau tau	110-145	5+12/fb	2011+12	15%
3) $H \rightarrow bb$	110-135	5+12/fb	2011+12	10%
4) $H \rightarrow WW \rightarrow l\nu l\nu$	110-600	5+12/fb	2011+12	20%
5) $H \rightarrow ZZ \rightarrow 4l$	110-1000	5+12/fb	2011+12	1-2%

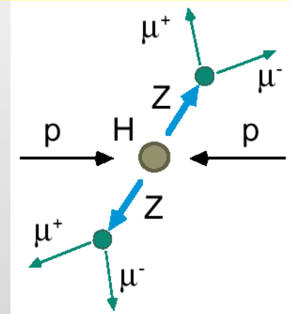
By now all the analyses are updated to the full statistics for CMS and ATLAS (except tau tau)

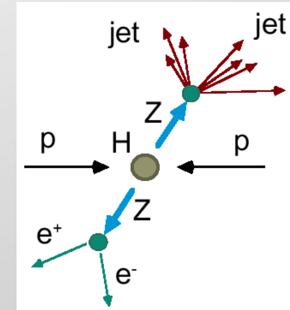
Higgs Boson Searches (simulation)

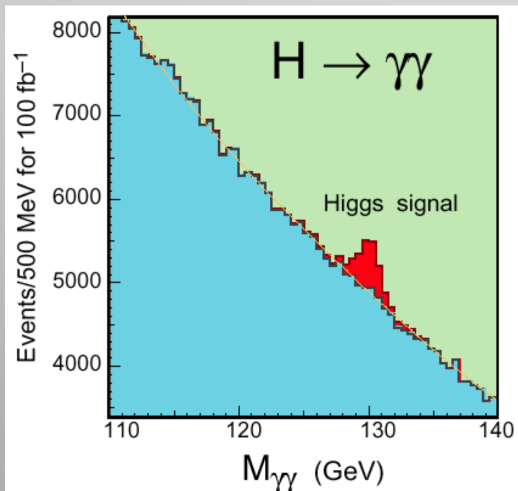
Low M_H < 140 GeV/c²	Medium 130<M_H<500 GeV/c²	High M_H > ~500 GeV/c²

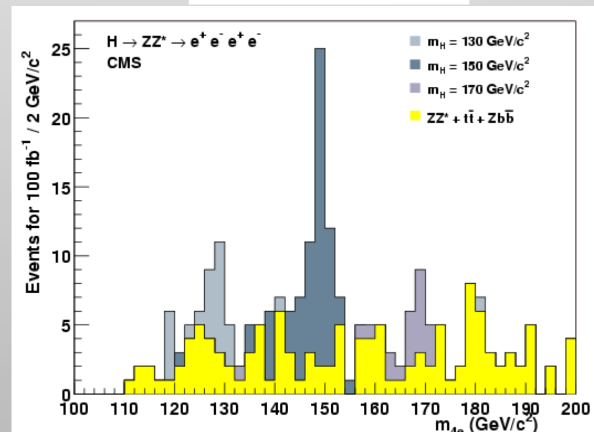
simulation

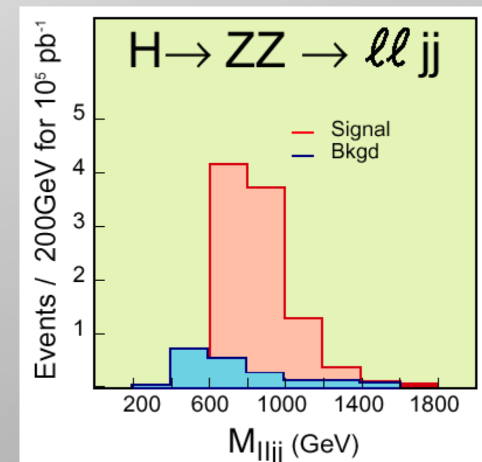


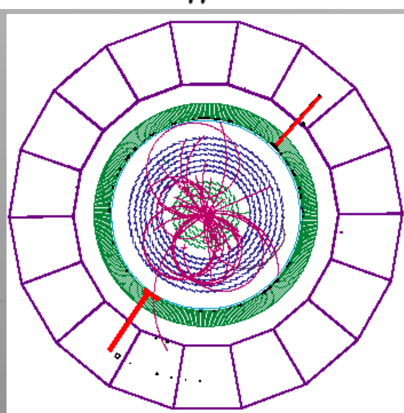


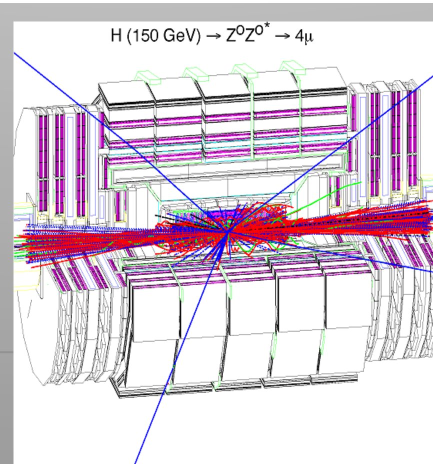


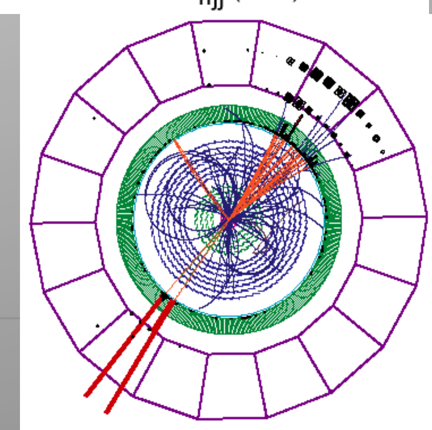










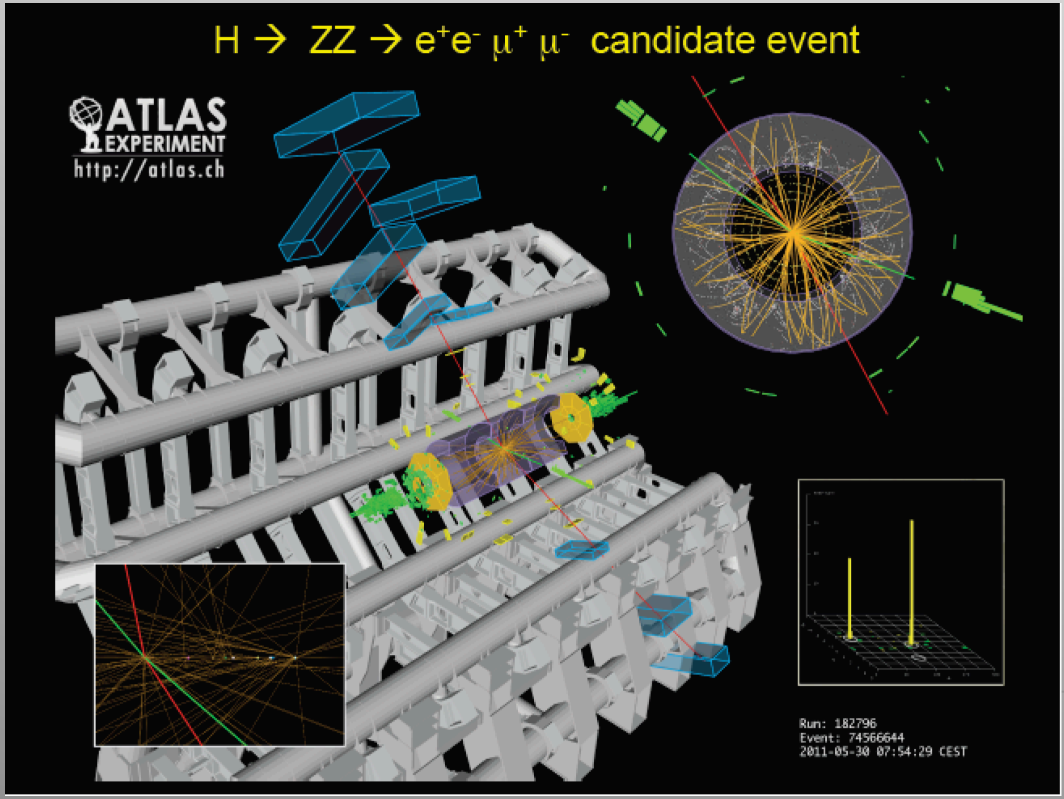


Searches for the Higgs Particle

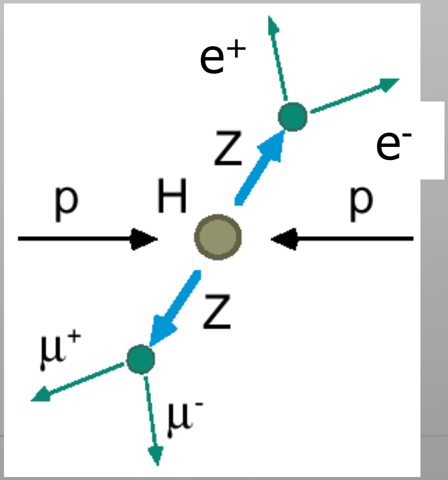
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

Example: Higgs(?) decays into ZZ and Z bosons decays into μμ and ee

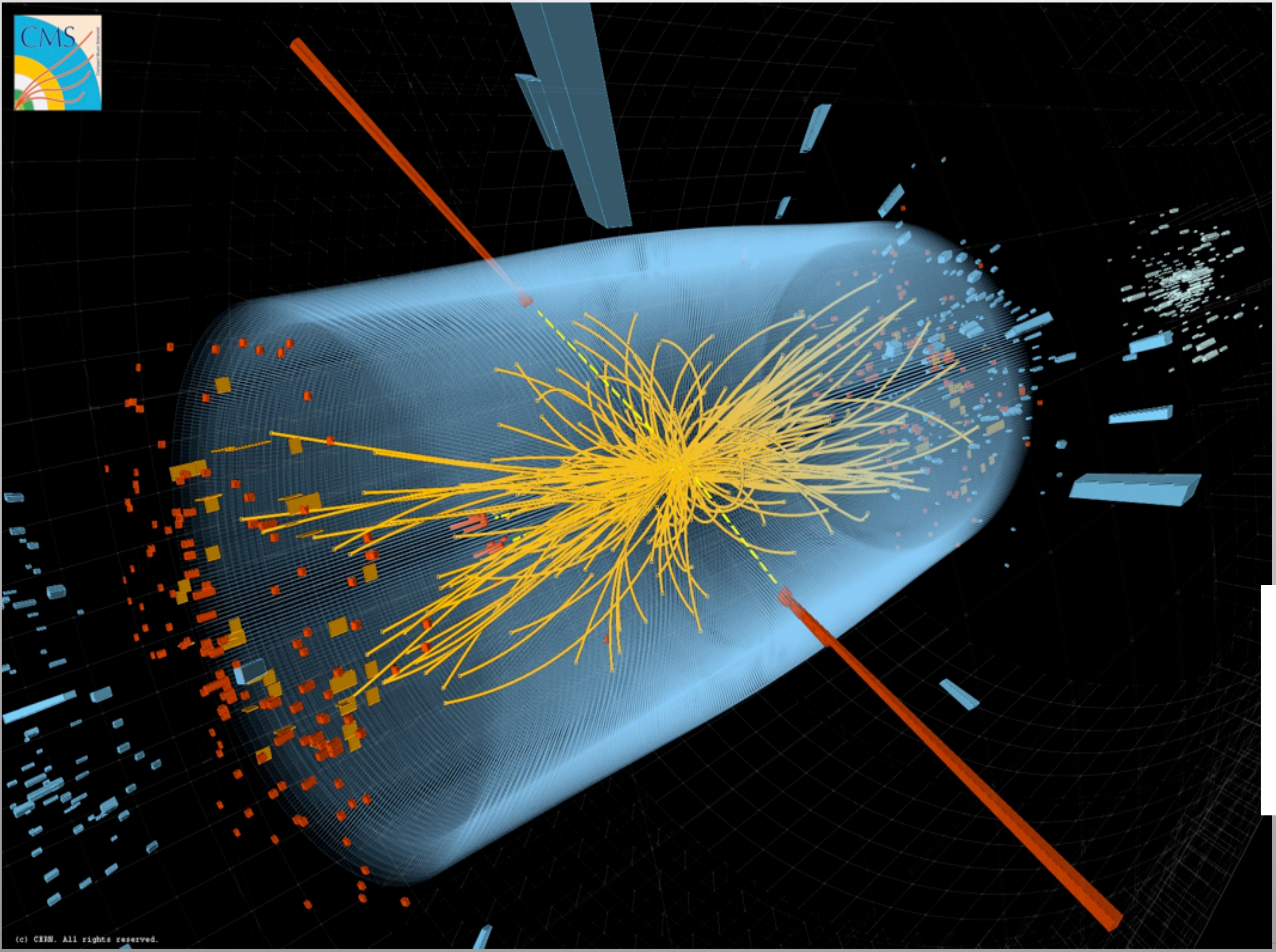
So we look for 2 muons and 2 electrons in the detector

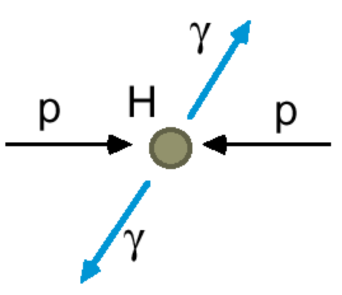


But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for sure on event by event (we can reconstruct the total mass with the 4 leptons)



A Collision with two Photons

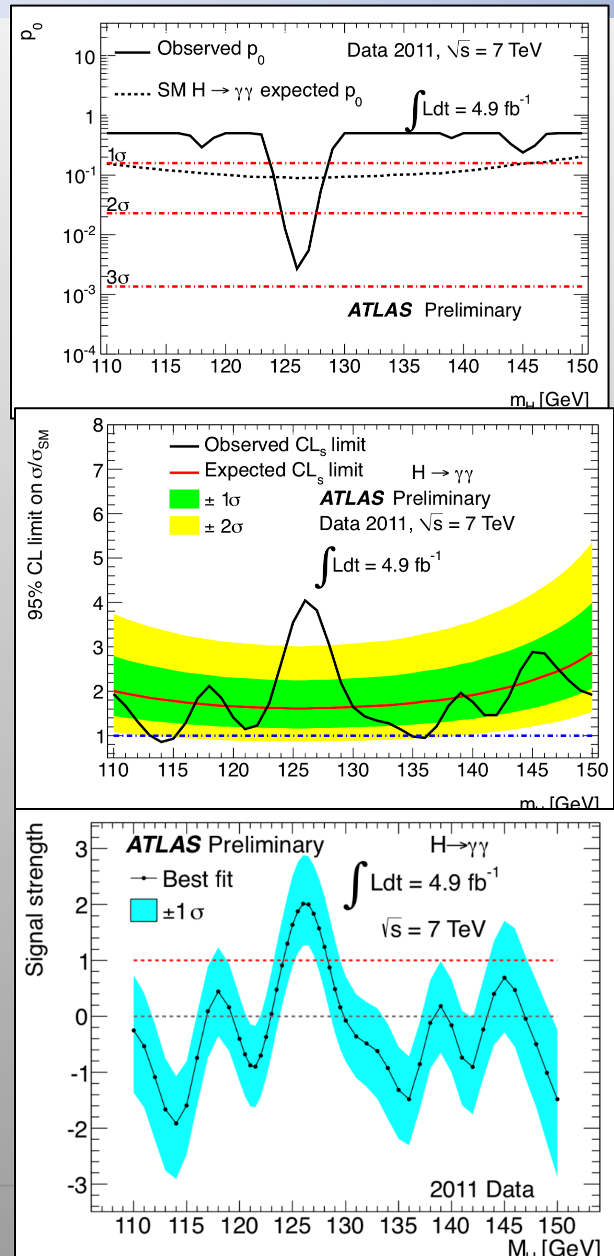




A Higgs or
a 'background' process without a Higgs?

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
- estimate signal strength (relative to expectation)
- See lecture of A. Read



December 2011
A Higgs in the making?

3 sigma= "Evidence"

1 chance in 1000 to be wrong!

5 sigma="Discovery"

1 chance in 3 million To be wrong!!!

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

Melbourne

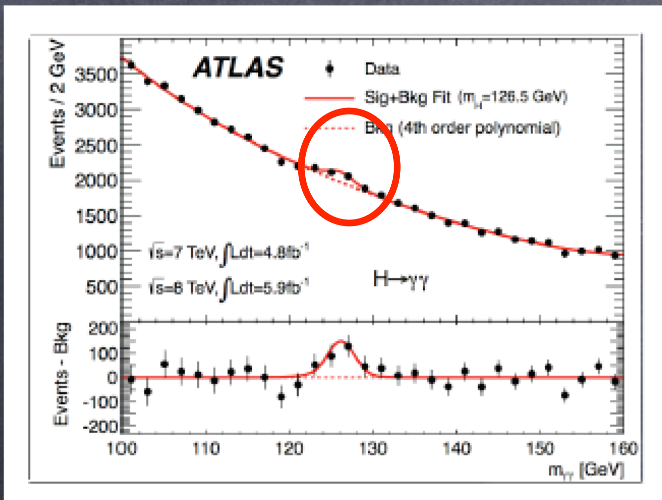
Followed live around the world…

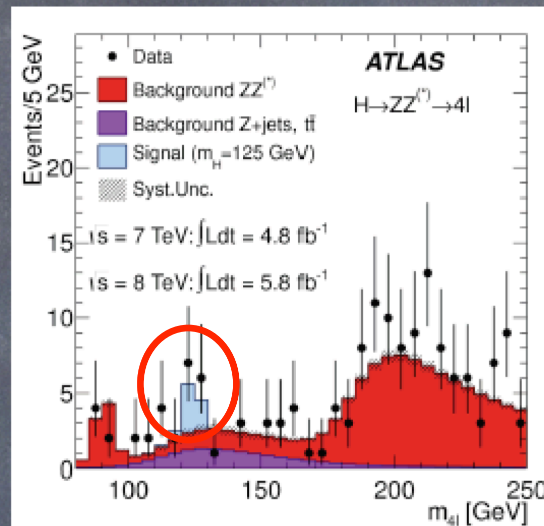
Summer 2012: Results

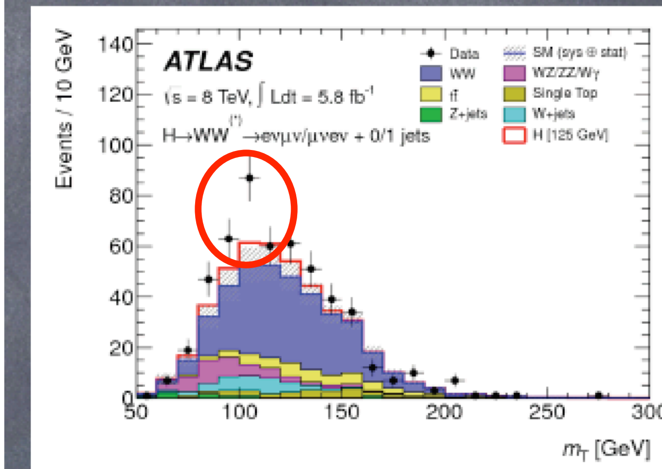
Higgs → 2 photons!!

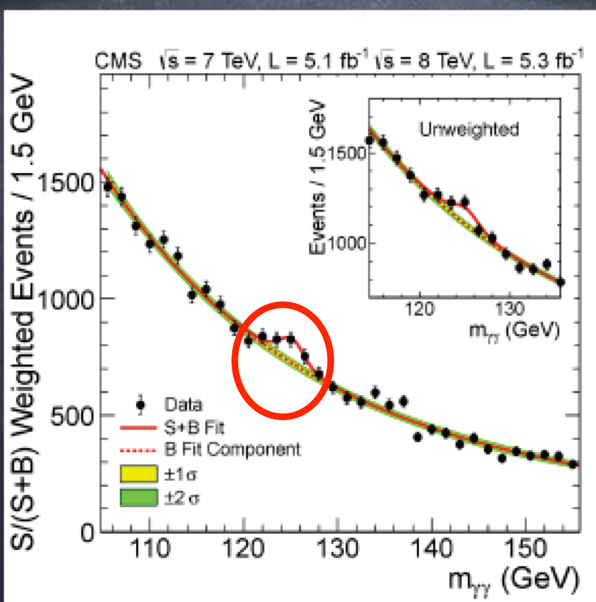
Higgs → 2Z →4 leptons!!

