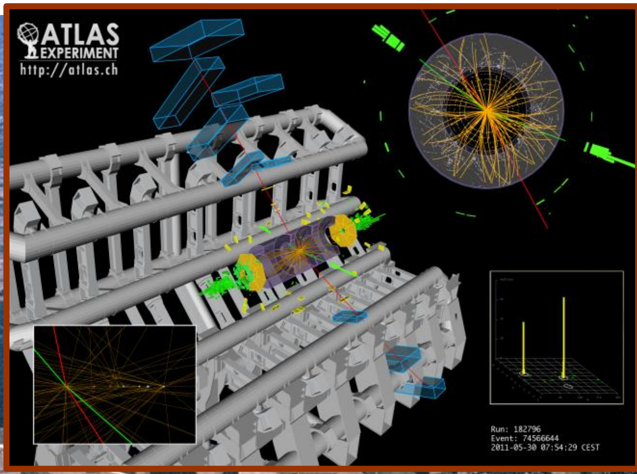


Challenges and accomplishments of the Large Hadron Collider

Morris Loeb Colloquium, Fabiola Gianotti (CERN)

ATLAS Muon Spectrometer
(strong contributions from Harvard)

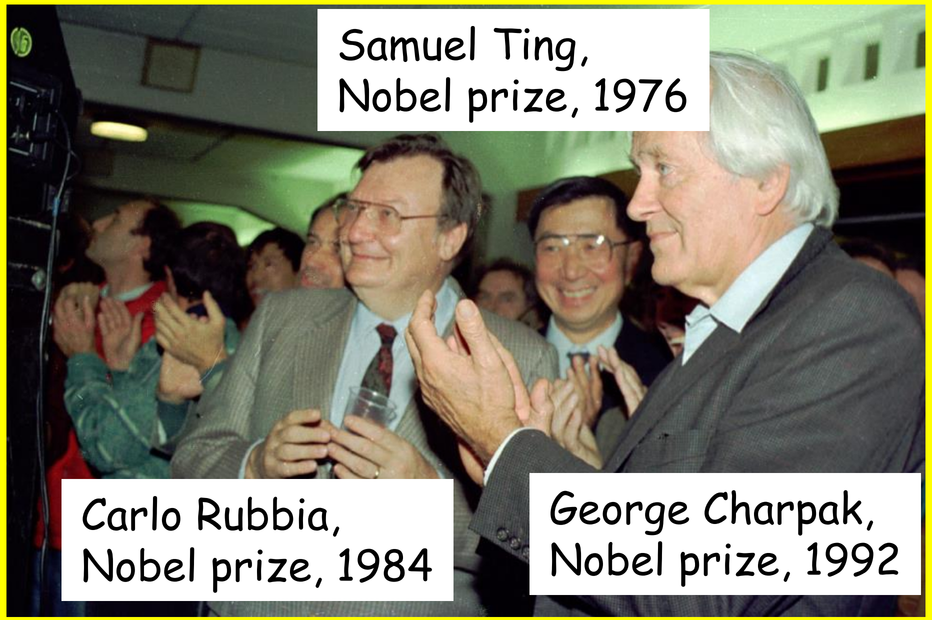
And now we have entered into a new era, practically with the opening of the twentieth century, that of the utter abolition of national boundaries so far as scientific endeavor is concerned. Morris Loeb

CERN: European Organization for Nuclear Research
The world's largest particle physics laboratory
(based in Geneva, Switzerland)

More than 50 years of:

- fundamental research and discoveries (and Nobel prizes ...)
- technological innovation and technology transfer to society
  (e.g. the World Wide Web)
- training and education (young scientists, school students and teachers)
- bringing the world together (10000 scientists from > 60 countries)

CERN staff member T. Berners-Lee, inventor of the WEB, with Kofi Annan and CERN DG Luciano Maiani



Samuel Ting, Nobel prize, 1976

Carlo Rubbia, Nobel prize, 1984

George Charpak, Nobel prize, 1992

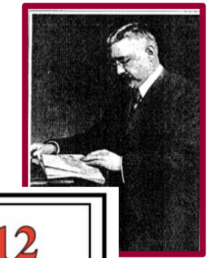
CERN was founded 1954: 12 European States
Today: 20 Member States

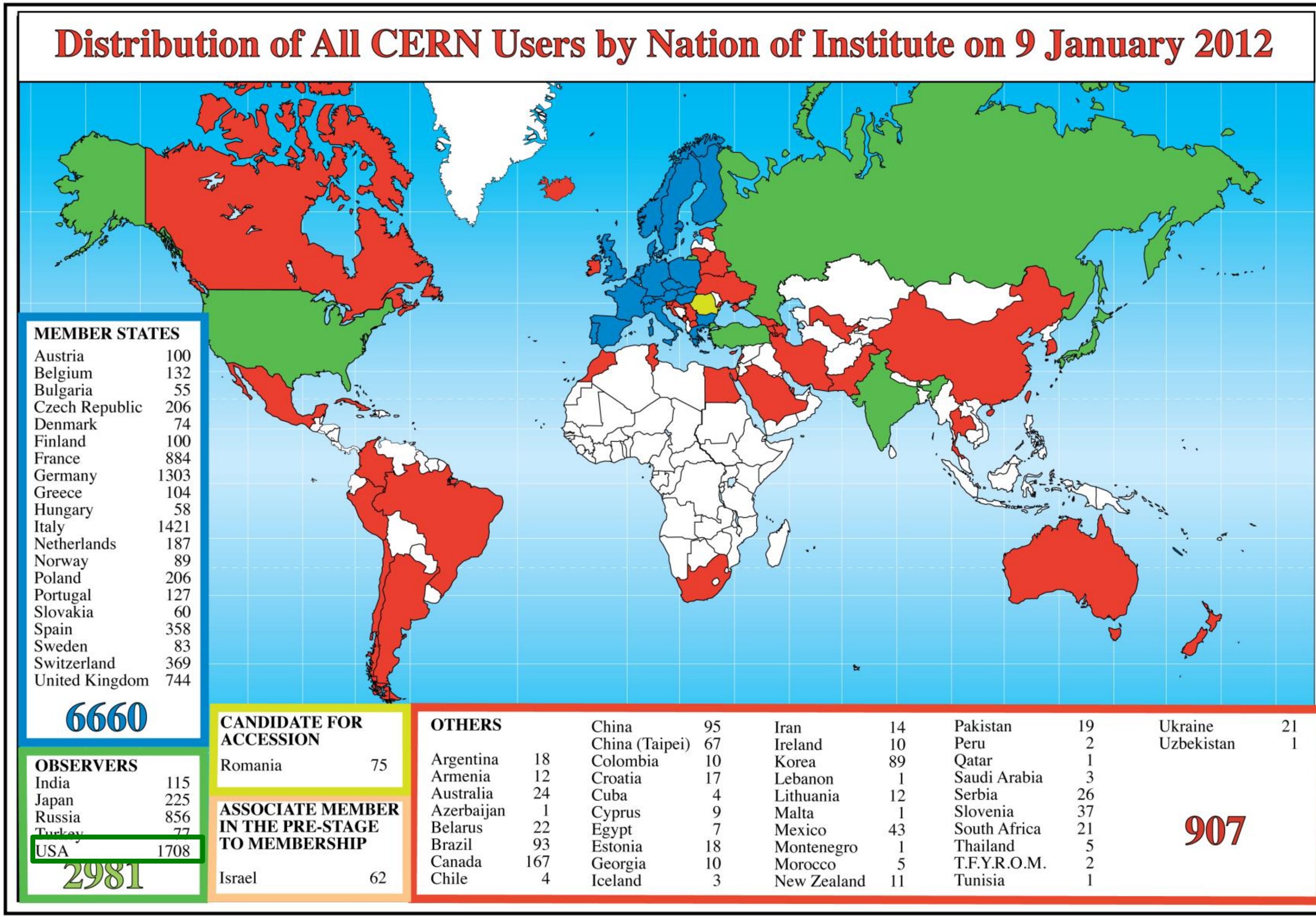
Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

Observers: India, Japan, the Russian Federation, United States of America, Turkey, the European Commission and UNESCO

~ 2300 staff
> 10000 users
Budget (2012) ~1B USD (1 cappuccino/European citizen):
each Member State contributes in proportion to its income

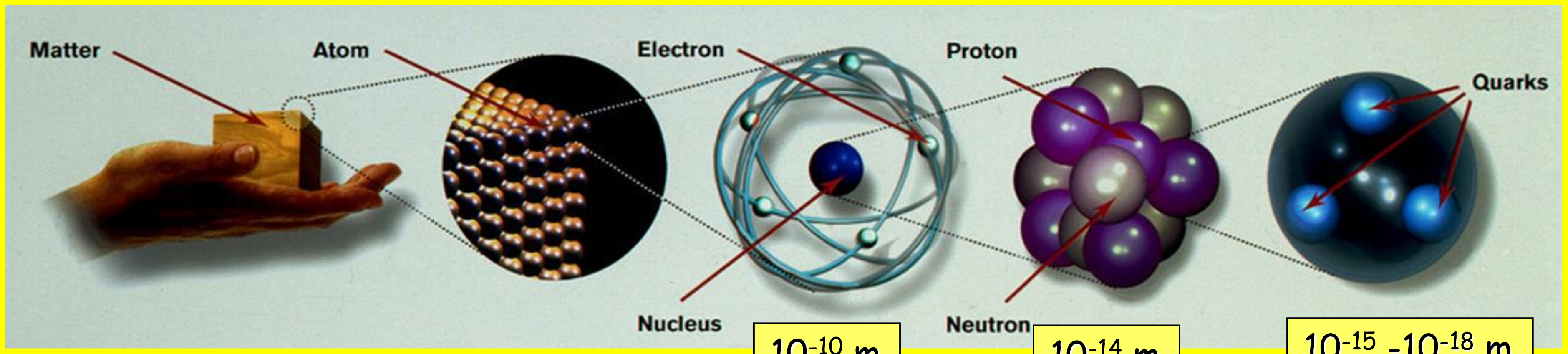
More than 10000 users from > 60 countries





CERN's primary mission is SCIENCE

Study the elementary particles (e.g. the building blocks of matter: electrons and quarks) and their interactions



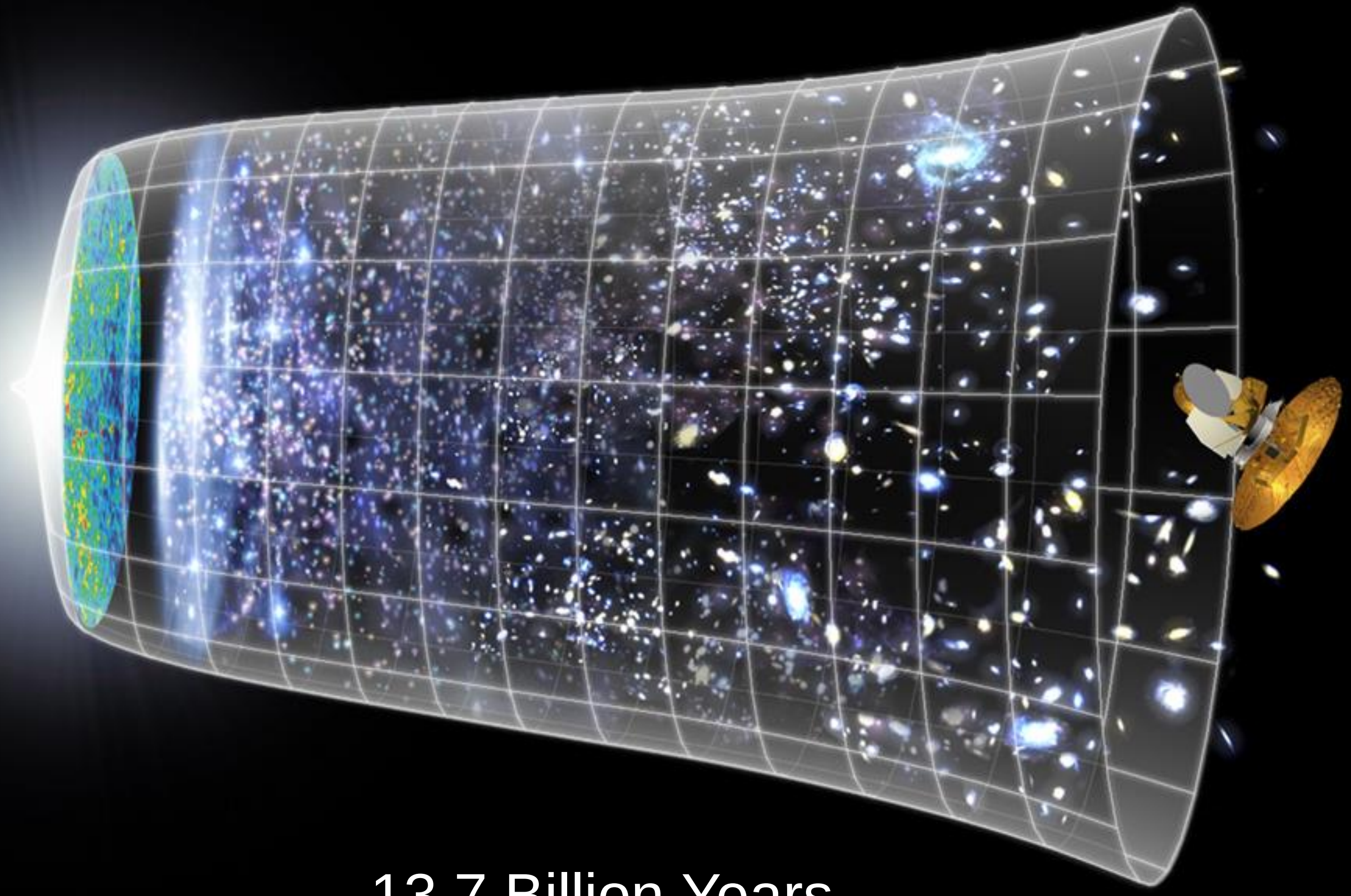
10^{-10} m

10^{-14} m

10^{-15} - 10^{-18} m

Particle physics at accelerators probes matter (e.g. quarks) on a scale of 10^{-18} m → insight also into the structure and evolution of the Universe
→ from the very small to the very big ...

Evolution of the Universe



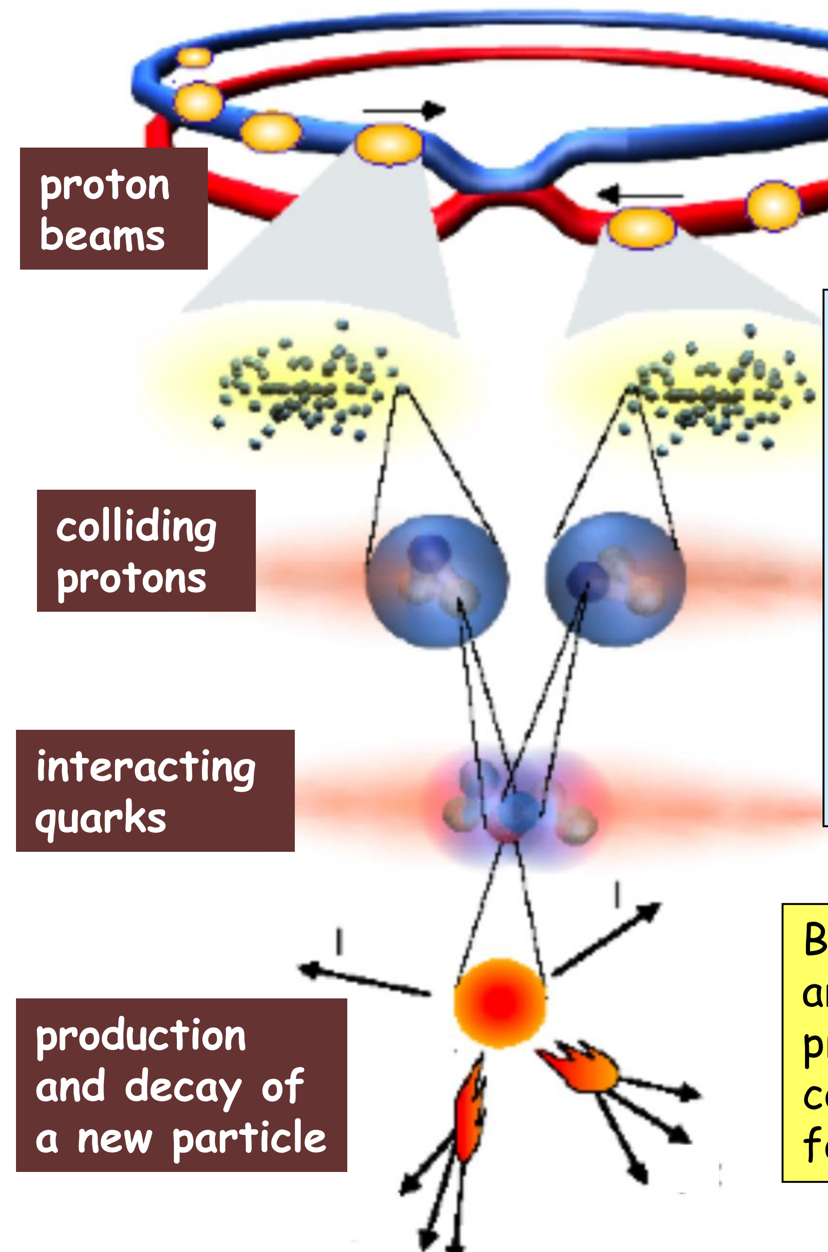
Big Bang

13.7 Billion Years

Today

10^{28} cm

To study the elementary particles and their interactions:



We accelerate two beams of particles (e.g. protons) and make them collide

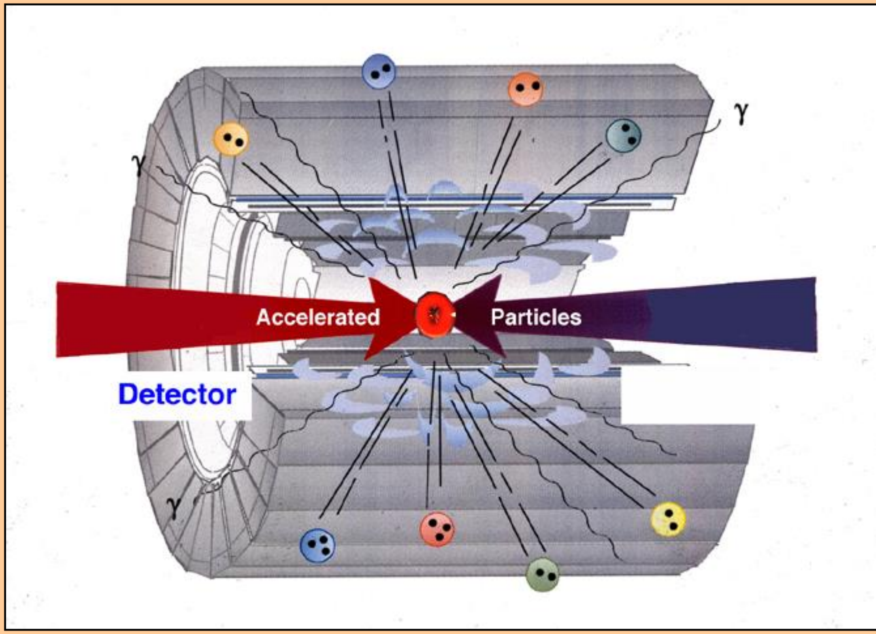
With these high-E collisions we can:

- Study how the fundamental constituents of the proton (quarks and gluons) interact
- Study/discover (new) heavy particles ($E=mc^2$). The higher the accelerator energy, the heavier the produced particles can be. These particles then decay into lighter (known) particles: electrons, photons, etc.
- Reproduce energy (temperature) conditions of early Universe (back to 10^{-11} s after Big Bang)

By placing high-tech powerful instruments (detectors) around the collision point we can detect the collision products and reconstruct what happened in the collision (which phenomena, which particles and forces were involved, etc.)

Therefore, we need three things:

Accelerators: underground tunnels (usually rings) containing electric fields to accelerate particles to very high energy (incrementally at each turn), and magnets to bend the beams inside the ring and bring them into collision
Powerful giant microscopes to explore the smallest constituents of matter



Detectors: massive instruments which register the collision products and allow to identify the produced particles and measure their energy and trajectory.

Computing: to store, distribute and analyze the vast amount of data produced by the detectors and thus reconstruct the "event" occurred in the collision.

The Large Hadron Collider (LHC) at CERN

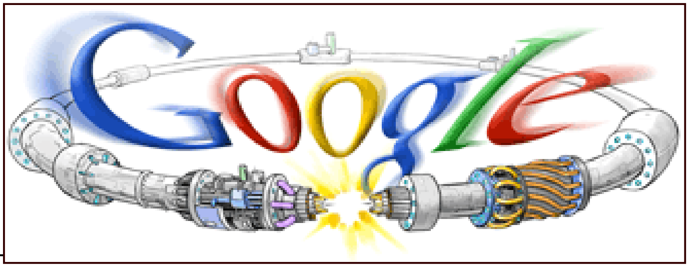
the most powerful accelerator

.... and also ....

the most high-tech and complex detectors
the most advanced computing infrastructure
the most innovative concepts and technologies
(cryogenics, new materials, electronics, data transfer and storage, etc. etc...)
the widest international collaborations

ever achieved in accelerator particle physics.
One of the most ambitious projects in science in general.

Operation started 20 November 2009
(> 20 years from concept to start of operation)



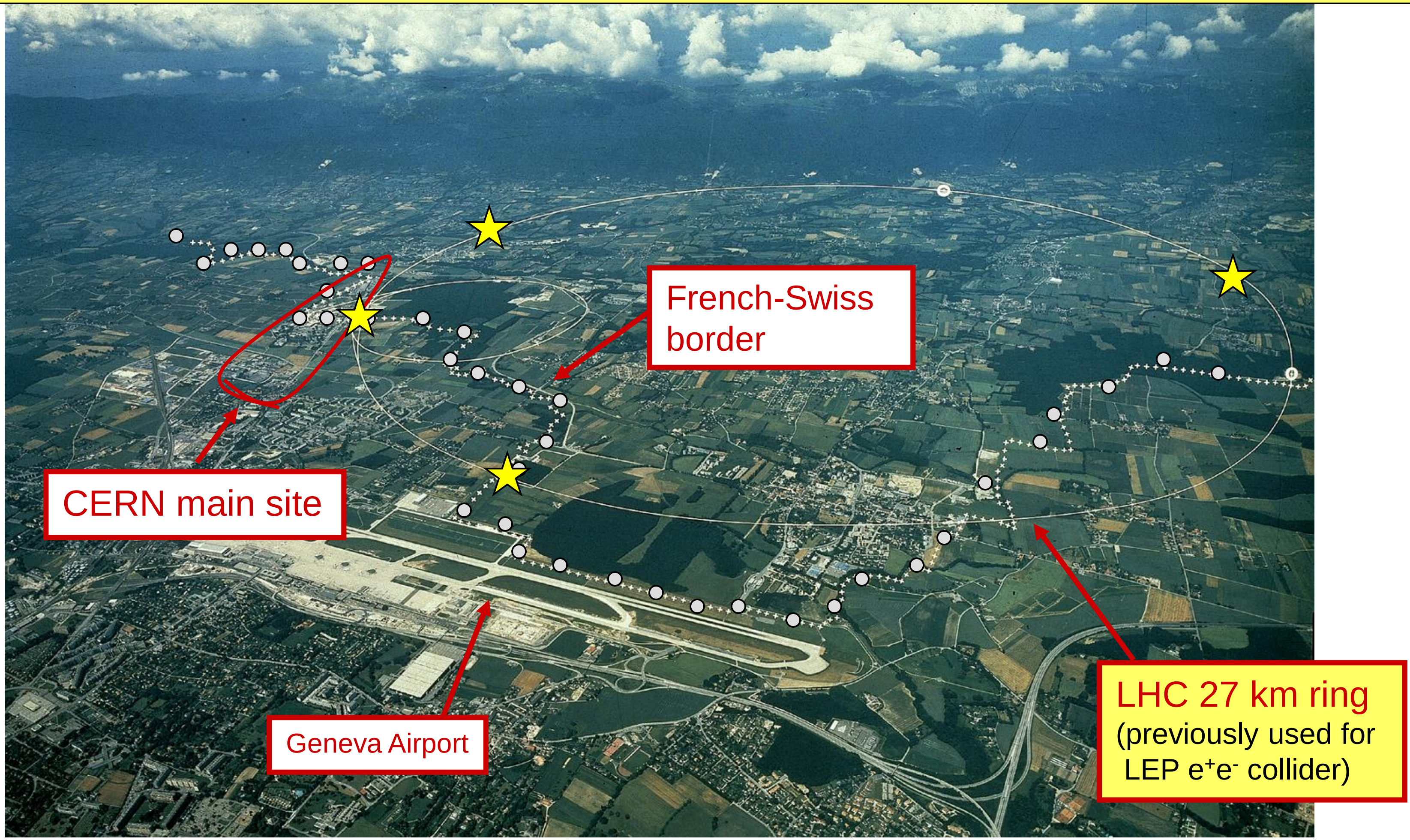
Few milestones of a long path …

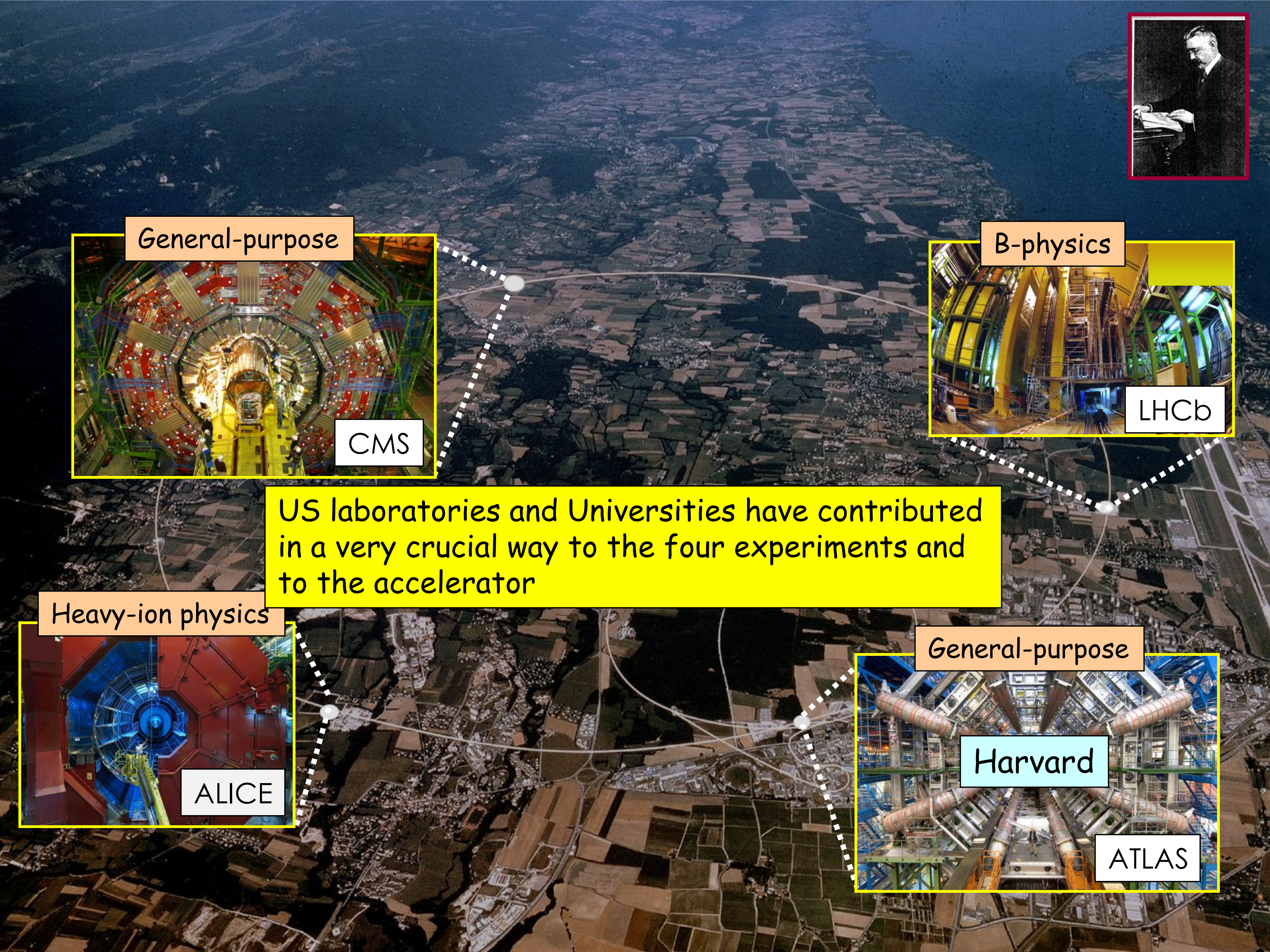
1984 : First studies for a high-energy pp collider in the LEP tunnel
1989 : Start of SLC and LEP e^+e^- colliders
1993 : SSC is cancelled → US physicists join the LHC
1994 : LHC approved by the CERN Council
1995 : Top-quark discovered at the Tevatron
1996 : Construction of LHC machine and experiments start
2000 : End of LEP2
2003 : Start of LHC machine and experiments installation
2009 : 23 November: first LHC collisions ($\sqrt{s}$ = 900 GeV)
2010 : 30 March: first collisions at $\sqrt{s}$ = 7 TeV
➔ Inauguration of a (~ 20-year ?) long physics programme
2012 : 1st May: first collisions at $\sqrt{s}$ = 8 TeV
2012 : 4th July: discovery of a Higgs-like boson
2013 : 14th February: end of LHC "Run 1" → start 2-year shut-down (LS1)

A ~ 40-year project:
> 20 years from conception to start of operation
+ 20 (?) years of physics exploitation

The LHC has required:
- most innovative technologies (superconducting magnets, cryogenics, electronics, data transfer and storage, etc…)
- new concepts, a lot of ingenuity to address challenges and solve problems
- huge efforts of the worldwide community (ideas, technology, people, money)

- LHC : 27 km accelerator ring, 100 m below ground, across French-Swiss border
- Two proton beams accelerated in opposite directions → collide at four points, where four big experiments have been installed
- Beam energy until today: 4 TeV → collision energy: 8 TeV (1 TeV= 10^{-7} Joule)
  Design energy (to be achieved in 2015): $\sqrt{s}$ ~ 14 TeV (x7 Tevatron)
- 1st LHC run: March 2010-February 2013

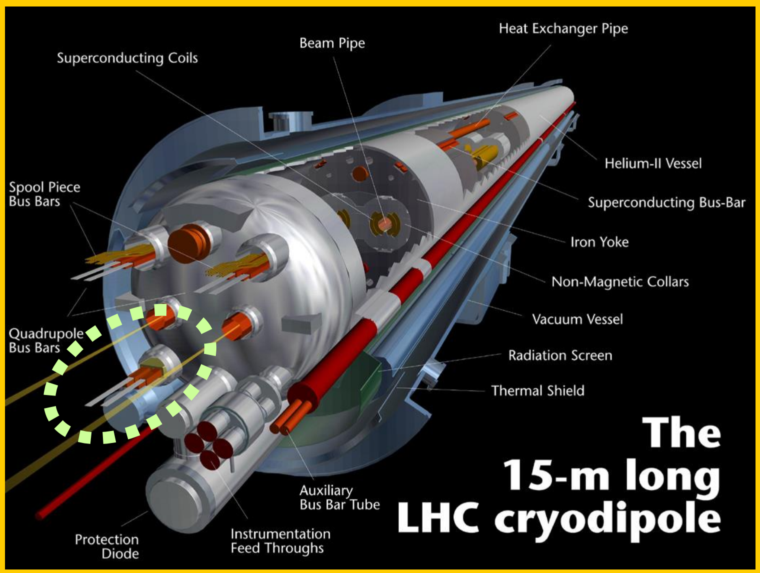



General-purpose
CMS
B-physics
LHCb
US laboratories and Universities have contributed in a very crucial way to the four experiments and to the accelerator
Heavy-ion physics
ALICE
General-purpose
Harvard
ATLAS

The most challenging component of the accelerator is the system of 1232 high-tech superconducting dipole magnets, providing a field of 8.3 T (needed to bend 7 TeV beams inside a 27 km ring) → p(TeV) = 0.3 B(T) R(km)

7600 km of NbTi superconducting cable.

