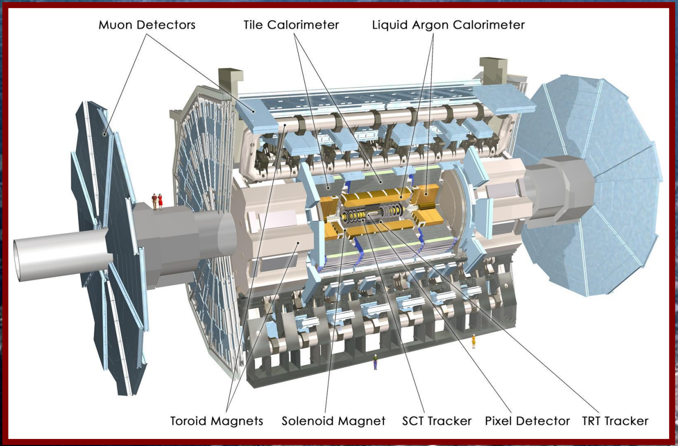
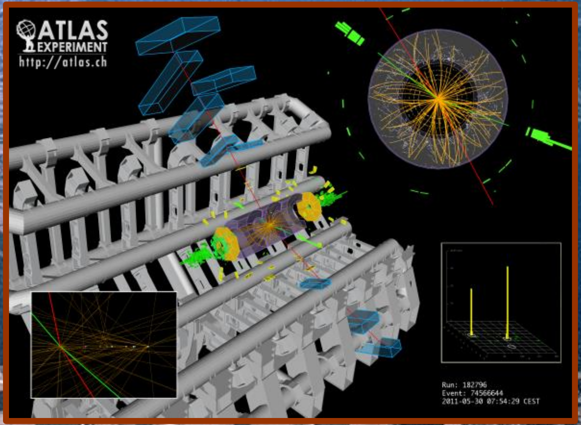




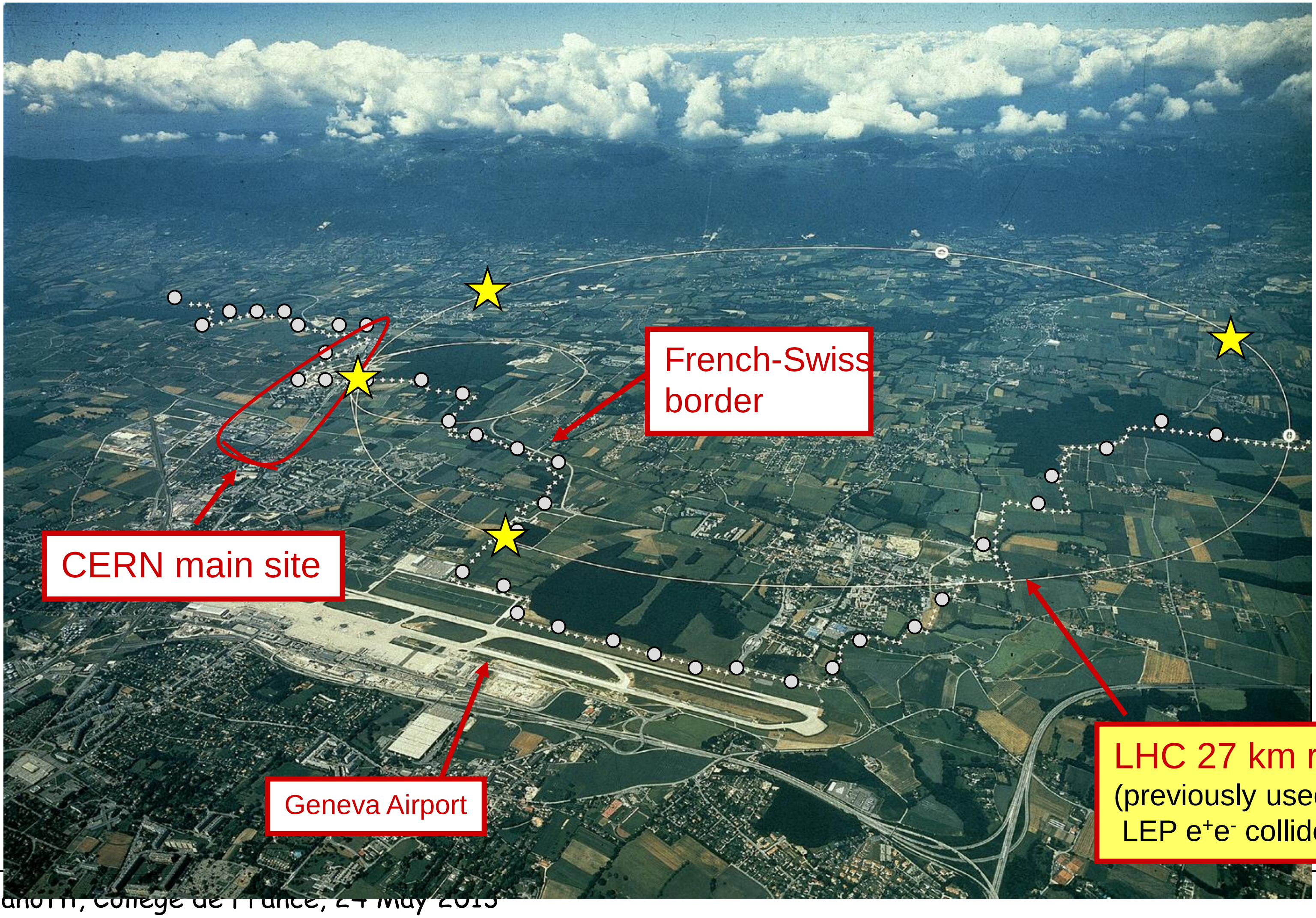
Un boson nommé Higgs: the experimental challenges of a very special discovery