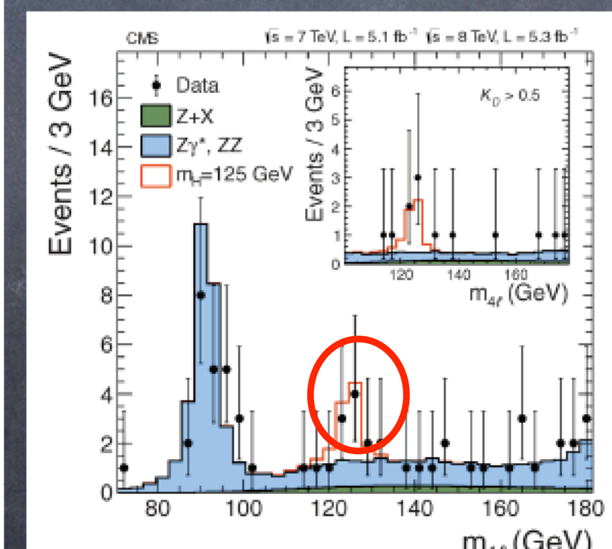
Higgs → 2W →2l2ν!!

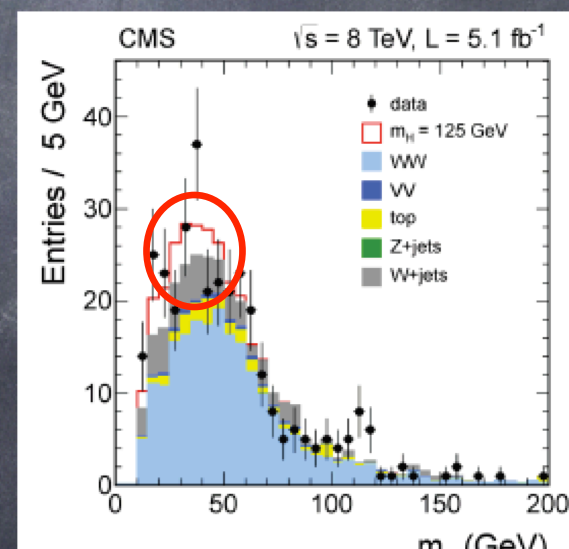












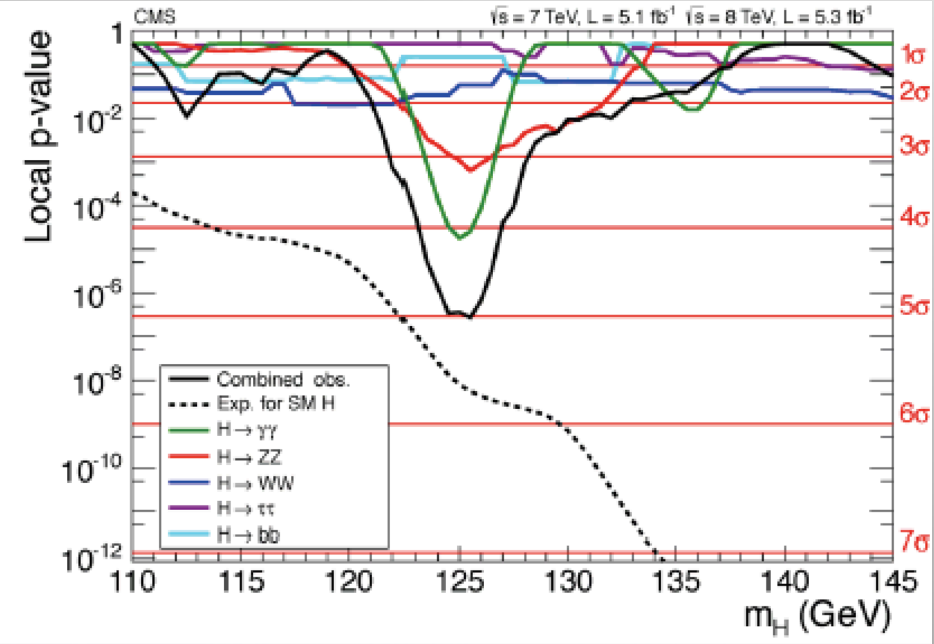
Summer 2012: Results

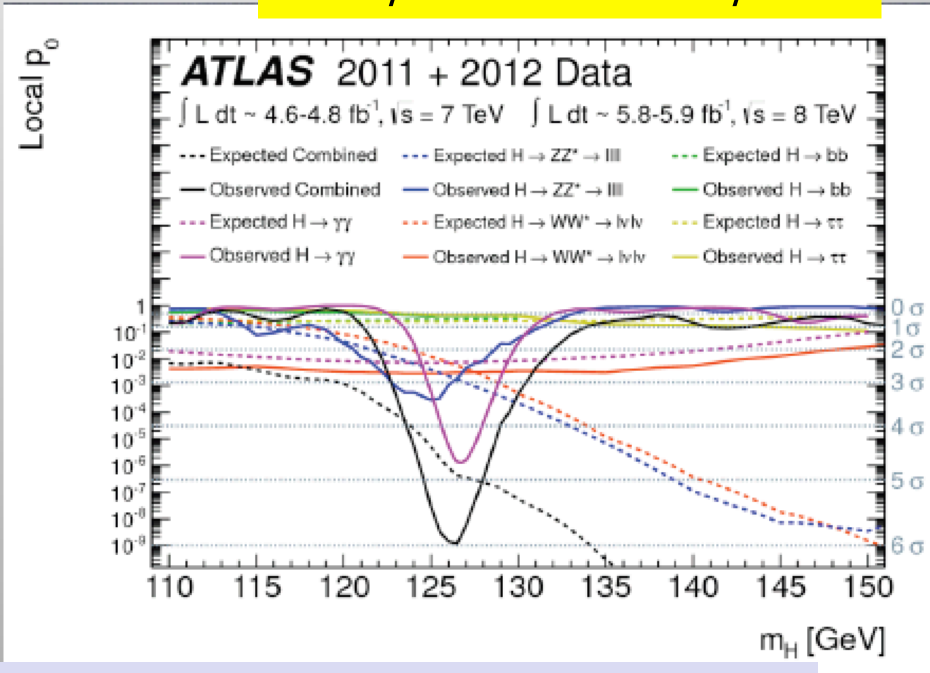
Both experiments see an excess ~125 GeV in the γγ, ZZ and WW channel

→Adding up al the channels gives the following combination

Shown is the compatibility with a 'background only hypothesis"

5 fb^{-1}/2011 and 5 fb^{-1}/2012



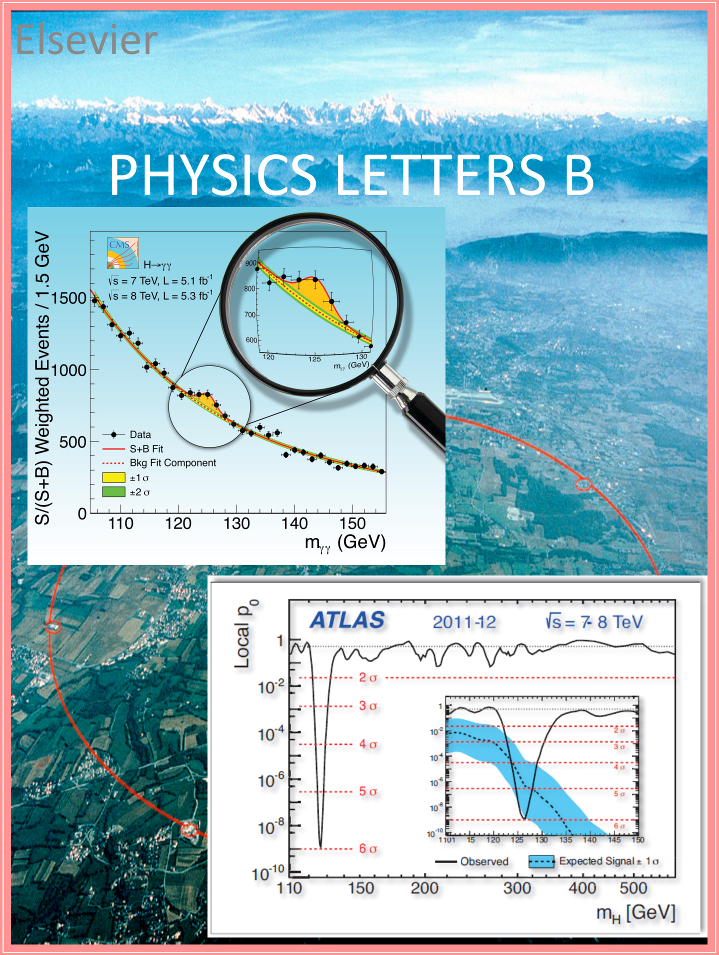


CMS and ATLAS observe a new boson with a significance of about 5 sigma (1 chance in 3 million to be wrong!!!)

The particle is consistent with a Higgs-like boson

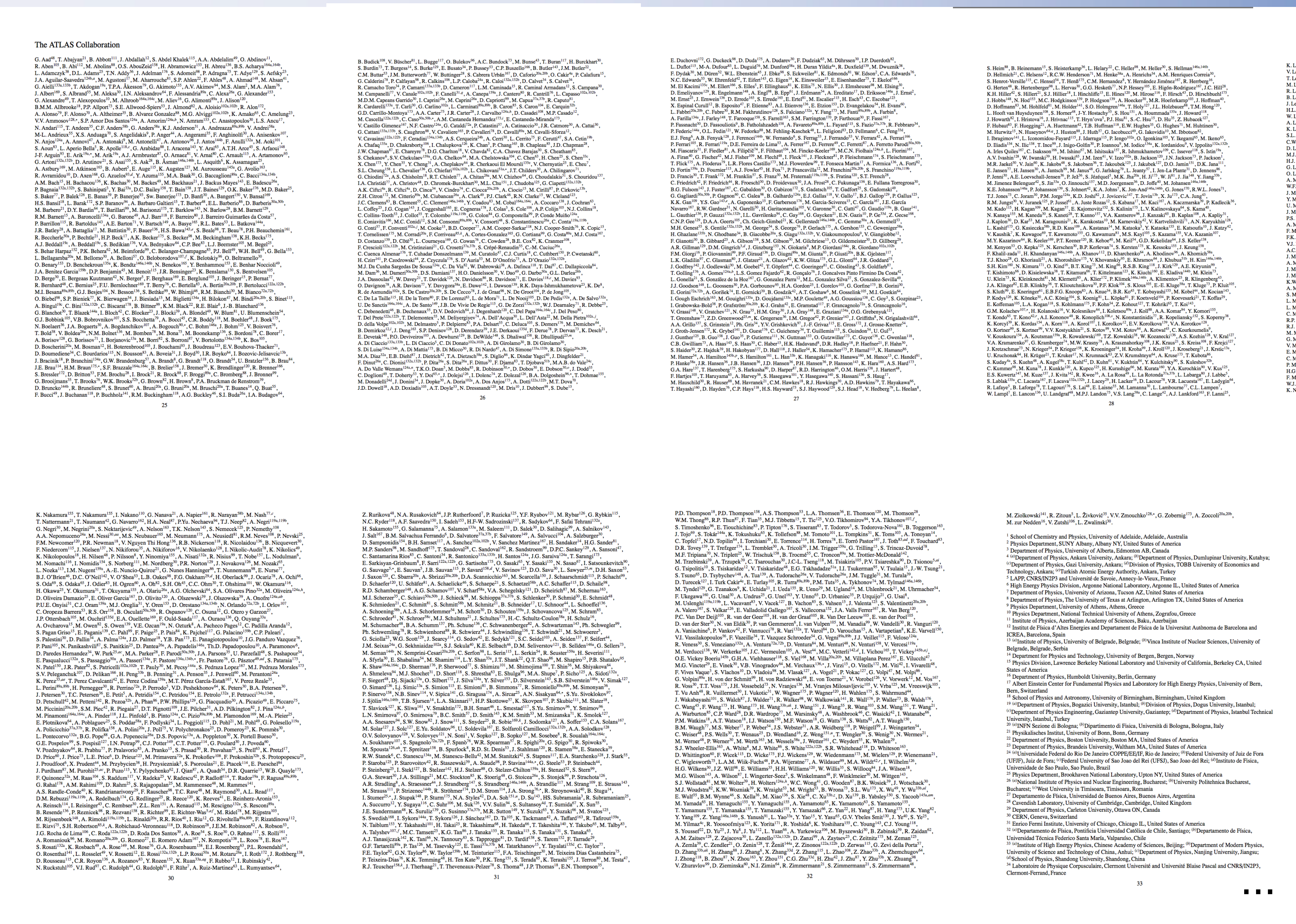
Higgs Publications…

Special booklet PLB edition with
the ATLAS and CMS papers
More than 1400 citations…



Also…

Higgs Publications Authors...



...

Example ATLAS

>3000 authors

(9 pages out of 33)

> 800 PhD students (CMS)

The Press… (5th July 2012)

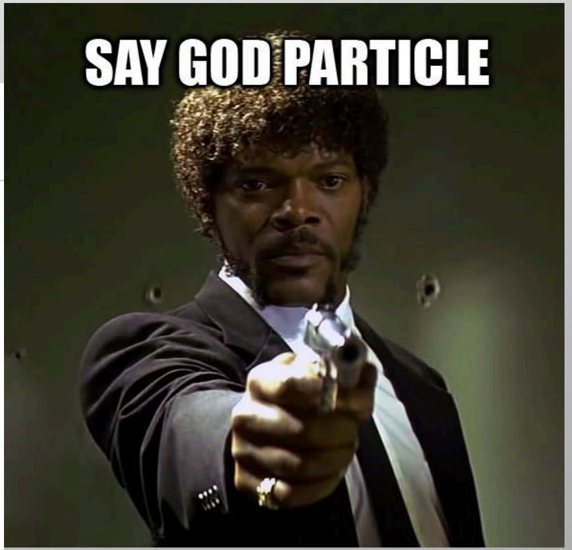
The discovery of the Higgs made the headlines worldwide

Hawking lost $100 bet over Higgs boson

What Comes After Higgs Boson?

the 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

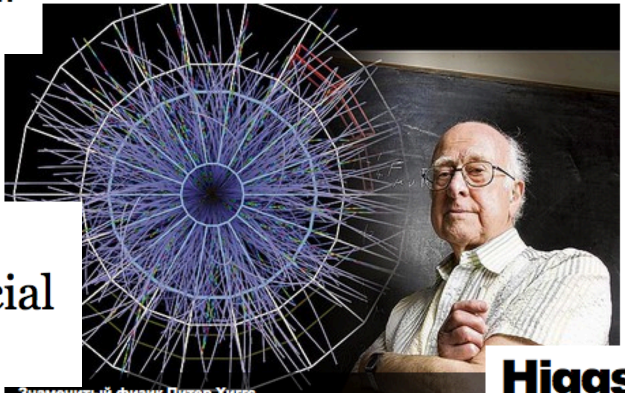
В CERN открыли бозон Хиггса

Текст

— 3.07.12 15:13 —

ТЕКСТ: АЛЕКСАНДРА БОРИСОВА

D: SCIENCEUNSEEN.COM



Знаменитый физик Питер Хиггс

Discovery of Higgs Boson Bittersweet News in Texas

Scientists Set The Higgs Boson To Music

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?

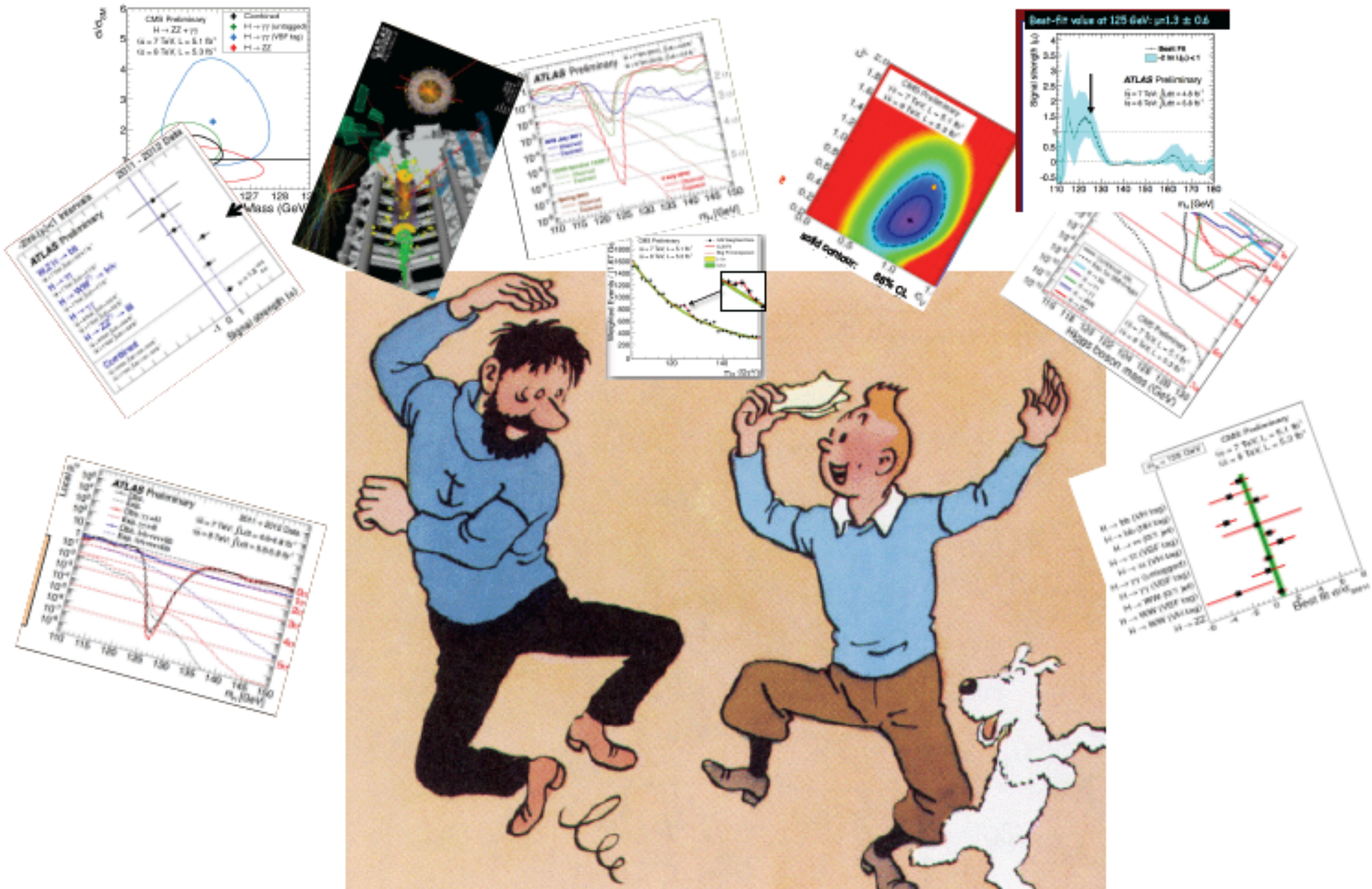
Higgs boson researchers consider move to Cloud computing

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

The Theorists…

A. Pomarol ICHEP2012

… and finally plenty of new relevant data has begun to fall over us!



The Community (The day after…)

Confronting the MSSM and the NMSSM with the Discovery of a Signal in the two Photon Channel at the LHC
R. Benbrik, M. Gomez Bock, S. Heinemeyer, O. Stal, G. Weiglein, L. Zeune

Have We Observed the Higgs (Imposter)?
Ian Low, Joseph Lykken, Gabe Shaughnessy

2:1 for Naturalness at the LHC?
Nima Arkani-Hamed, Kfir Blum, Raffaele Tito D'Agnolo, JiJi Fan

The apparent excess in the Higgs to di-photon rate at the LHC: New Physics or QCD uncertainties?
I. Baglio, A. Djouadi, R. M. Godbole

Testing No-Scale F-SU(5): A 125 GeV Higgs Boson and SUSY at the 8 TeV LHC
Tianjun Li, James A. Maxin, Dimitri V. Nanopoulos, Joel W. Walker

Higgs boson of mass 125 GeV in GMSB models with messenger-matter mixing
A. Albaid, K.S. Babu

125 GeV Higgs Boson, Enhanced Di-photon Rate, and Gauged U(1)_PQ-Extended MSSM
Haipeng An, Tao Liu, Lian-Tao Wang

Higgs discovery: the beginning or the end of natural EWSB?
Marc Montull, Francesco Riva

The Social Higgs
Daniele Bertolini, Matthew McCullough

Could two NMSSM Higgs bosons be present near 125 GeV?
John F. Gunion, Yun Jiang, Sabine Kraml

First Glimpses at Higgs' face
J. R. Espinosa, C. Grojean, M. Muhlleitner, M. Trott

Precision Unification in λSUSY with a 125 GeV Higgs
Edward Hardy, John March-Russell, James Unwin

Implications of the Higgs Boson Discovery for mSUGRA
Sujeet Akula, Pran Nath, Gregory Peim

Global Analysis of the Higgs Candidate with Mass ~ 125 GeV
John Ellis, Tevong You

The Higgs sector of the phenomenological MSSM in the light of the Higgs boson discovery
Alexandre Arbey, Marco Battaglia, Abdelhak Djouadi, Farvah Mahmoudi

Is the resonance at 125 GeV the Higgs boson?
Pier Paolo Giardino, Kristjan Kannike, Martti Raidal, Alessandro Strumia

Constraining anomalous Higgs interactions
Tyler Corbett, O. J. P. Eboli, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia

Higgs After the Discovery: A Status Report
Dean Carmi, Adam Falkowski, Eric Kuflik, Tomer Volansky, Jure Zupan

Are There Hints of Light Stops in Recent Higgs Sear
Matthew R. Buckley, Dan Hooper

The Theories

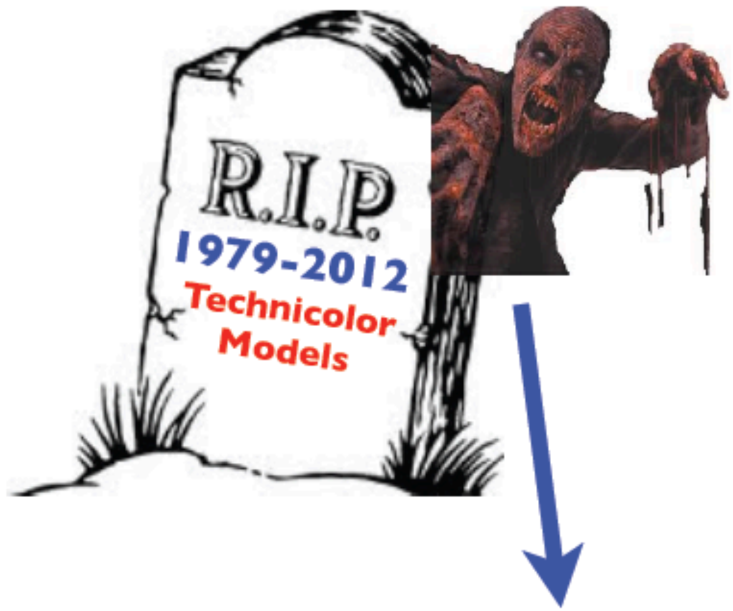
But not so excellent for all theorists:

Specially for fans of **Higgsless models:**

The Theories ??

but be careful about resurrections...