Work at 1.9K in a bath of 120 tons of superfluid Helium



2015: collision energy ~ 14 TeV after repair/consolidation of magnet interconnects during LS1 (following Sept. 2008 accident)

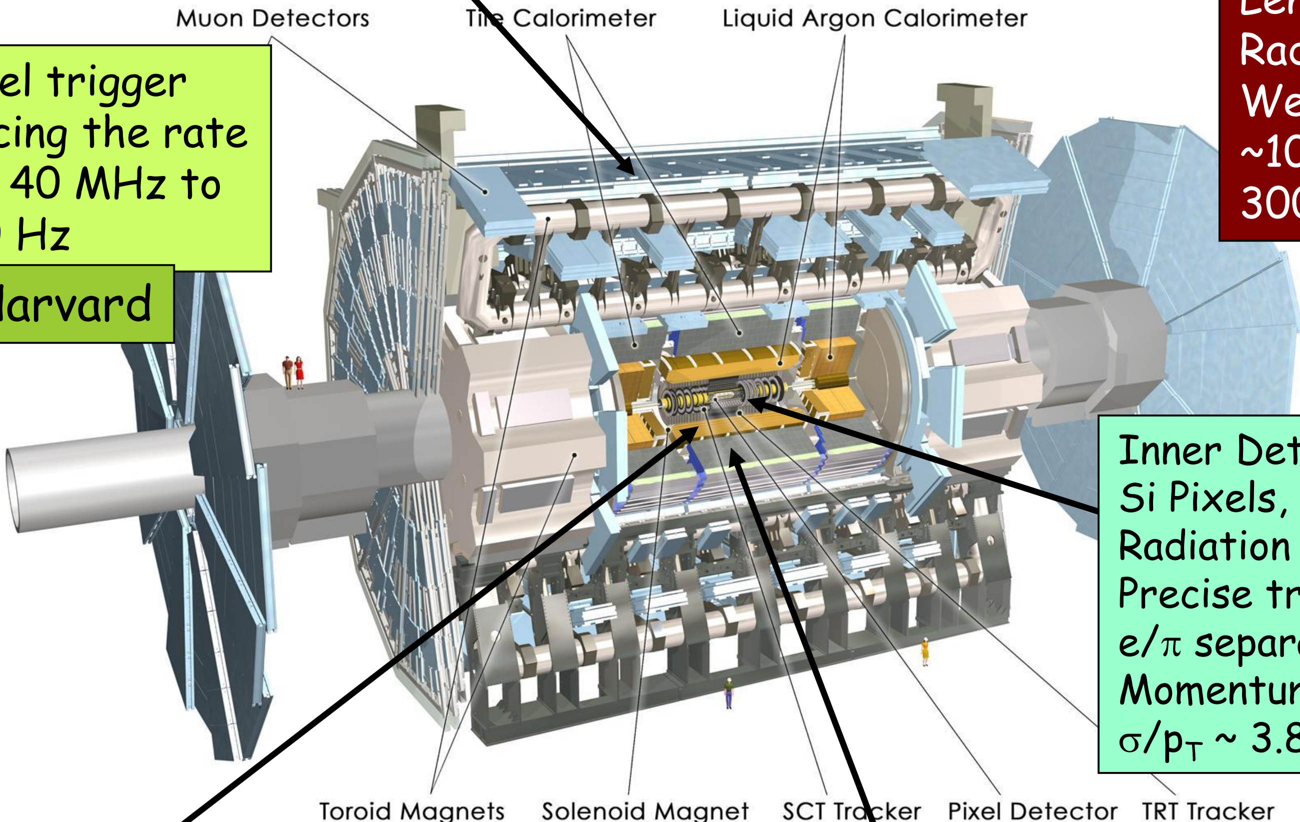
Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Harvard

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz

Harvard



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Harvard

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
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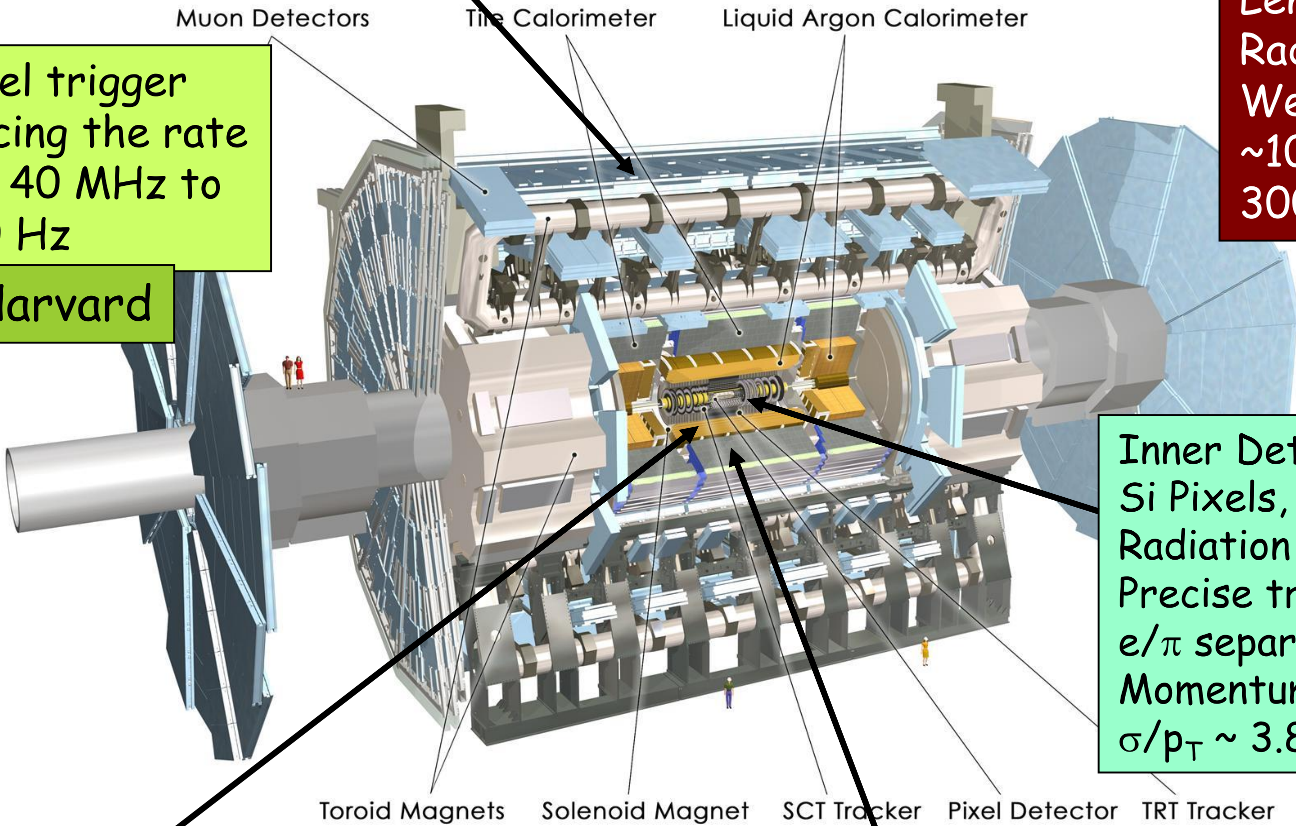

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Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\ p_T(\mathrm{GeV}) \oplus 0.015$

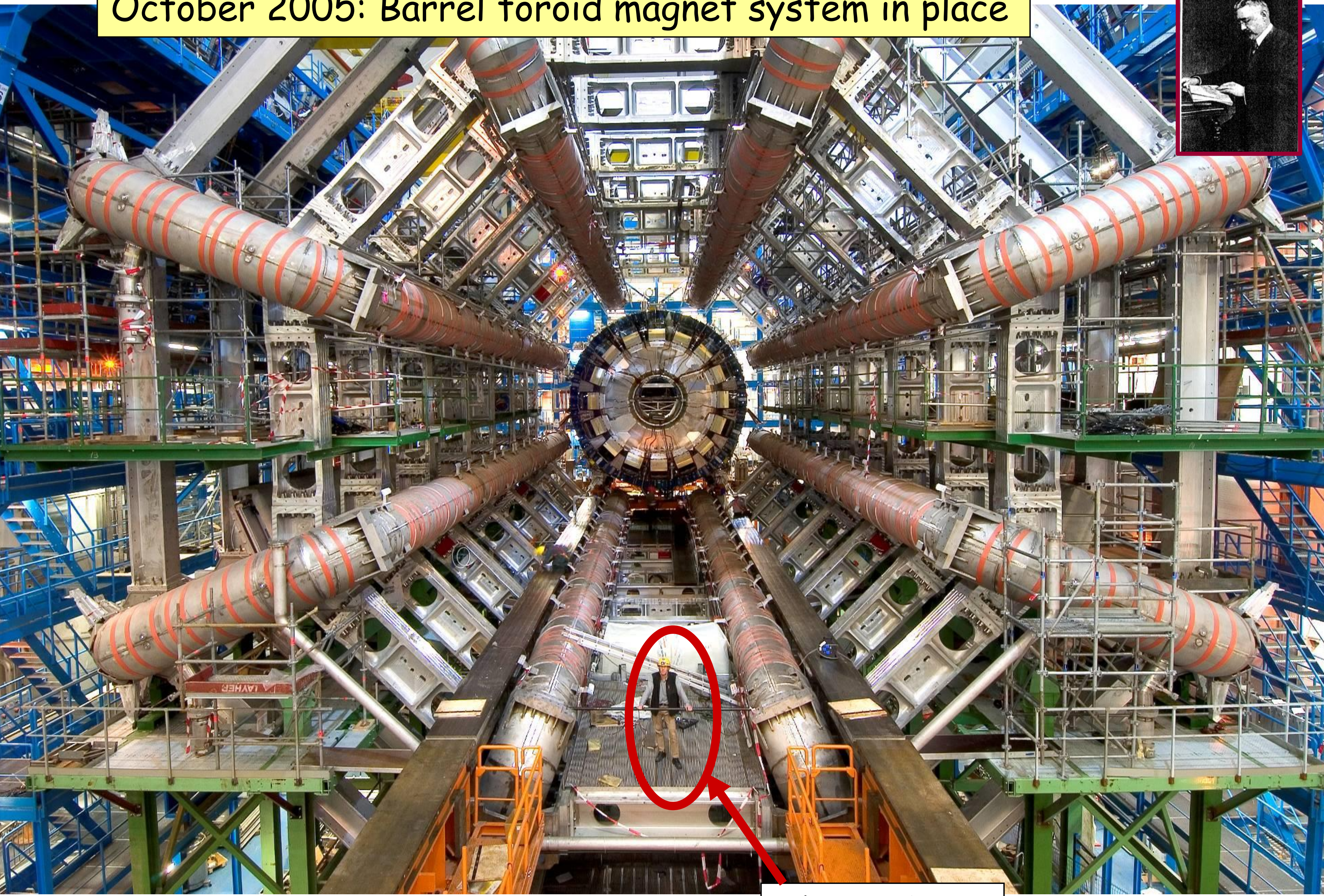
EM calorimeter: Pb-LAr Accordion
e/γ trig
E-resolu

city

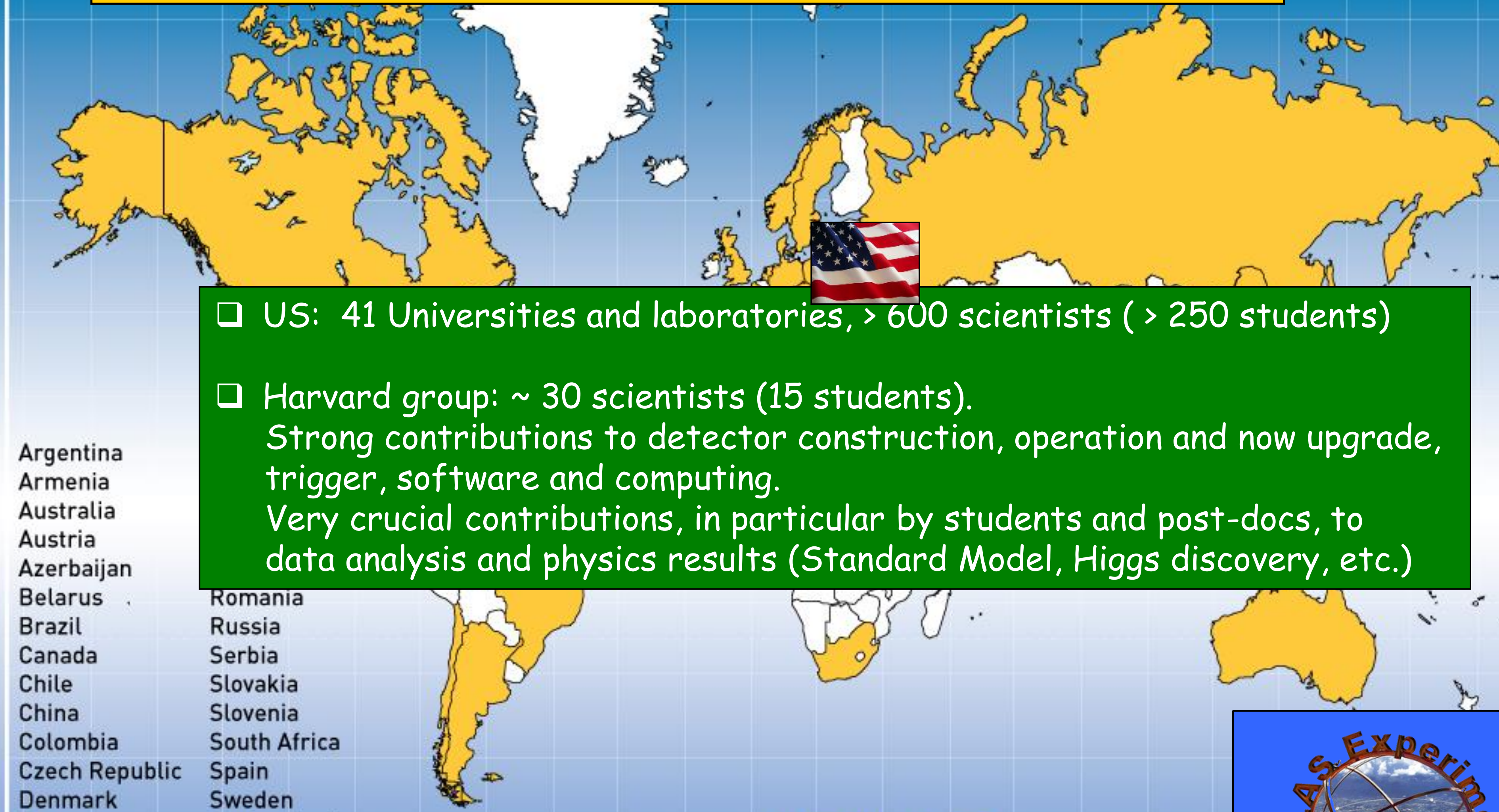
- Size : to measure and absorb high-E particles from the collision
- 10^8 independent sensitive elements: to track ~1000 particles per event and reconstruct their trajectories with ~10 μm precision
- Fast response (25-50 ns): 40 million beam-beam collisions per second

ATLAS cavern (-100 m) in June 2003

October 2005: Barrel toroid magnet system in place



~ 3000 scientists from 176 Institutions from 38 Countries



- US: 41 Universities and laboratories, > 600 scientists (> 250 students)

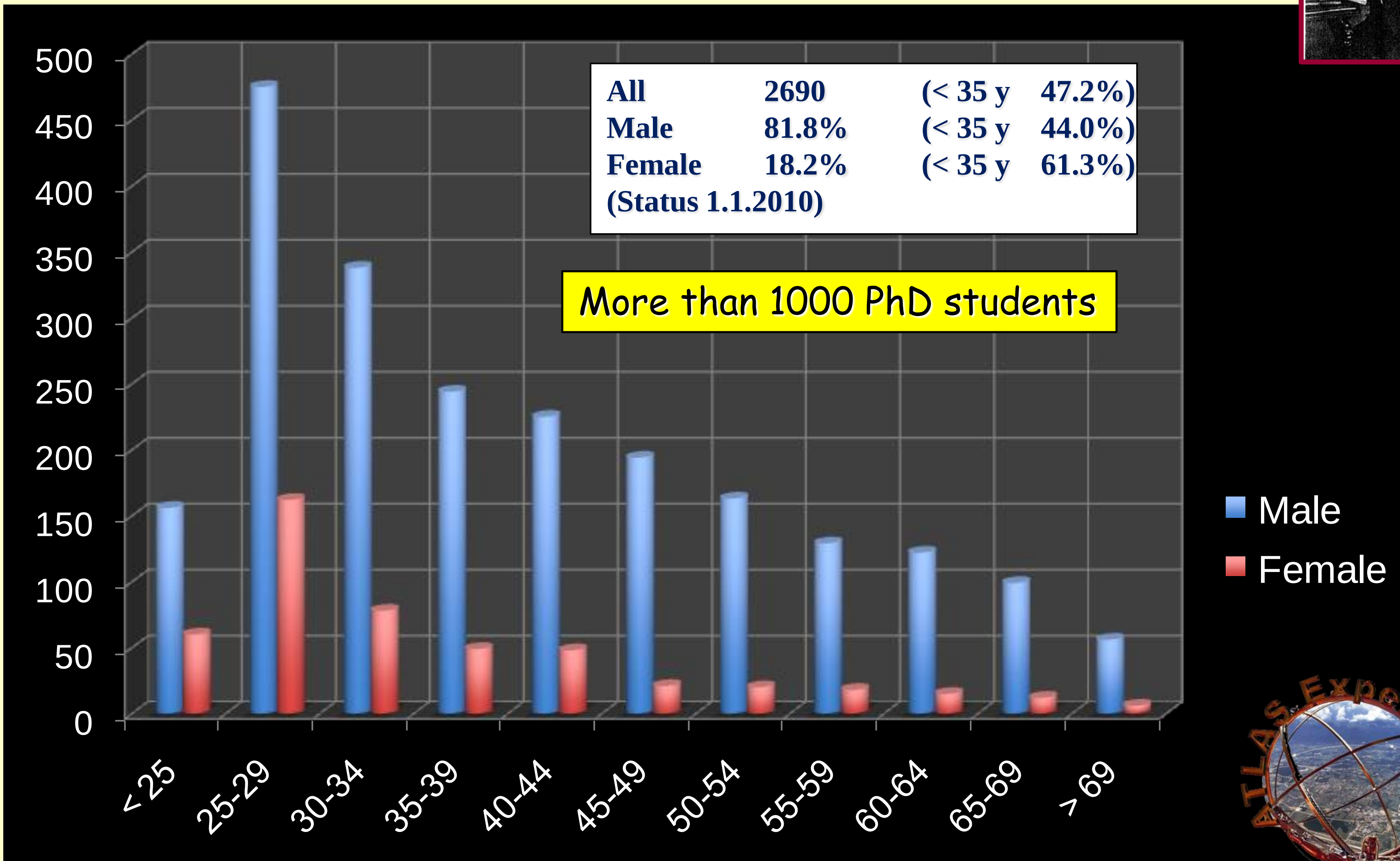
- Harvard group: ~ 30 scientists (15 students).
  Strong contributions to detector construction, operation and now upgrade, trigger, software and computing.
  Very crucial contributions, in particular by students and post-docs, to data analysis and physics results (Standard Model, Higgs discovery, etc.)

Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan

Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR

ATLAS Collaboration

Age distribution of the ATLAS population



A few additional numbers which usually impress the public …

Number of turns of the LHC ring made by protons in one second: ~ 11000

Number of beam-beam collisions per second at design operation: 40 million
Beam transverse size at the collision point: 16 μm (~ 4 times smaller than that of a typical a human hair)

Magnets work at … outer space

Energy … at 12 knots

The CMS … iron than the Tour Eiffel

WHY ???

3000 km of cables used to transfer the signals from the ATLAS detector to the control rooms

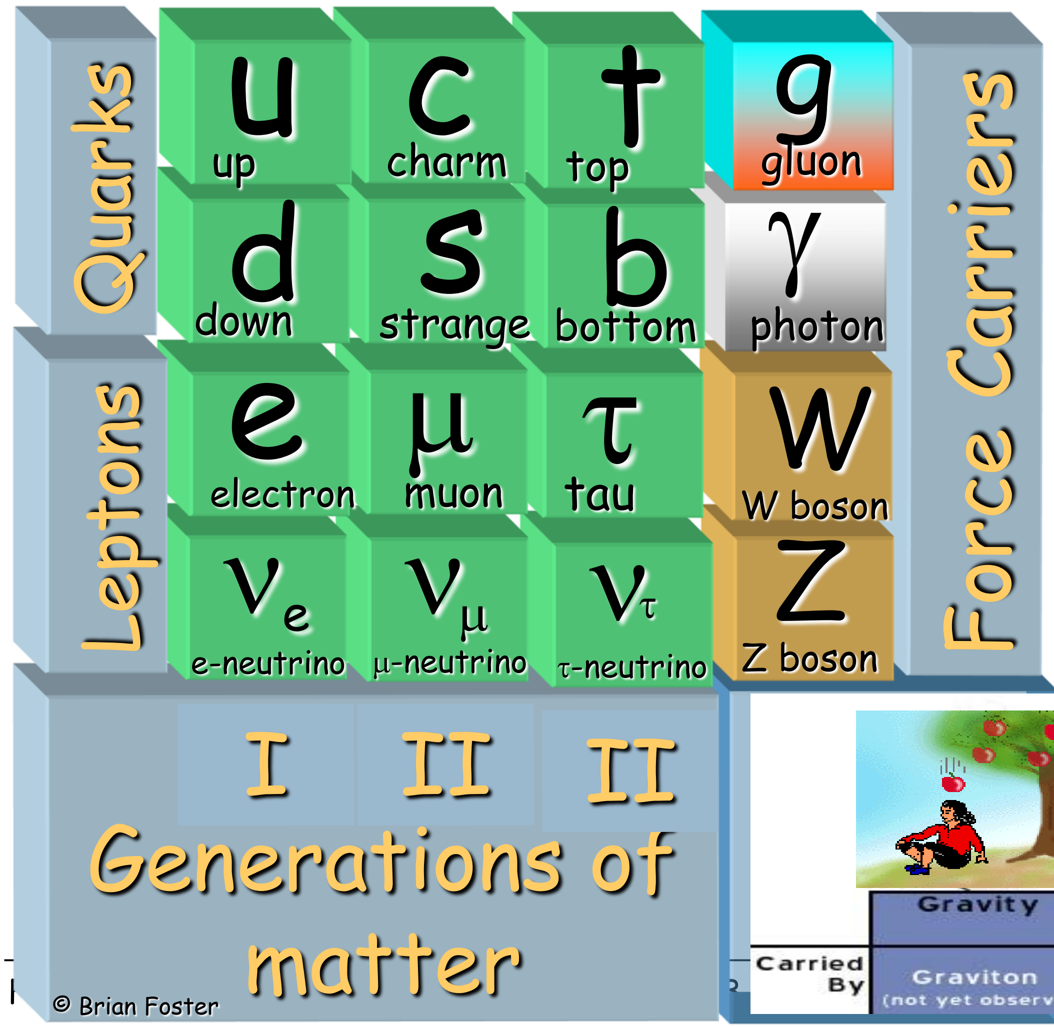
Each LHC experiment produces ~ 10 PB of data per year (1 PB=10^6 GB)
This corresponds to ~ 20 million DVD (a 20 km stack …)

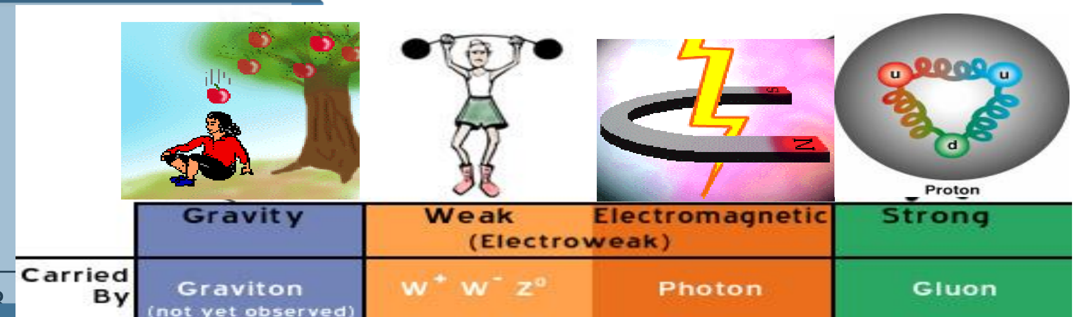
Cost: 6B USD

Etc. etc.

The elementary particles and their interactions are described by a very successful theory: the Standard Model. All particles foreseen by the SM have been observed, and the SM predictions have been verified with extremely high precision over the last 35 years by experiments at CERN, SLAC, Fermilab and other labs all over the world

Particles and forces





However: the SM is not a complete theory

Some of today's outstanding questions

What is the origin of the particle masses ? ✓ — ATLAS, CMS

What is the nature of the Universe dark matter ? — ATLAS, CMS

Why is there so little antimatter in the Universe ? — LHCb
(Nature's favouritism allowed us to exist …)

New Physics beyond the Standard Model is needed to answer these and other questions. The huge amount of precise experimental data collected so far indicate that this New Physics could manifest itself at the ~ TeV energy scale being explored by the LHC

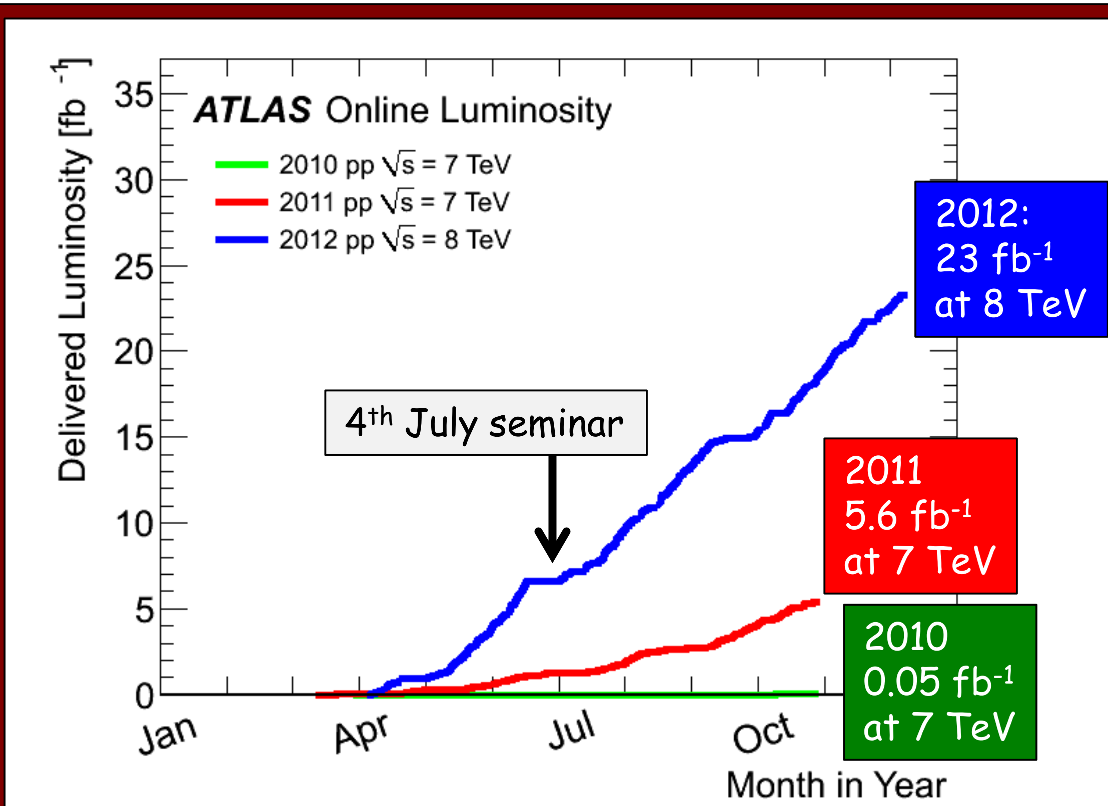
life (10^{-11} s after the Big Bang) ? — …CMS

Are there other forces in addition to the known four ?
Are there additional (microscopic) space dimensions ? — ATLAS, CMS

Etc. etc.