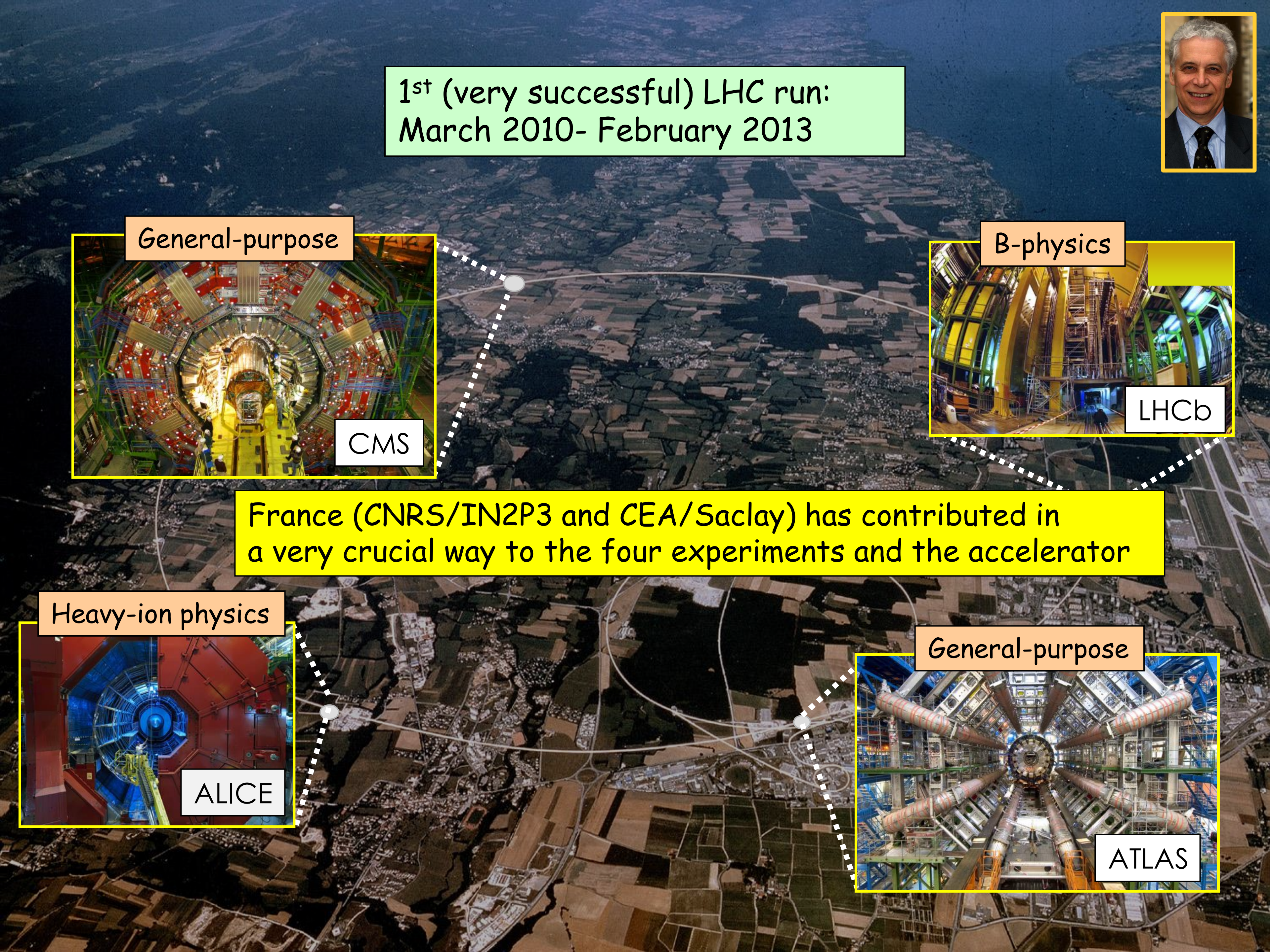
Fabiola Gianotti, CERN Physics Department
Colloque de Clôture de Gabriele Veneziano
Collège de France, 24/5/2013