It is *not unconceivable* that a light dilaton appears in Higgsless theories



This indeed happened

Dilaton

(Goldstone of the spontaneous breaking of scale invariance)

Couples as a Higgs up to an overall scale → **A Higgs impostor**

However, less and less likely...

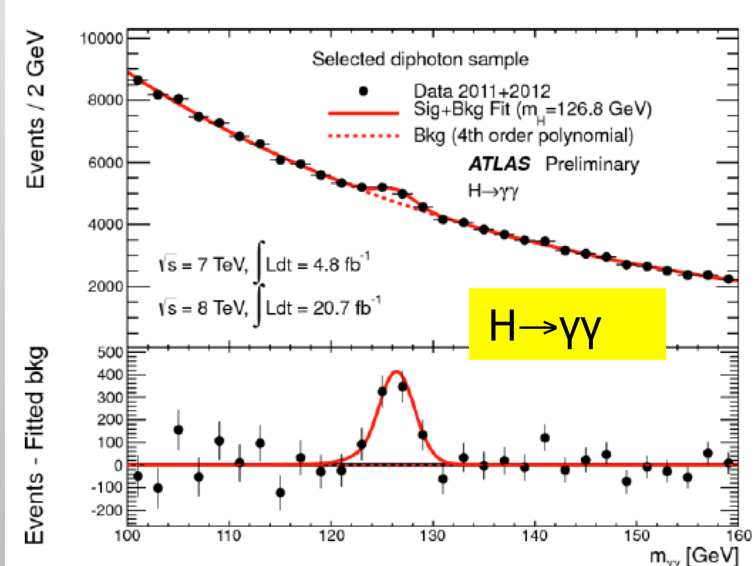
Is it really the Higgs Boson?

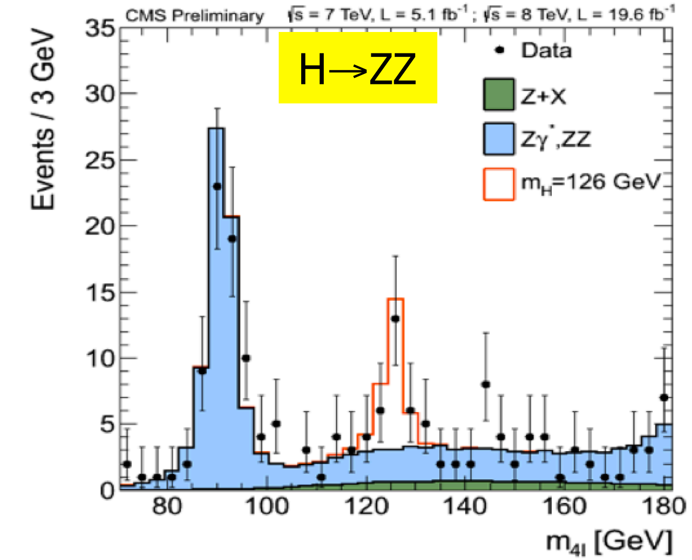
We, experimentalists, called it a "Higgs-like" particle

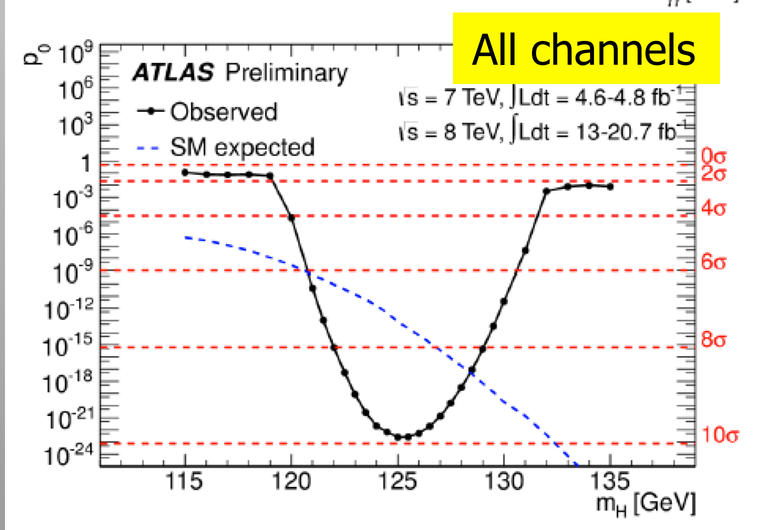
- Does this new particle have all the properties that we expect a Higgs Boson to have?
  - So far it seems to couple as expected to photons, heavy Z and W bosons, but at the time of the discovery it was not seen that they also couple to quarks or leptons
- What are the quantum numbers of this new particle?
  - 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?

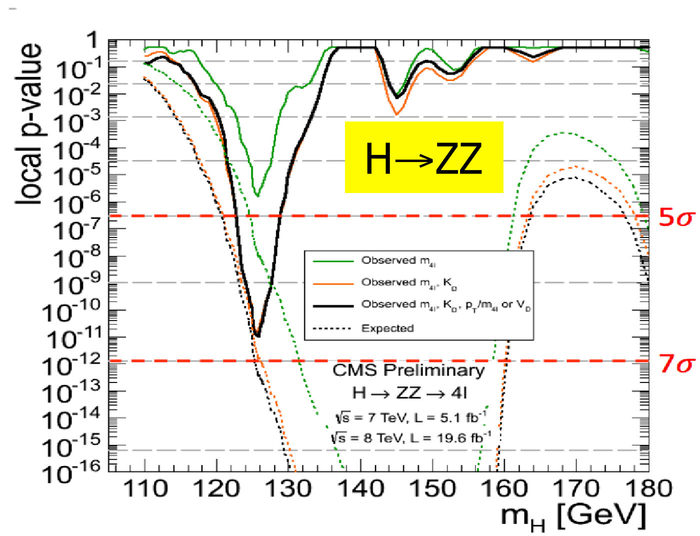
Still a lot of questions to be answered in summer 2012!!
Let's look at the new updates with full 2012 data (~ 25 fb^{-1})

Update with the Full 2012 Data Sample







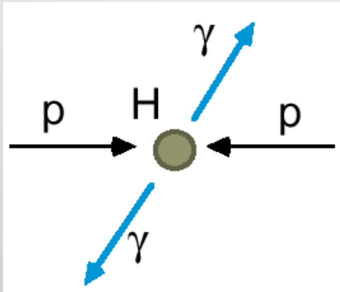


Increased data sample with a factor of ~3

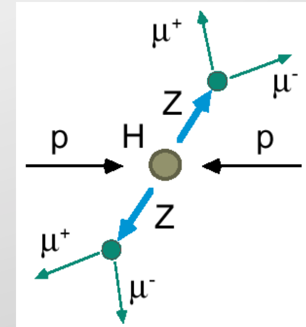
The particle is clearly still with us, now with a significance of >10σ !!

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

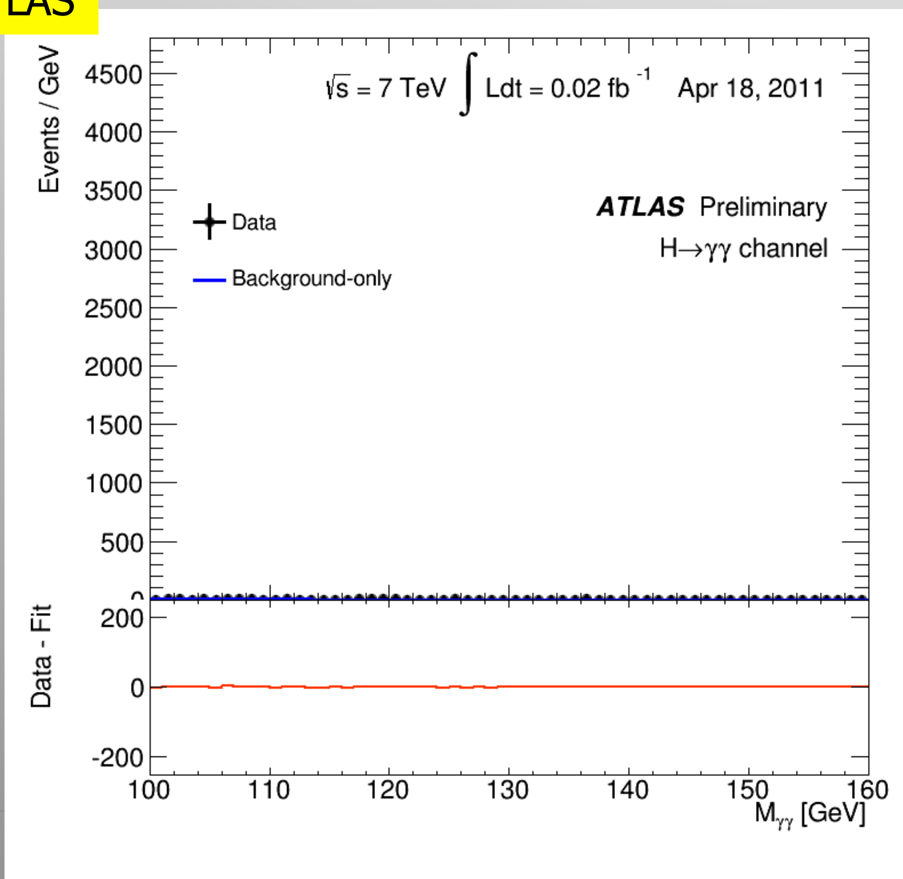
The Birth of a Particle



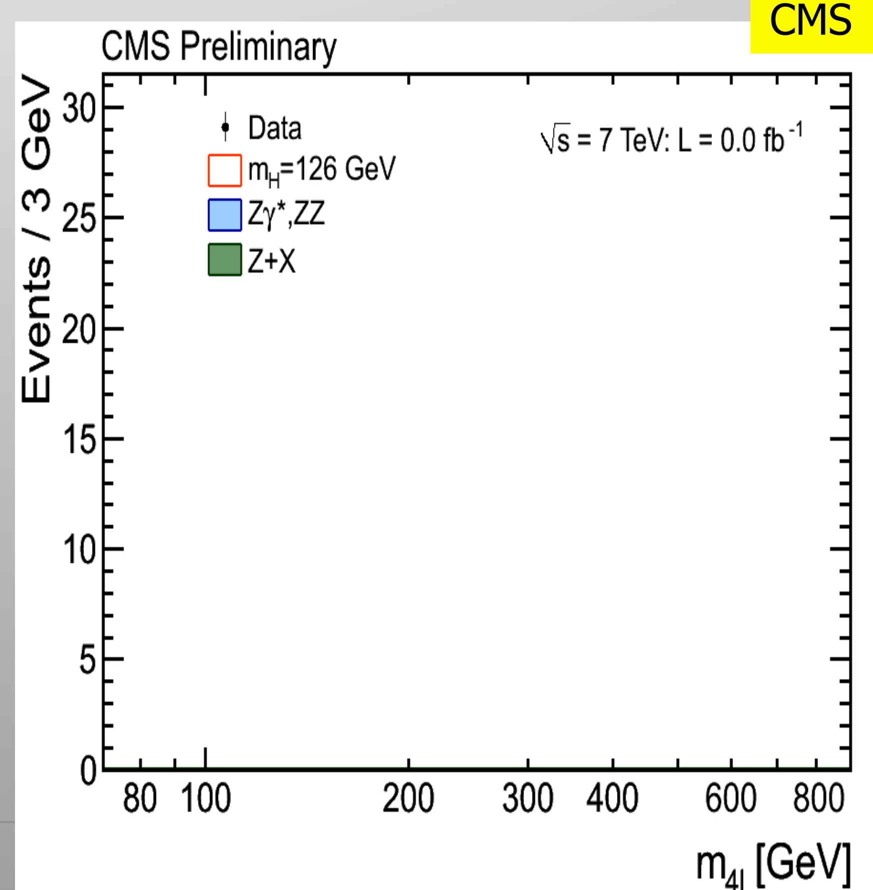
"History" of the data accumulation during the last two years



ATLAS



CMS



Does this Particle Decay into Fermions?

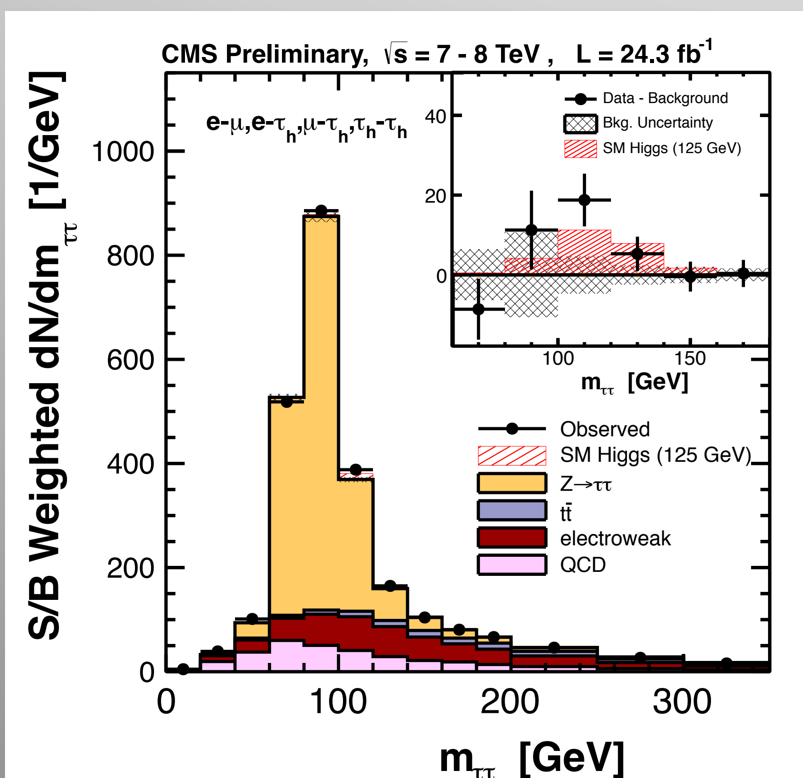
- The BEH Mechanism was proposed in 1964 to give mass to the W and Z boson
- Does it also give mass to the fermions? Does the particle couple to fermions?

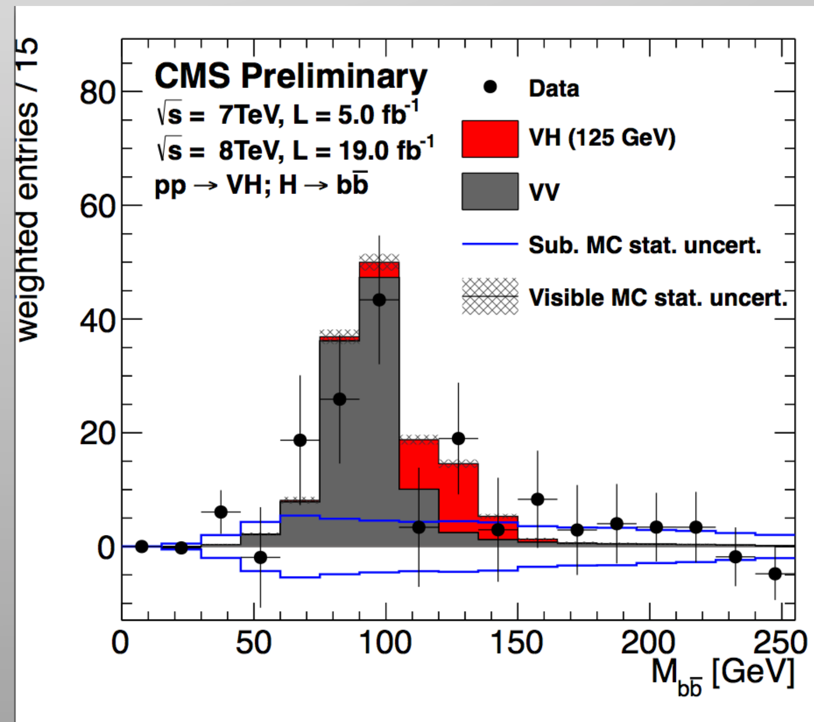
  ⇒ Direct test: check for the decays H→ tau tau and H → b quark pairs

CMS

Higgs →ττ leptons
Hadronic and leptonic decays

Higgs → b-quark pairs
Only possible in VH and VBF processes

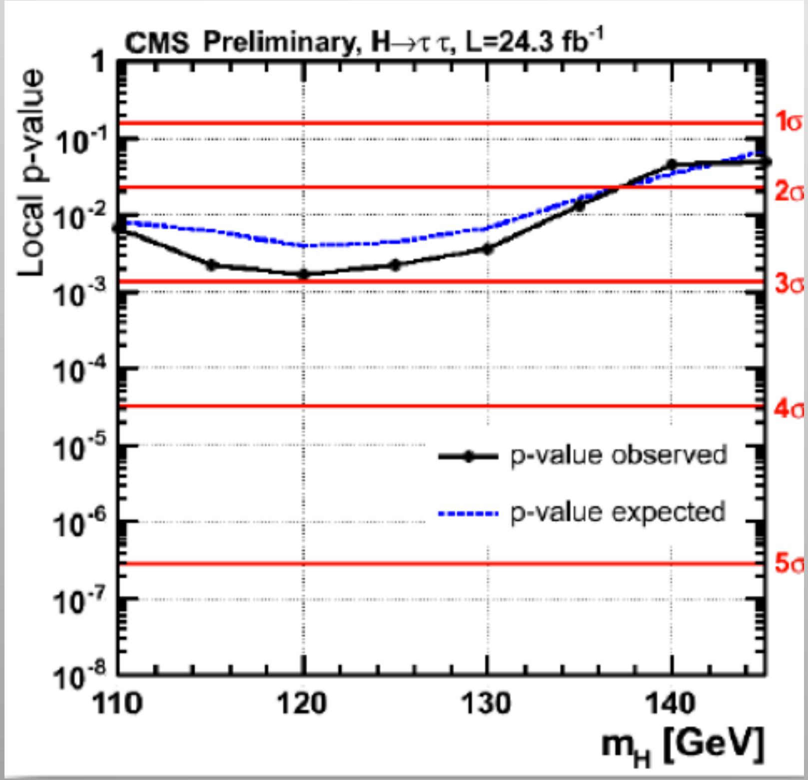




Background subtracted distribution

Does this Particle Decay into Fermions?