Since first collisions in November 2009:

- Accelerator, experiments and computing performed far beyond expectation
  → huge amount of data recorded and analyzed (ATLAS: 5 billion events)
- Standard Model and known particles "rediscovered" and measured in new energy regime
- Many physics scenarios beyond SM explored and ruled out
- Higgs boson discovered by ATLAS and CMS



n. of protons per bunch — n. of bunches — n. of turns per second

$$L = \frac{N^2 k_b f}{4\pi \sigma_x \sigma_y}$$

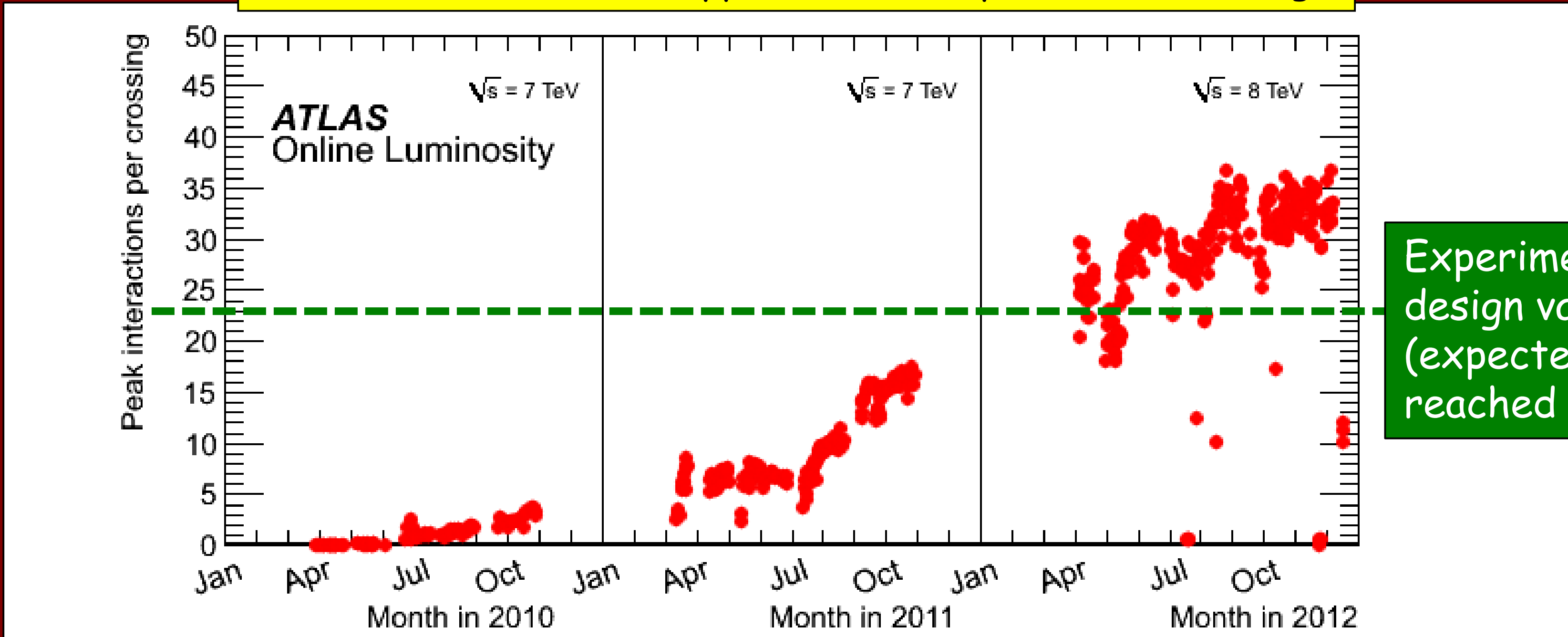
beam size at IP

Achieved peak luminosity:
~ 7.7 x10^{33} cm^{-2} s^{-1} (x18 Tevatron)

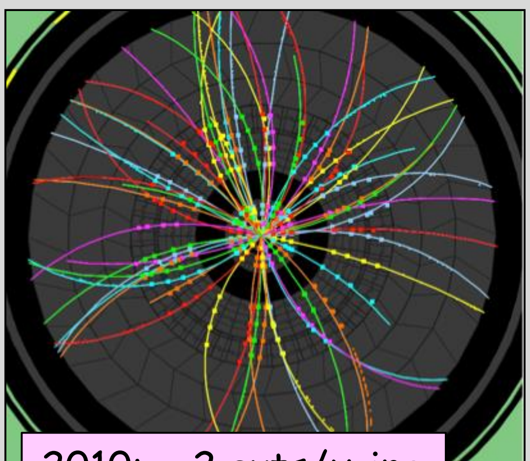
$$N = \int L dt \times \sigma (pp \rightarrow X)$$

ATLAS: very high data-taking efficiency (~ 93.5%) and data-quality (~ 96%)

The prize to pay for the high luminosity: pile-up
(number of simultaneous pp interactions per bunch crossing)



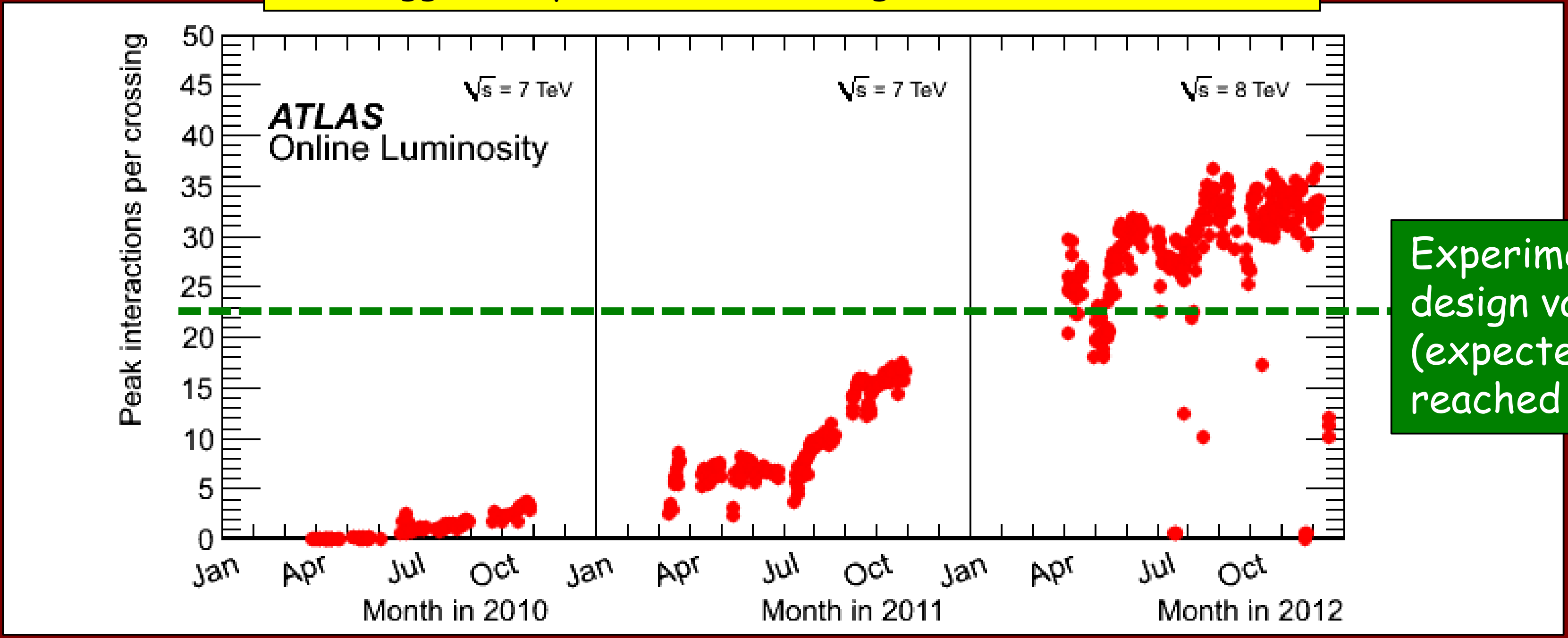
Experiment's design value (expected to be reached at $L=10^{34}$!)


2010: ~ 2 evts/x-ing


2011: ~ 10 evts/x-ing


2012: ~ 20 evts/x-ing

The prize to pay for the high luminosity: pile-up
(the biggest experimental challenge in 2012)



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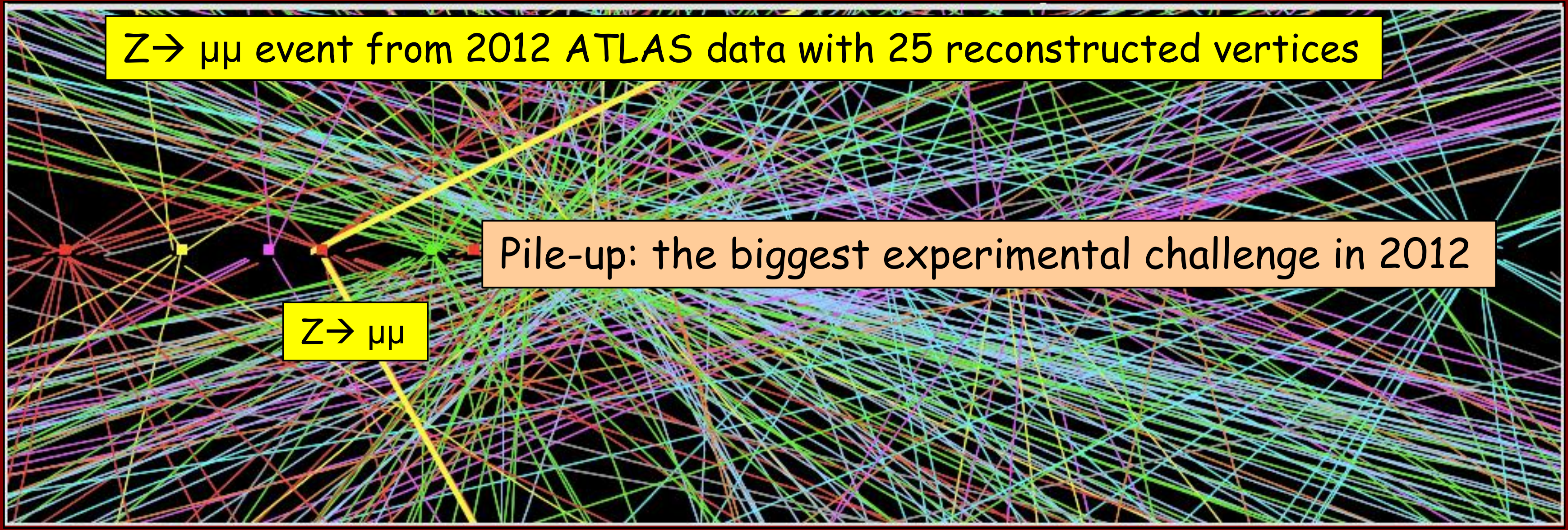
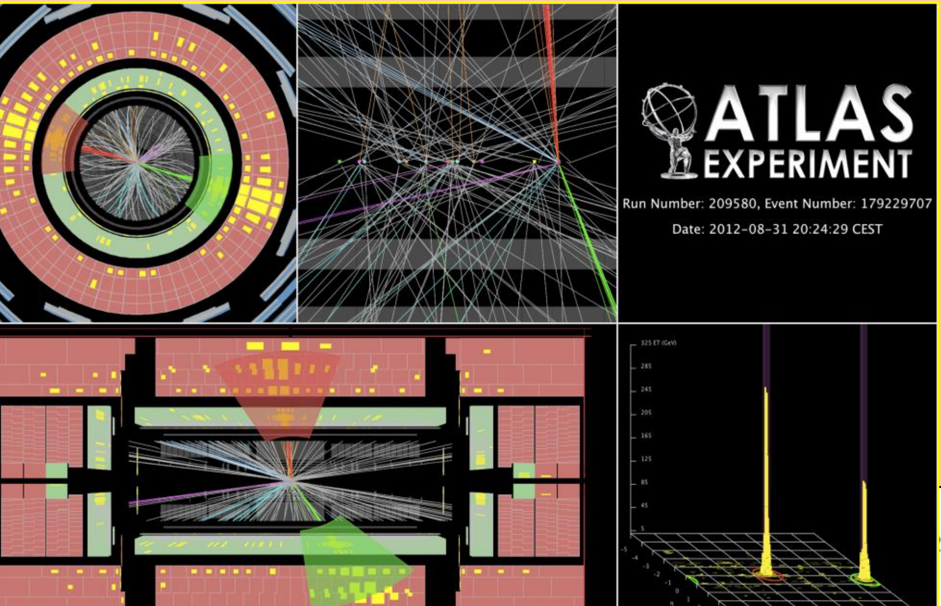
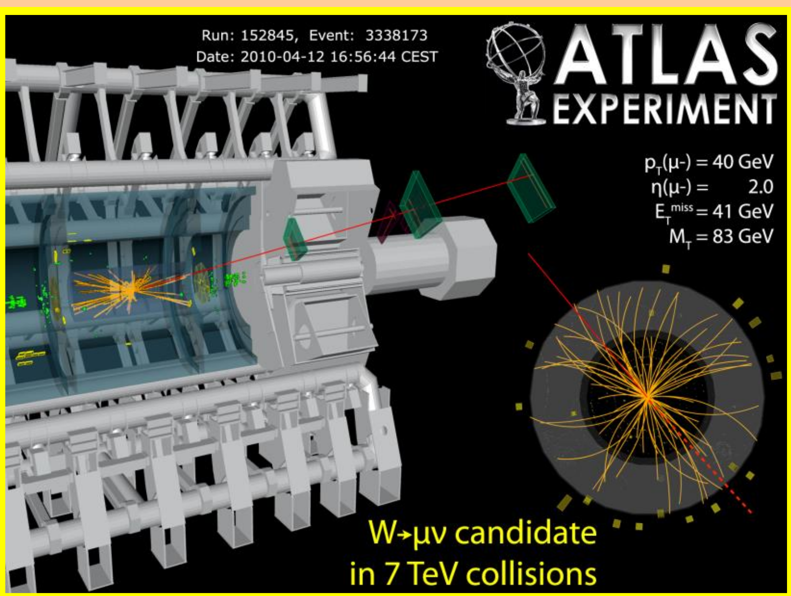


A huge scientific output



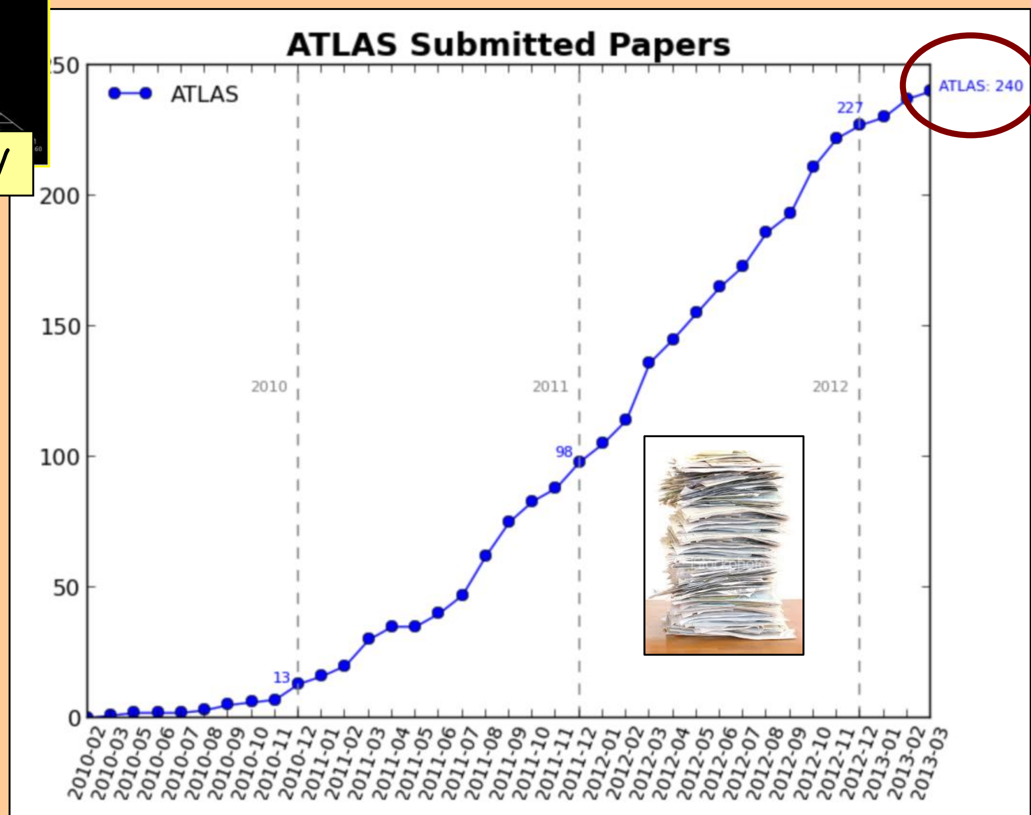
m_{jj} = 4.7 TeV $p_T(j_{1,2})$ = 2.3-2.2 TeV, E_T^{miss} = 47 GeV



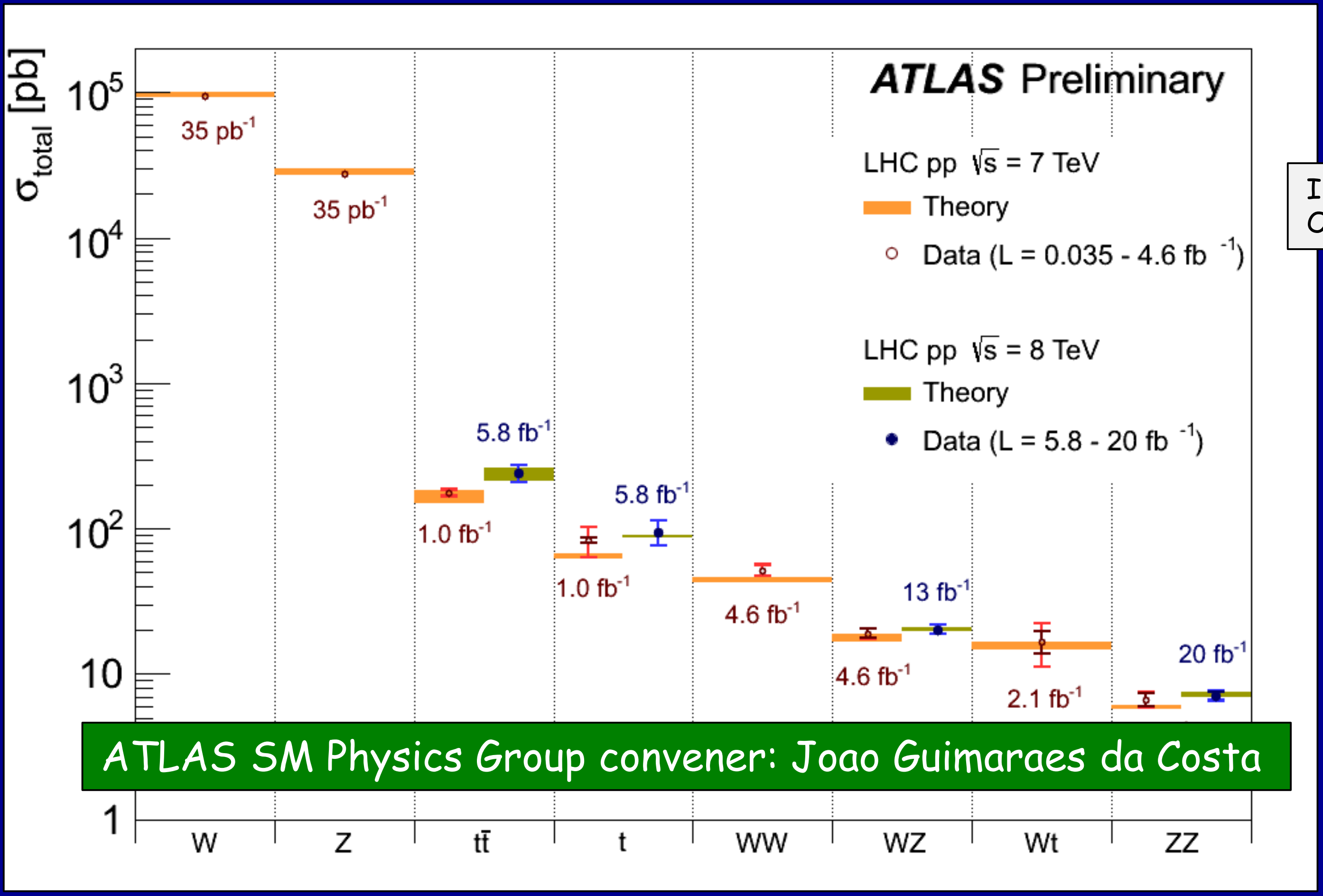
Number of events in full 2010-2012 dataset (~ 25 fb^{-1}) after all selections:

$W \to l\nu$ ~ 100 M
$Z \to ll$ ~ 10 M
$tt \to l+X$ ~ 0.4 M
Higgs candidates ~ 600
[~1 $H \to \gamma\gamma$ (~1 $H \to 4l$) produced every 50′ (14h) at 7×10^{33}]

l=e,μ



Cross-section measurements of known processes (examples …)



ATLAS SM Physics Group convener: Joao Guimaraes da Costa

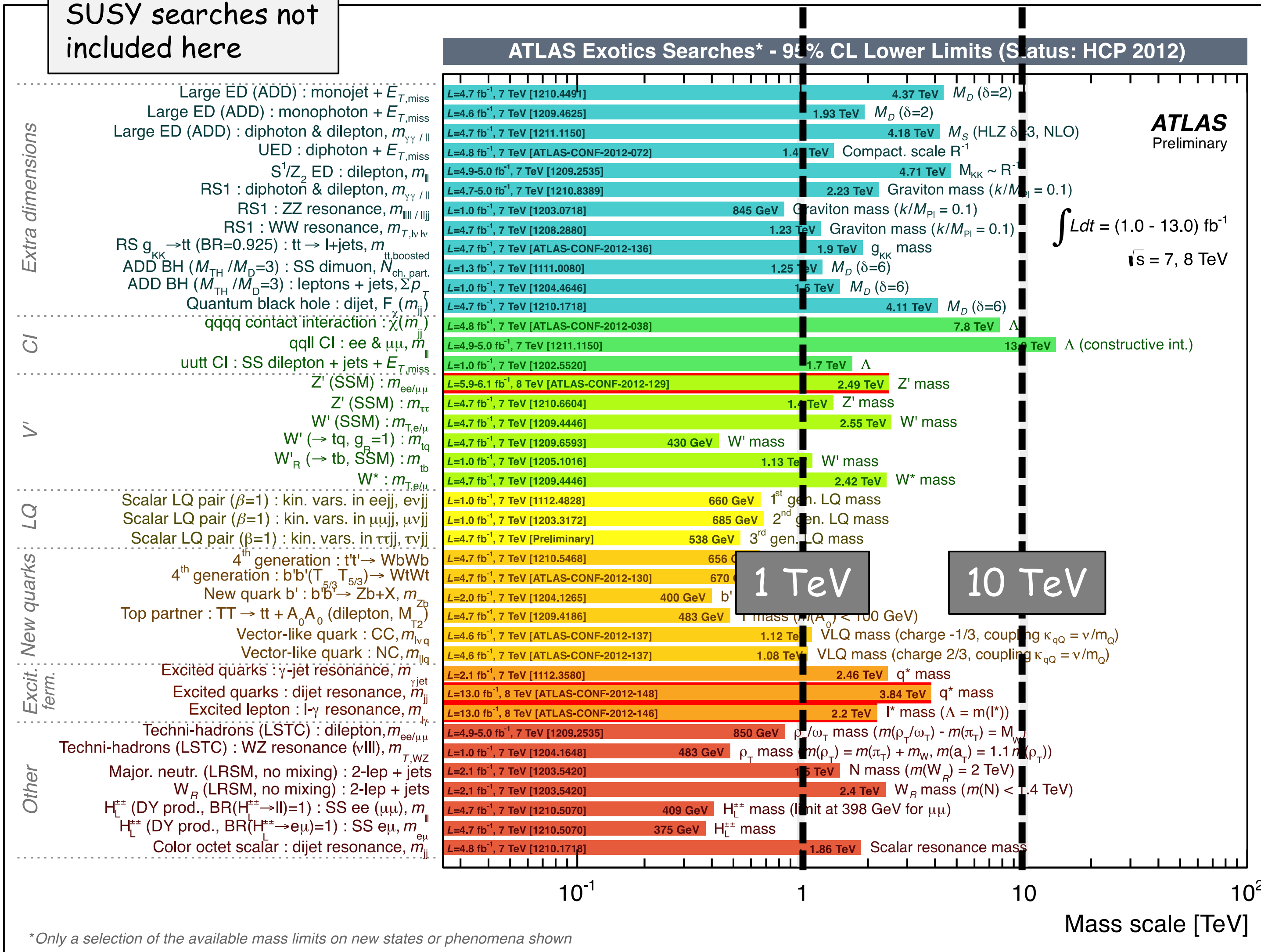
Inner error: statistical
Outer error: total

- Important to test SM at 8 TeV, constrain theory predictions, backgrounds to searches
- Good agreement with SM expectation
- Experimental precision starts to challenge theory uncertainty (e.g. tt)

Exploration of the energy frontier

Huge number of models and topologies investigated

SUSY searches not included here

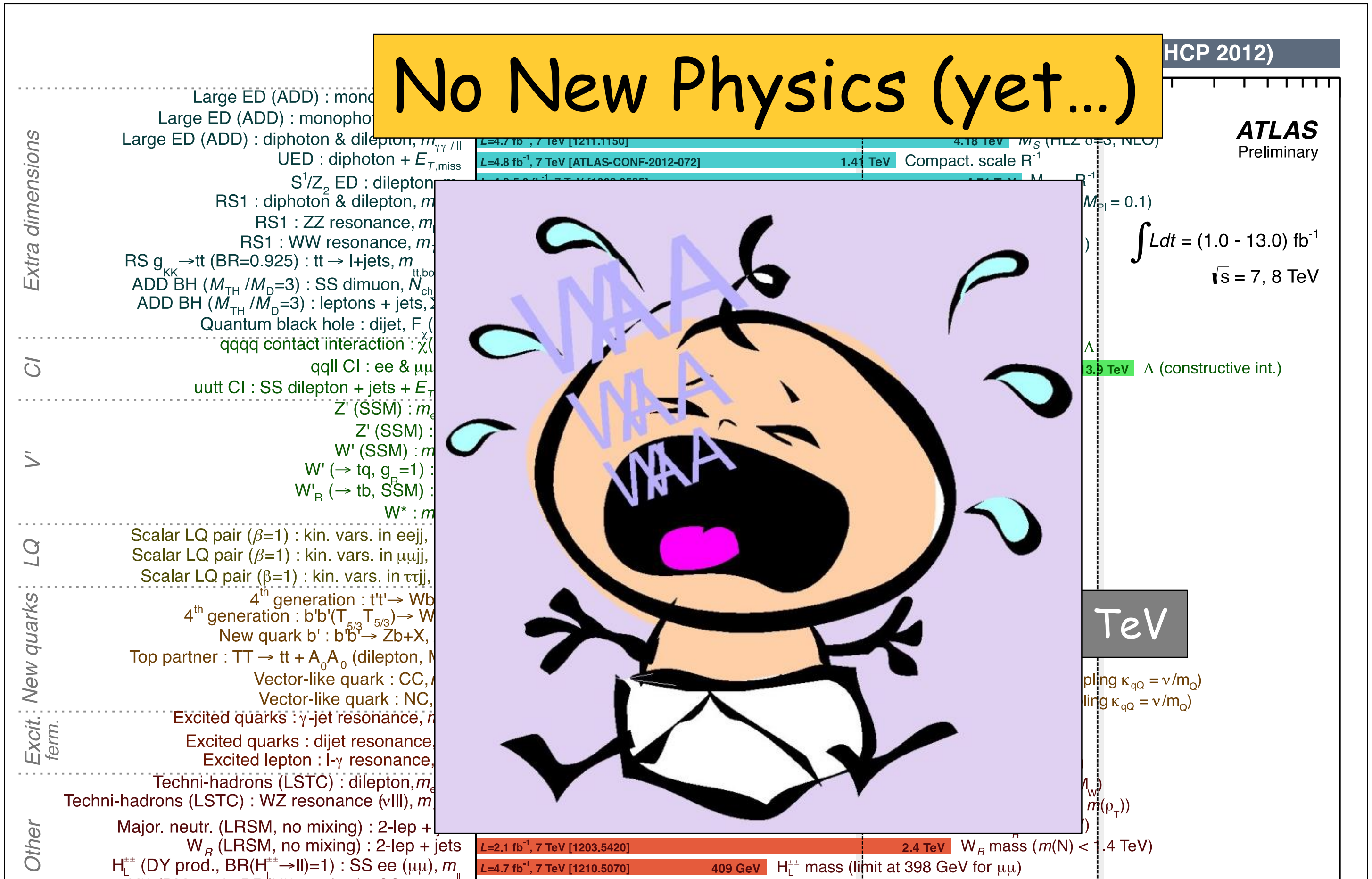


Exotics Models:

- Extra dimensions:
  - RS KK Graviton
    - (dibosons, dileptons, diphotons)
  - RS KK gluons (top antitop)
  - ADD (monojets, monophotons, dileptons, diphotons)
  - KK Z/gamma boosns (dileptons)
- Grand Unification symmetries
  - (dielectons, dimuons, ditaus)
  - Leptophobic topcolor Z' boson
    - (dilepton ttbar, l+j, all had)
- S8- color octet scalars (dijets)
- String resonance (dijets,)
- Benchmark Sequential SM Z', W'
- W' (lepton+MET, dijets, tb)
- W* (lepton+MET, dijets)
- Quantum Black Holes (dijet)
- Black Holes (l+jets, same sign leptons)
- Technihadrons (dileptons, dibosons)
- Dark Matter
  - WIMPs (Monojet, monophotons)
- Excited fermions
  - q*, Excited quarks (dijets, photon+jet)
  - l*, excited leptons (dileptons+photon)
- Leptoquarks (1st, 2nd, 3rd generations)
- Higgs -> hidden sector
  - (displaced vertices, lepton jets)
- Contact Interaction
  - llqq CI
  - 4q CI (dijets)
- Doubly charged Higgs (
  - multi leptons, same sign leptons)
- 4th generation
  - t'->Wb, t'->ht, b'-Zb, b'->Wt
    - (dileptons, same sign leptons, l+J)
- VLQ-Vector Like quarks
- Magnetic Monopoles (and HIP)
- Heavy Majorana neutrino and RH W

Exploration of the energy frontier

Huge number of models and topologies investigated



No New Physics (yet…)

TeV

Exotics Models:

Extra dimensions:
- RS KK Graviton (dibosons, dileptons, diphotons)
- RS KK gluons (top antitop)
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Doubly charged Higgs (
- multi leptons, same sign leptons)

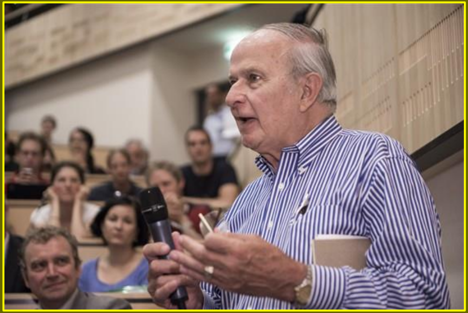
4th generation
- t'->Wb, t'->ht, b'-Zb, b'->Wt
- ons, l+J)

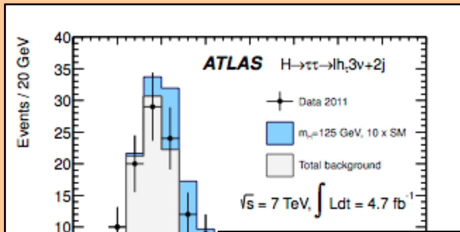
W

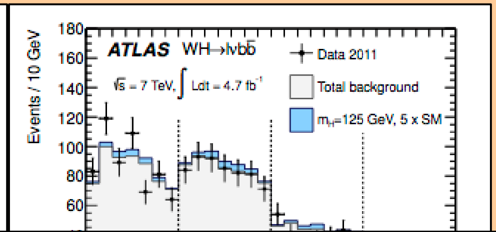
But
- ❑ searches far from being complete → surprises may hide in present data
- ❑ energy today ~ 1.7 smaller than design value and integrated luminosity ~12 smaller

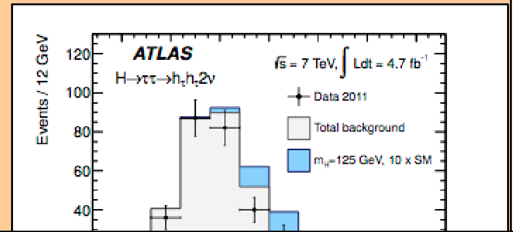
An historical day : 4th July 2012

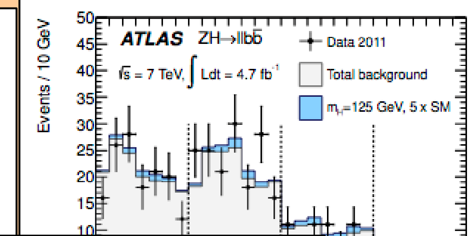
Since then … a lot of progress made …







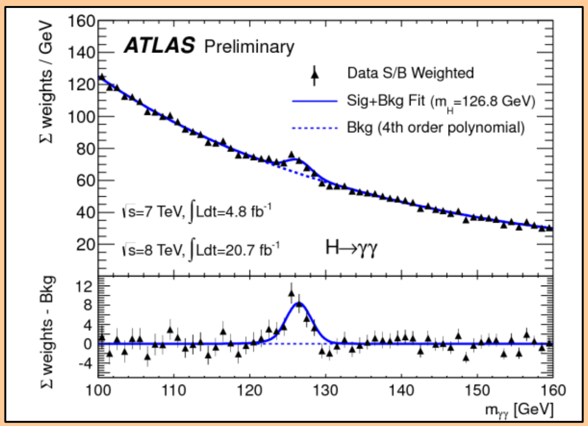


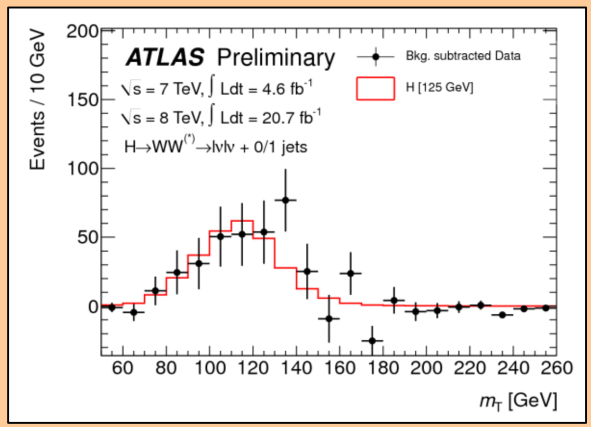


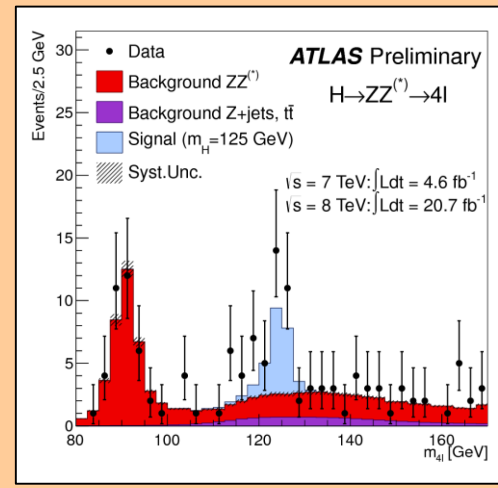
Higgs studies: most recent results from ATLAS