COLLÈGE
DE FRANCE
1530

- ❑ LHC: 27 km accelerator ring, 100 m below ground, across French-Swiss border
- ❑ Two proton beams accelerated in opposite directions

  Beam energy as of today: 4 TeV → collision energy 8 TeV (x4 Tevatron)
- ❑ Design collision energy (to be achieved in 2015): ~ 14 TeV (1 TeV= 10^{-7} Joule)
- ❑ They collide at four points, where four big experiments have been installed





1st (very successful) LHC run:
March 2010- February 2013

General-purpose

CMS

B-physics

LHCb

France (CNRS/IN2P3 and CEA/Saclay) has contributed in a very crucial way to the four experiments and the accelerator

Heavy-ion physics

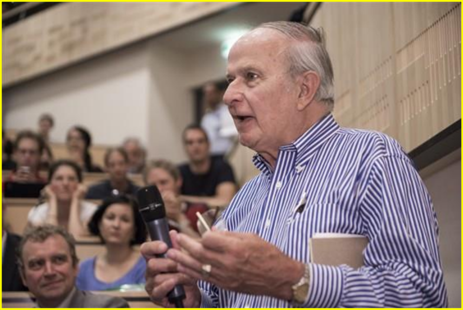
ALICE

General-purpose

ATLAS

An historical day : 4th July 2012

The culmination of a long path …



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)

> 20 years from conception to start of operation

2010 : 30 March: first collisions at $\sqrt{s}$ = 7 TeV
2012 : 1st May: collision energy to $\sqrt{s}$ = 8 TeV
2012 : 4th July: discovery of a Higgs-like boson
2013 : 14th Feb: end of "Run 1" → start 2-year shut-down → $\sqrt{s}$ ~ 14 TeV in 2015

+ 20 years of physics exploitation ?