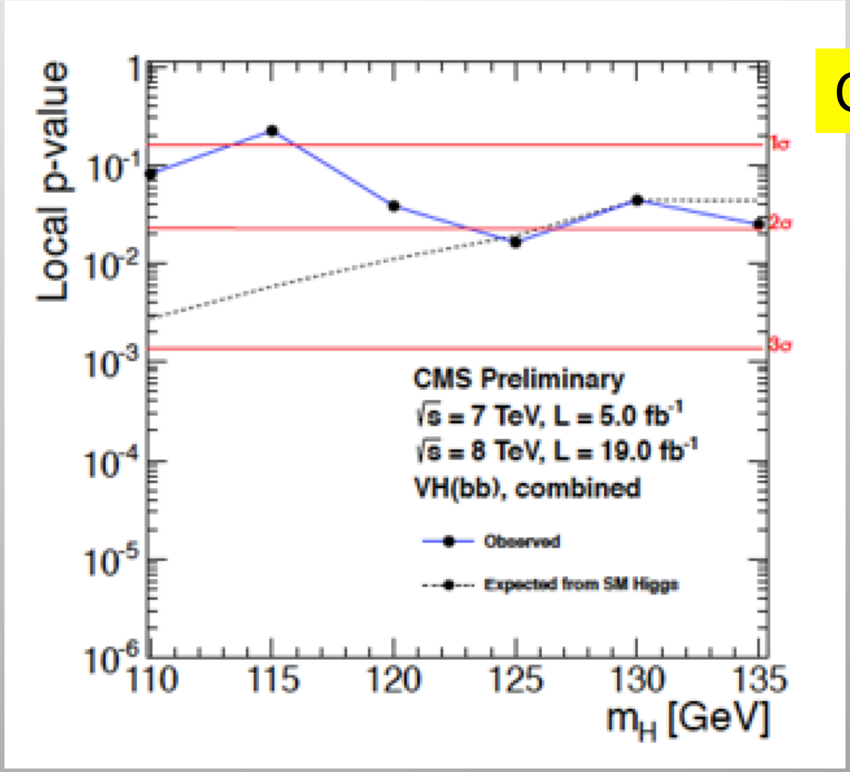
Higgs →ττ leptons



Significance 2.85σ at 125 GeV

Higgs → b-quark pairs

CMS



Significance 2.1σ at 125 GeV

A mild excess is building up also for these channels with ~ 3.4σ

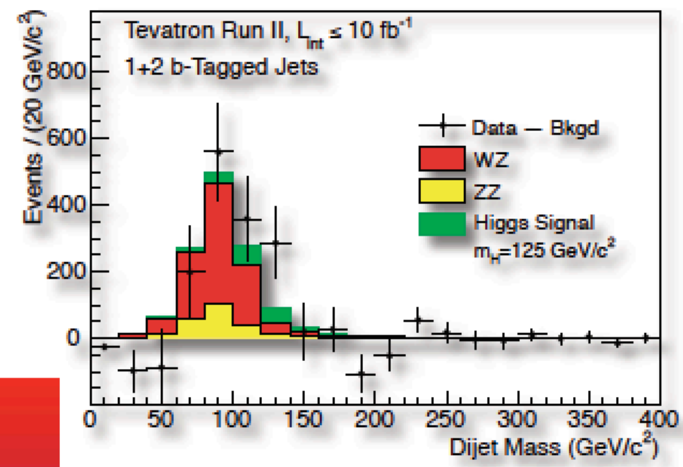
Tevatron Higgs Results - Final

Tevatron results: proton anti-proton collisions at 1.96 TeV

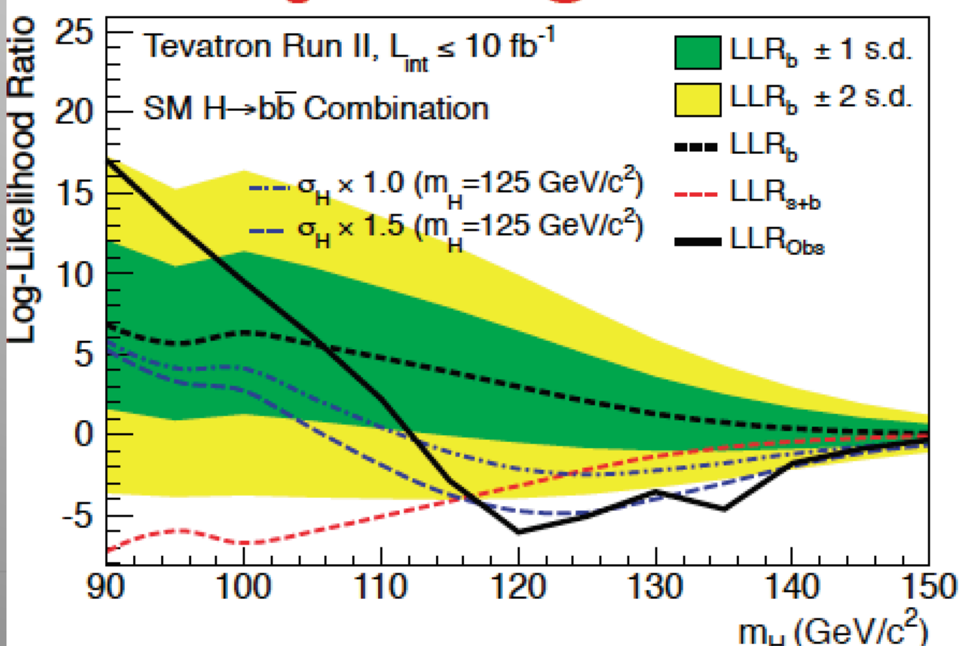
- Sensitivity is dominated by the VH(bb) channel
- Evidence for VZ(bb) production consistent with $\sigma_{SM} = 4.4 \pm 0.3$ pb
- Spin-parity is being investigated as well

$\sigma_{VZ} = 3.0 \pm 0.6 \pm 0.7$ pb

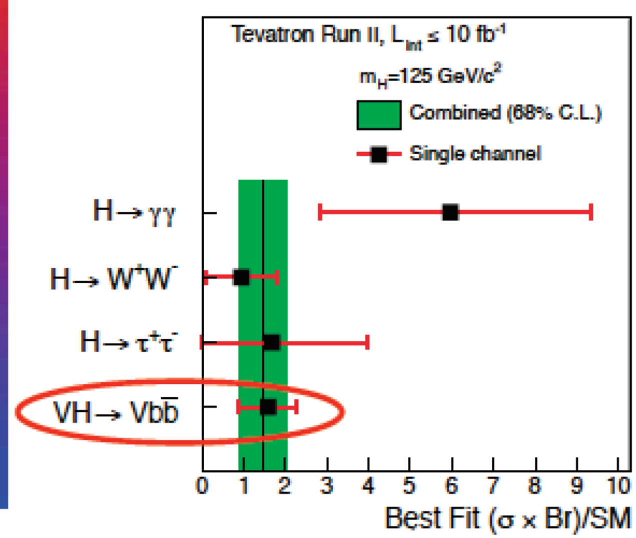
~3σ significance



~3σ significance @ m_H = 125 GeV



CDF & D0 Collaborations
arXiv:1303.6346

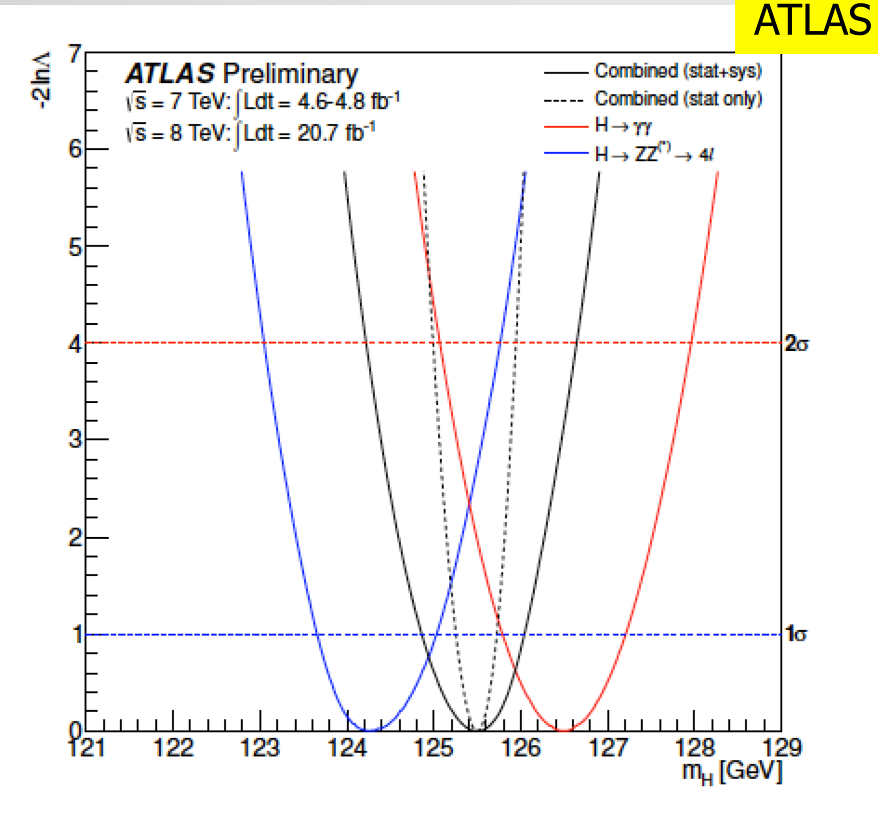


Channel Combination & Higgs Properties

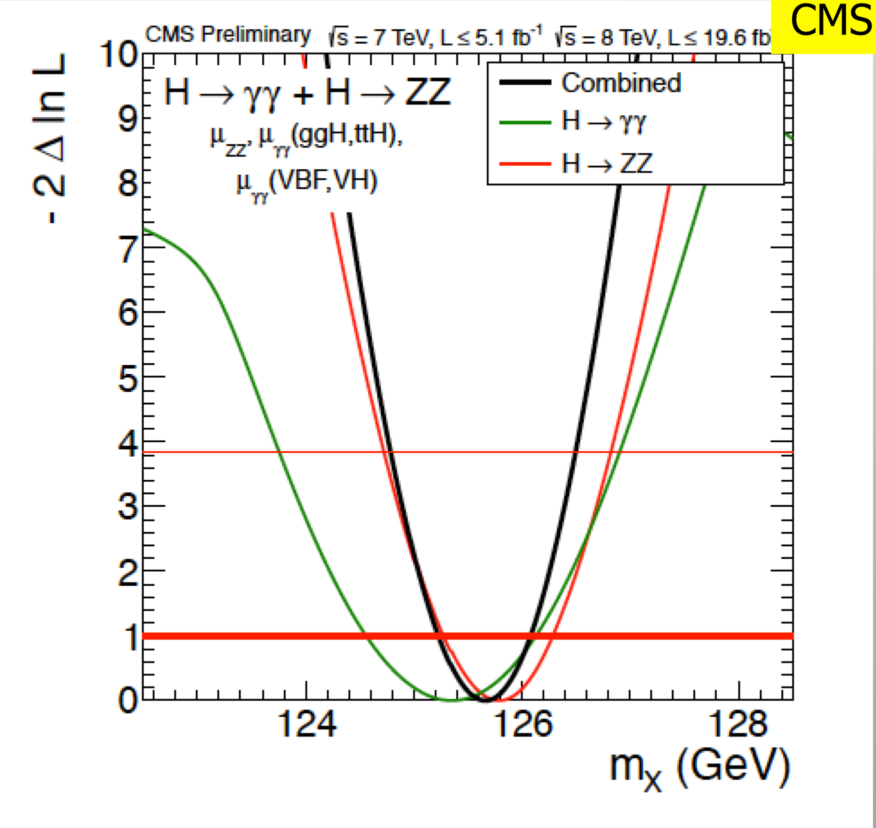
The Mass of the Particle

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

ATLAS



CMS



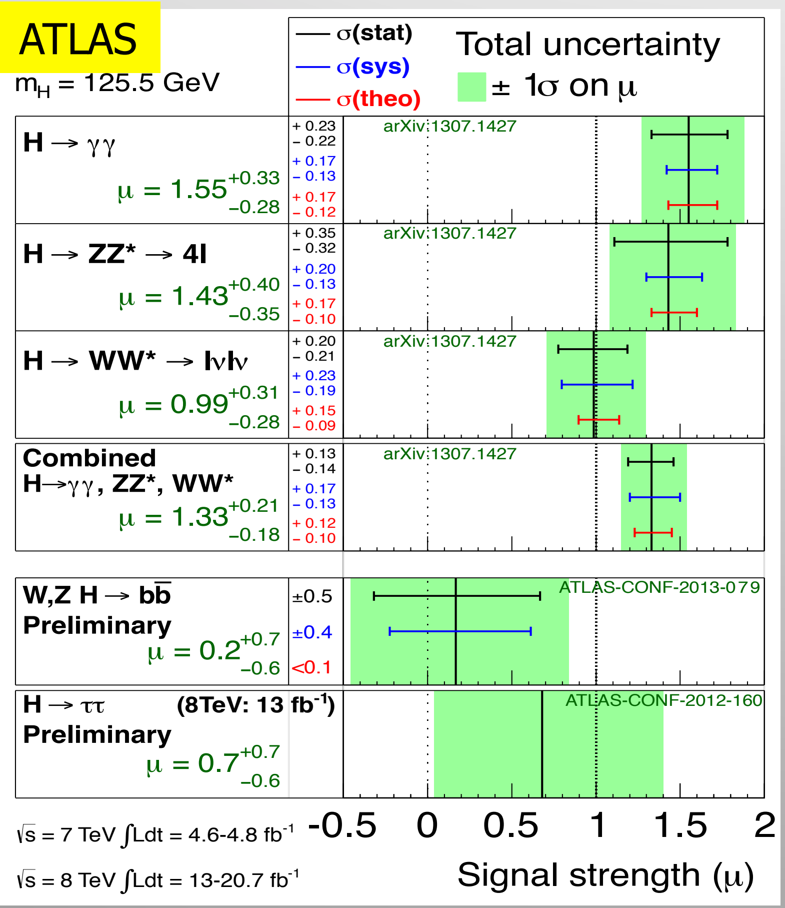
$\hat{m}_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)\ \mathrm{GeV}$

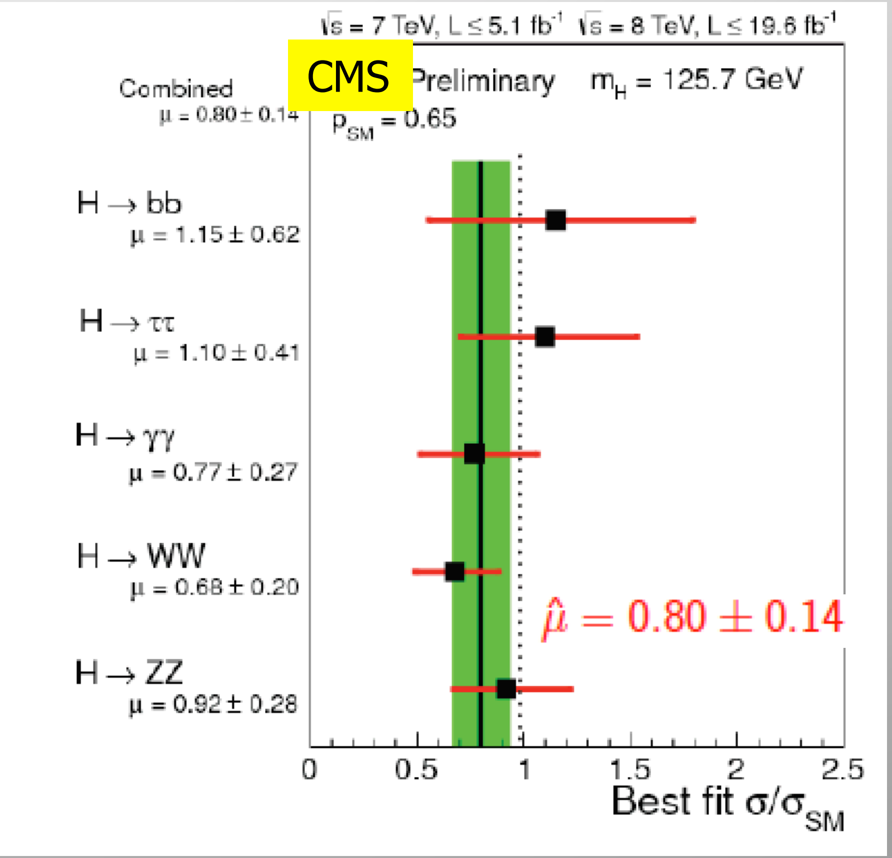
$\hat{m}_H = 125.7 \pm 0.3(stat) \pm 0.3(syst)\ \mathrm{GeV}$

ATLAS and CMS observe the same particle!! ☺

Signal Strength

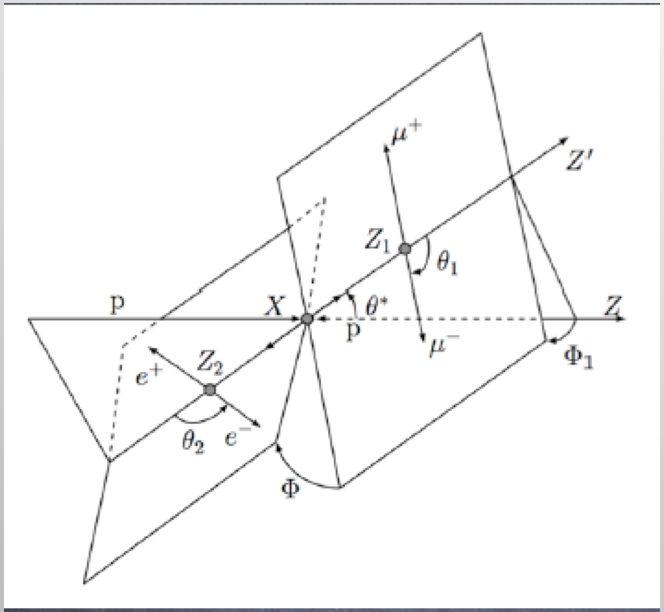
- Signal strength μ is the observed over Standard Model expected cross section
- For $\mu=1$ the production rate is compatible with Standard Model expectation





ATLAS a bit above and CMS a bit below $\mu=1$…

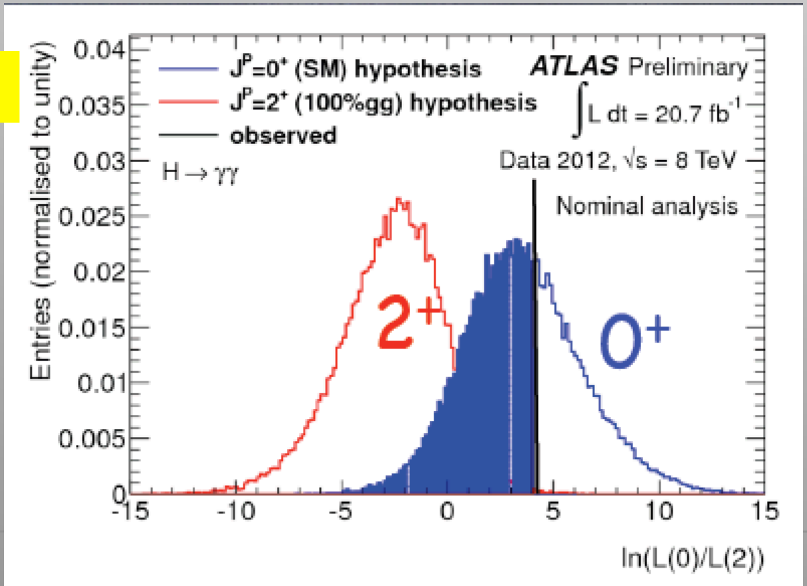
The Spin of the New Particle



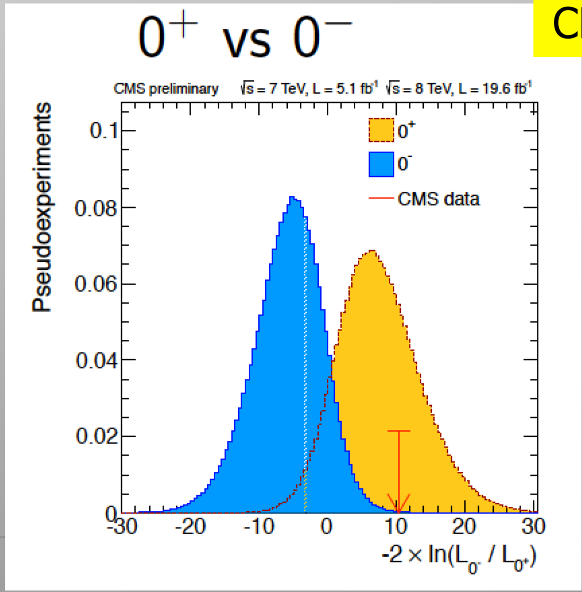
- Study angular correlations in the decays of the particle; build likelihoods and test spin- and parity hypotheses
- Use the ZZ, 2-photon and WW final states