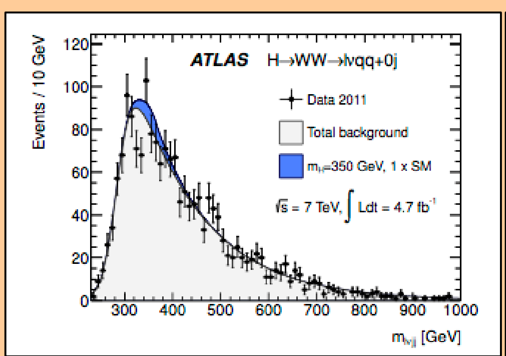
Based on:

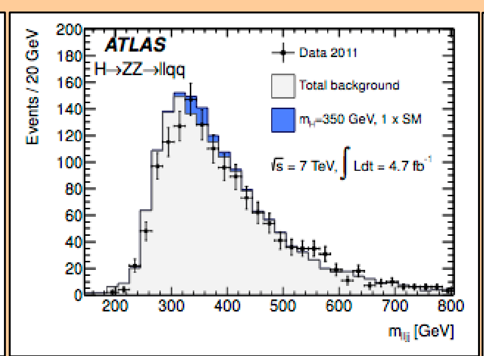
- ❑ Full recorded dataset, 25 fb^{-1}, for H→ γγ, H→ ZZ* → 4l, H→ WW* → lνlν
- ❑ ~ 18 fb^{-1} for H→ ττ, W/ZH→ bb

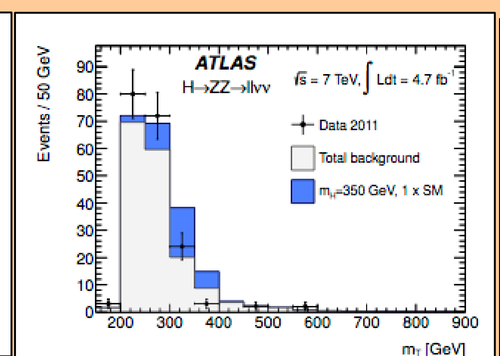


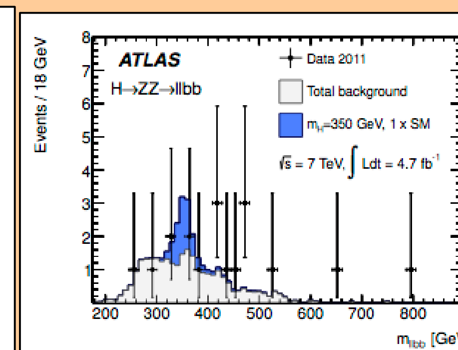




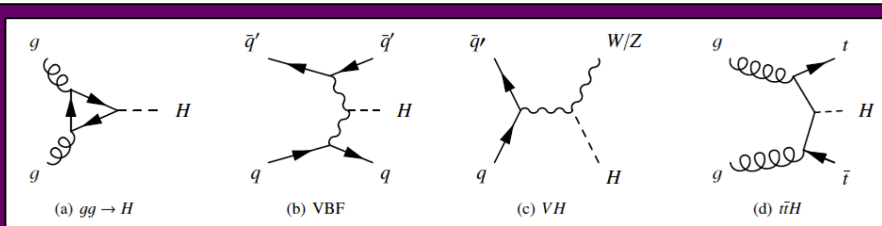


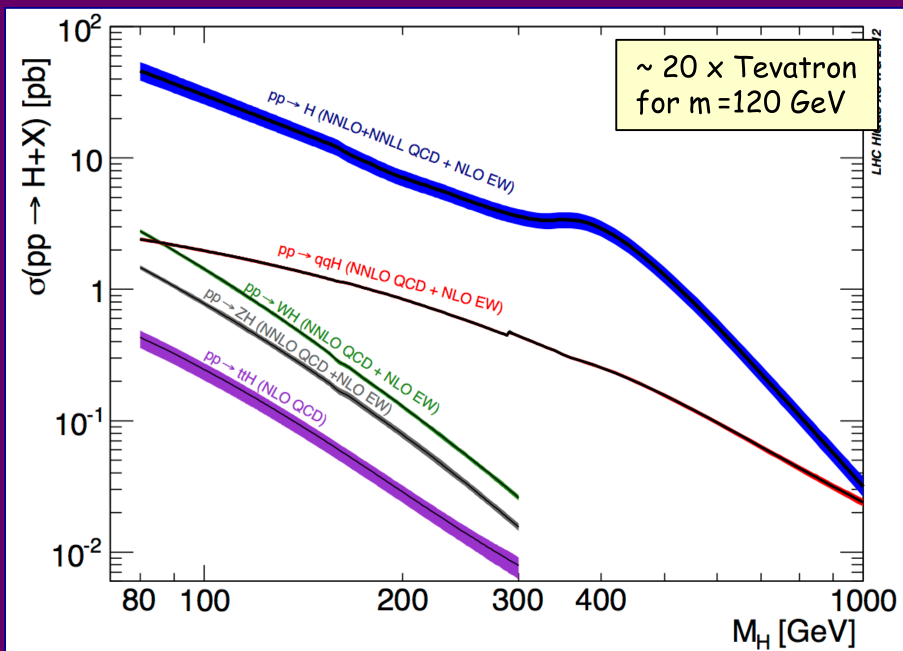


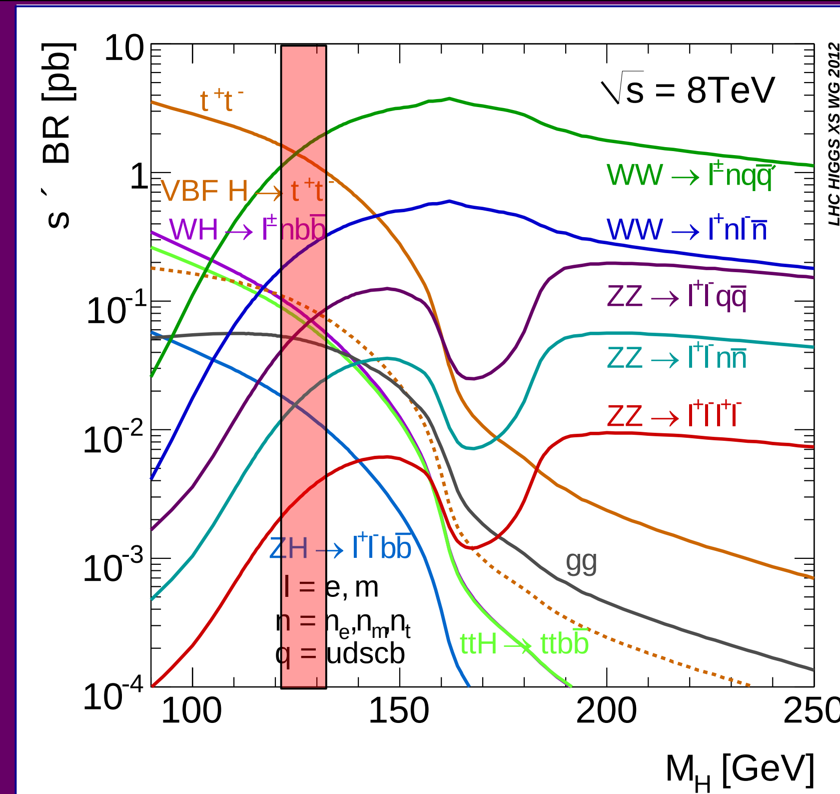




SM Higgs production cross-section and decay modes







Most sensitive channels (decreasing order) for 120 < m < 130 GeV:

H→ ZZ*→ 4l, H→ γγ, H→ WW*→ lνlν

H→ ττ

W/ZH→ W/Z bb

Challenges: tiny rates, small S/B, complex final states

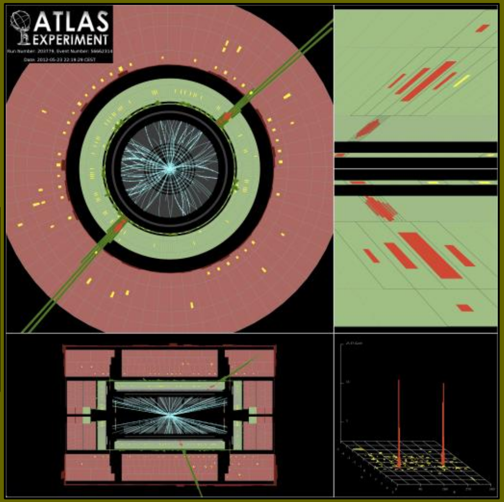
Huge efforts of theory community to compute NLO/NNLO cross-sections for signal and for (often complex !) backgrounds.

$H \to \gamma\gamma$

$\sigma \times BR \sim 50$ fb $m_H \sim 126$ GeV

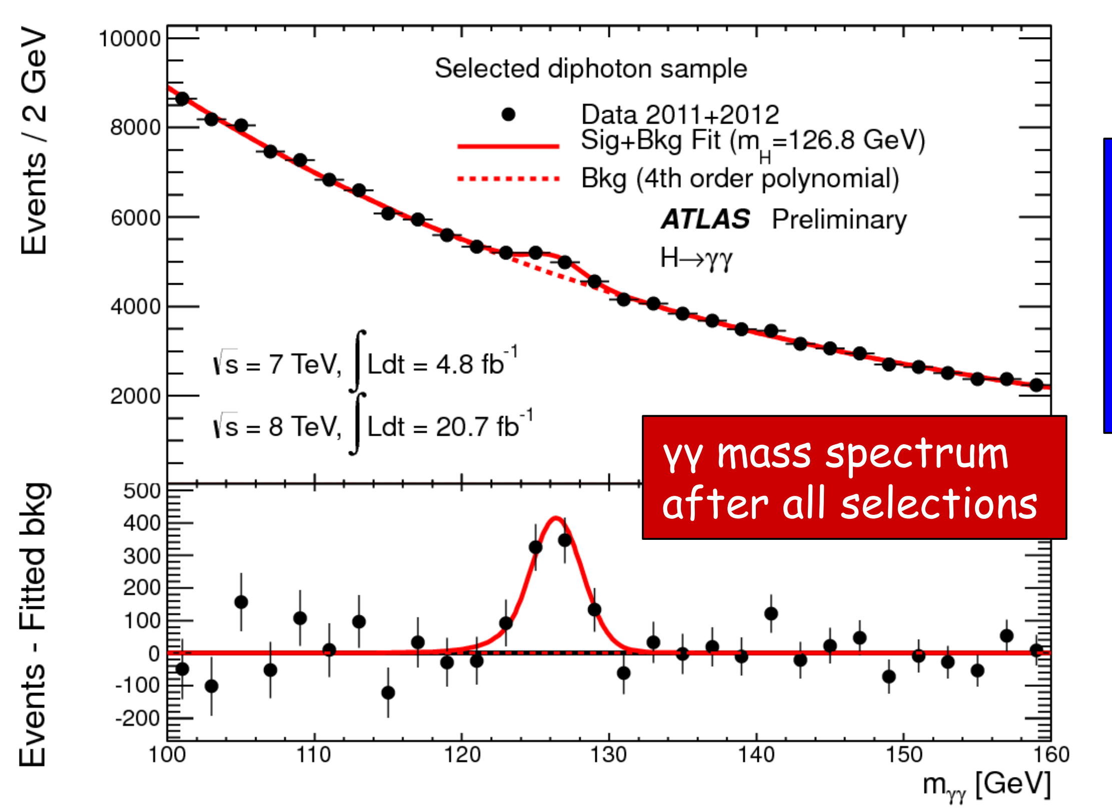
- Simple topology: two high-p_T isolated photons $E_T(\gamma_1, \gamma_2) > 40, 30$ GeV
- Main background: $\gamma\gamma$ continuum (irreducible)
- Background smooth but HUGE → small S/B ratio (~ 3%)

Most crucial experimental issue: excellent $\gamma\gamma$ mass resolution (electromagnetic calorimeter) to observe narrow signal peak above background



After all selections, expect ($m_H \sim 126$ GeV):
~ 400 signal events
~ 16000 background events in mass window

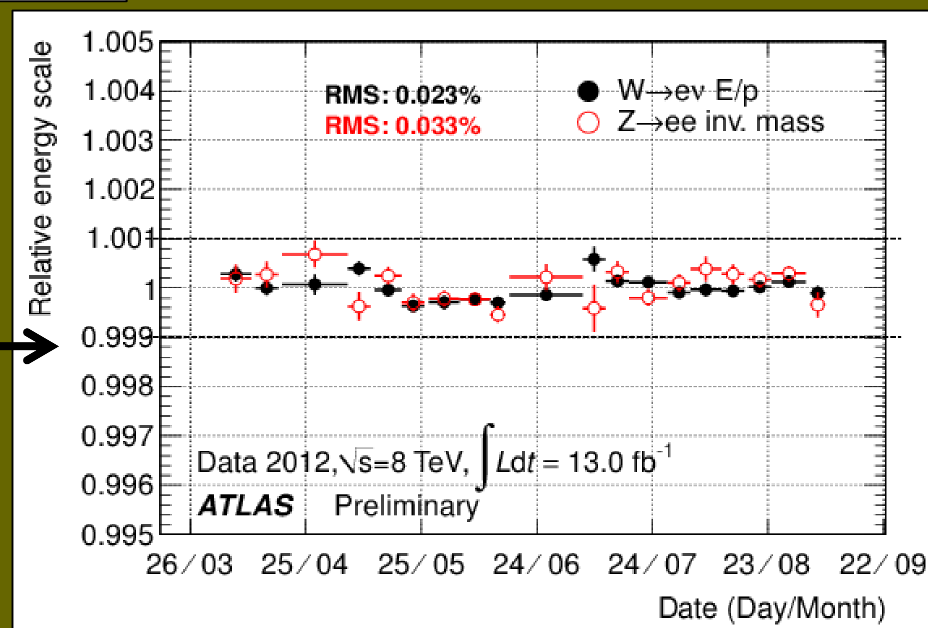
To increase sensitivity to specific production processes (→ measure as many Higgs couplings as possible) events divided into categories, e.g. events with two high-mass forward jets (→ enhance contribution of VBF process), events with additional leptons (→ enhance WH/ZH), etc.



γγ mass spectrum after all selections

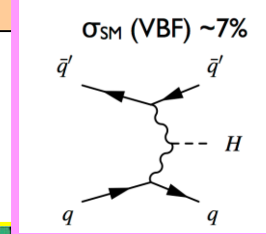
- Clear peak at m_H ~ 126.5 GeV:
- Probability it comes from background fluctuation: ~ 10^{-13}
  → 7.4 σ signal significance
  (4.1 σ expected from SM H)

One of the crucial ingredients to observe such a narrow peak: stability of EM calorimeter energy response vs time during 2012 run better than 0.1%

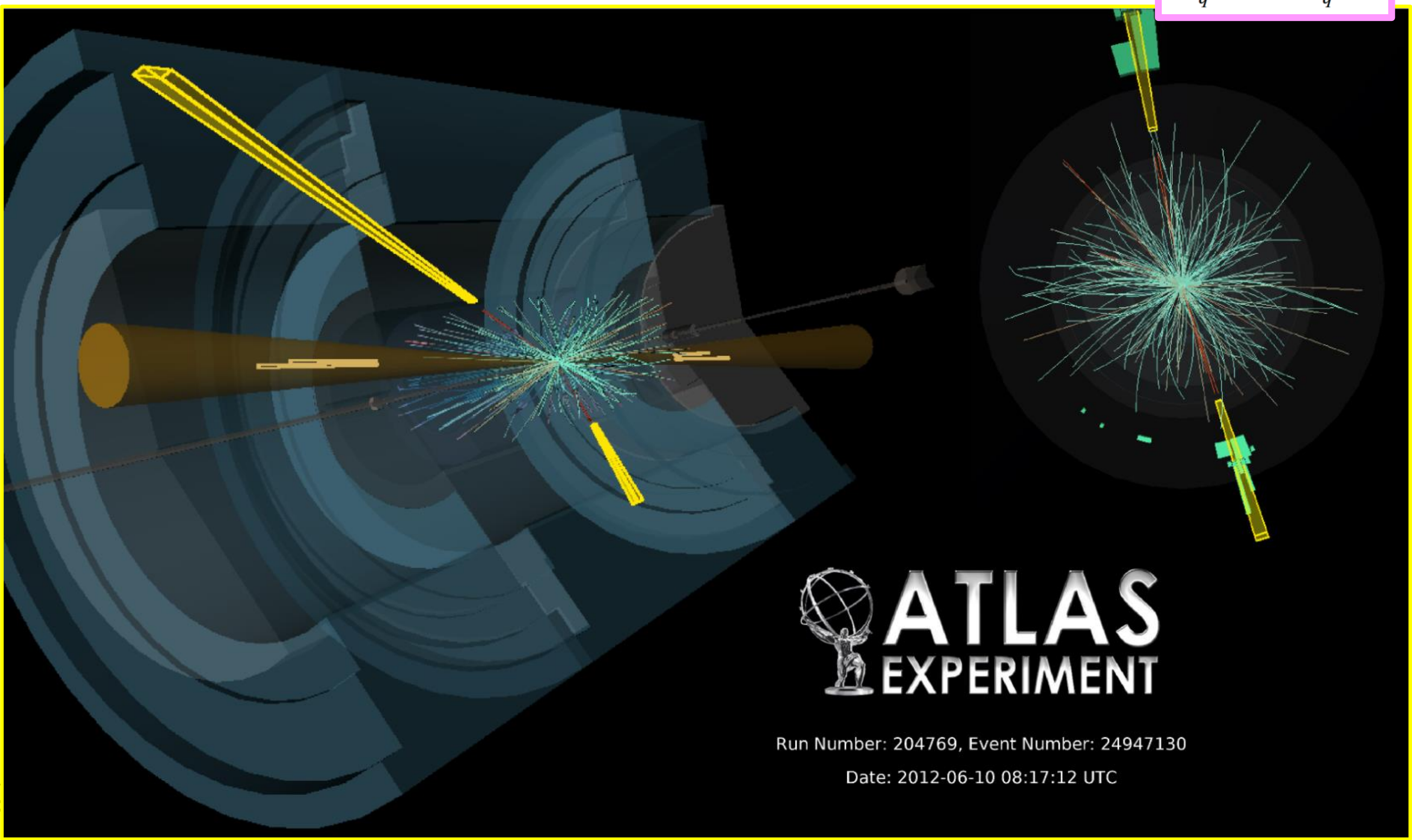


$H \rightarrow \gamma\gamma$ candidate with $m_{\gamma\gamma}$= 126.9 GeV

E_T (γ_1, γ_2) = 80.1, 36.2 GeV,
E_T (j_1, j_2) = 121.6, 82.8 GeV, η (j_1, j_2) = 2.7, -2.9, m (jj)= 1.67 TeV



Likely from Vector-Boson-Fusion production



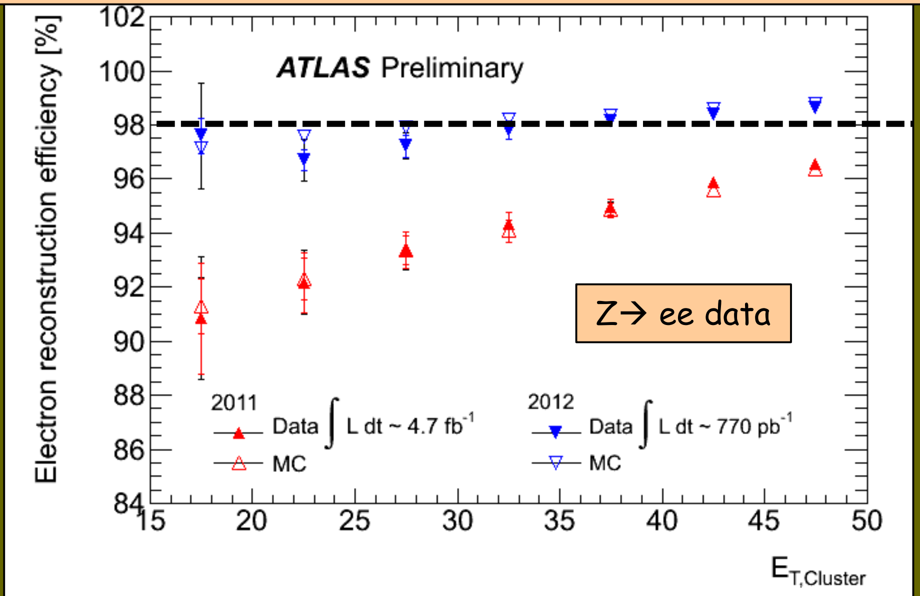
$H \rightarrow ZZ^* \rightarrow 4l$ ($4e$, 4μ, $2e2\mu$)

$\sigma \times BR \sim 2.5$ fb $m_H \sim 126$ GeV

- Very small cross-section, but:
  - -- mass can be fully reconstructed → events cluster in a (narrow) peak
  - -- pure: S/B ~ 1
- Events with 4 leptons $p_T^{1,2,3,4}$ > 20, 15, 10, 7-6 (e-μ) GeV selected
- Main backgrounds: $ZZ^{(*)}$: irreducible

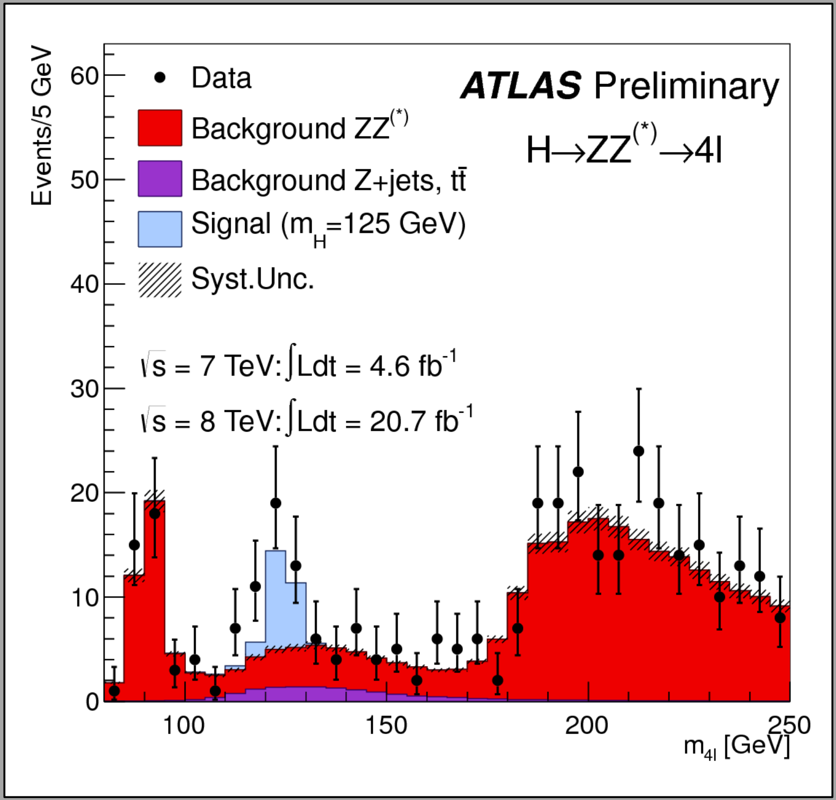
Crucial experimental aspect: high lepton acceptance, reconstruction and identification efficiency down to lowest p_T

Improved $e^{\pm}$ reconstruction to recover Brem losses



Huge efforts made at the end of 2011 to improve $e^{\pm}$ reconstruction and identification efficiency at low p_T and pile-up robustness paid dividends
→ allowed fast discovery

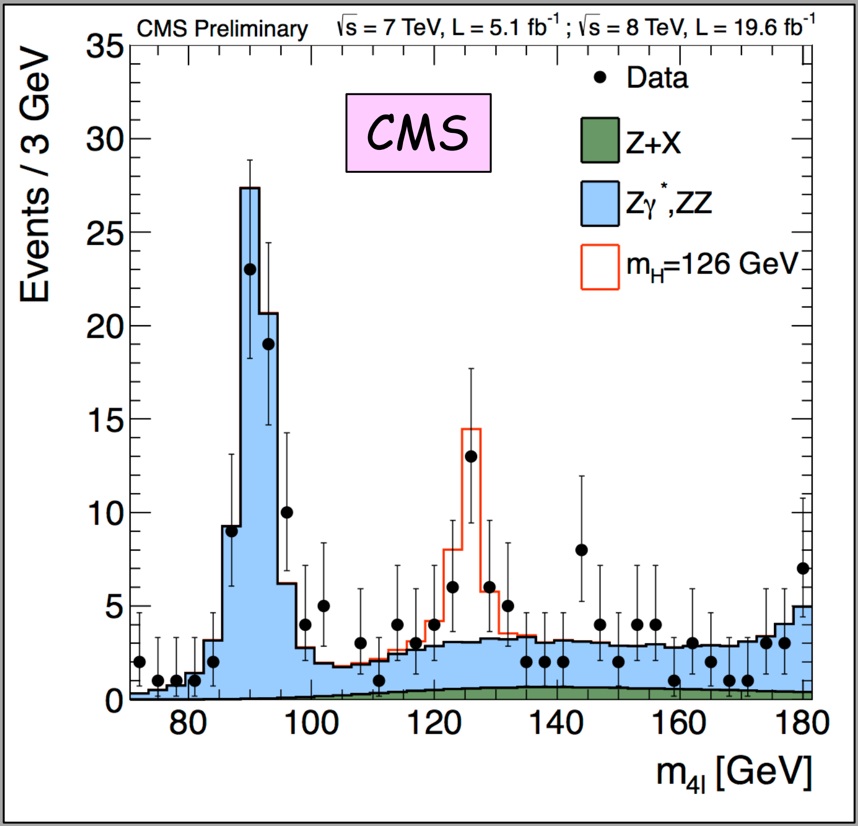
4l mass spectrum after all selections



In the region 125 ± 5 GeV

Observed	32 events
Expected from background only	11.1 ± 1.4
Expected from Higgs signal	15.9 ± 2.1

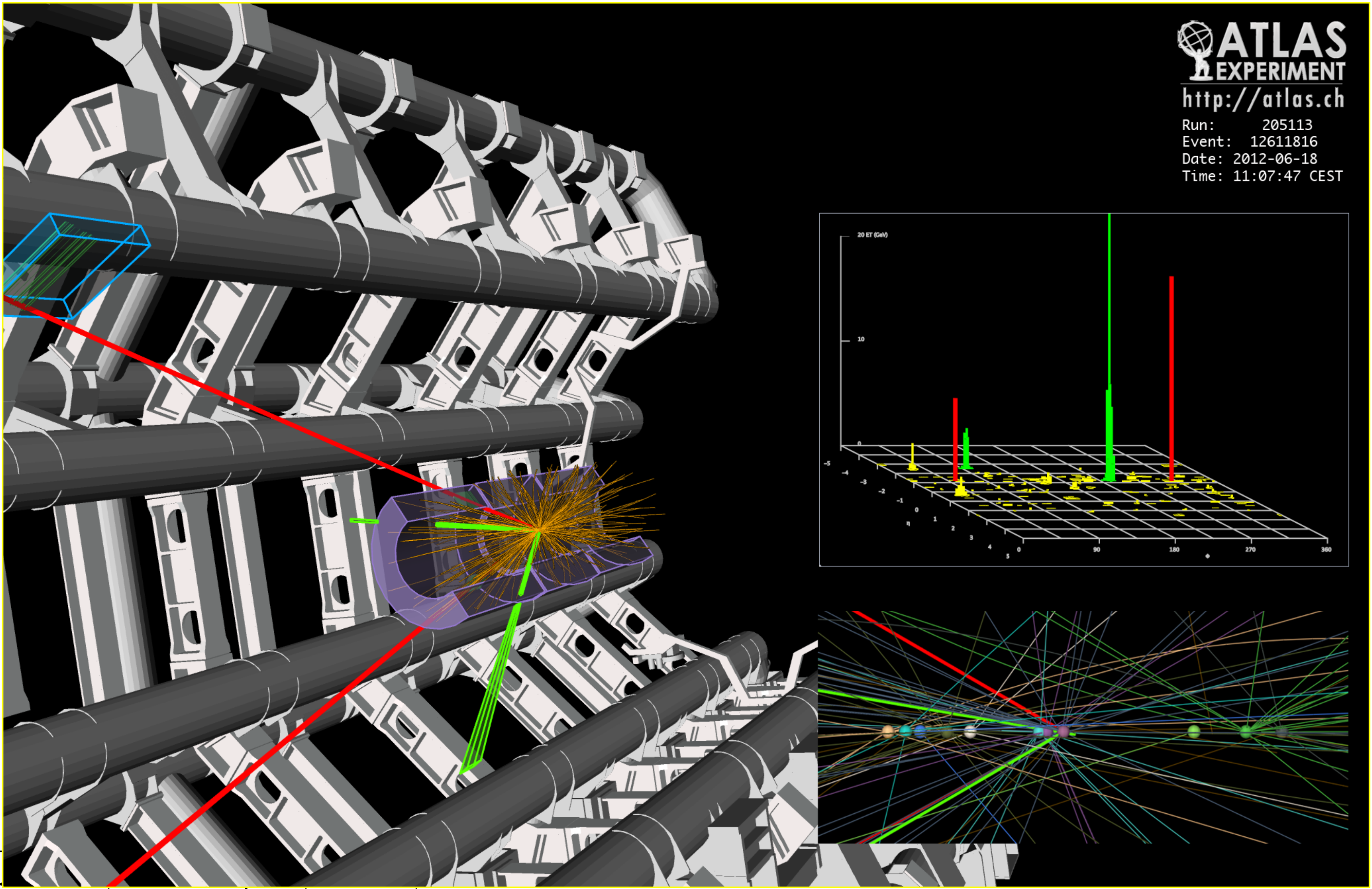
	4μ	$2e2\mu$	$4e$
Data	13	13	6
Expected S/B	1.9	~1.3	1.1
Reducible/total B	15%	~50%	50%



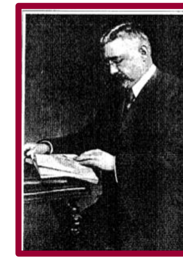
- Clear peak at $m_H \sim 124.5$ GeV
- Probability it comes background fluctuation: $\sim 10^{-10} \rightarrow 6.6\ \sigma$ signal significance ($4.4\ \sigma$ expected from SM H)

2e2μ candidate with $m_{2e2\mu}$= 123.9 GeV

p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV
12 reconstructed vertices



Putting all channels together: 10 σ significance or probability that what ATLAS observes comes from background fluctuation: 10^{-24} !

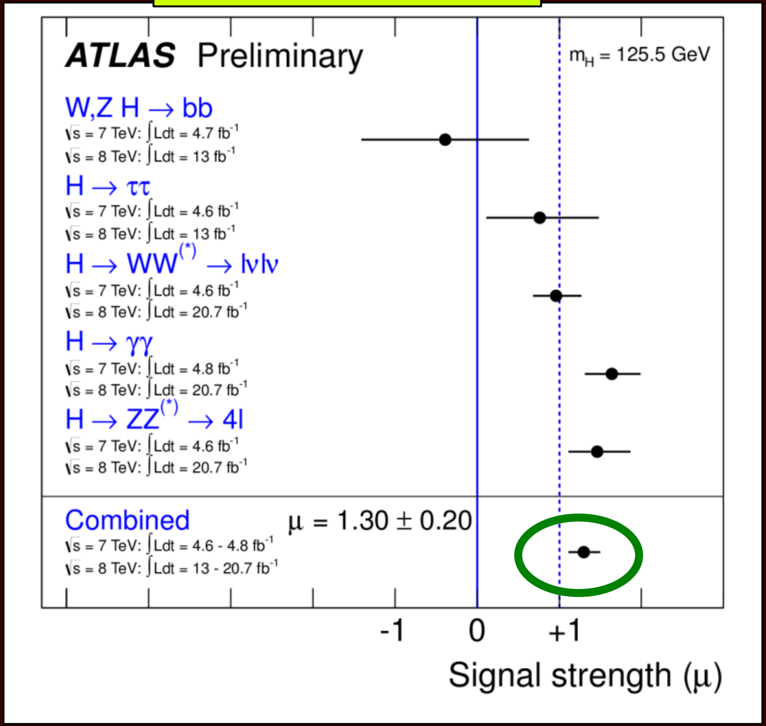


↓

A new phase: measuring the properties of the new particle
(only a few examples here …)

The first 2 questions:
- ❑ is it A Higgs boson ?
- ❑ is it THE SM Higgs boson ?