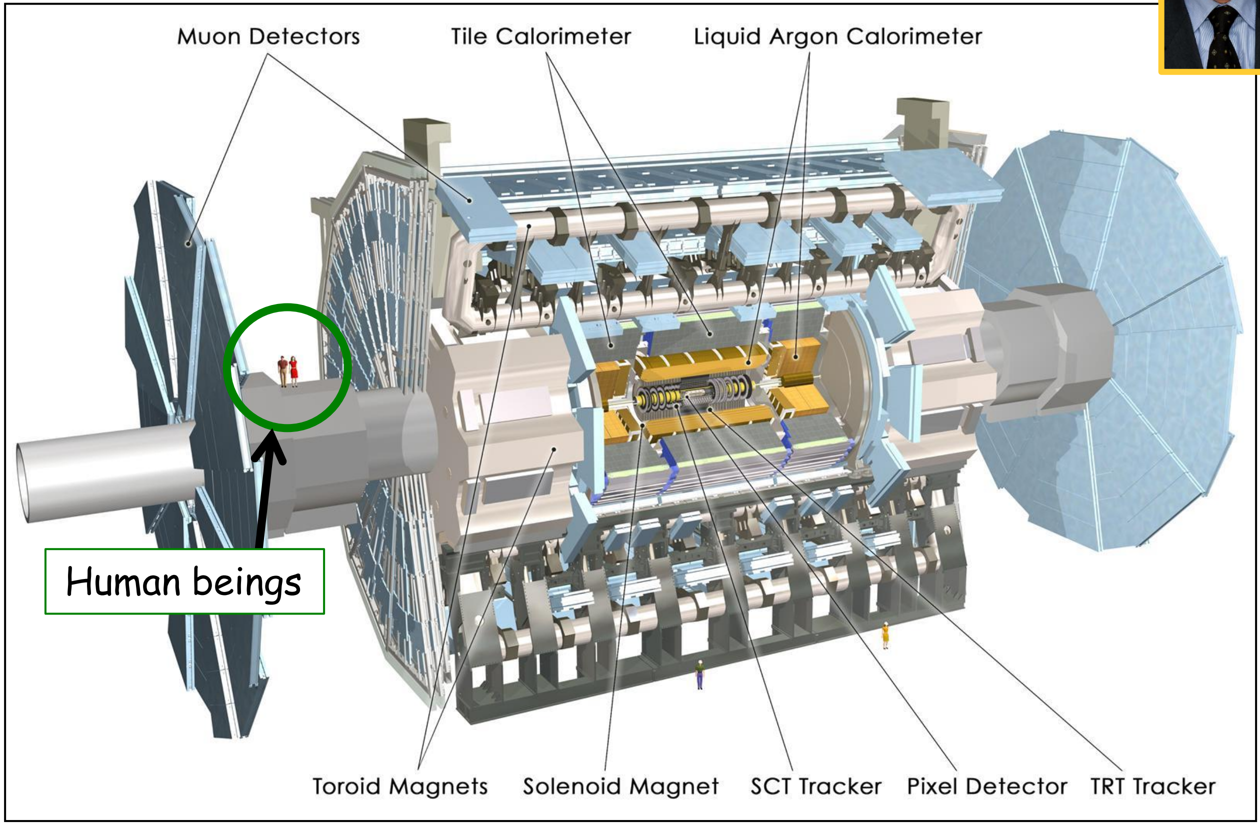
The LHC has required:

☐ innovative technologies (superconducting magnets, cryogenics, electronics, computing, ..)
☐ new concepts, lot of ingenuity to address challenges and solve problems
☐ huge efforts of the worldwide community (ideas, technology, people, money)

Unprecedented accelerator and experiments
(complexity, technology, performance)