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

ATLAS

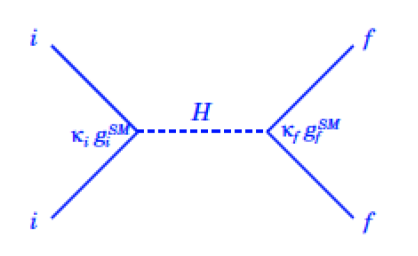


CMS

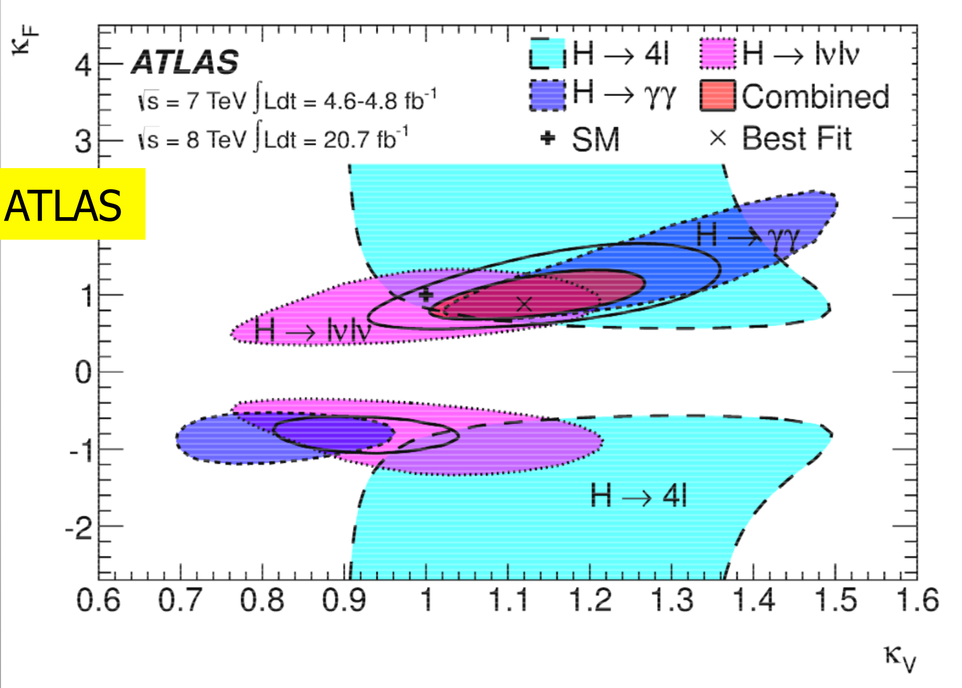


Couplings to the New Particle

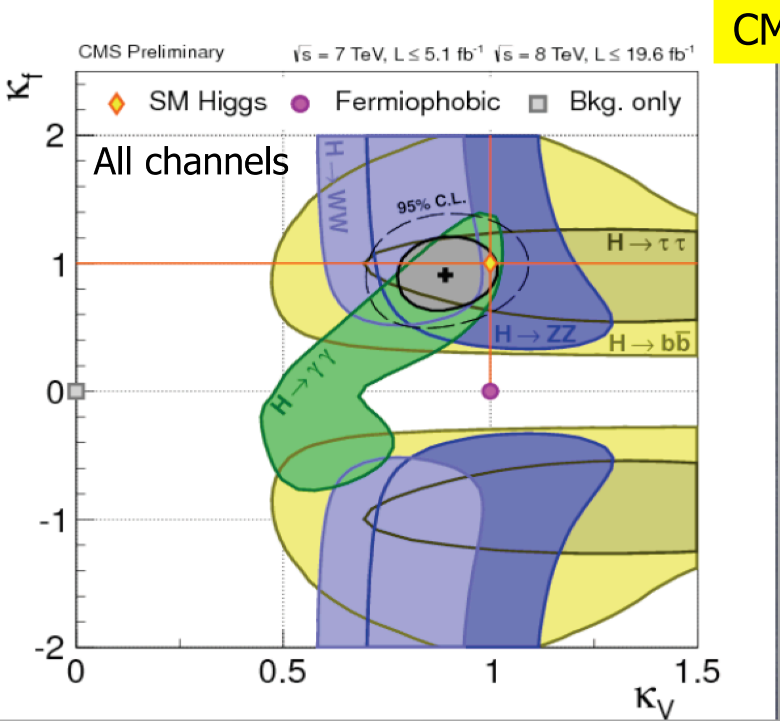
- Use information of all production and decay channels
- κ_f and κ_V are scale factors w.r.t. the Standard Model values for fermions and vector bosons



ATLAS

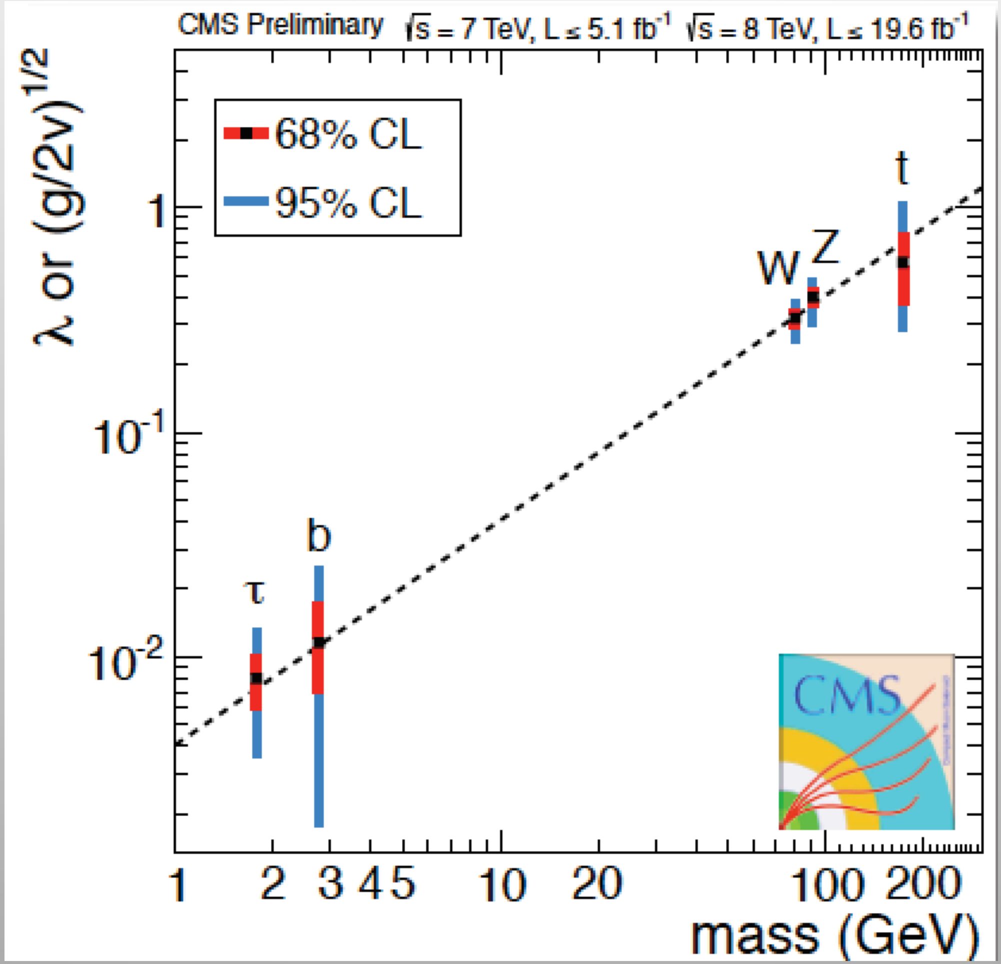


CMS



⇒ Couplings compatible Standard Model values, but large uncertainties …Future data will decide…

…Shown in a different way

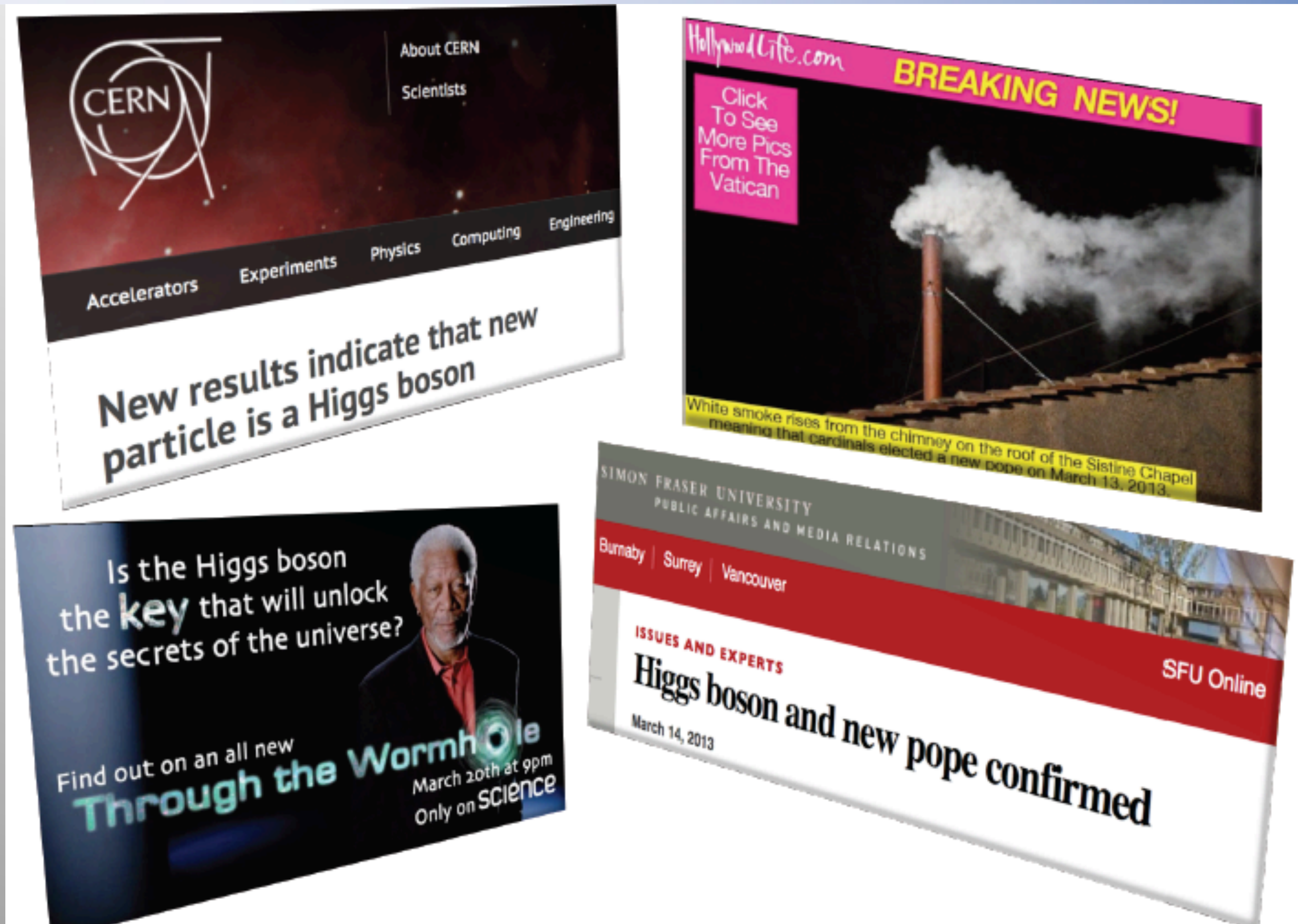


For the fermions, the values of the fitted yukawa couplings are shown, while for vector bosons the square-root of the coupling for the hVV vertex divided by twice the vacuum expectation value of the Higgs boson field.

The News Since July 2012

- Results based on the full data set of 2011-2012 have been released this spring.
- The discovery of the new particle has been confirmed with more added collisions
- Signals in the fermion-channels start building up
- We tested the spin: it is compatible with a 0+ state and not with (simple) 0- or spin 2 (1) states
- The mass is getting measured better with time, 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…)

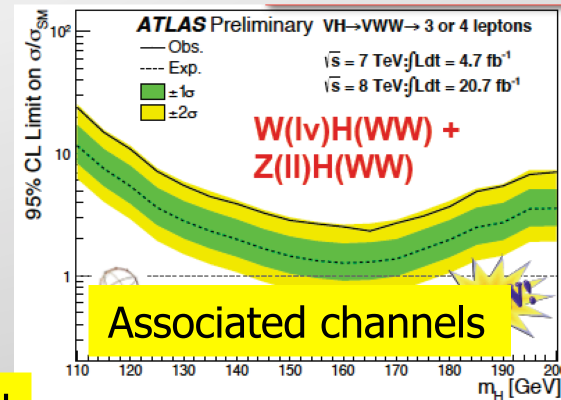
March 2013 News

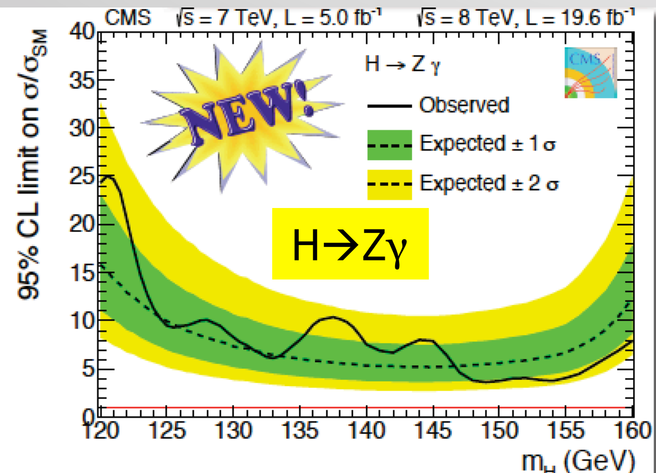


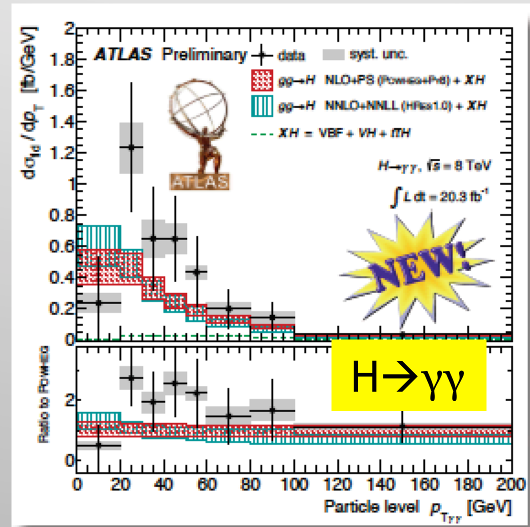
Following the data released by ATLAS and by CMS last March, we now call it a Higgs boson (instead of a Higgs-like boson)

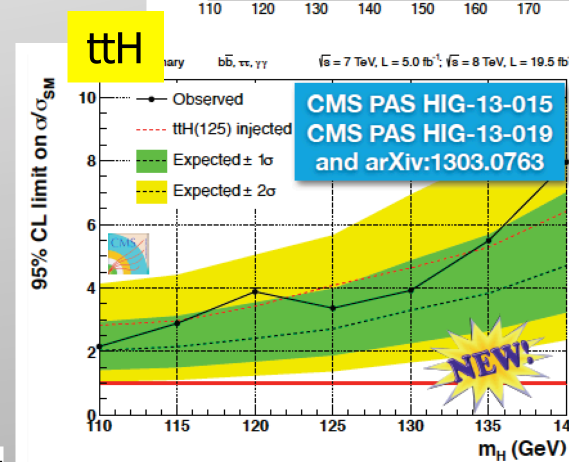
News From EPS Stockholm

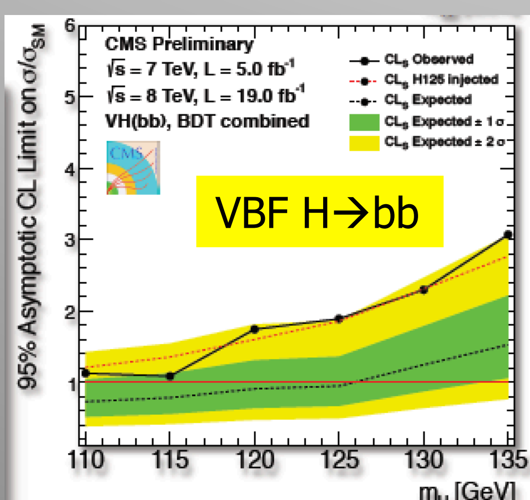
New result on additional channel and first differential distributions for H→γγ. But the picture did not change => Next stop 13-14 TeV collisions in 2015-2016

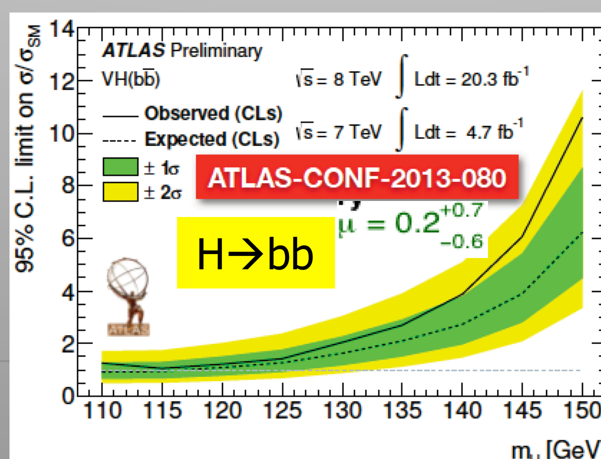


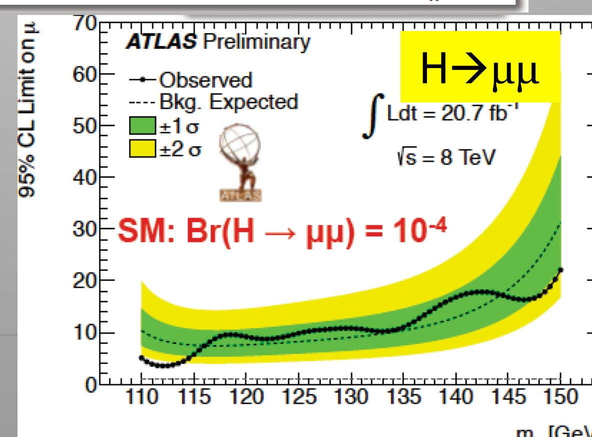




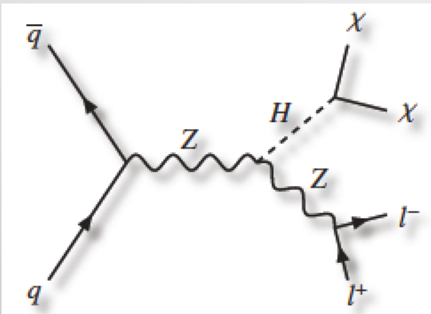






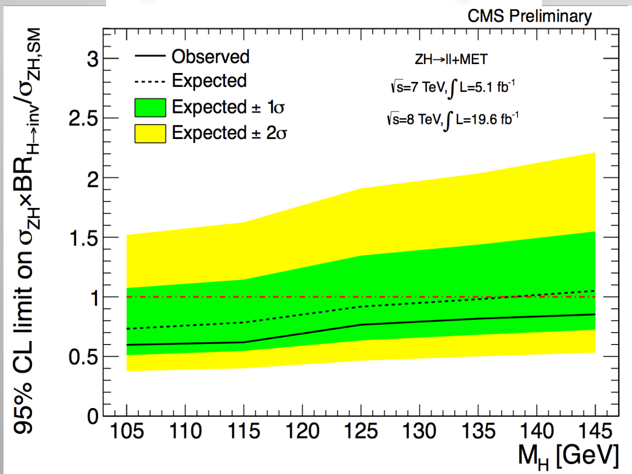


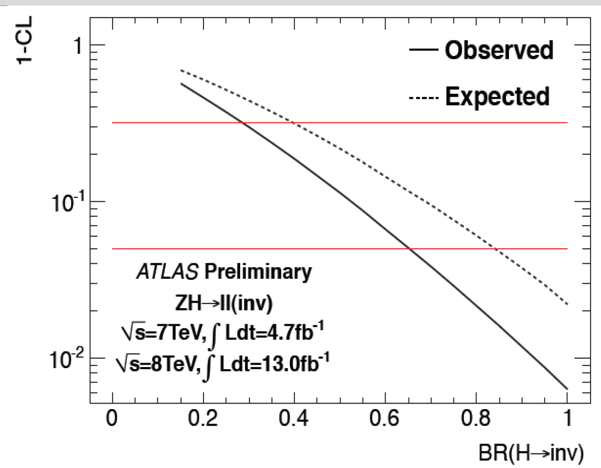
Invisible Higgs Decay Channel



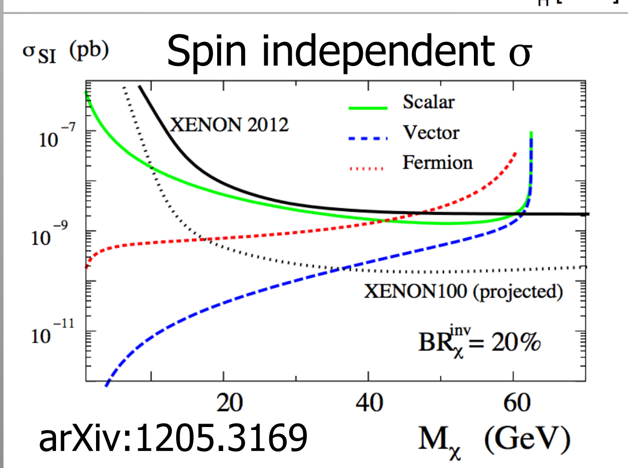
Light Dark Matter may couple to a Higgs
If $m_\chi < M_H/2$ then Higgs can decay "invisibly"
Study case: Z+H → 2 leptons + missing E_T