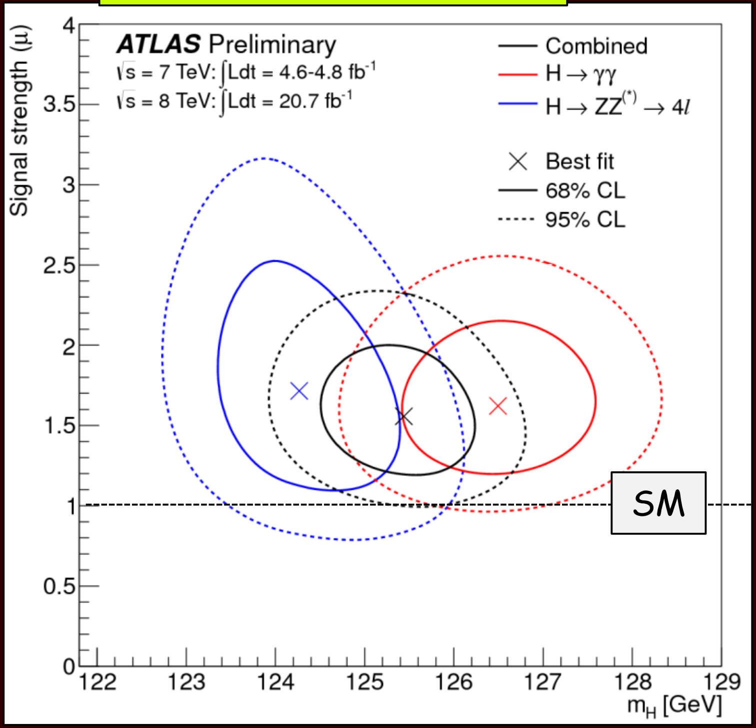
Signal strength



μ = measured signal production rate normalized to SM Higgs expectation at m_H = 125.5 GeV

Best-fit value for m_H=125.5 GeV:
μ = 1.3 ± 0.13 (stat) ± 0.14 (syst)
→ in agreement with SM expectation

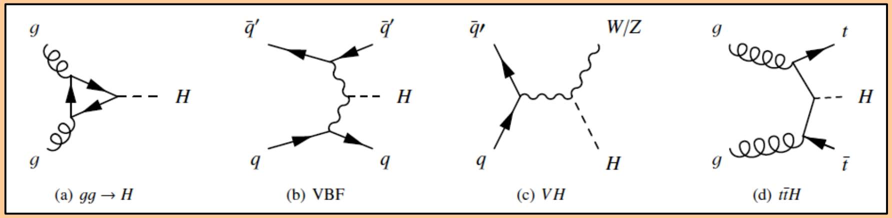
Mass measurement

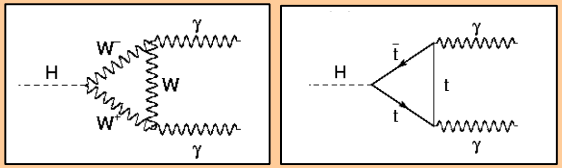


Measured mass from high-resolution H→ γγ and H→ 4l channels:

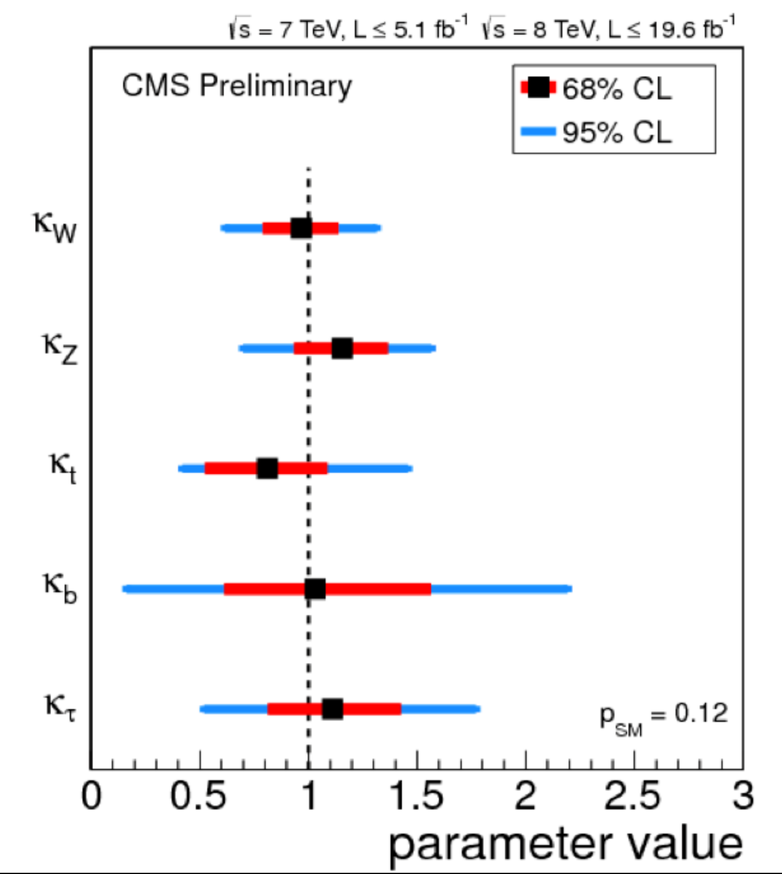
$$m_H(\text{combined}) = 125.5\ \text{GeV} \pm 0.2\ (\text{stat})\ ^{+0.5}_{-0.6}\ (\text{syst})\ \text{GeV}$$

Couplings

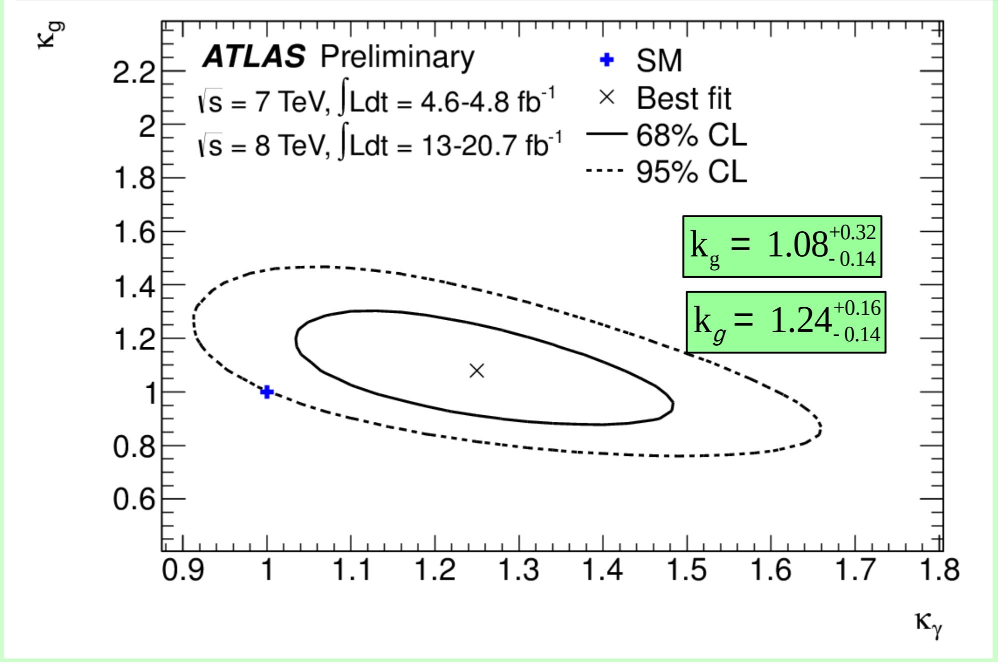




$$k_i^2 = \frac{G_i^{data}}{G_i^{SM}}$$



New particles in the $gg \to H$ and $H \to \gamma\gamma$ loops ?



→ New particle couples to other particles with strength proportional to their masses (to accomplish its job → Higgs mechanism) → 1st "fingerprint" of the Higgs boson
→ No significant New Physics contributions to its couplings (within present uncertainty)

2^{nd} "fingerprint" of the Higgs boson: zero spin

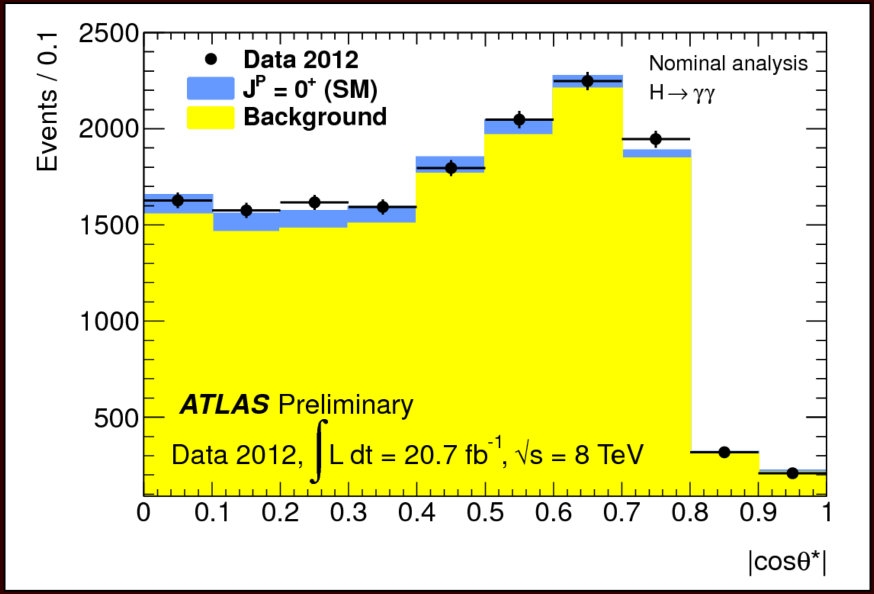
[Matter particles (electrons, quarks, …) : spin ½; force carriers (γ, W, Z, g): spin 1]

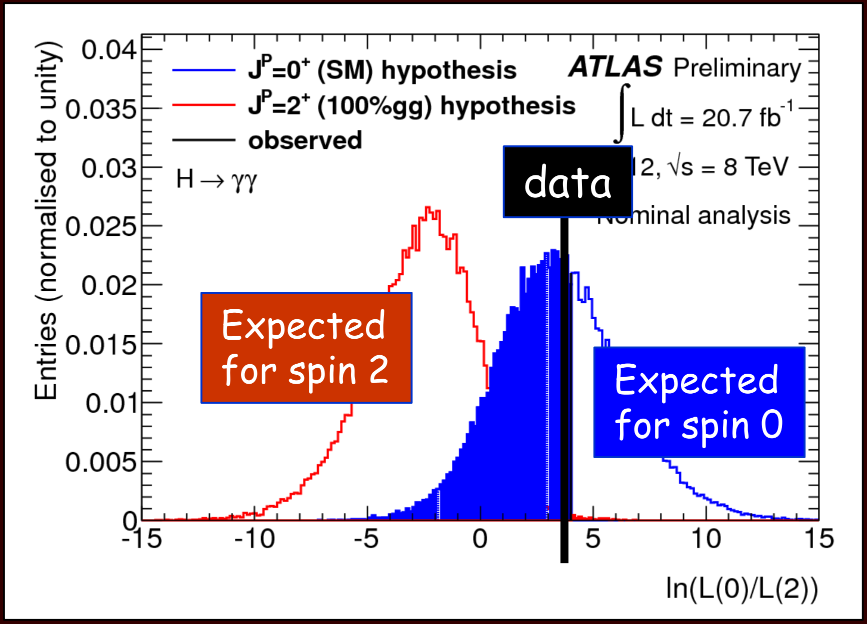
H→ γγ

Spin information from distribution of polar angle θ* of the di-photon system in the Higgs rest frame

Compare θ* distribution in the region of the peak for:

- spin-0 hypothesis: flat before cuts
- spin-2 hypothesis: ~ $1+6\cos^2\theta^* + \cos^4\theta^*$ for Graviton-like (minimal models)



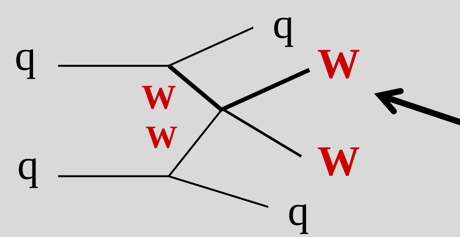


Data disfavour 2^+ hypothesis at 99.3% CL. (66% CL) for pure gg → G (mixture of gg/qq → G)

The first "elementary" scalar ever !?

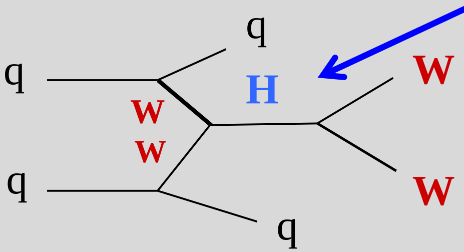
Consequences also for Universe evolution (inflation triggered by a scalar field)

Two additional questions



Does this new particle fix the SM problems at high energy ?

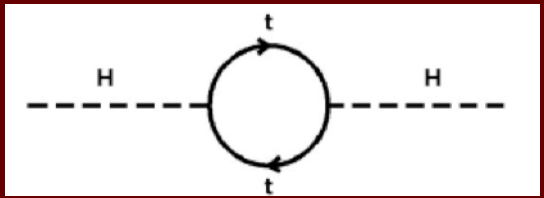
This process violates unitarity (cross section diverges → unphysical) at m(WW) ~ TeV
if this process does not exist

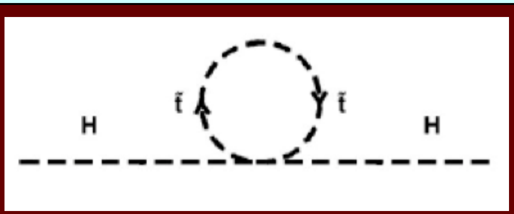


→ Need to verify that the discovered particle accomplishes this task → need $\sqrt{s}$ ~ 14 TeV and ~3000 fb^{-1}

Why is the Higgs so light ?

Is m_H stabilized by (close-by, ~TeV scale) new physics or is it fine-tuned ?





In the SM, top-loop corrections to m_H diverge as ~ Λ^2 (energy scale up to which the SM is valid)

Searches for stop quarks so far unsuccessful
Will continue with more data and energy in 2015++

The next steps …

With the data recorded in this first run (~25 fb^{-1} per experiment):

- 4-5 σ from each of H→ γγ, H→ lνlν, H→ 4l per experiment (in part achieved already)
- ~3 σ from H→ ττ and ~3 σ from W/ZH → W/Zbb per experiment (the latter already achieved by the Tevatron)
- Separation $0^+/2^+$ and O^+/O^- at 4σ level combining ATLAS and CMS ?
- Improved measurements of couplings (in particular combining ATLAS and CMS)

Further ahead (present LHC plans):

2013-2014: shut-down (LS1)
2015-2017: $\sqrt{s}$ ~ 14 TeV, L ~ 10^{34} , ~ 100 fb^{-1}
2018: shut-down (LS2)
2019-2021: $\sqrt{s}$ ~ 14 TeV, L ~ 2×10^{34} , ~ 300 fb^{-1}
2022-2023: shut-down (LS3)
2023- 2030 ?: $\sqrt{s}$ ~ 14 TeV, L ~ 5×10^{34} , ~ 3000 fb^{-1} (HL-LHC)

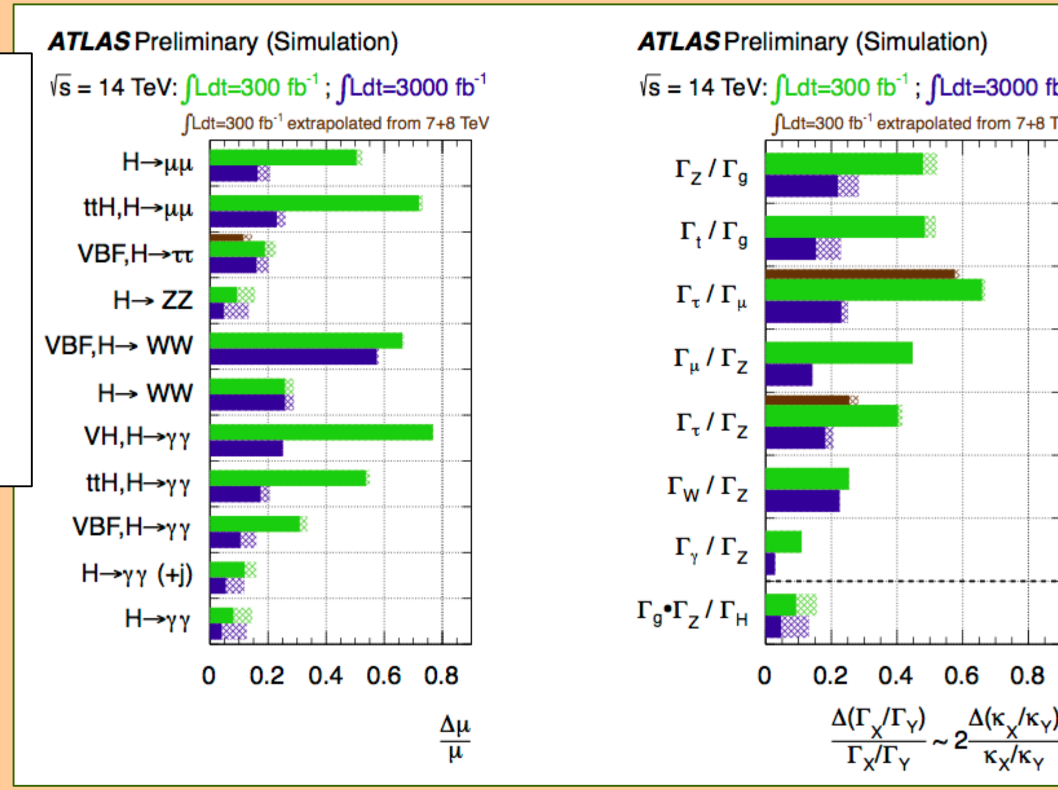
With 100-300 fb^{-1} :

- ❑ Mass can be measured to 0.1% (~ 100 MeV) dominated by e/μ/γ E-scale systematics
- ❑ Spin/CP can be determined to > 5σ for a pure 0^+ state.

Without constraints, ratios of couplings can be measured with typical precisions:

- ❑ 10-50% with ~ 300 fb^{-1}
- ❑ 3-25% with 3000 fb^{-1}

per experiment.
Down to few % in some cases if less conservative systematics (e.g. theory error halved)

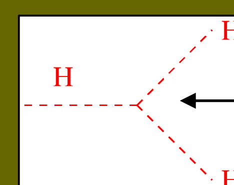


Measurements of rare decays with 3000 fb^{-1} :

- ❑ ttH → ttγγ: 200 events
- ❑ H → μμ : 6σ

per experiment

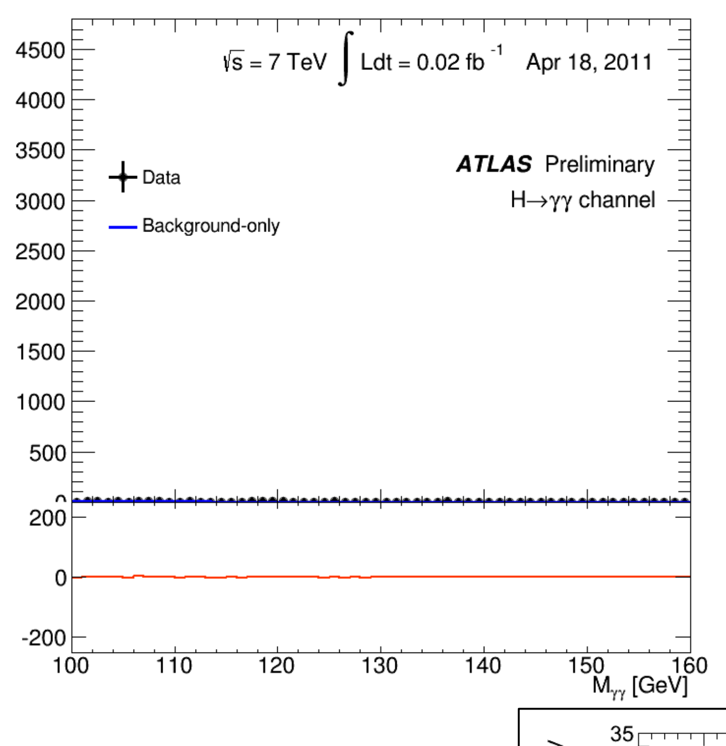
Higgs self-couplings: ~ 3σ per experiment expected from HH → bbγγ channel with 3000 fb^{-1}; HH→ bbττ also promising
~ 30% measurement of Λ/Λ_{SM} may be achieved

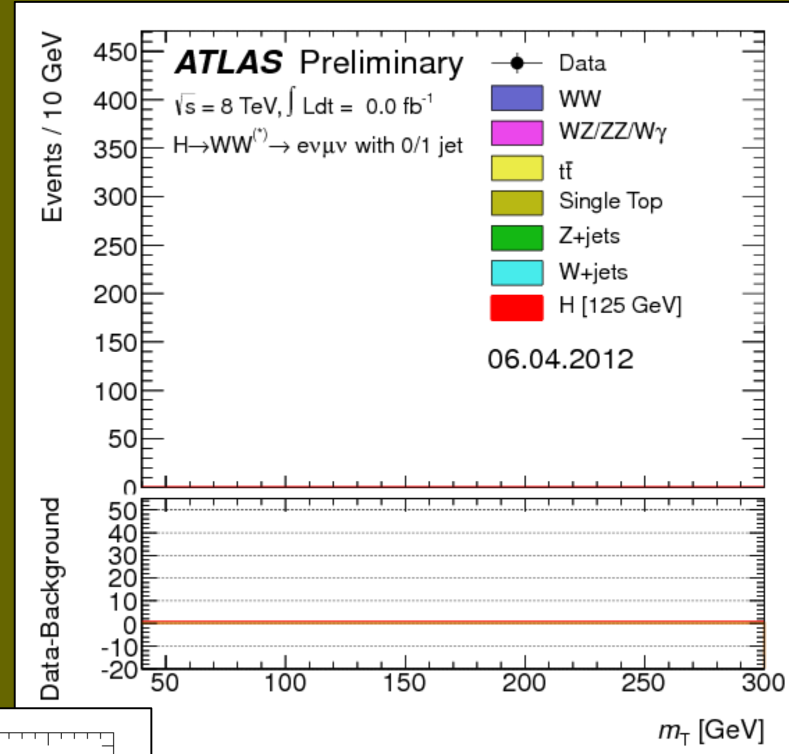


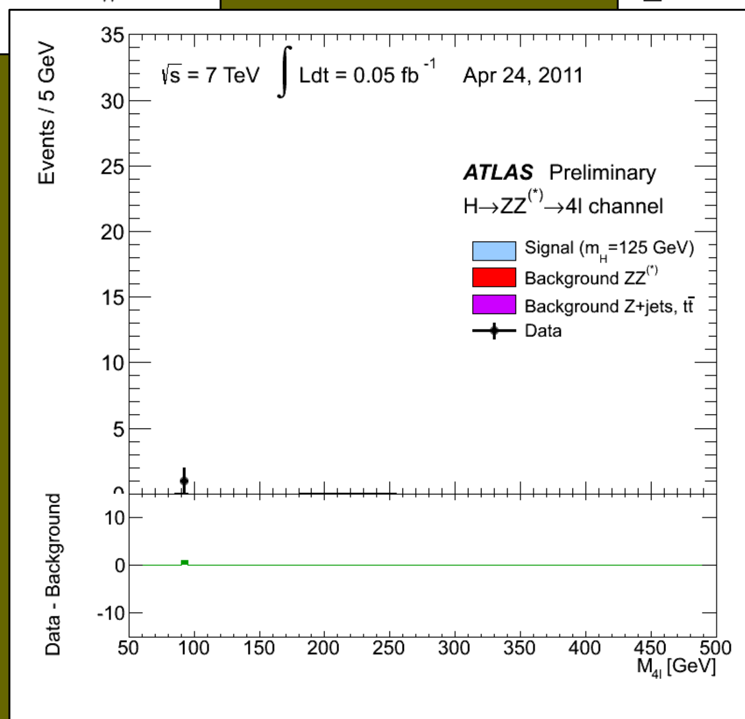
~ λv
$m_H^2 = 2 \lambda v^2$

Note: -- these results are very preliminary (work of a few months) and conservative
-- physics potential of LHC upgrade is much more than just Higgs

Birth and evolution of a signal







Conclusions

The first LHC proton-proton run (2009-2012) has been EXTRAORDINARY !

ATLAS has recorded ~ 27 fb^{-1} and has operated very effectively and smoothly in all its components (from detector/ trigger to software and computing and release of physics results) during three challenging and demanding years. Machine, experiments, computing (and people !) have been stressed beyond "design performance"

The ATLAS physics output, summarized so far in ~ 250 papers on collision data and more than 470 Conference notes, includes:

- Measurements of SM physics with increasing emphasis on exclusive, complex final states
- Searches for new physics in a huge number of topologies and scenarios → limits reach several TeV in many cases → moving to ~14 TeV is now necessary to make progress
- The fantastic discovery of a very special particle, which indeed looks like the SM scalar

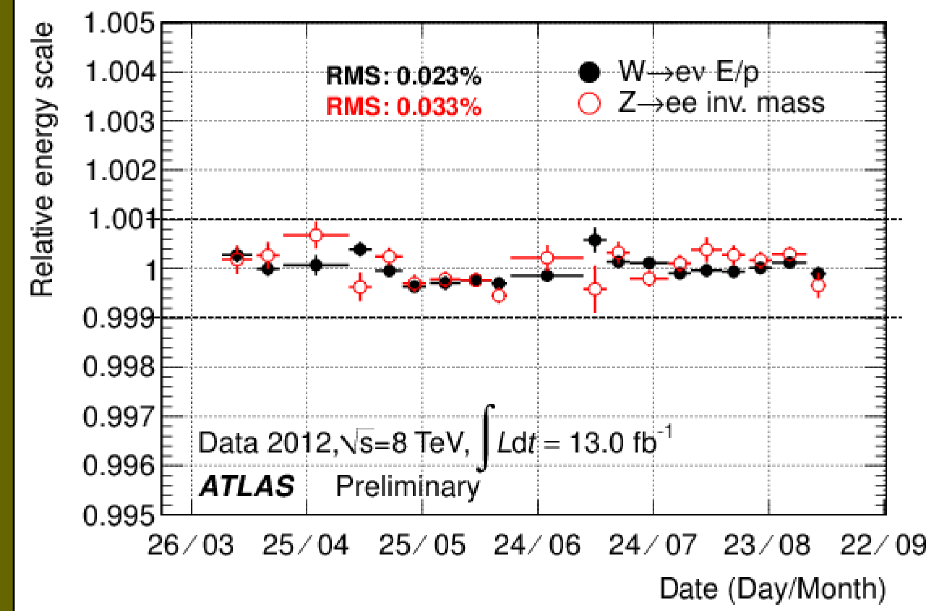
The era of precise measurements of the new boson has started.
In parallel, the quest for New Physics at the TeV scale continues
→ LHC and its upgrade will have a lot to say

These accomplishments are the results of more than 20 years of talented work and extreme dedication of those involved in the LHC project

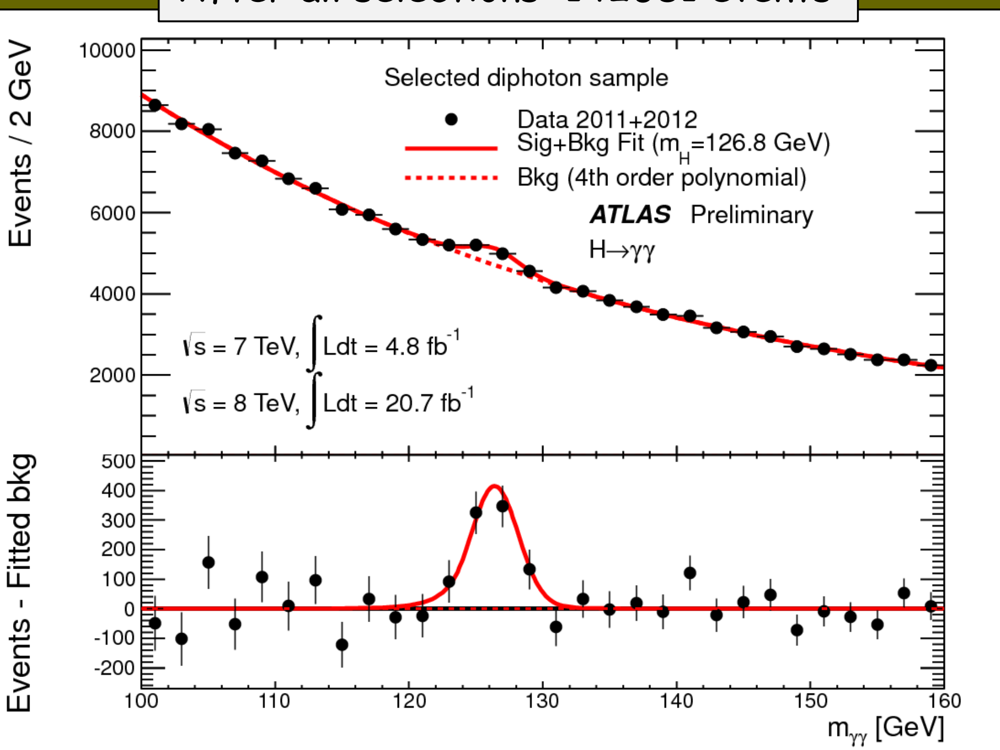
More in general, they are the results of the ingenuity, vision and painstaking work of the full HEP community (accelerator, instrumentation, computing, exp. physics, theory)

SPARES

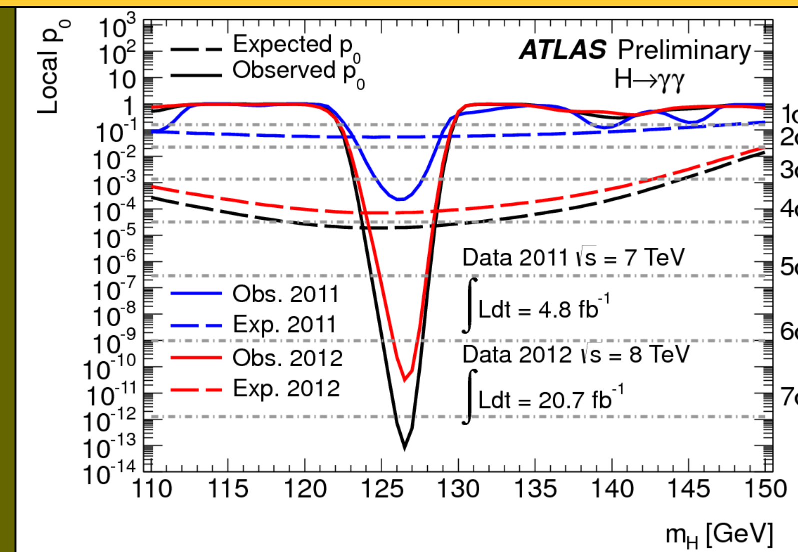
Stability of EM calorimeter vs time during 2012 run better than 0.1%