ATLAS

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

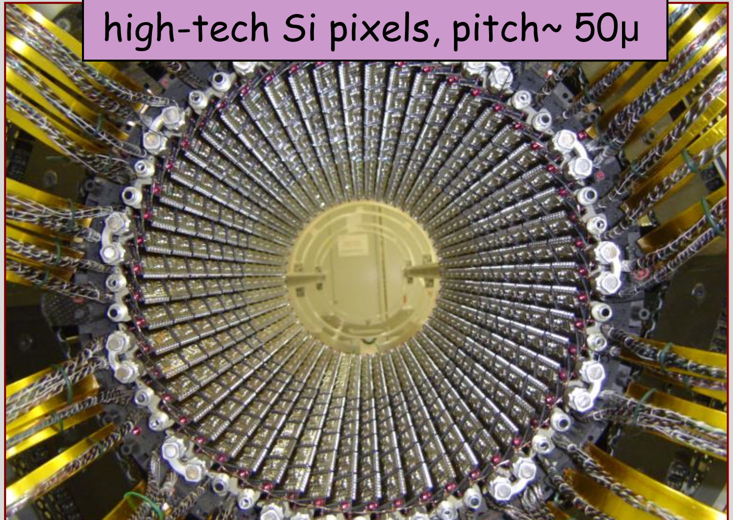


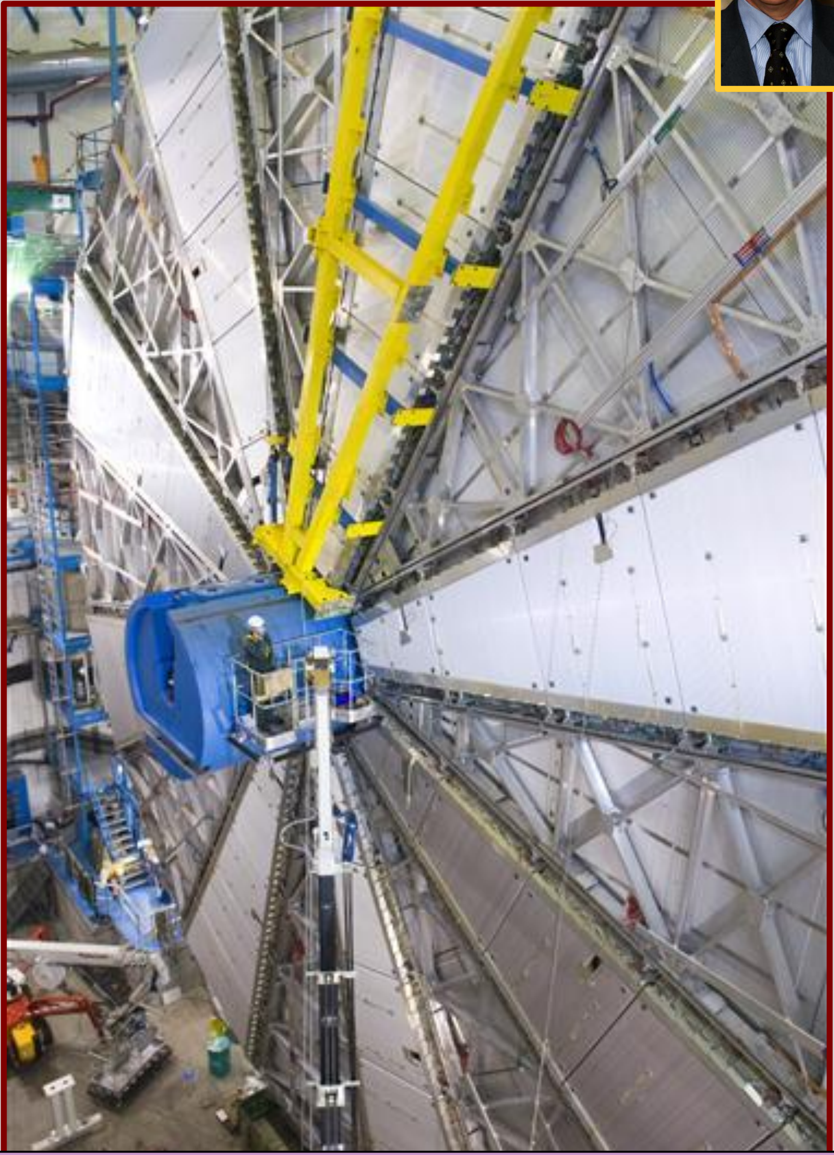
- ☐ Size : to measure and absorb high-E particles from the collision
- ☐ 10^8 independent sensitive elements ("individual signals"): to track ~1000 particles per event and reconstruct their trajectories with ~10 μm precision
- ☐ Fast response (25-50 ns): to cope with 40 million beam-beam collisions per second
- ☐ Computing resources: ~ 10 PB of data per year per experiment
- ☐ Human resources: 3000 physicists from 38 countries (7 laboratories from IN2P3/CEA, ~ 200 French scientists)

3 examples of the very strong French contribution to ATLAS

Electromagnetic "Accordion" calorimeter: a novel geometry detector (introduced by Daniel Fournier, LAL/Orsay)

Pixel detector: 80 million high-tech Si pixels, pitch~ 50µ

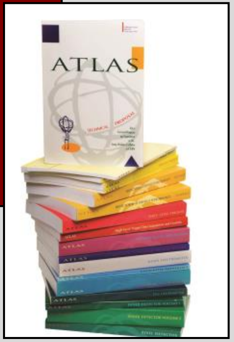




Muon Spectrometer: ~ 5500 gas-based devices (mainly drift chambers) covering > 1 football field

AND ....