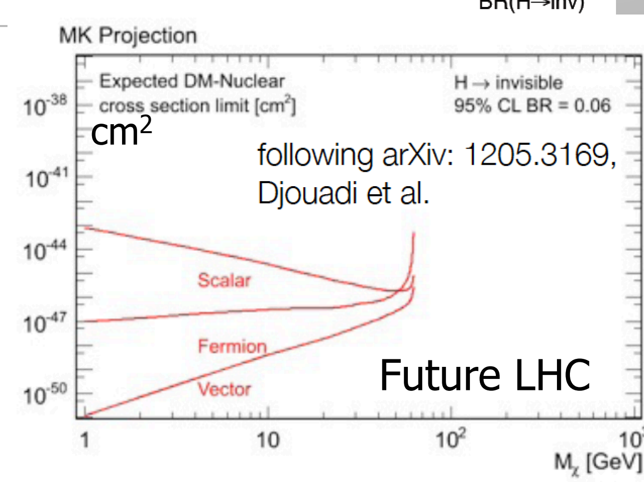
No evidence for invisible decays found so far





- ATLAS (4.7+13.0 fb^{-1}):
  - $Br(H\to\chi\chi)$ < 65% (84% exp.) @ 95% CL, m_H = 125 GeV
- CMS (5+20 fb^{-1}):
  - $Br(H\to\chi\chi)$ < 75% (91% exp.) @ 95% CL, m_H = 125 GeV



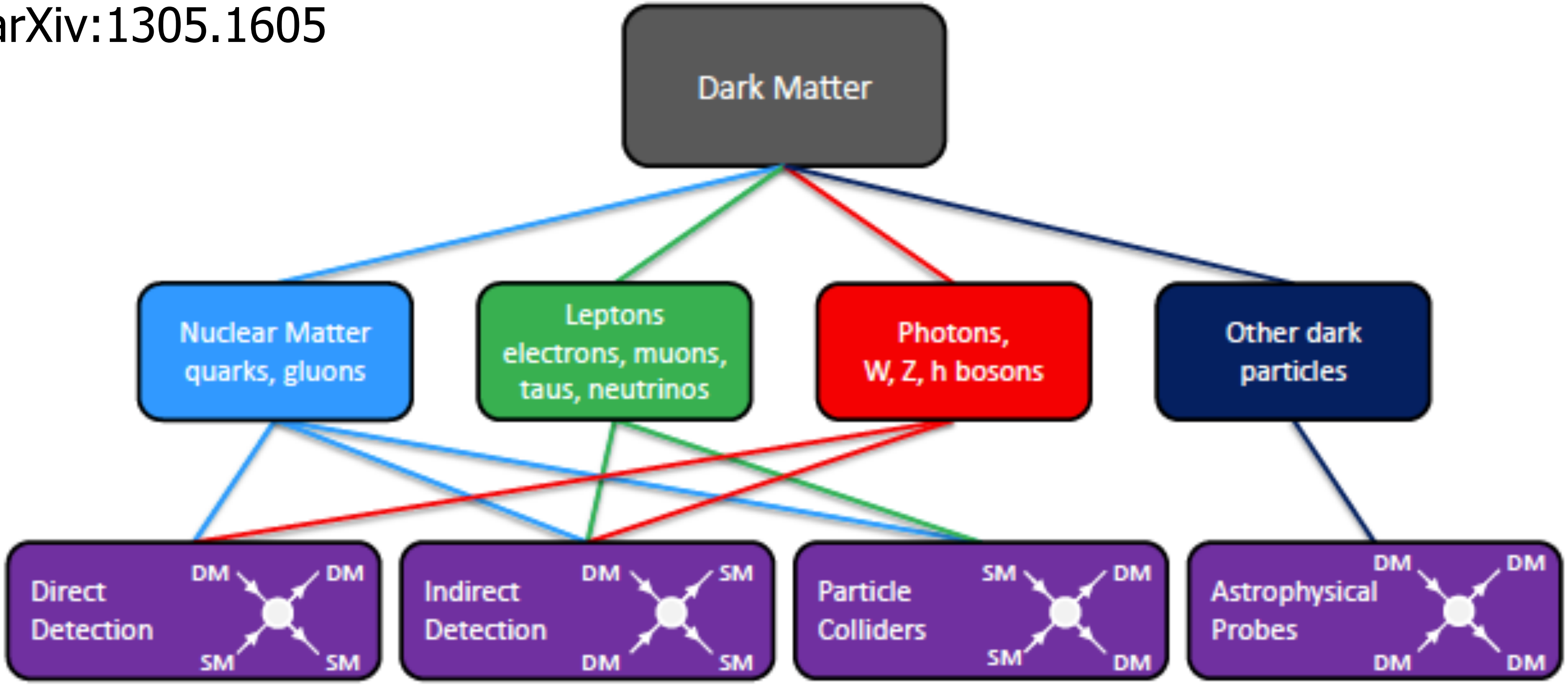


More production channels are being analyses

Dark Matter @ LHC?

Search for WIMP candidates in events with Missing Transverse Momentum
EG: SUSY searches, monojet and mono-photon Searches, W' searches…

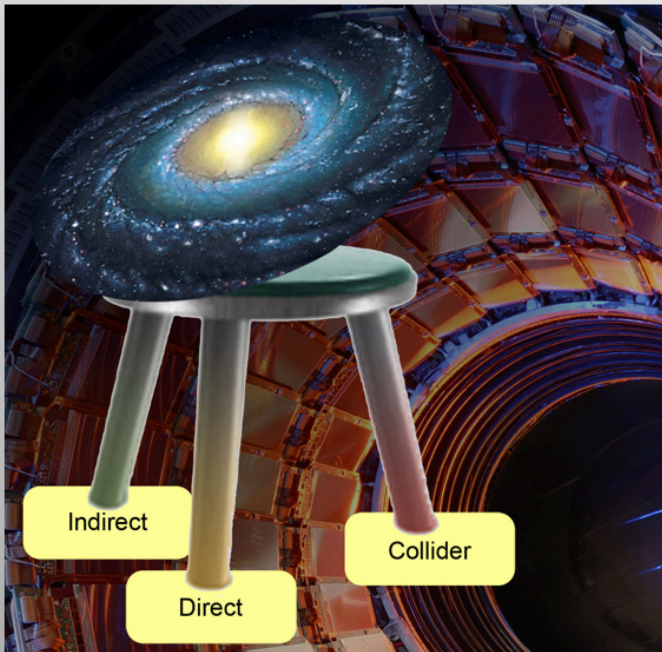
arXiv:1305.1605

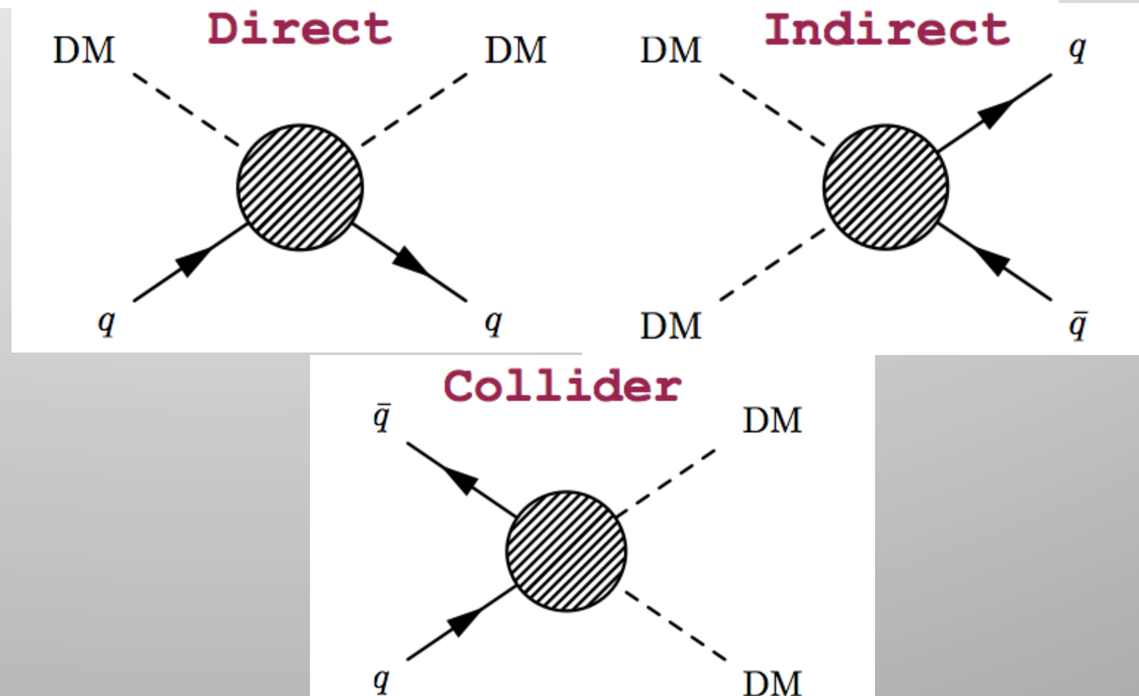


+ CAST experiment, searching for axion DM

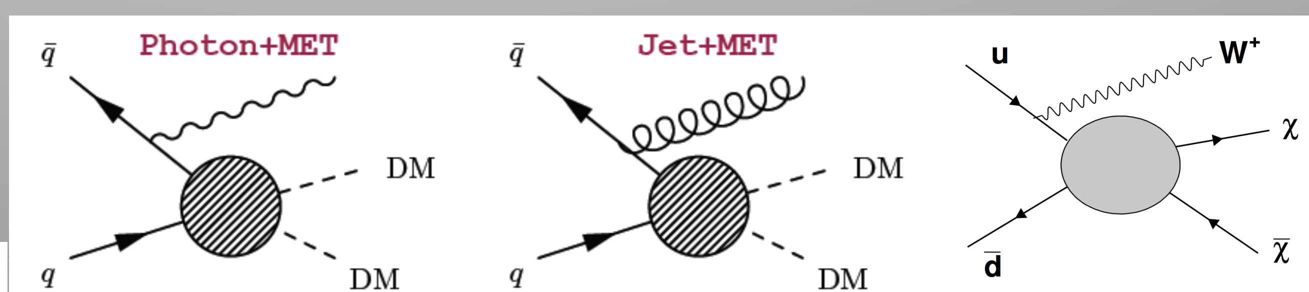
The Other Dark Matter Connection

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





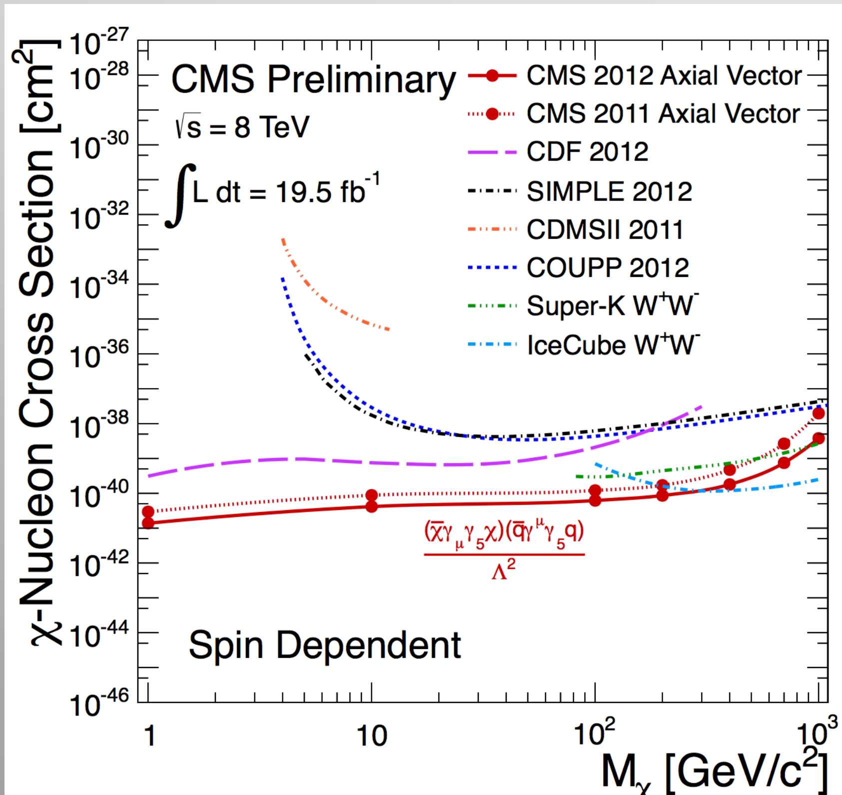
Use effective theory to relate measurements to Dark Matter studies

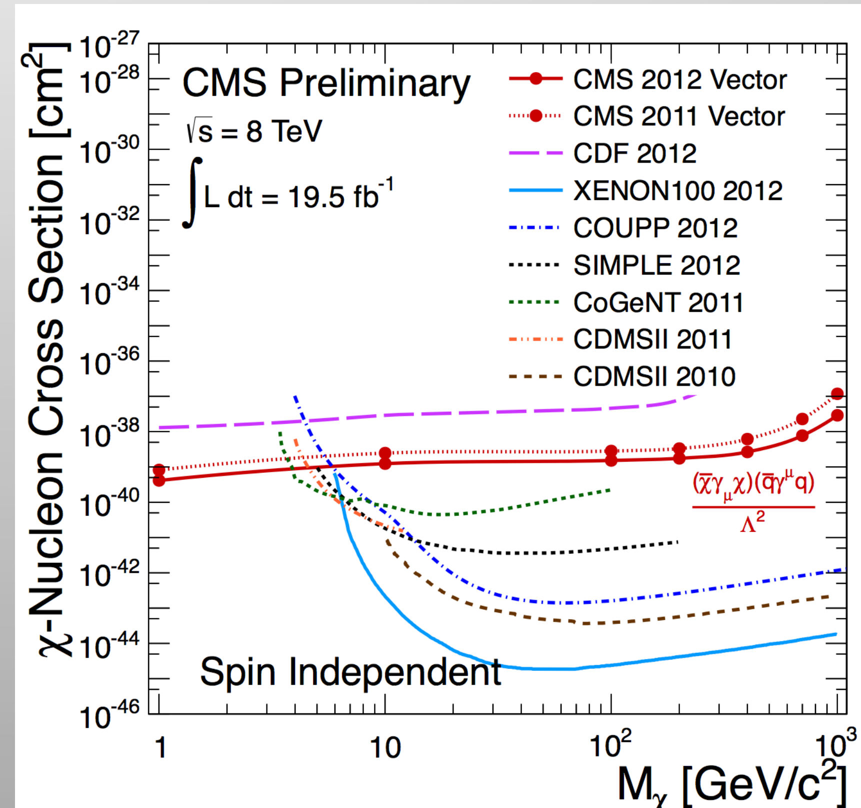


See P. Gondolo's lectures

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)

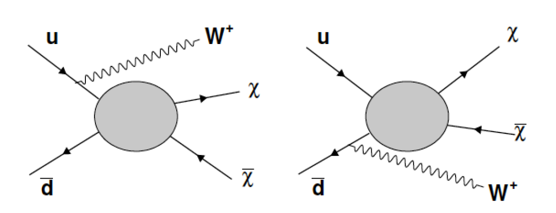


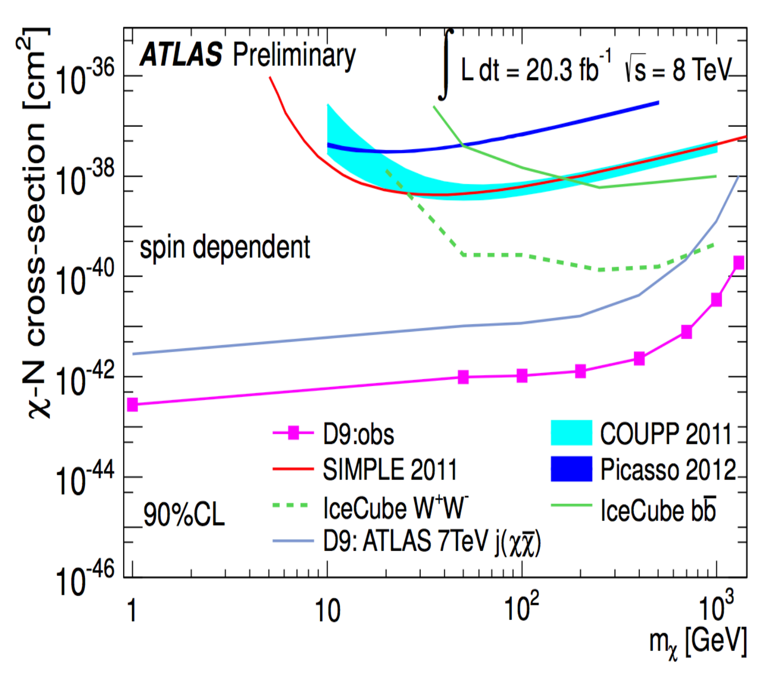


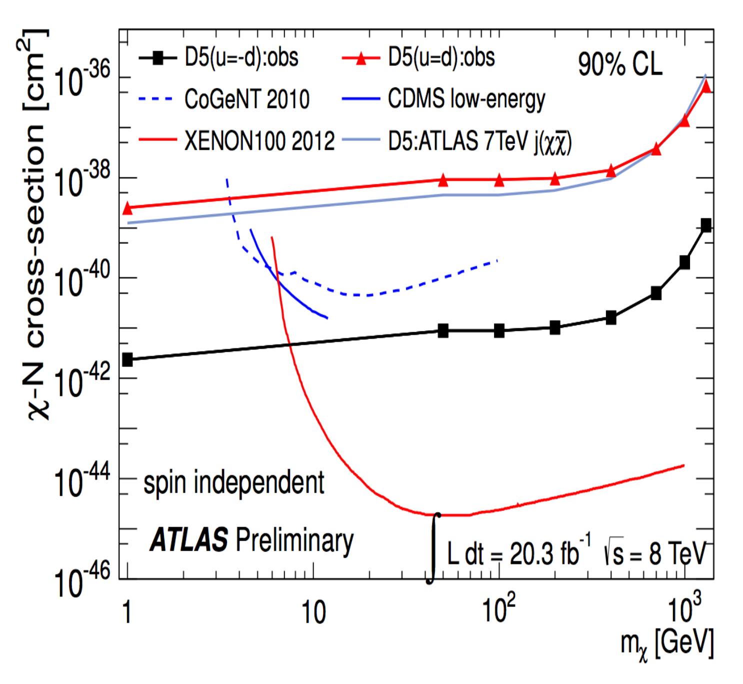
Competitive limits with direct searches (under the effective theory assumptions)

The 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)

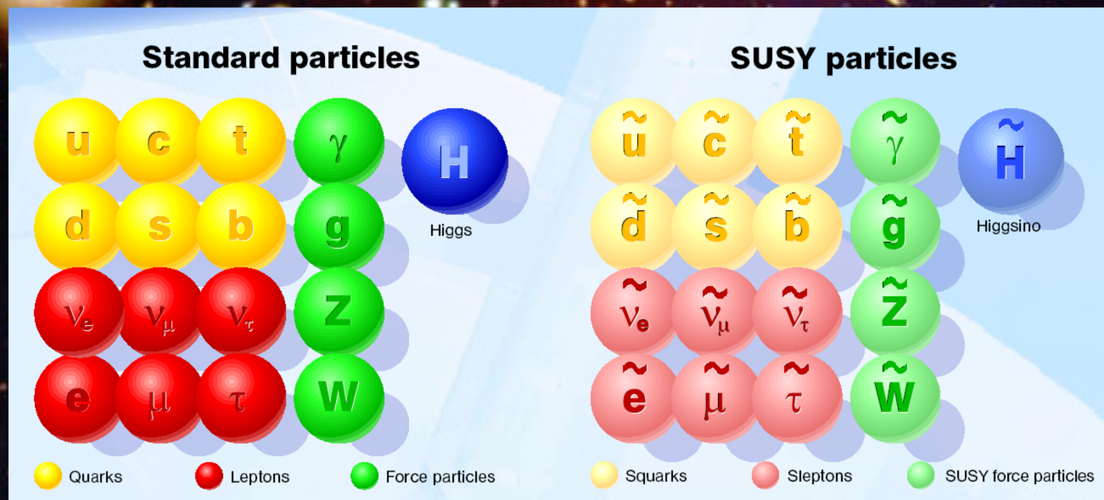


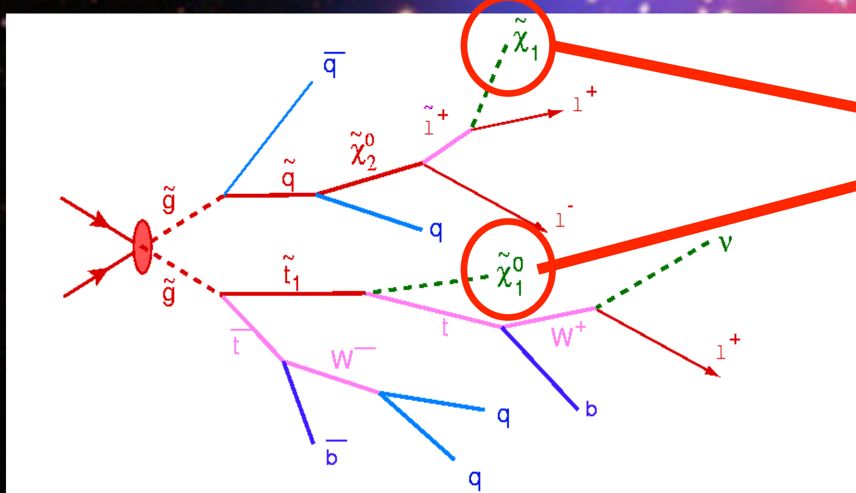




Competitive if DM-u quark coupling different from DM-d quark coupling

Supersymmetry: a new symmetry in Nature?