After all selections: 142681 events



Consistency of data with background-only expectation



m_H=126.5 GeV: 7.4 (4.1) σ significance observed (expected from from SM H)

$H \rightarrow ZZ^* \rightarrow 4l$ (4e, 4μ, 2e2μ)

σ x BR ~ 2.5 fb   m ~ 126 GeV

- Very small cross-section, but:
  - -- mass can be fully reconstructed → events should cluster in a (narrow) peak
  - -- pure: S/B ~ 1
- 4 leptons: $p_T^{1,2,3,4}$ > 20,15,10,7-6 (e-μ) GeV; $50 < m_{12} < 106$ GeV; $m_{34} > 12$ GeV
- Main backgrounds:
  - -- $ZZ^{(*)}$: irreducible
  - -- Zbb, Z+jets, tt with two leptons from b-jets or q-jets (suppressed with isolation and impact parameter cuts on two softest leptons)

Crucial experimental aspects:

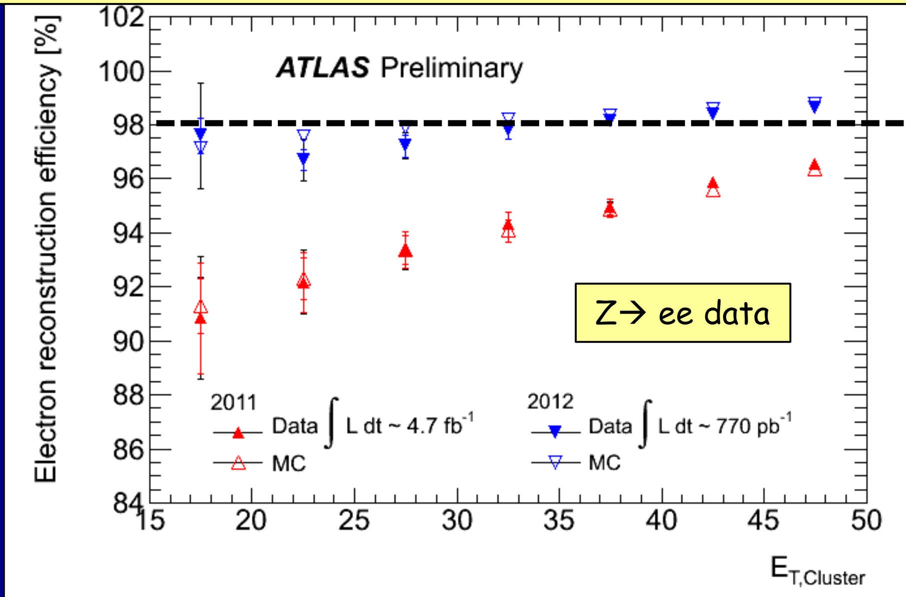
- High lepton acceptance, reconstruction and identification efficiency down to lowest p_T
- Good lepton energy/momentum resolution
- Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region:
  - → cannot rely on MC alone (theoretical uncertainties, b/q-jet → lepton modeling, ..)
  - → need to validate MC with data in background-enriched control regions

Main improvements in 2012 analysis:

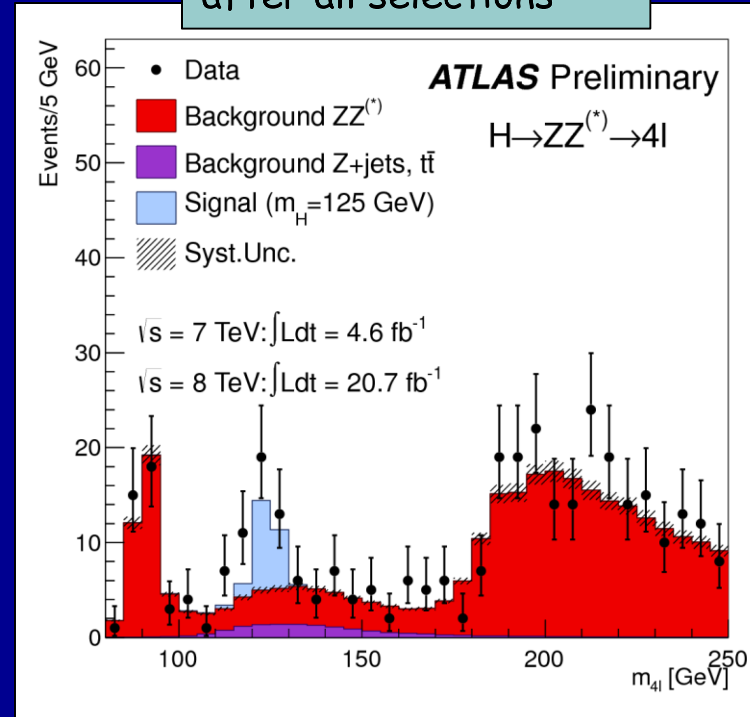
- kinematic cuts optimized/relaxed to increase signal sensitivity at low mass
- increased $e^{\pm}$ reconstruction and identification efficiency at low p_T and pile-up robustness

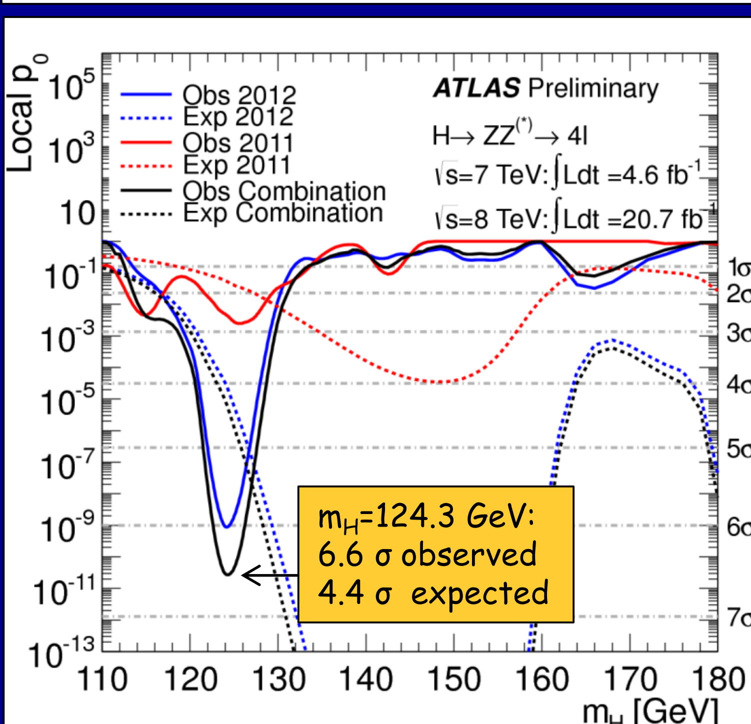
→ Gain 20%-30% in sensitivity compared to previous analysis

Improved $e^{\pm}$ reconstruction to recover Brem losses



Reconstructed 4l mass after all selections





In the region 125 ± 5 GeV

Observed	32 events
Expected from background only	11.1 ± 1.4
Expected from Higgs signal	15.9 ± 2.1

	4μ	2e2μ	4e
Data	13	13	6
Expected S/B	1.9	~1.3	1.1
Reducible/total B	15%	~50%	50%

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ ($e\nu e\nu$, $\mu\nu\mu\nu$, $e\nu\mu\nu$)

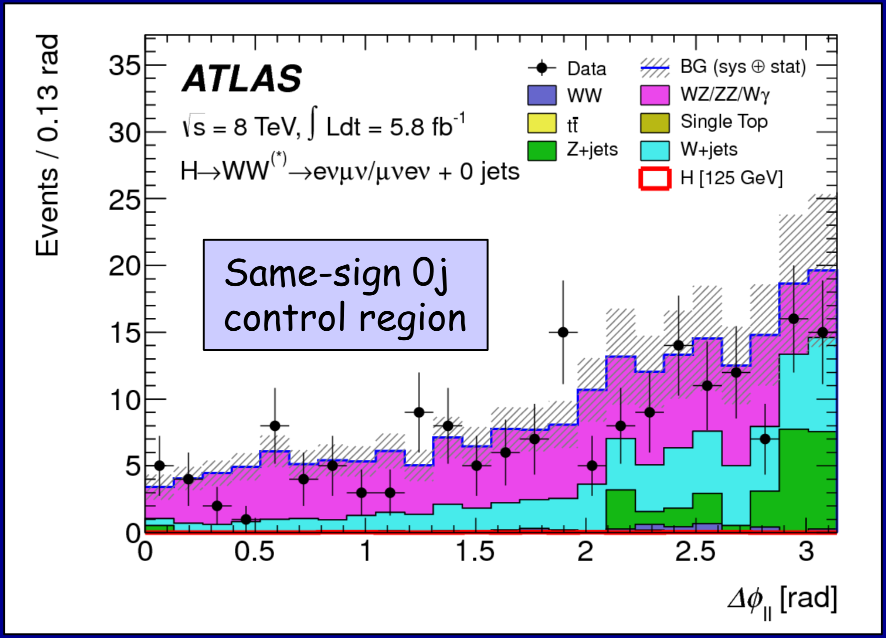
$\sigma \times BR \sim 200$ fb for m~ 125 GeV

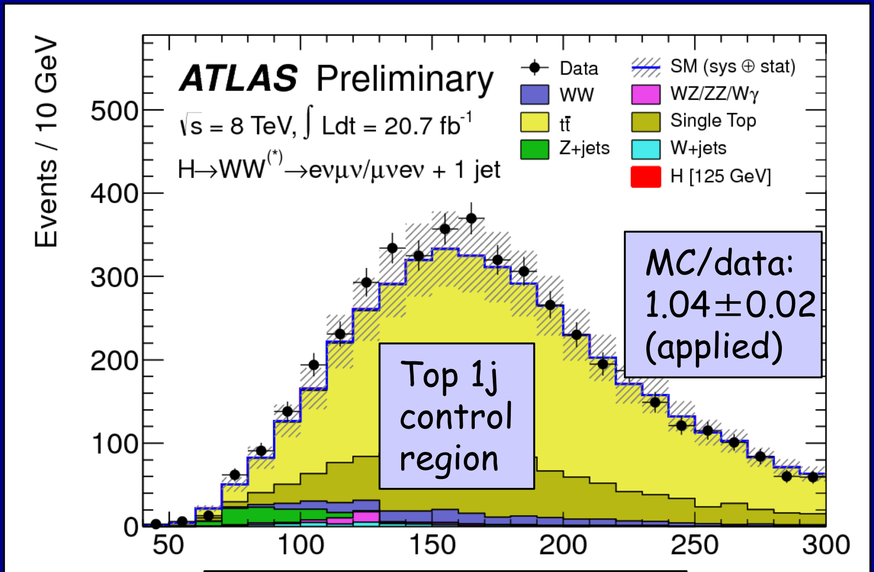
- Large cross section
- However: 2ν in final state → mass peak cannot be reconstructed → "counting channel"

- 2 isolated opposite-sign leptons, $p_T > 25, 15$ GeV
- Main backgrounds: WW, top, Z+jets, W+jets
  → large E_T^{miss}, $m_{ll} \neq m_Z$, b-jet veto ..+ topological cuts: p_{Tll}, m_{ll}, $\Delta\phi_{ll}$ (smaller for scalar)

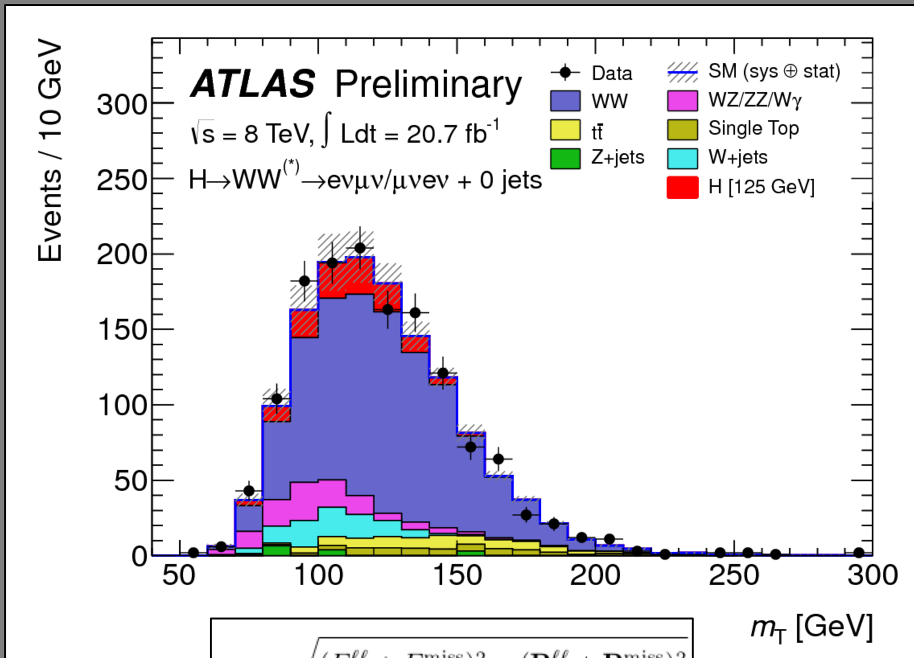
Crucial experimental aspects:

- understanding of E_T^{miss}
- very good modeling of background in signal region → use signal-free control regions in data to constrain MC → use MC to extrapolate to signal region

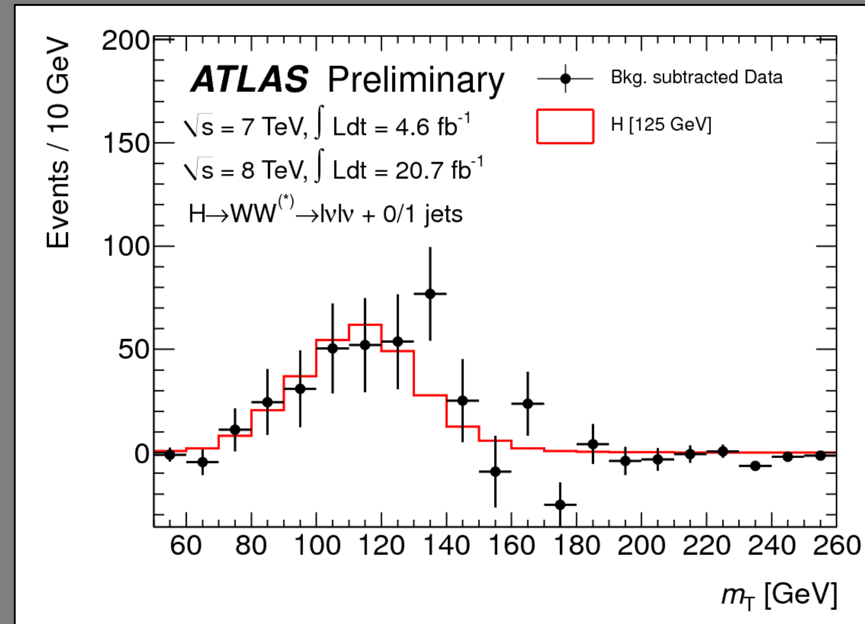




$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

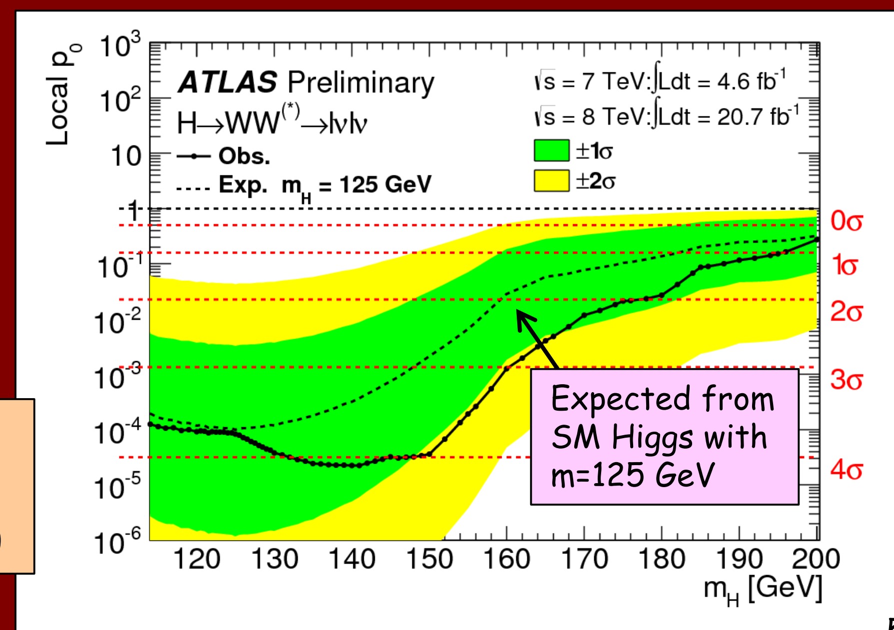


$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$



After all selections, $\sqrt{s}$=8 TeV

Observed:	1195 events
expected from background only	1036 ± 100
expected from signal m_H=125 GeV	148 ± 30



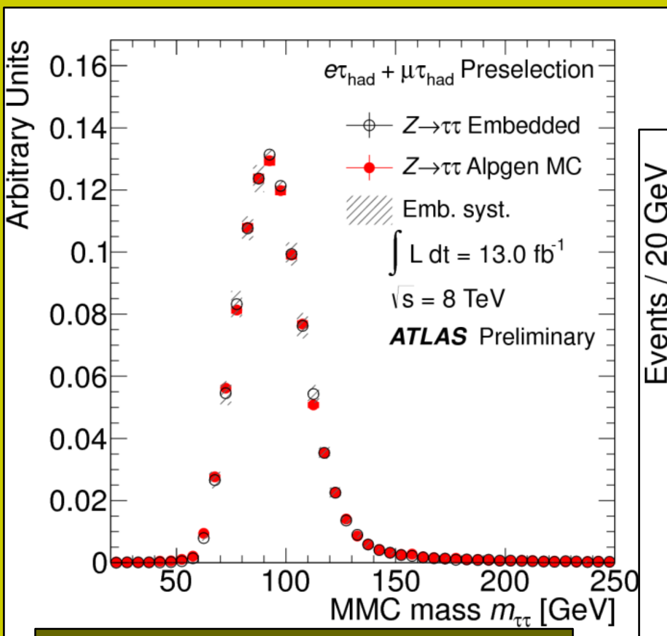
Broad excess, extending over > 50 GeV in mass, due to poor mass resolution
m_H=125 GeV: 3.7σ (3.8σ) observed (expected)

$H \rightarrow \tau\tau \rightarrow \tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$

$\sigma \times BR \sim 1.3$ pb $m_H \sim 125$ GeV

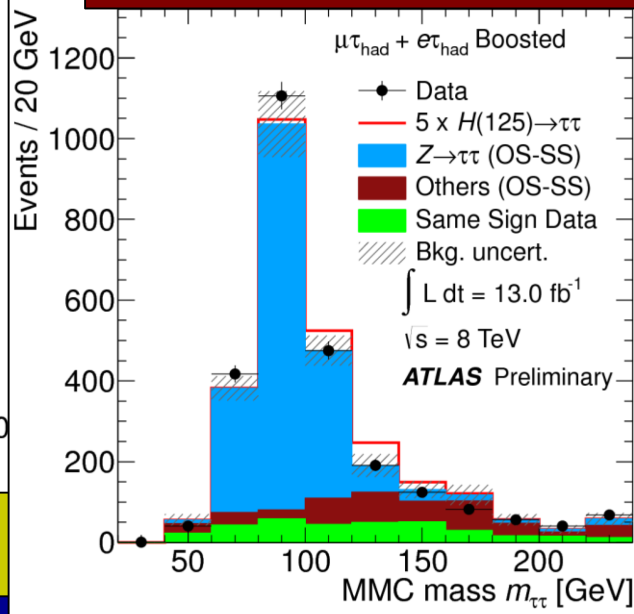
- Important for coupling measurements
- Huge backgrounds: $Z \rightarrow \tau\tau$, top, fakes
  Dominant/irreducible $Z \rightarrow \tau\tau$ from "embedded" $Z \rightarrow \mu\mu$ data (μ replaced by simulated τ)
  → event modeling from data; signal-free sample for background determination

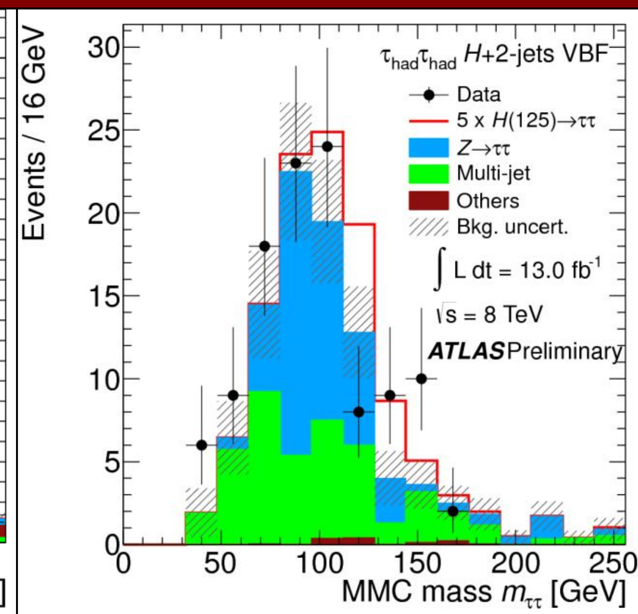
- Events split in categories, 0, 1, 2 (VBF, VH) jets, plus boosted
  → higher sensitivity and S/B with ≥ 1 jet
  → $\tau\tau$ mass resolution (13-20%) better for boosted system (→ better Z/H separation)
- After all cuts: expect ~ 250 events at 8 TeV; S/B ~ 0.5-1% overall (4-10% VBF)

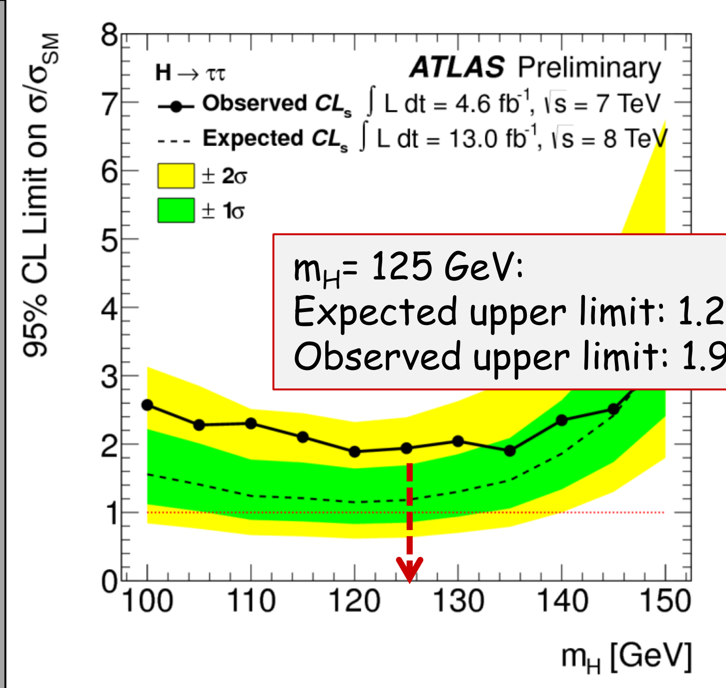


Excellent agreement $Z \rightarrow \tau\tau$ (embedded) data-simulation

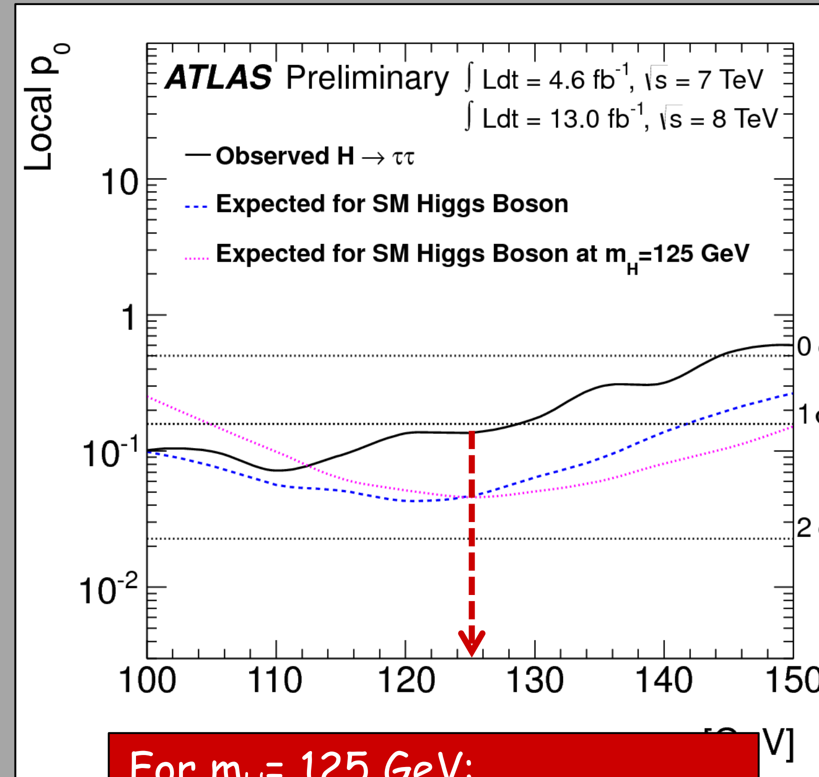
Higgs discrimination based on $\tau\tau$ mass
$m_{\tau\tau}$ distributions after cuts for most sensitive categories



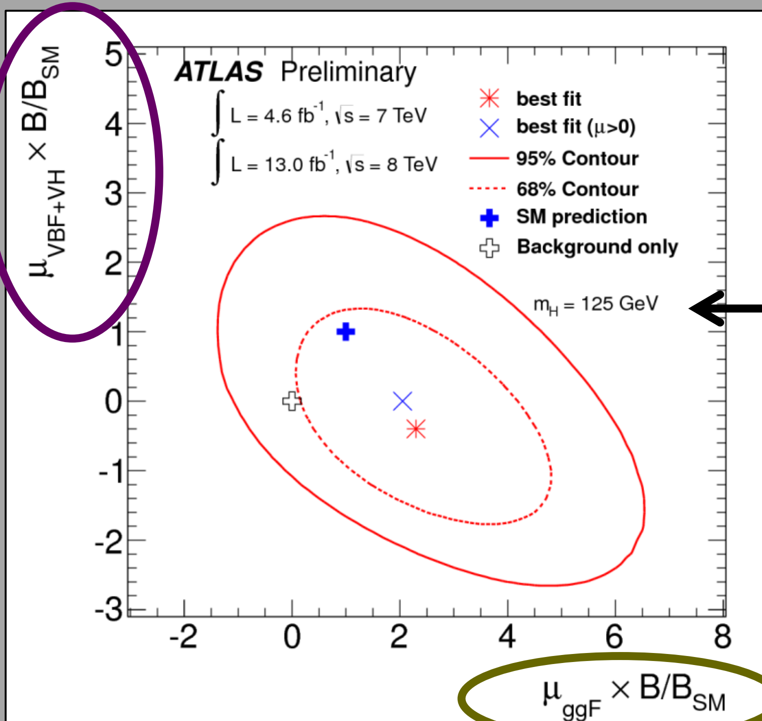




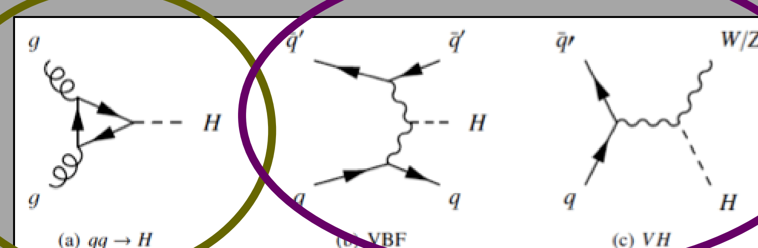
m_H= 125 GeV:
Expected upper limit: 1.2 x SM
Observed upper limit: 1.9 x SM



For m_H= 125 GeV:
1.1 σ observed (1.7 σ expected)
μ = 0.7 ± 0.7



Signal strength for different production modes (VBF+VH vs ggF)



$W/ZH \rightarrow l\nu bb, llbb, \nu\nu bb$

$\sigma \times BR \sim 150$ fb $m_H \sim 125$ GeV

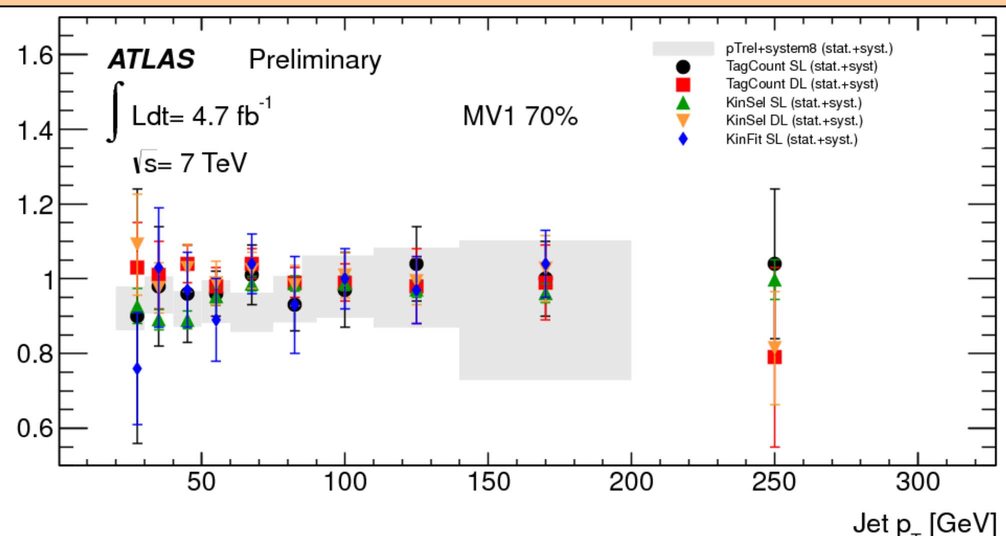
- Important for coupling measurements
- 2 b-tagged jets + 0/1/2 leptons; p_T^V / E_T^{miss} categories as larger S/B for boosted Higgs
- Higgs discriminating variable is reconstructed m_{bb} mass: ~ 16% resolution

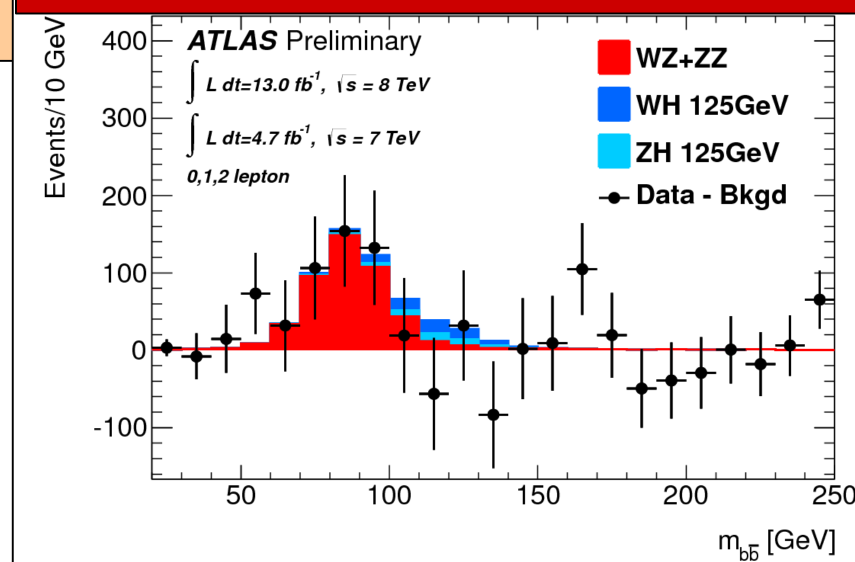
- Large and complex (flavour composition !) backgrounds from W/Z+jets and top
- V+q, V+c from pre-tag/1-tag control samples, V+b and top from final fit to 2-tag sample
- After all cuts: S/B ~ 0.5-5%, increasing with p_T^V / E_T^{miss}
- Dominant systematic uncertainty from b/c-tagging and Jet/E_T^{miss} scale