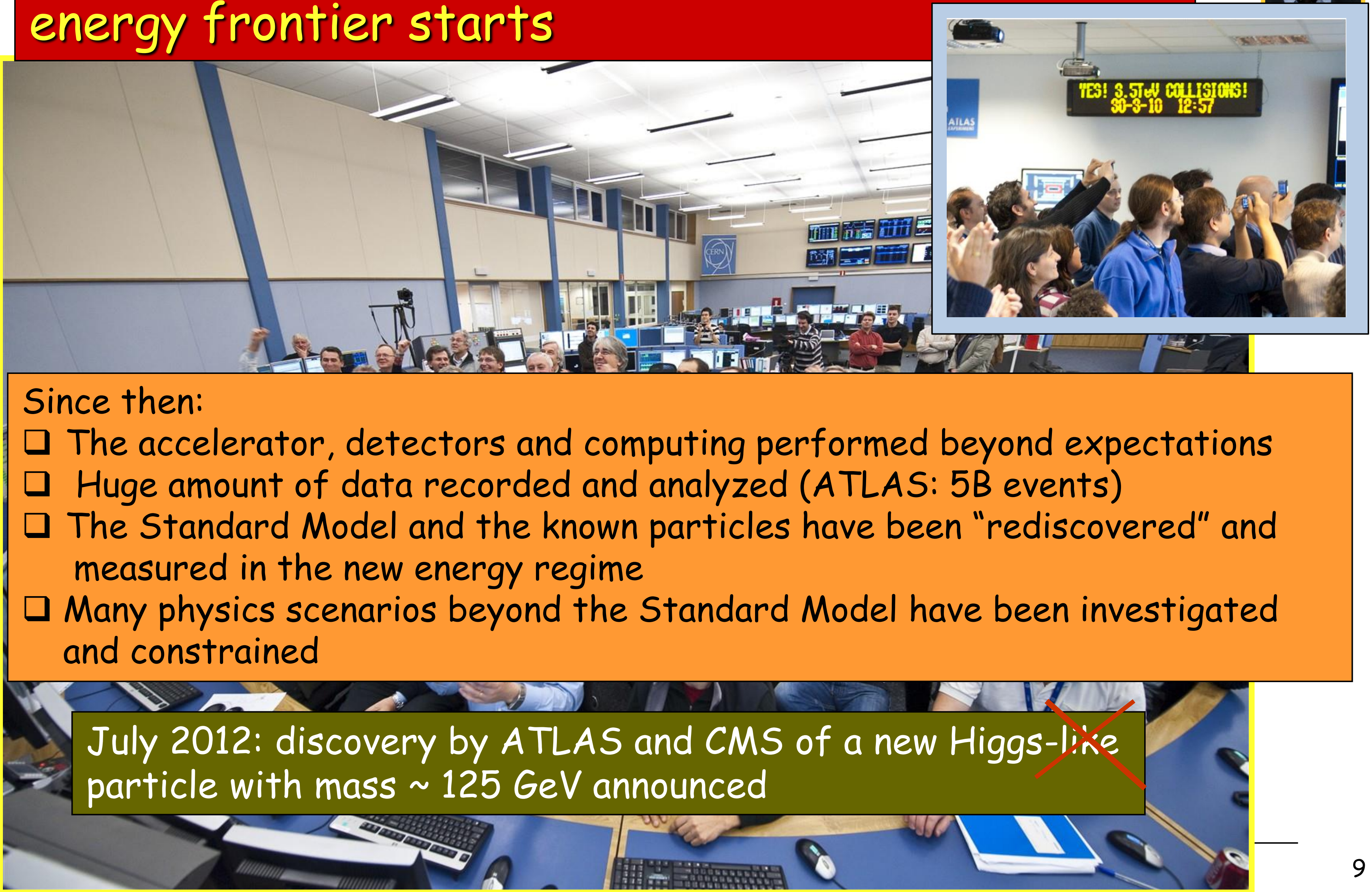
Thousands of quality controls of individual components
15 years of tests with beams,
20 years of detector and physics simulations,
8 years of world-wide computing data challenges,
17 Technical Design Reports



WHY ???