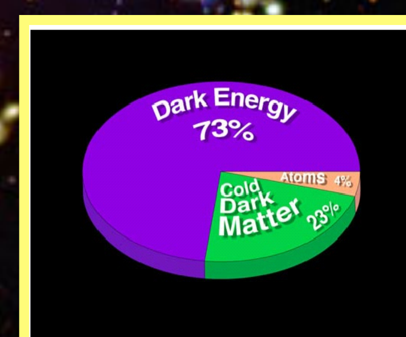




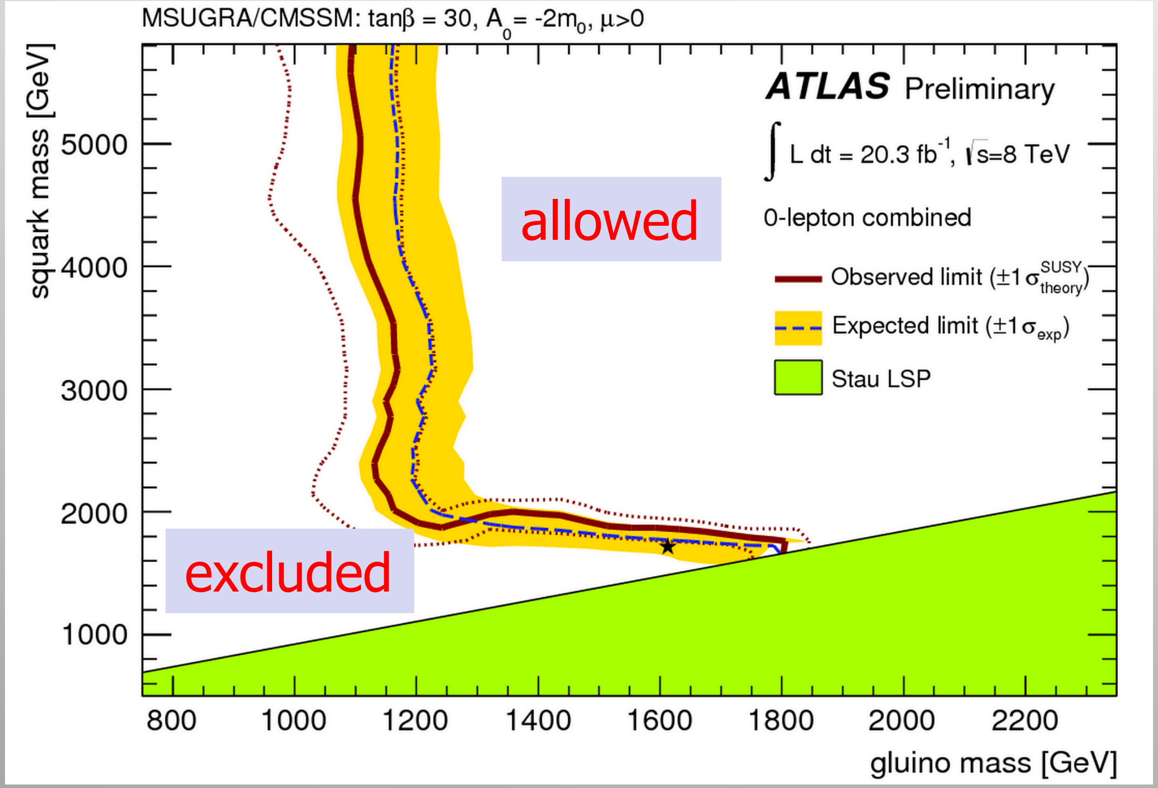
SUSY particle production at the LHC

Candidate particles for Dark Matter

⇒ Produce Dark Matter in the lab



SUSY Searches: No signal yet to date…



- 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 at the GUT scale

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

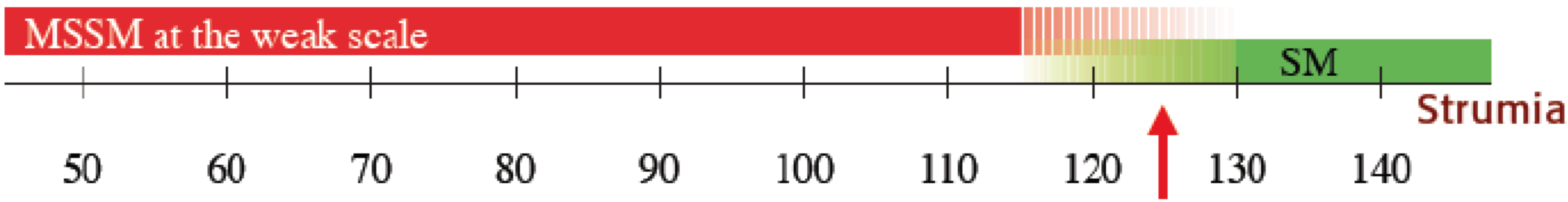
So these particles are heavier than 1000 times the proton

Explore other than the simplest/constrained SUSY models

A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



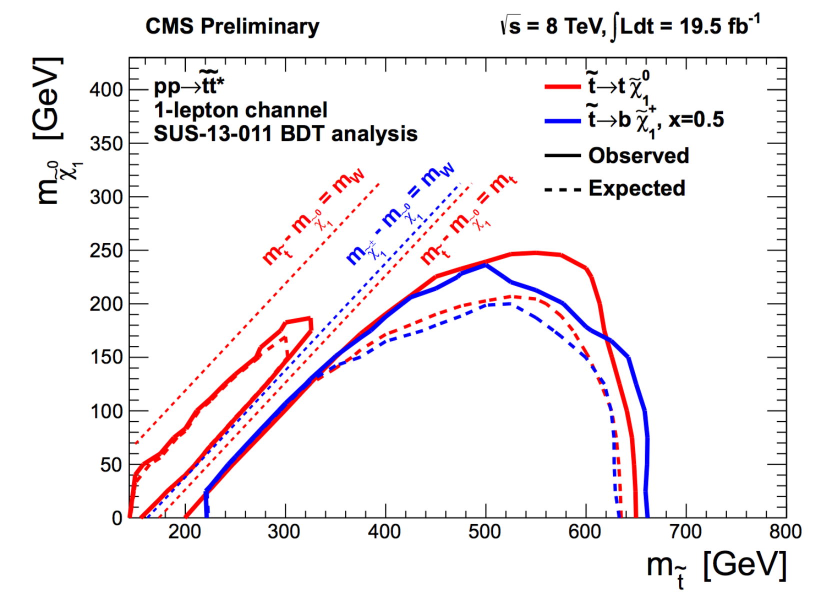
The Higgs:
so simple yet so unnatural

Guido Altarelli

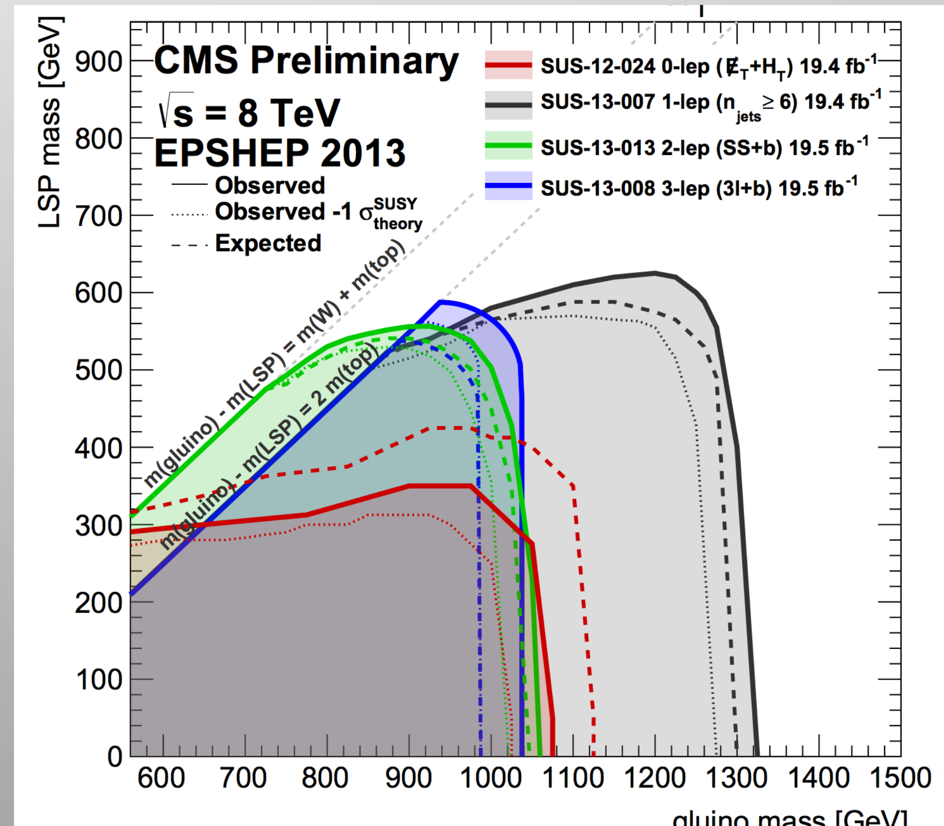
Stockholm Nobel Symposium
May 2013

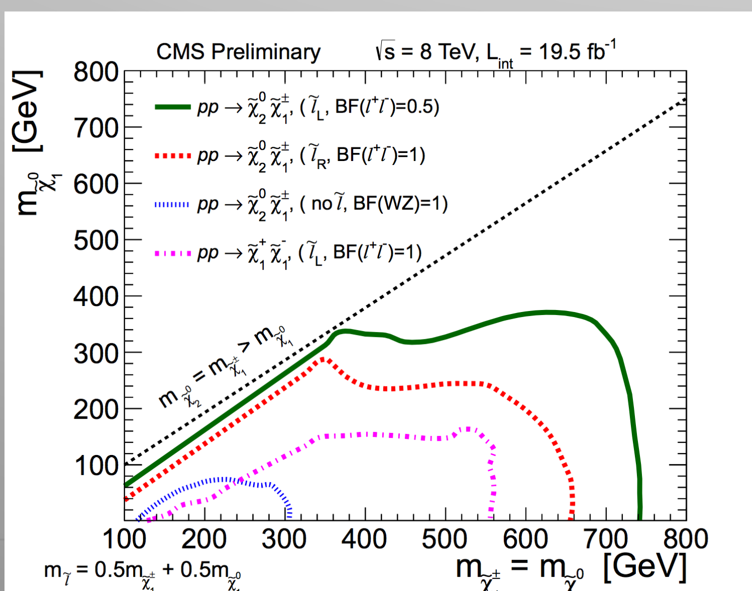
Naturalness: Requires Top squarks < ~1 TeV, gluino < ~1.5 TeV…
So far no evidence found…

SUSY Searches: LSP limits…



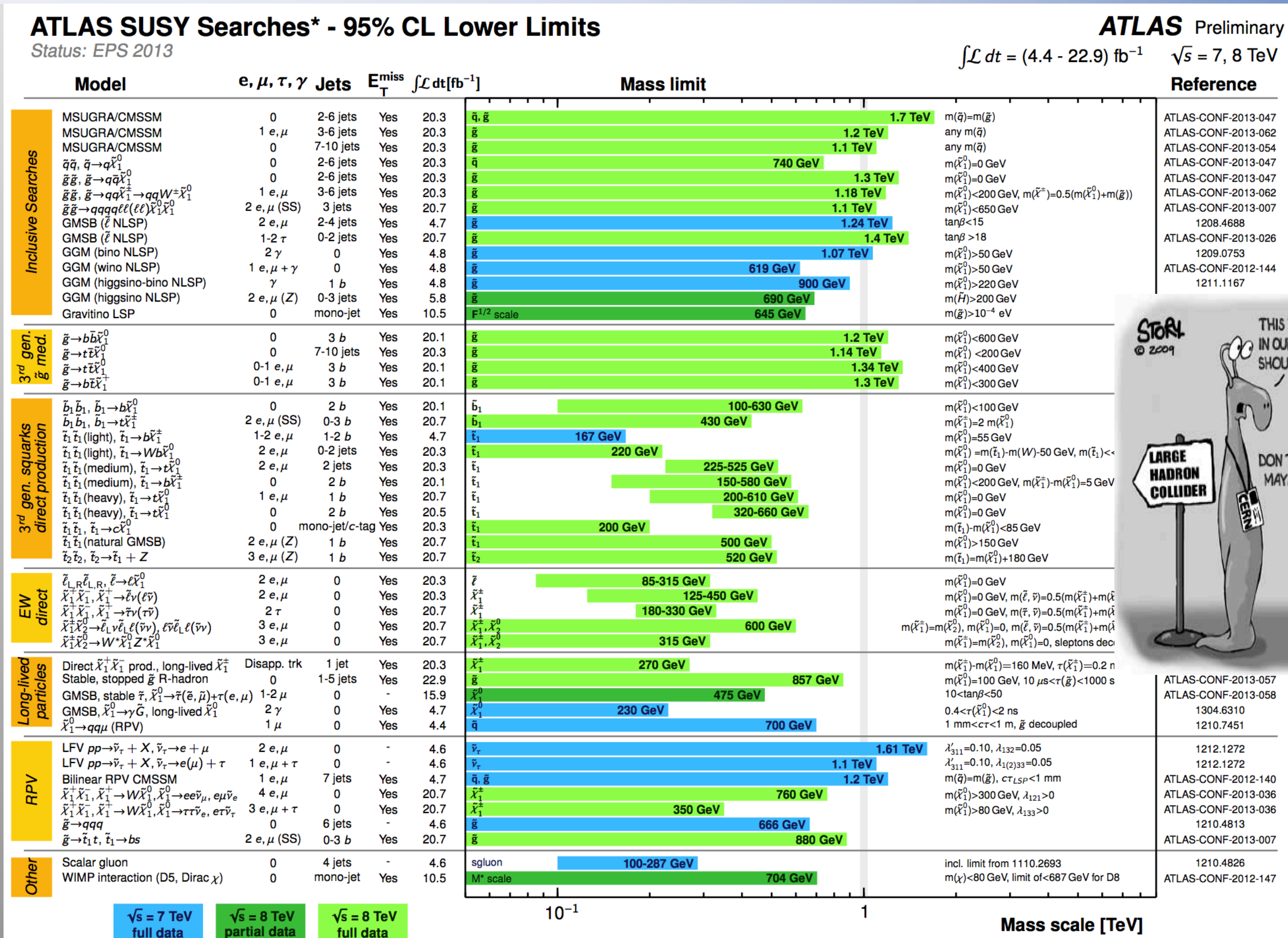
Various limits on sparticles:
No 'light' Lightest SUSY Particle (LSP) so far





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

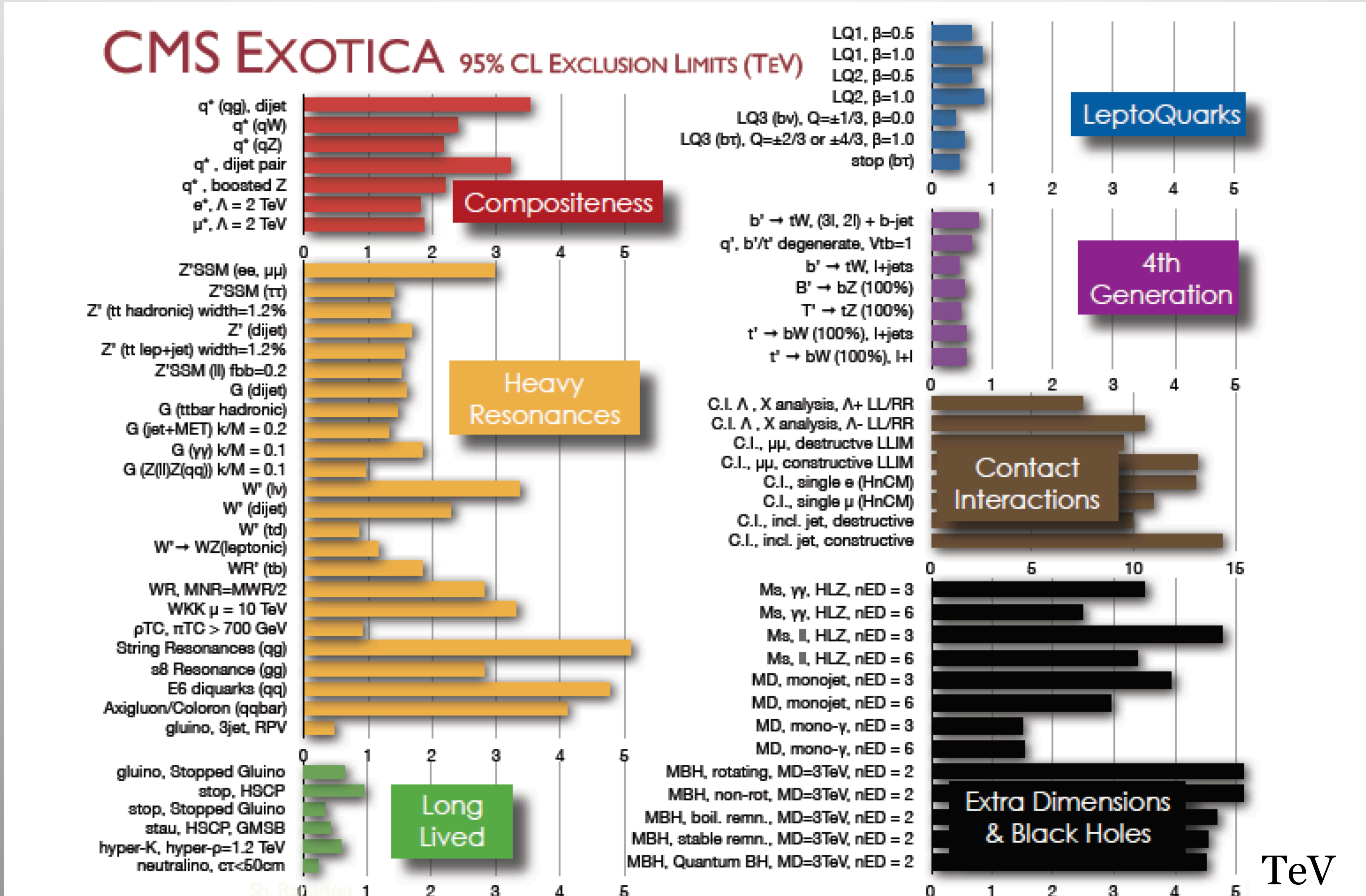
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	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 dec	
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

10^{-1} 1 Mass scale [TeV]

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

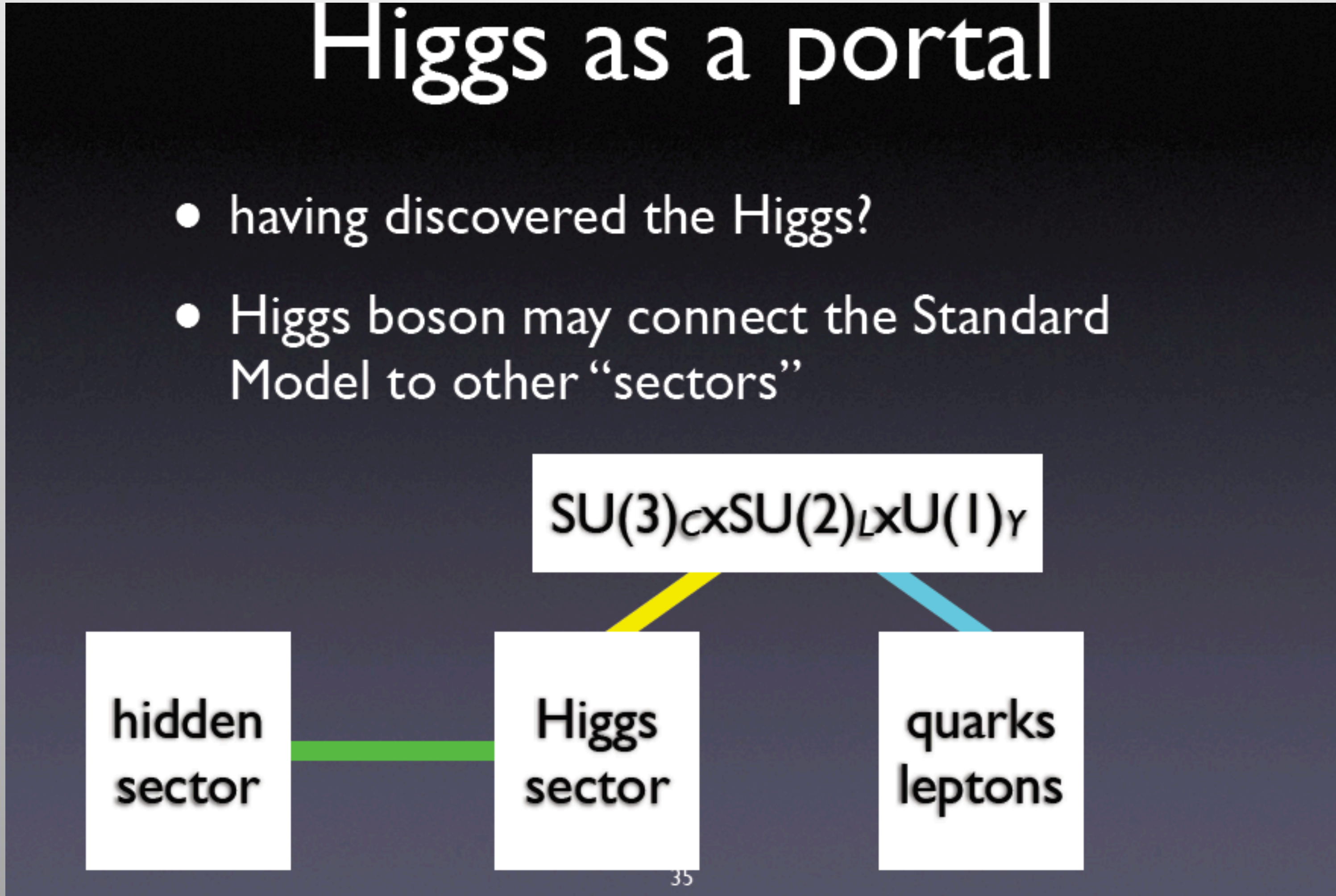
*similar results obtained by CMS

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?)