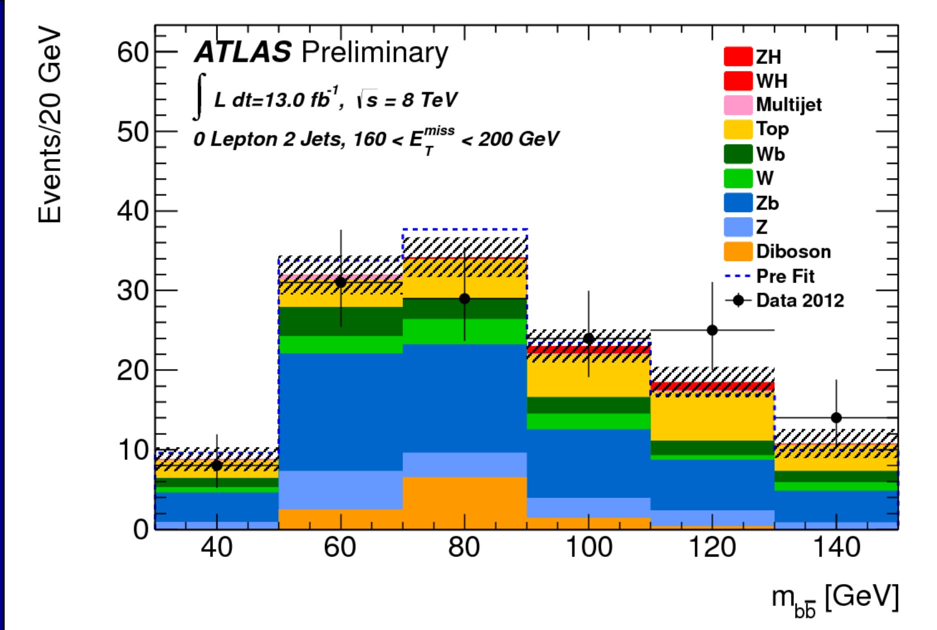
Observation of WZ/ZZ with $Z \rightarrow bb$ peak from fit to data after subtraction of all non-di-boson backgrounds

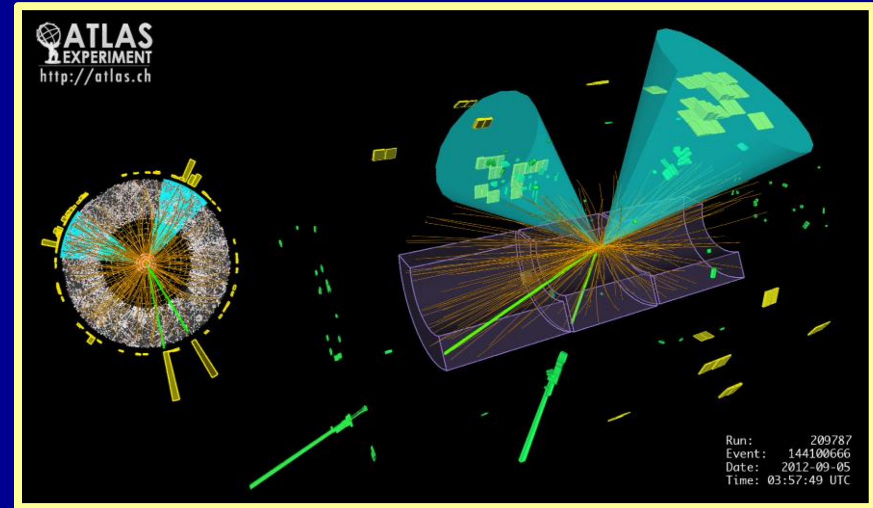
- 4σ excess
- Measured/SM rate: 1.09 ± 0.28

Ratio data/MC for b-tag efficiency from tt events (tt covers high p_T, complementary to other methods)

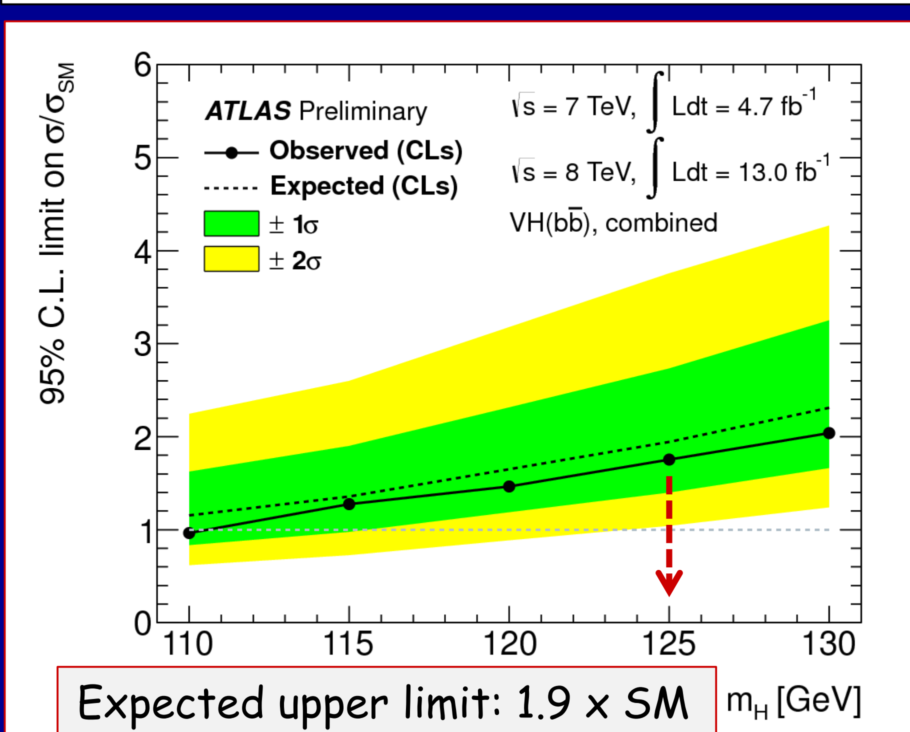




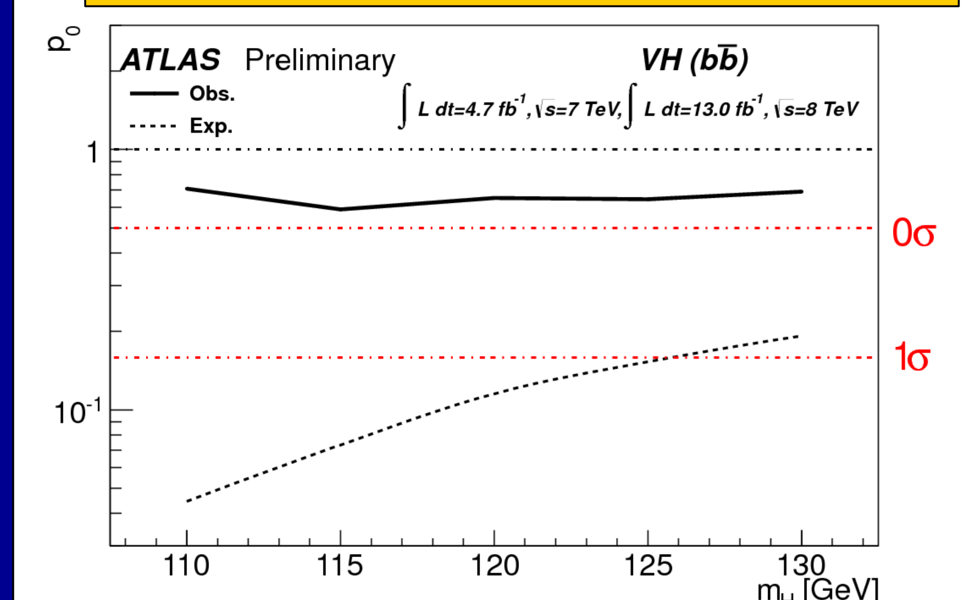




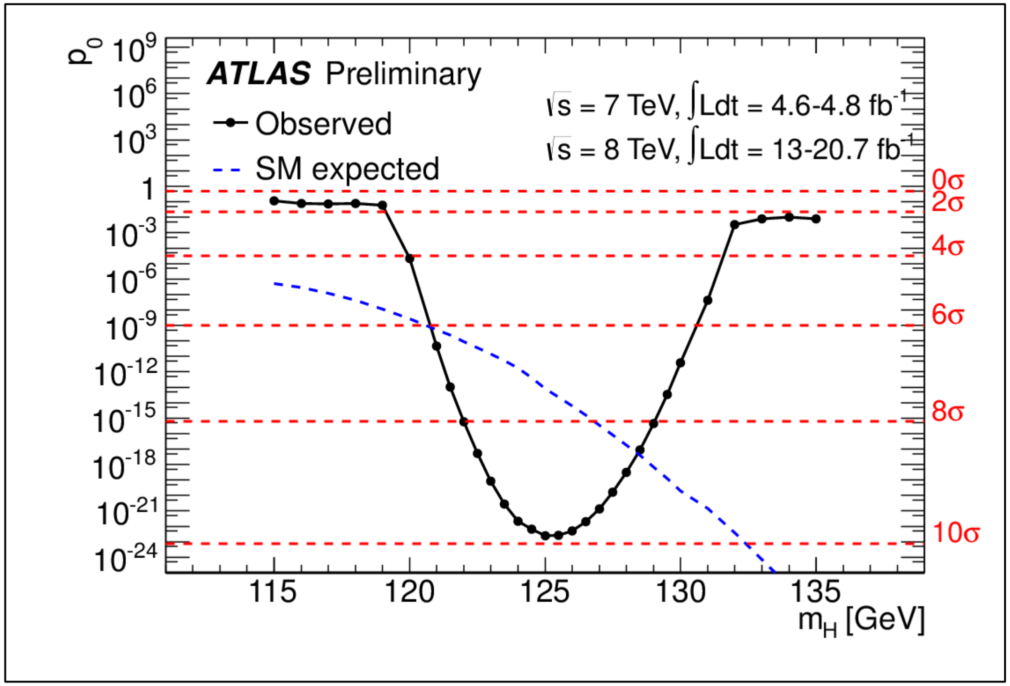
7 TeV data: 2σ deficit compared to background-only expectation
8 TeV data: 1σ excess
→ combined μ= -0.4 ±0.7 (stat) ± 0.7 (syst)



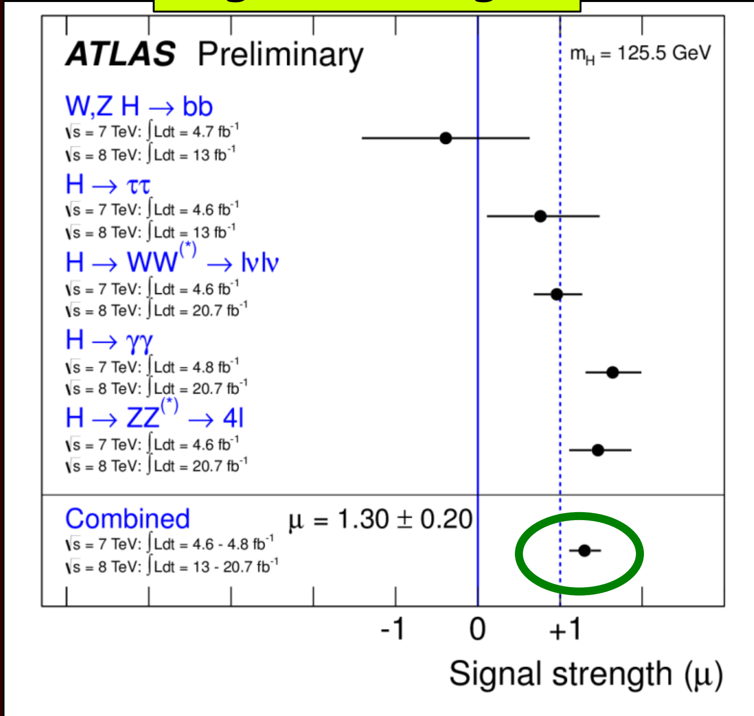
Expected upper limit: 1.9 x SM
Observed upper limit: 1.8 x SM



All channels together: 10 σ significance
or probability of background fluctuation: 10^{-24} !



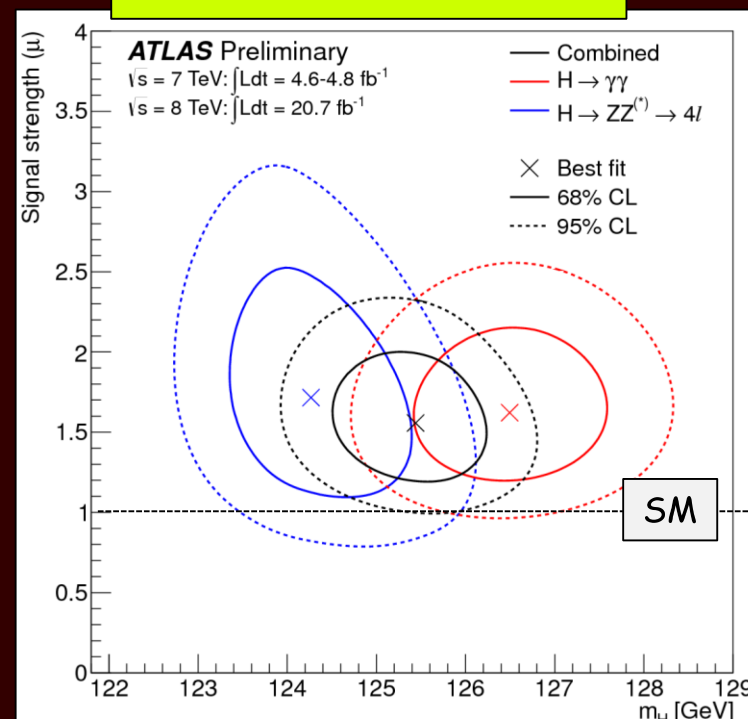
Signal strength



μ = measured signal production rate normalized to SM Higgs expectation at $m_H = 125.5$ GeV

Best-fit value for m_H=125.5 GeV:
$\mu = 1.3 \pm 0.13$ (stat) $\pm$ 0.14 (syst)
→ in agreement with SM expectation

Mass measurement



Estimated mass from high-resolution H→ γγ and H→ 4l channels:

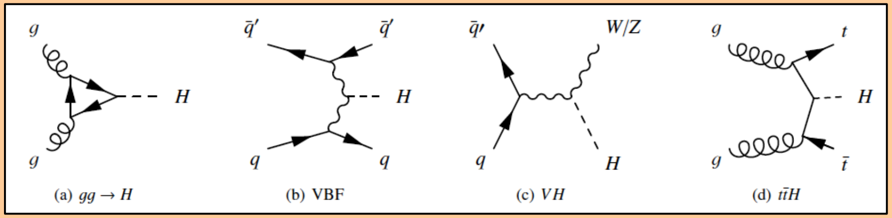
m_H(combined) =125.5 GeV ± 0.2 (stat) $^{+0.5}_{-0.6}$(syst) GeV

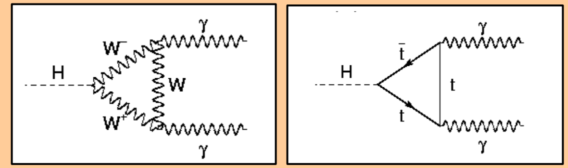
$m_H(\gamma\gamma)$ =126.8 GeV ± 0.2(stat) ± 0.7(syst) GeV

m_H (4l) =124.3 GeV $^{+0.6}_{-0.5}$(stat) $^{+0.5}_{-0.3}$(syst) GeV

Probability for same particle: 1.5-8%

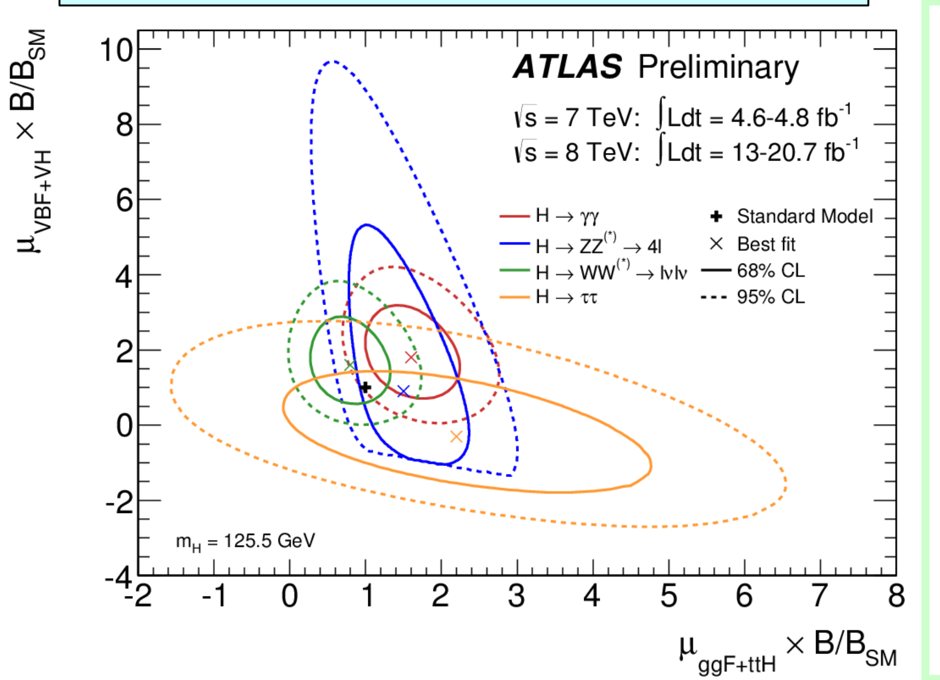
First measurements of couplings (examples …)



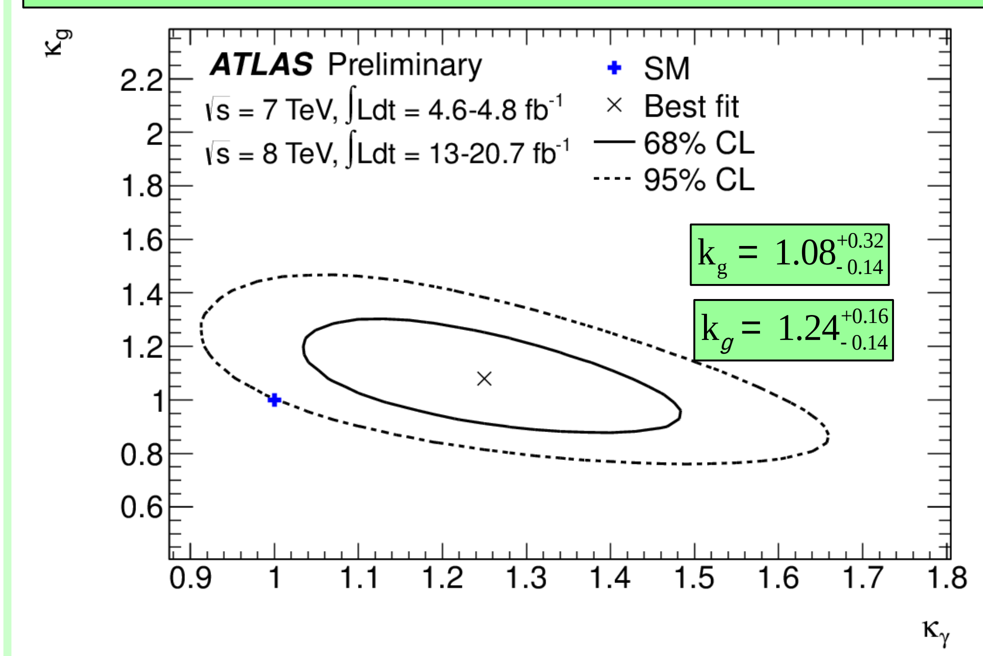


$$k_i^2 = \frac{G_i^{data}}{G_i^{SM}}$$

Measuring individual production modes (ggF, VBF, …)

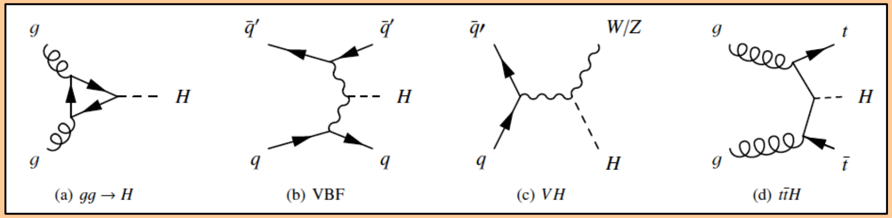


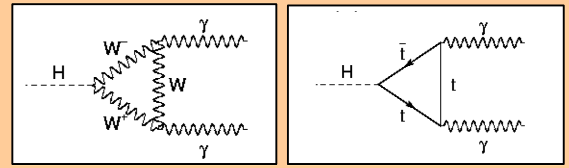
New particles in the gg → H and H→ γγ loops ?



Combined ratio VBF+VH/ggF+ttH over 4 channels
→ 3.3σ significance of non-vanishing VBF+VH

$$\mu_{VBF+VH}/\mu_{ggF+t\bar{t}H} = 1.2^{+0.7}_{-0.5}$$





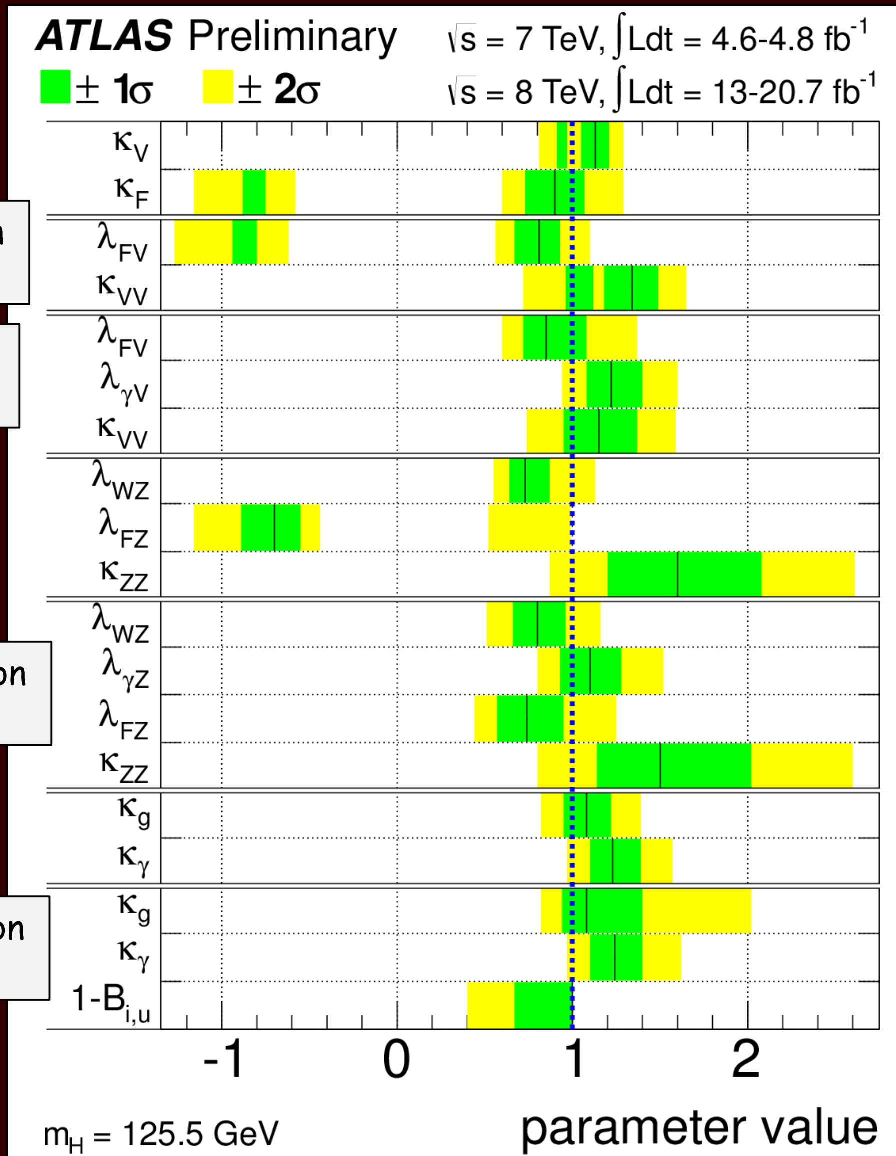
$$k_i^2 = \frac{G_i^{data}}{G_i^{SM}}$$

No assumption on Γ_H

No assumption on Γ_H, k_γ

No assumption on k_γ

No assumption on Γ_H



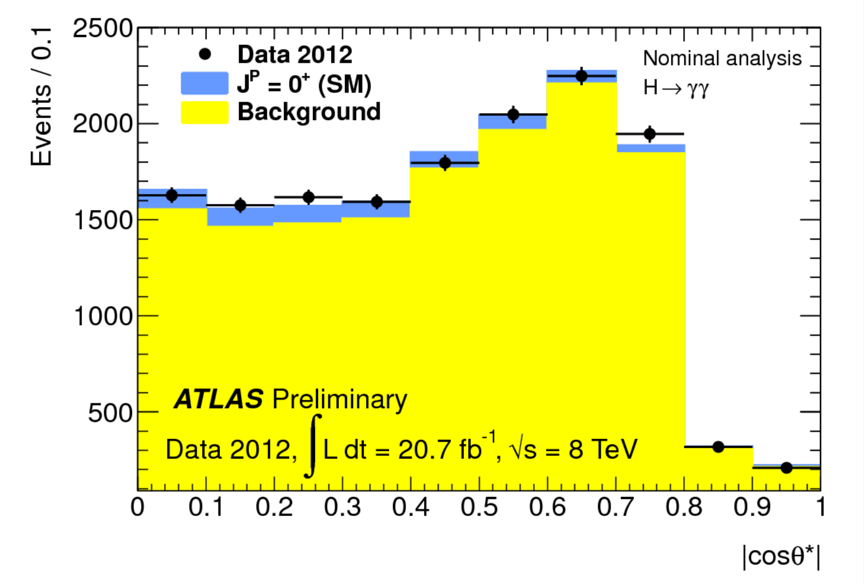
Is this new particle the first elementary scalar ? → Spin studies

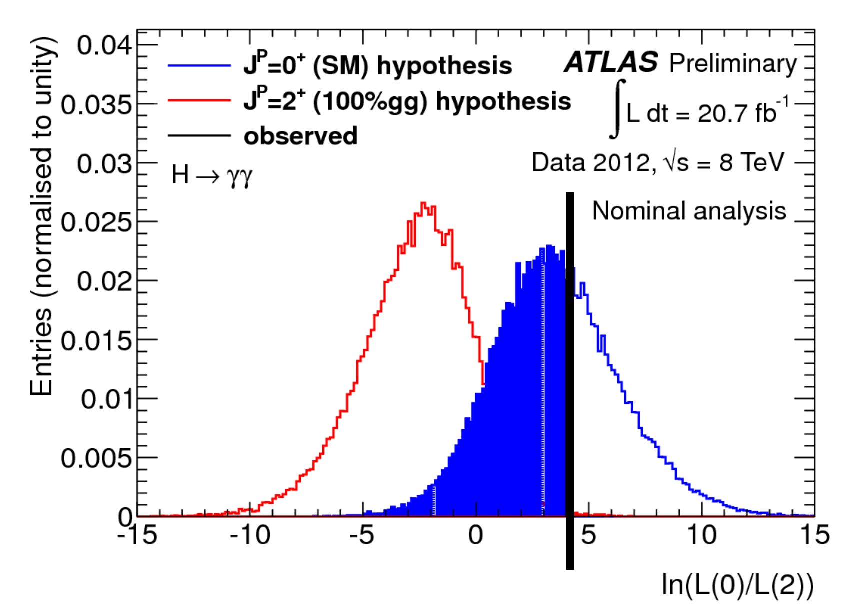
$H \to \gamma\gamma$

Spin information from distribution of polar angle θ* of the di-photon system in the Higgs rest frame

Compare θ* distribution in the region of the peak for:

- ❑ spin-0 hypothesis: flat before cuts
- ❑ spin-2 hypothesis: ~ $1+6\cos^2\theta^* + \cos^4\theta^*$ for Graviton-like (minimal models)

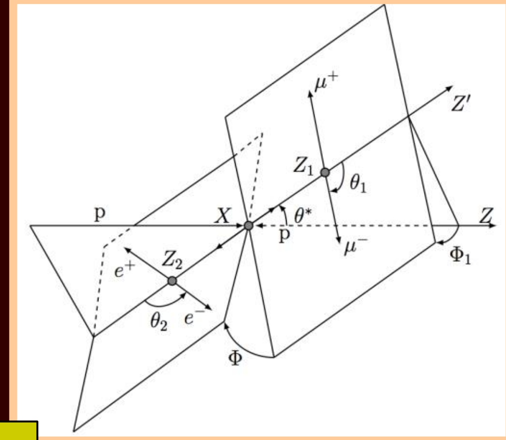




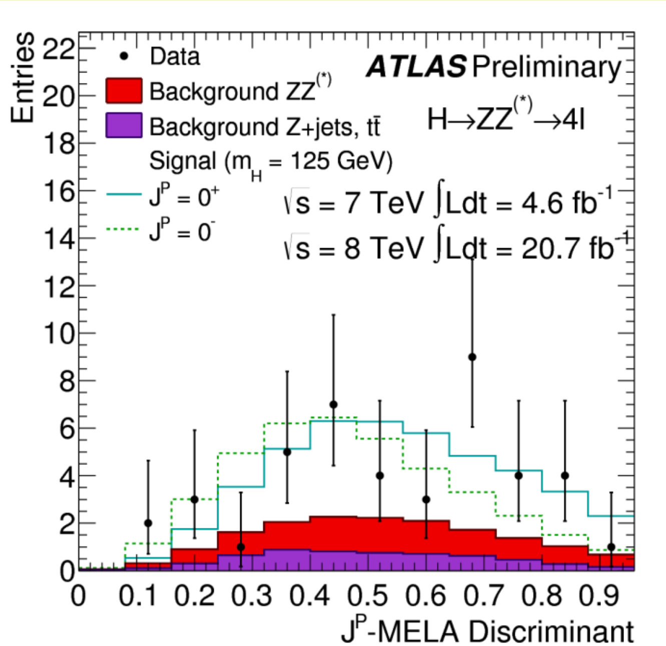
Fit to data disfavours 2^+ hypothesis at 99.3% CL. (66% CL) for pure gg → G (mixture of gg/qq → G) production (separation $0^+/2^+$ decreases with increasing qq contribution)

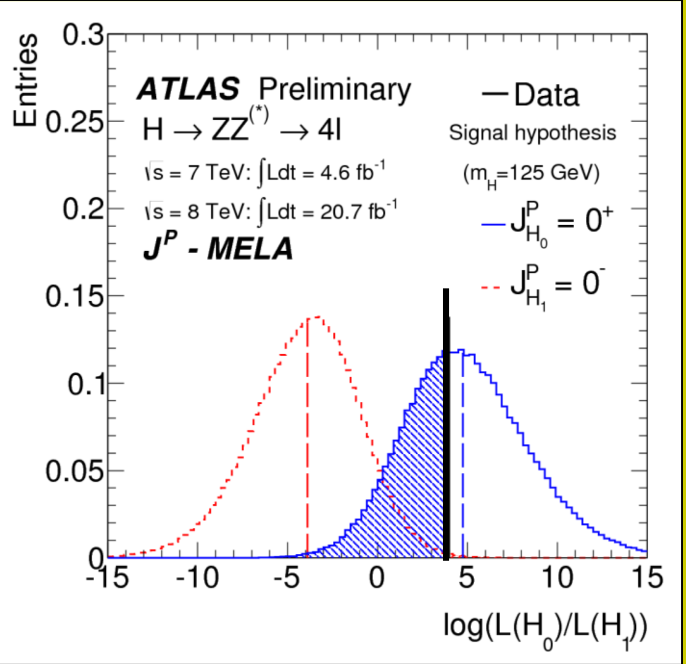
H→ 4l

Spin-parity information from distribution of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants



0^+ vs 0^- hypothesis

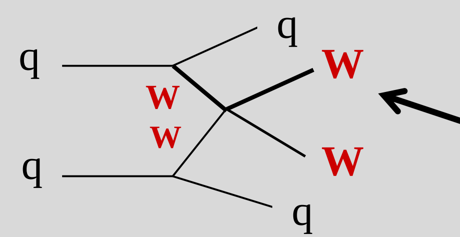




G-like spin-2
gg production

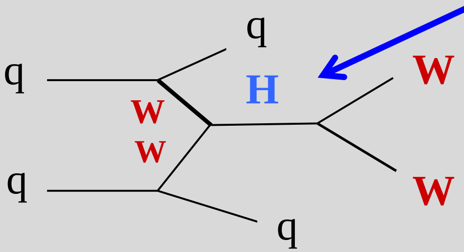
0^- excluded at 99.6% C.L. when compared to 0^+

Two additional questions



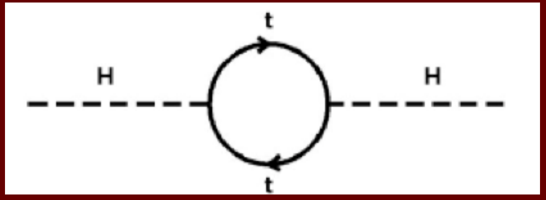
Does this new particle fix the SM problems at high energy ?

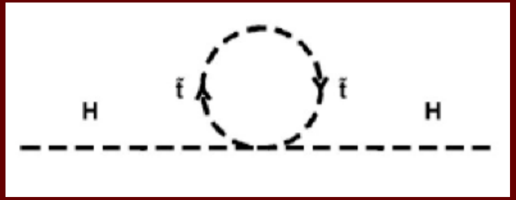
This process violates unitarity (cross section diverges → unphysical) at m(WW) ~ TeV
if this process does not exist



→ Need to verify that the discovered particle accomplishes this task → need $\sqrt{s}$ ~ 14 TeV and ~3000 fb^{-1}

Why is the Higgs so light ? → Is m_H stabilized by (close-by, ~TeV scale) new physics or is it fine-tuned ?

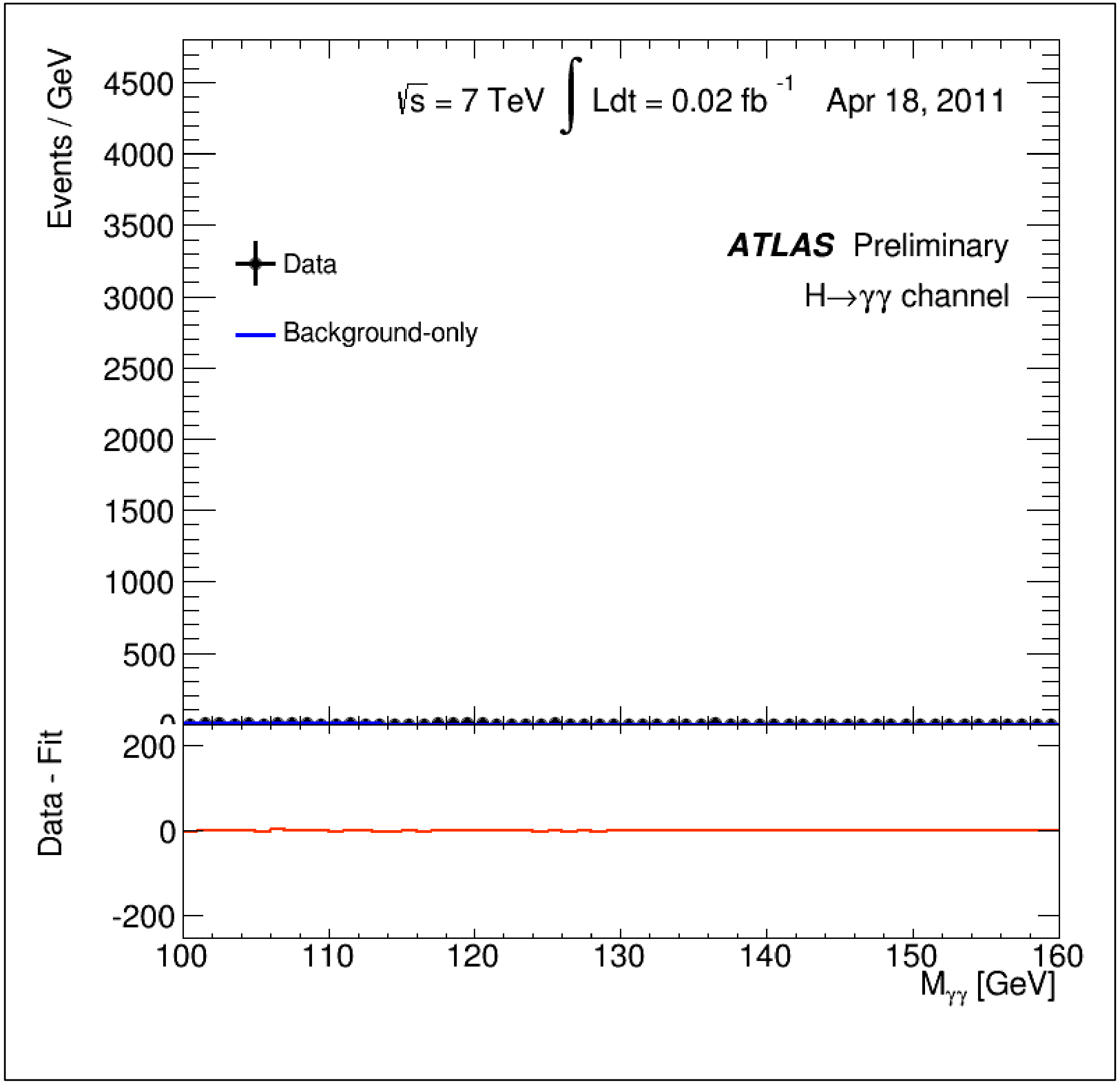




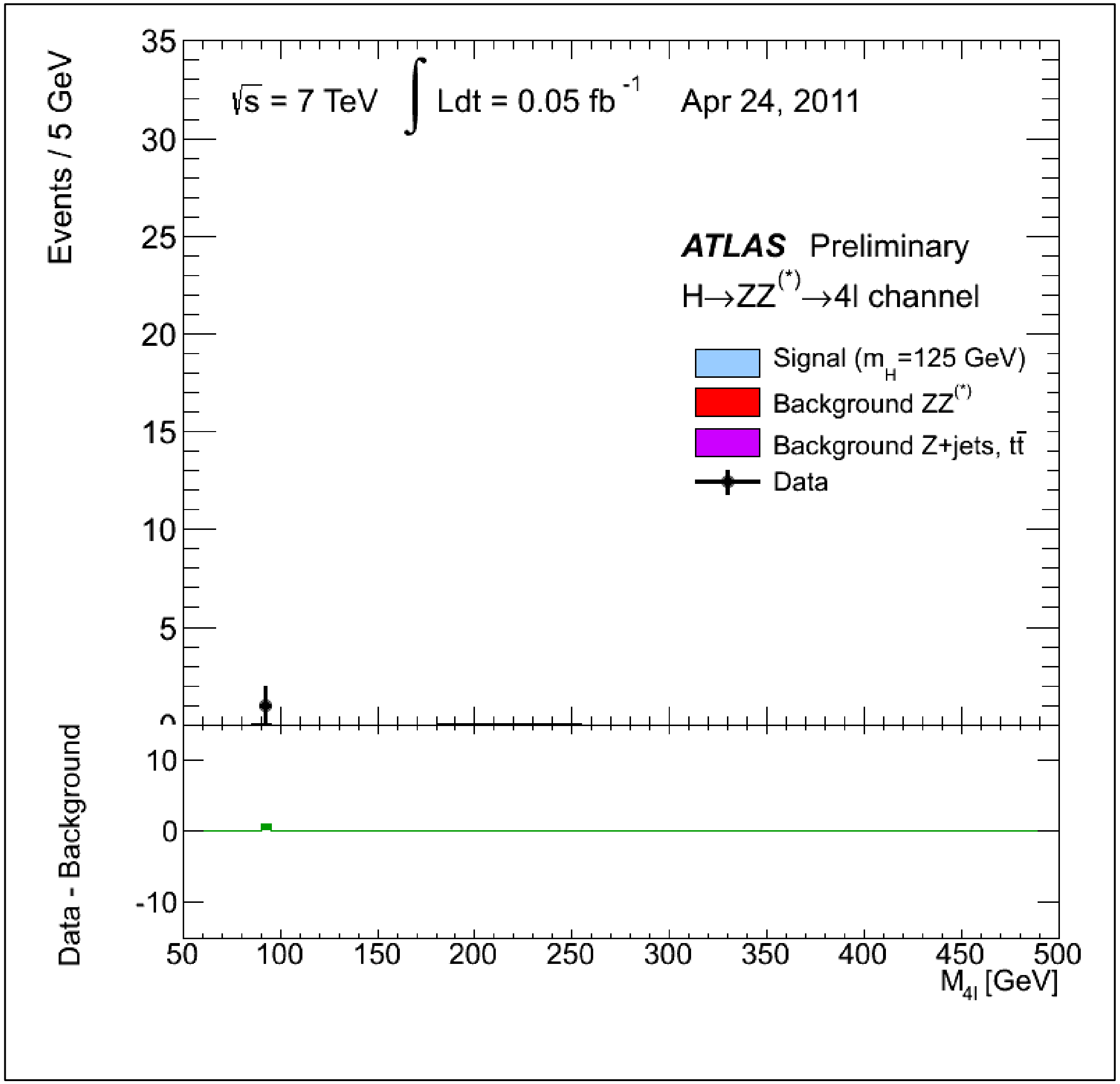
In the SM, top-loop corrections to m_H diverge as ~ Λ^2 (energy scale up to which the SM is valid)

Searches for stop quarks so far unsuccessful
Will continue with more data and energy in 2015++

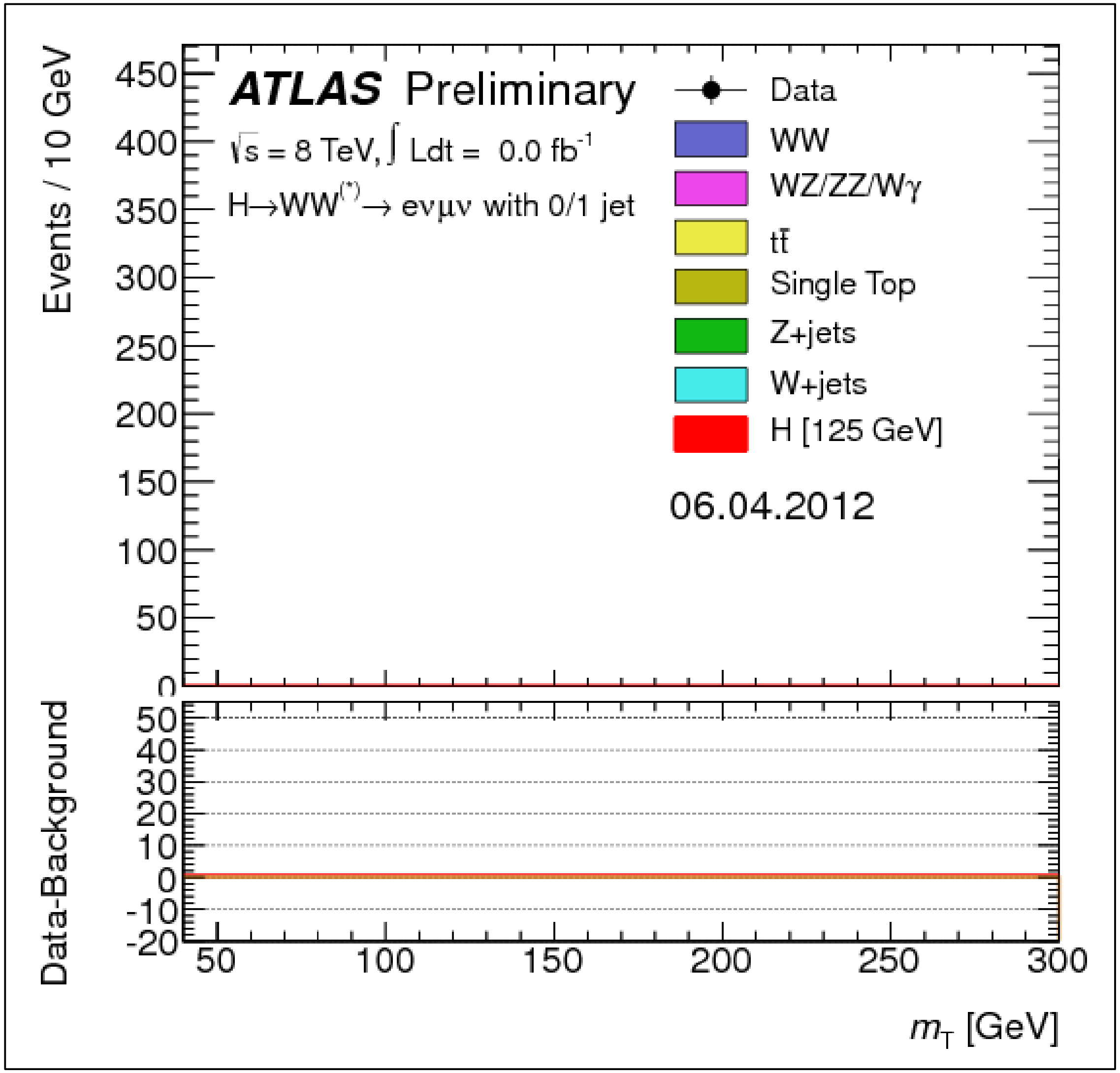
Birth and evolution of a signal: $H \to \gamma\gamma$



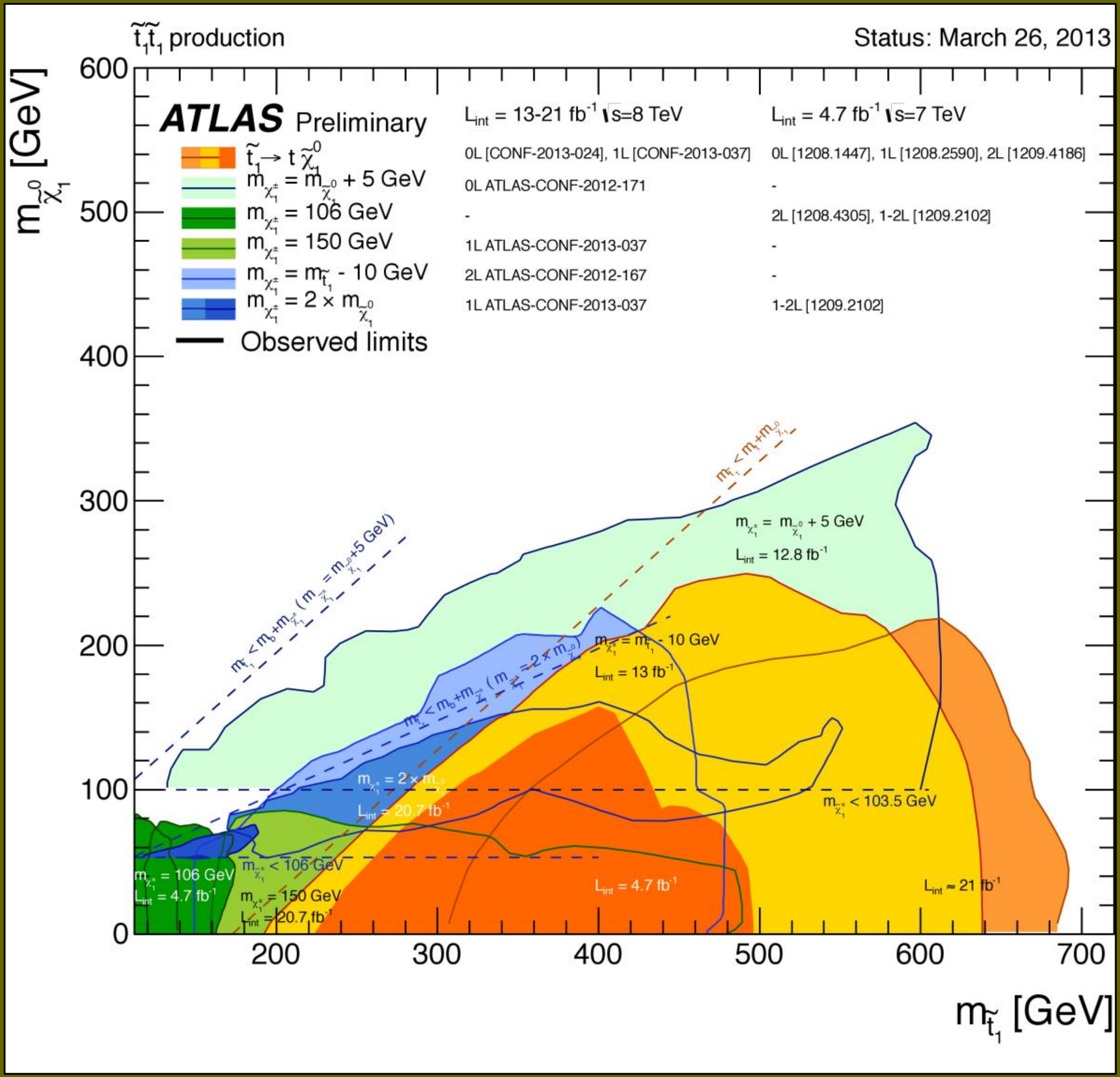
Birth and evolution of a signal: H→ 4l

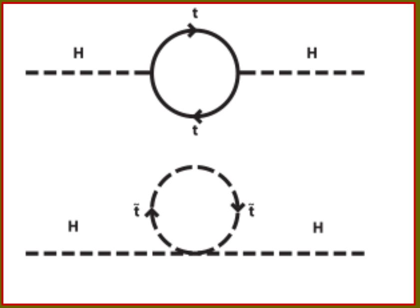


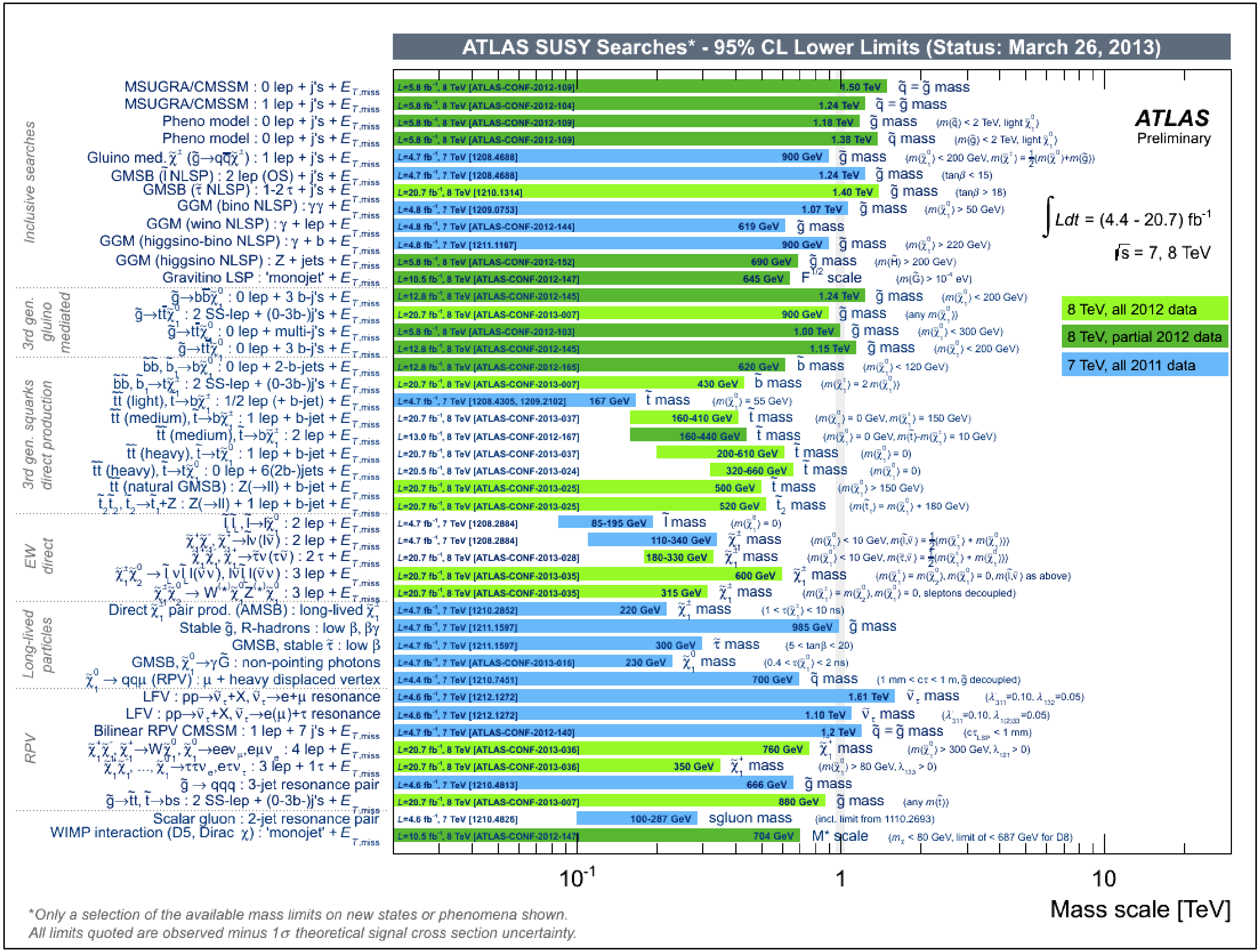
Birth and evolution of a signal: H→ WW → lvlv



Is the Higgs mass stabilized by New Physics ?






ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)
ATLAS Preliminary
$\int L dt = (4.4 - 20.7)\ fb^{-1}$
$\sqrt{s}$ = 7, 8 TeV
8 TeV, all 2012 data
8 TeV, partial 2012 data
7 TeV, all 2011 data
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$ — 1.50 TeV $\tilde{q} = \tilde{g}$ mass
MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$ — 1.24 TeV $\tilde{q} = \tilde{g}$ mass
Pheno model : 0 lep + j's + $E_{T,miss}$ — 1.18 TeV $\tilde{g}$ mass
Pheno model : 0 lep + j's + $E_{T,miss}$ — 1.38 TeV $\tilde{q}$ mass
Gluino med. $\tilde{\chi}^{\pm}$: 1 lep + j's + $E_{T,miss}$ — 900 GeV $\tilde{g}$ mass
GMSB ($\tilde{l}$ NLSP) : 2 lep (OS) + j's + $E_{T,miss}$ — 1.24 TeV $\tilde{g}$ mass
GMSB ($\tilde{\tau}$ NLSP) : 1-2 τ + j's + $E_{T,miss}$ — 1.40 TeV $\tilde{g}$ mass
GGM (bino NLSP) : $\gamma\gamma$ + $E_{T,miss}$ — 1.07 TeV $\tilde{g}$ mass
GGM (wino NLSP) : γ + lep + $E_{T,miss}$ — 619 GeV $\tilde{g}$ mass
GGM (higgsino-bino NLSP) : γ + b + $E_{T,miss}$ — 900 GeV $\tilde{g}$ mass
GGM (higgsino NLSP) : Z + jets + $E_{T,miss}$ — 690 GeV $\tilde{g}$ mass
Gravitino LSP : 'monojet' + $E_{T,miss}$ — 645 GeV $F^{1/2}$ scale
3rd gen. gluino mediated
$\tilde{g} \to b\bar{b}\tilde{\chi}^0_1$: 0 lep + 3 b-j's + $E_{T,miss}$ — 1.24 TeV $\tilde{g}$ mass
$\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$: 2 SS-lep + (0-3b-)j's + $E_{T,miss}$ — 900 GeV $\tilde{g}$ mass
$\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$: 0 lep + multi-j's + $E_{T,miss}$ — 1.00 TeV $\tilde{g}$ mass
$\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$: 0 lep + 3 b-j's + $E_{T,miss}$ — 1.15 TeV $\tilde{g}$ mass
3rd gen. squarks direct production
$\tilde{b}\tilde{b}$: 0 lep + 2-b-jets + $E_{T,miss}$ — 620 GeV $\tilde{b}$ mass
$\tilde{b}\tilde{b}$: 2 SS-lep + (0-3b-)j's + $E_{T,miss}$ — 430 GeV $\tilde{b}$ mass
$\tilde{t}\tilde{t}$ (light) : 1/2 lep (+ b-jet) + $E_{T,miss}$ — 167 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (medium) : 1 lep + b-jet + $E_{T,miss}$ — 160-410 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (medium) : 2 lep + $E_{T,miss}$ — 160-440 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (heavy) : 1 lep + b-jet + $E_{T,miss}$ — 200-610 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (heavy) : 0 lep + 6(2b-)jets + $E_{T,miss}$ — 320-660 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (natural GMSB) : Z(→ll) + b-jet + $E_{T,miss}$ — 500 GeV $\tilde{t}$ mass
$\tilde{t}_2\tilde{t}_2$: Z(→ll) + 1 lep + b-jet + $E_{T,miss}$ — 520 GeV $\tilde{t}_2$ mass
EW direct
$\tilde{l}_L\tilde{l}_L$: 2 lep + $E_{T,miss}$ — 85-195 GeV $\tilde{l}$ mass
$\tilde{\chi}^+_1\tilde{\chi}^-_1$: 2 lep + $E_{T,miss}$ — 110-340 GeV $\tilde{\chi}^{\pm}_1$ mass
$\tilde{\chi}^+_1\tilde{\chi}^-_1$: 2 τ + $E_{T,miss}$ — 180-330 GeV $\tilde{\chi}^{\pm}_1$ mass
$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$: 3 lep + $E_{T,miss}$ — 600 GeV $\tilde{\chi}^{\pm}_1$ mass
$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2 \to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$: 3 lep + $E_{T,miss}$ — 315 GeV $\tilde{\chi}^{\pm}_1$ mass
Long-lived particles
Direct $\tilde{\chi}^{\pm}_1$ pair prod. (AMSB) : long-lived $\tilde{\chi}^{\pm}_1$ — 220 GeV $\tilde{\chi}^{\pm}_1$ mass
Stable $\tilde{g}$, R-hadrons : low β, $\beta\gamma$ — 985 GeV $\tilde{g}$ mass
GMSB, stable $\tilde{\tau}$: low β — 300 GeV $\tilde{\tau}$ mass
GMSB, $\tilde{\chi}^0_1 \to \gamma\tilde{G}$: non-pointing photons — 230 GeV $\tilde{\chi}^0_1$ mass
$\tilde{\chi}^0_1 \to qq\mu$ (RPV) : μ + heavy displaced vertex — 700 GeV $\tilde{q}$ mass
RPV
LFV : pp→$\tilde{\nu}_\tau$+X, $\tilde{\nu}_\tau$→e+μ resonance — 1.61 TeV $\tilde{\nu}_\tau$ mass
LFV : pp→$\tilde{\nu}_\tau$+X, $\tilde{\nu}_\tau$→e(μ)+τ resonance — 1.10 TeV $\tilde{\nu}_\tau$ mass
Bilinear RPV CMSSM : 1 lep + 7 j's + $E_{T,miss}$ — 1.2 TeV $\tilde{q} = \tilde{g}$ mass
4 lep + $E_{T,miss}$ — 760 GeV $\tilde{\chi}^{\pm}_1$ mass
3 lep + 1τ + $E_{T,miss}$ — 350 GeV $\tilde{\chi}^{\pm}_1$ mass
$\tilde{g} \to qqq$: 3-jet resonance pair — 666 GeV $\tilde{g}$ mass
$\tilde{g} \to \tilde{t}t$, $\tilde{t} \to bs$: 2 SS-lep + (0-3b-)j's + $E_{T,miss}$ — 880 GeV $\tilde{g}$ mass
Scalar gluon : 2-jet resonance pair — 100-287 GeV sgluon mass
WIMP interaction (D5, Dirac χ) : 'monojet' + $E_{T,miss}$ — 704 GeV M* scale
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Searches for the SM scalar have guided conception, design and technological choices of ATLAS and CMS:

- ❑ one of the primary LHC goals
- ❑ among the most challenging processes → have set some of the most stringent performance (hence technical) requirements: lepton identification and energy and momentum resolution, b-tagging, E_T^{miss} measurement, forward-jet tagging, etc.

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeVstandalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

CMS: excellent μ momentum resolution (H→ 4μ !) but B=4T solenoid constrains HCAL radius

H→ γγ:
CMS: E-resolution
ATLAS: γ "pointing" and γ/jet separation

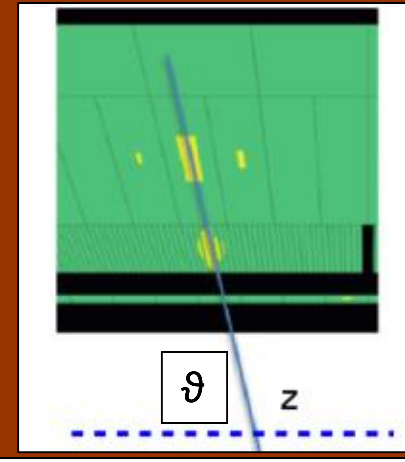
ATLAS: excellent HCAL → jets and E_T^{miss} (H→ lνlν)

$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

α=opening angle of the two photons

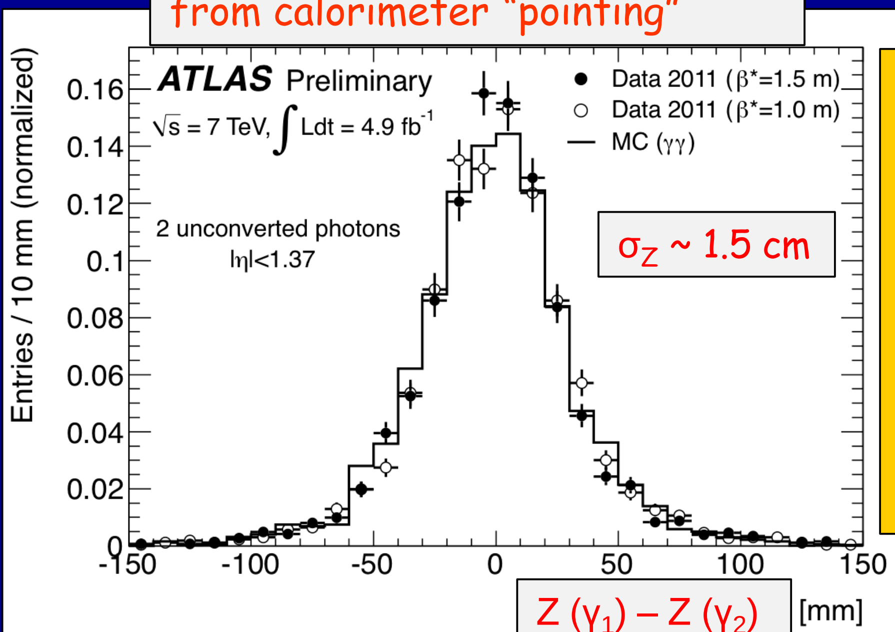
High pile-up: many vertices distributed over
σ_Z (LHC beam spot) ~ 5-6 cm
→ difficult to know which one has produced the γγ pair

Primary vertex from:
- ❑ EM calorimeter longitudinal (and lateral) segmentation
- ❑ tracks from converted photons



Measure γ direction with calo
→ get Z of primary vertex

Z-vertex measured in γγ events from calorimeter "pointing"



Note:
- ❑ Calorimeter pointing alone reduces vertex uncertainty from beam spot spread of ~ 5-6 cm to ~ 1.5 cm and is robust against pile-up
- → good enough to make contribution to mass resolution from angular term negligible
- ❑ Addition of track information needed to reject fake jets from pile-up in 2j categories