The Future of the LHC

LHC luminosity forecast

~30/fb at 3.5 & 4 TeV	**2012 DONE**
~400/fb at 6.5-7 TeV	**2021 goal (?)**
~3000/fb at 7 TeV	**2035 goal (??)**

question: how do we get 3000/fb by 2035?

*answer: with **HL-LHC***

The Future: Proposals Discussed

pp colliders

	Years	E_{cm} TeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Int. Luminosity 300 fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

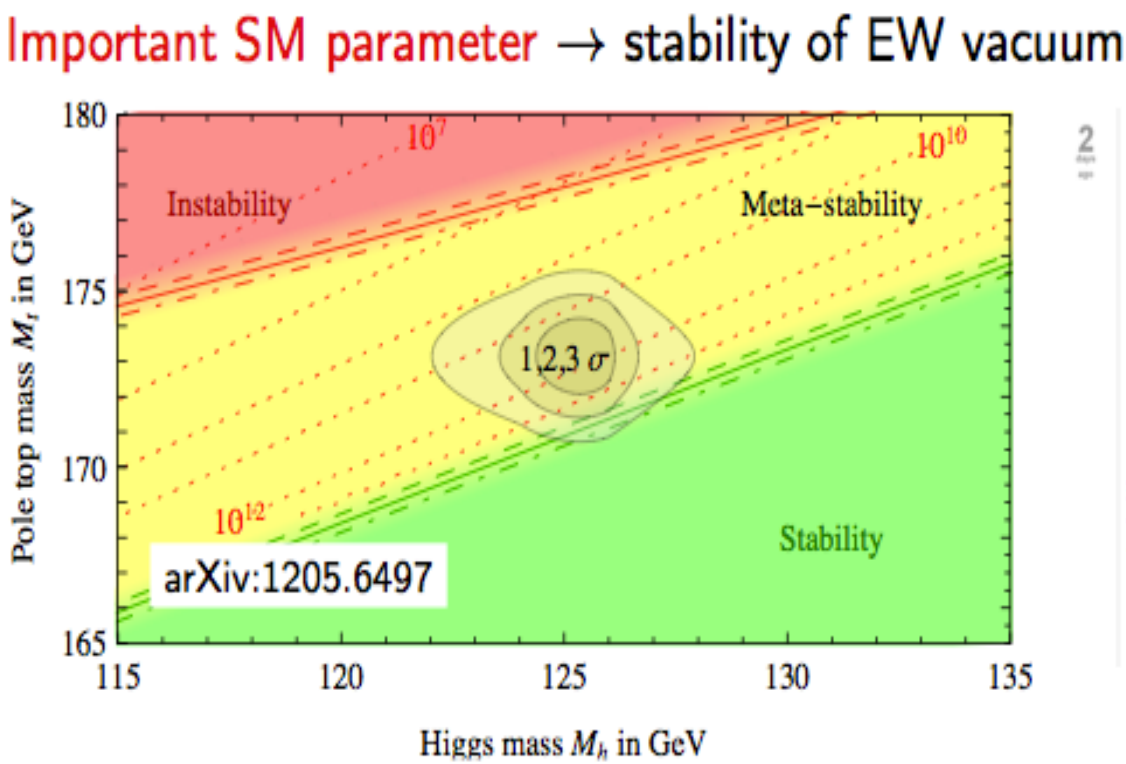
e+e- colliders

	Years	E_{cm} GeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Tunnel length km
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~30
ILC 1000		1000		~50
CLIC 500	>2030	500	2.3(1.3)	~13
CLIC 1400		1400(1500)	3.2(3.7)	~27
CLIC 3000		3000	5.9	~48
LEP3	>2024	240	1	LEP/LHC ring
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

+ proposals for photon colliders, muon collider,..

Discussed in 3 areas (US, Europe, Asia) Wait for LHC-14 TeV results?

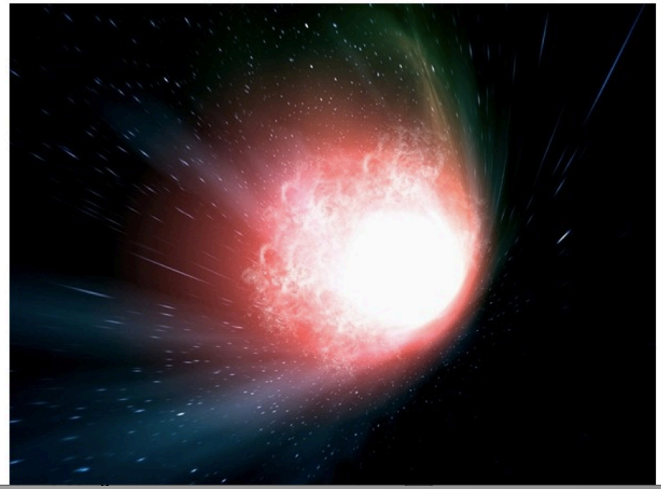
Consequences for our Universe?



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)

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



Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which behaved 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.

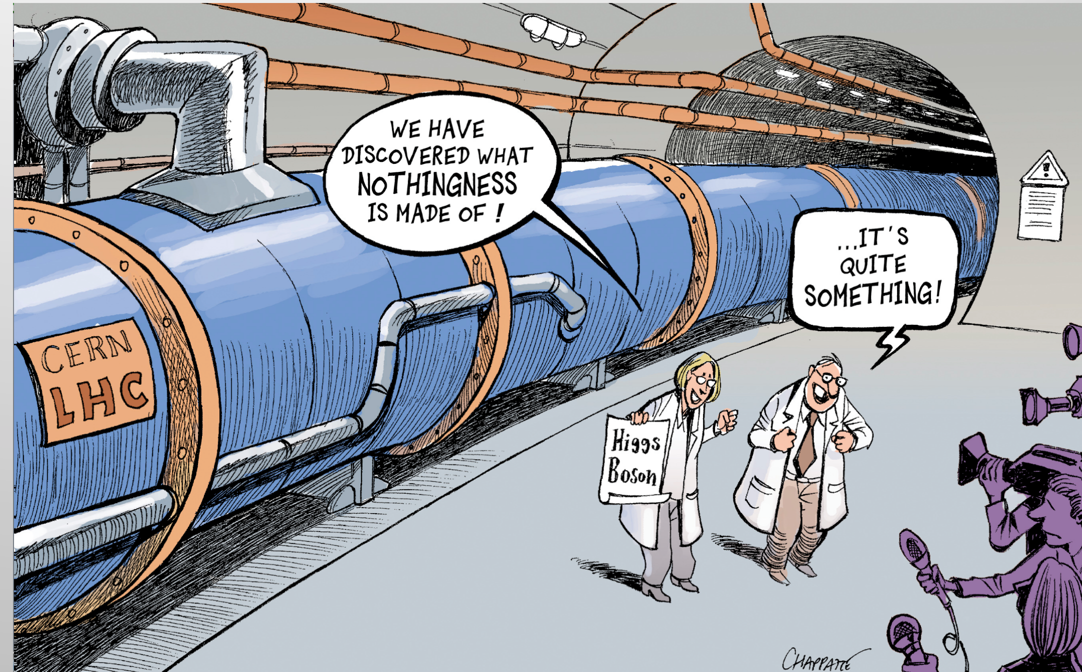
The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it from now onwards "a Higgs particle". This is a brand new particle, as we never seen before.

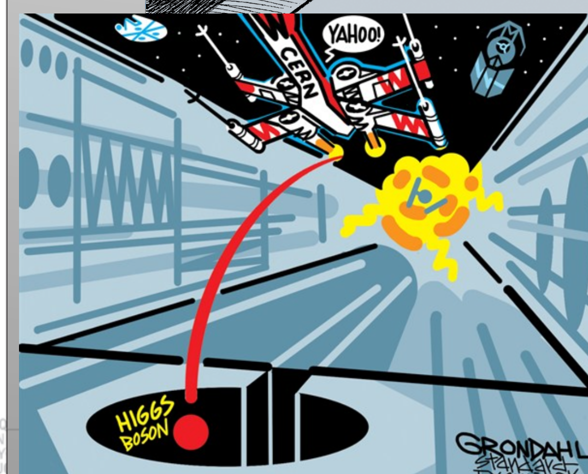
This Higgs boson is likely to carry the 'genetic code' for the physics Beyond the Standard Model. Present studies do not yet reveal any BSM signatures but have only a ~20% precision.

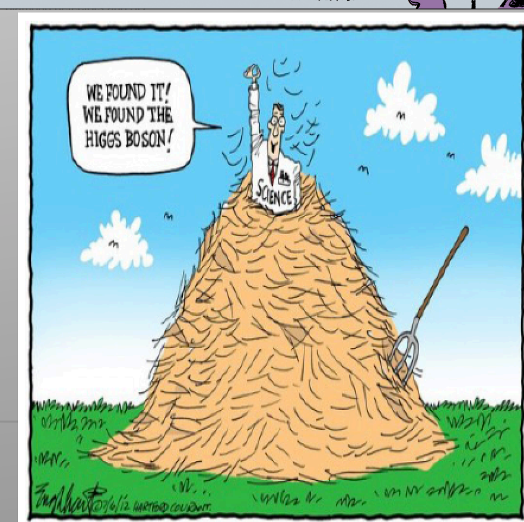
The Higgs and hopefully future Dark Matter particle discovery are major milestones on our road to understand the Universe better.

This is only the beginning!!!

More Higgs Boson Results







Effective Field Operators

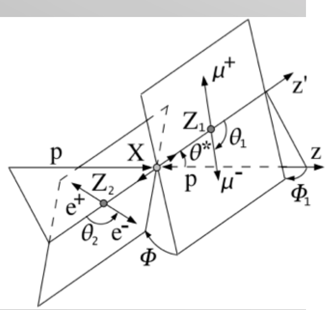
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

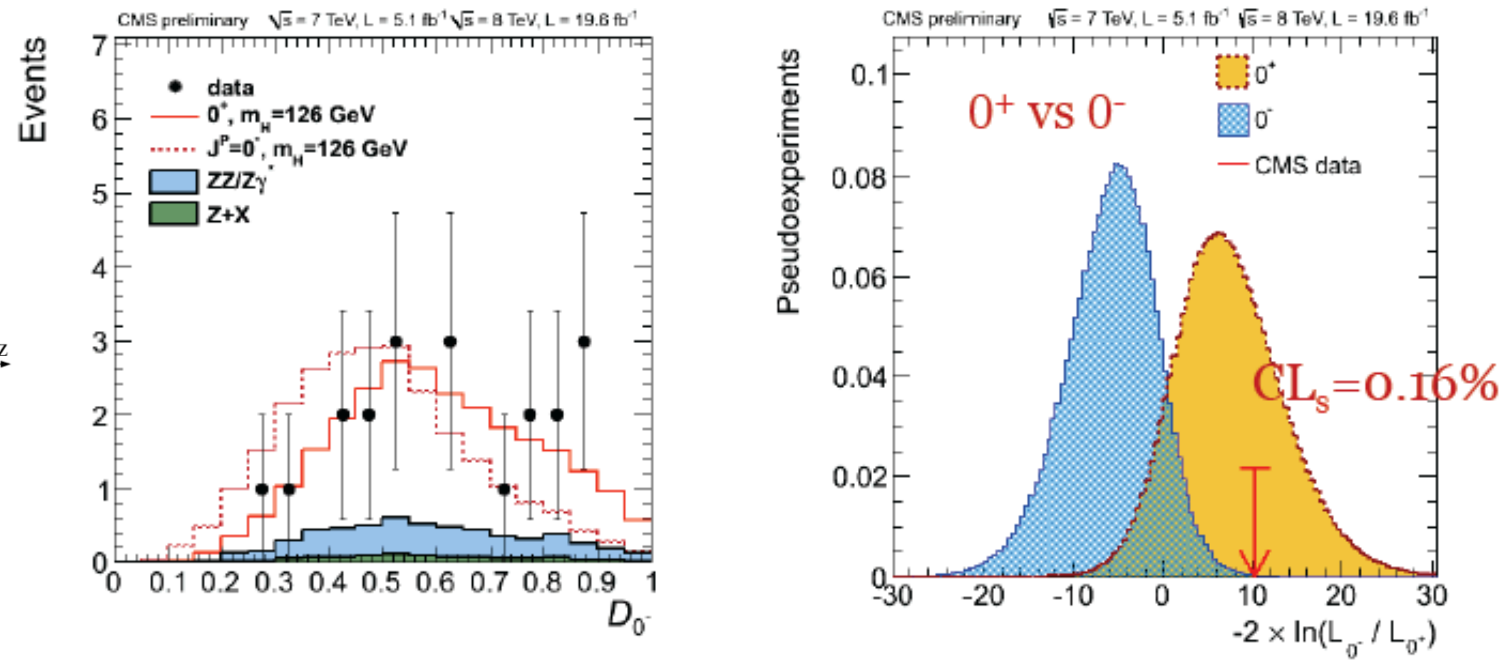
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.

Quantum Numbers: Spin Separation

- We use the angular analysis to define a likelihood for a spin hypothesis
- We test spin 0, 1, 2 and parity + or -. A Higgs particle is expected to have 0^+





We test many more hypotheses: CLS levels:

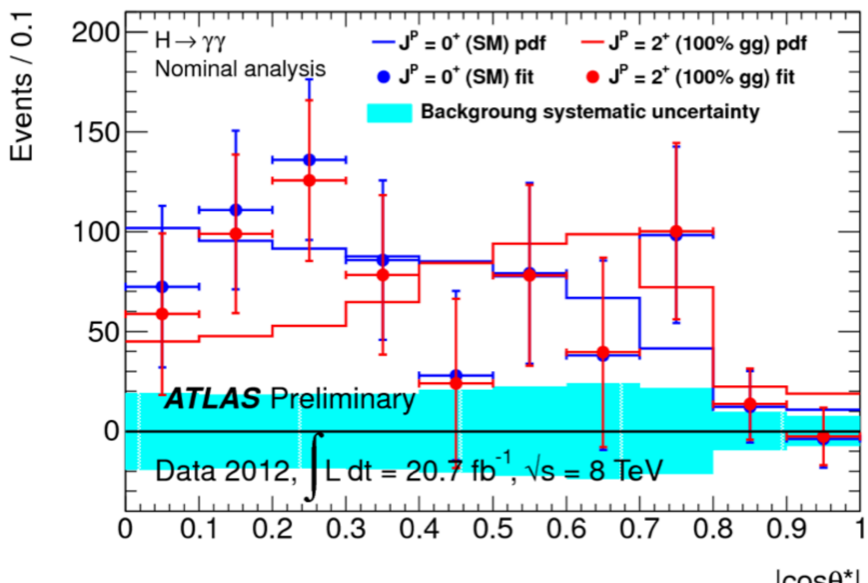
J^P	CL_s
0^-	0.16%
0_h^+	8.1%
2_{mgg}^+	1.5%
$2_{mq\bar{q}}^+$	<0.1%
1^-	<0.1%
1^+	<0.1%

New particle most compatible with a 0^+ state
… as it should be for a Higgs particle…

Quantum Numbers: Spin Separation

Spin from H→γγ

- Reconstruct decay angle from photons
- Sensitive to spin but not parity
- Fit background and signal in bins of cosθ*



Spin 0 favoured.

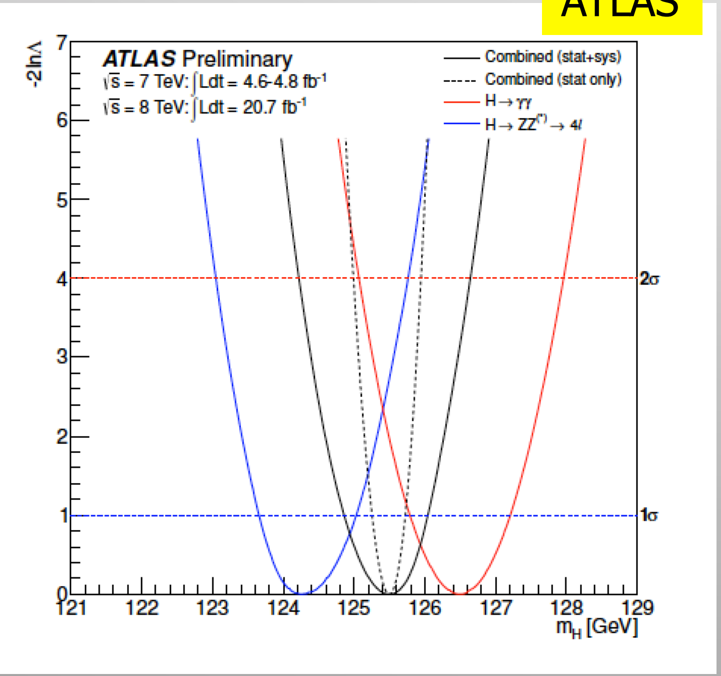
The Mass of the Particle

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

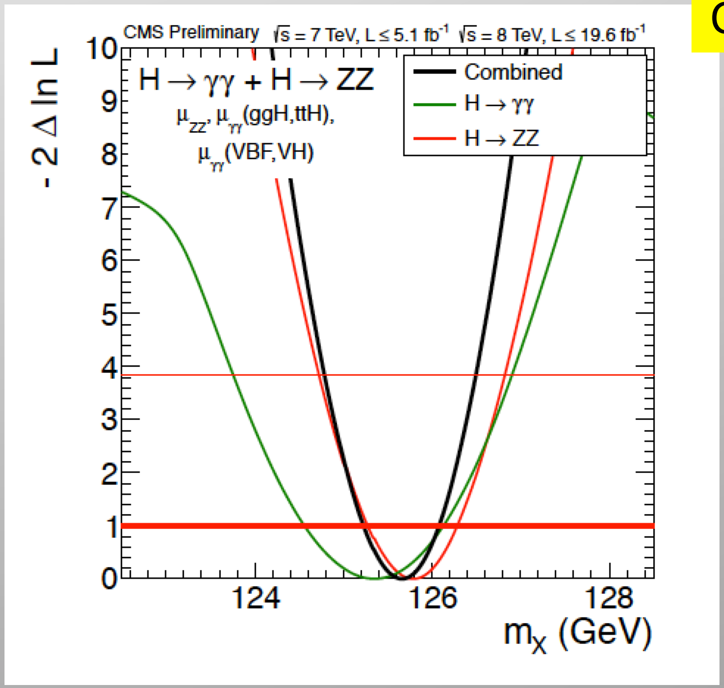
$$m_H^{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst)\ \mathrm{GeV}$$
$$m_H^{4\ell} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)\ \mathrm{GeV}$$

$$m_H^{\gamma\gamma} = 125.4 \pm 0.5(stat) \pm 0.6(syst)\ \mathrm{GeV}$$
$$m_H^{4\ell} = 125.8 \pm 0.5(stat) \pm 0.2(syst)\ \mathrm{GeV}$$

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!! ☺