The driving motivation has been New Physics at the TeV scale, coming from our theory colleagues (e.g. Grabriele Veneziano)

30 March 2010: first proton-proton collisions at an unprecedented energy → exploration of a new energy frontier starts

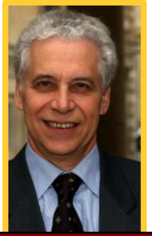


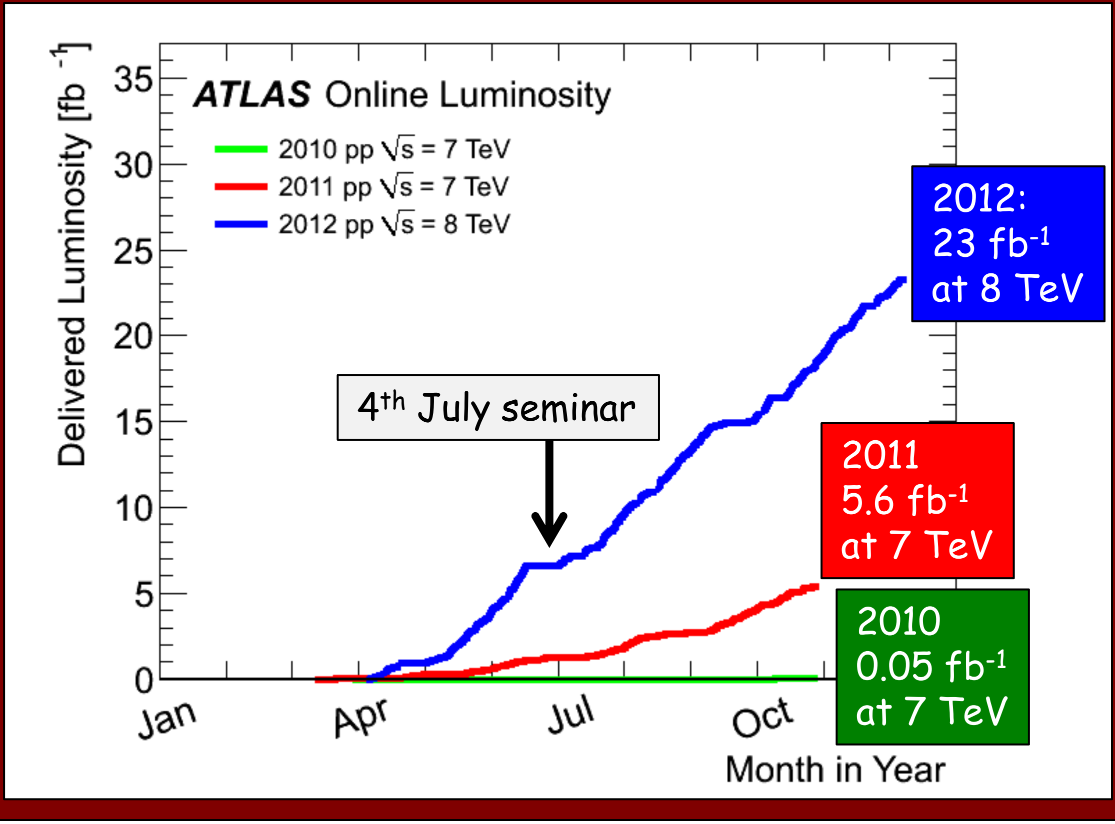
Since then:

- ❑ The accelerator, detectors and computing performed beyond expectations
- ❑ Huge amount of data recorded and analyzed (ATLAS: 5B events)
- ❑ The Standard Model and the known particles have been "rediscovered" and measured in the new energy regime
- ❑ Many physics scenarios beyond the Standard Model have been investigated and constrained

July 2012: discovery by ATLAS and CMS of a new Higgs-~~like~~ particle with mass ~ 125 GeV announced

SUPERB performance of the LHC in the first run → one of the key ingredients for the fast discovery of the Higgs boson





4th July seminar

2012:
23 fb^{-1}
at 8 TeV

2011
5.6 fb^{-1}
at 7 TeV

2010
0.05 fb^{-1}
at 7 TeV

Max peak luminosity:
~ 7.7 $\times 10^{33}$ cm^{-2} s^{-1}

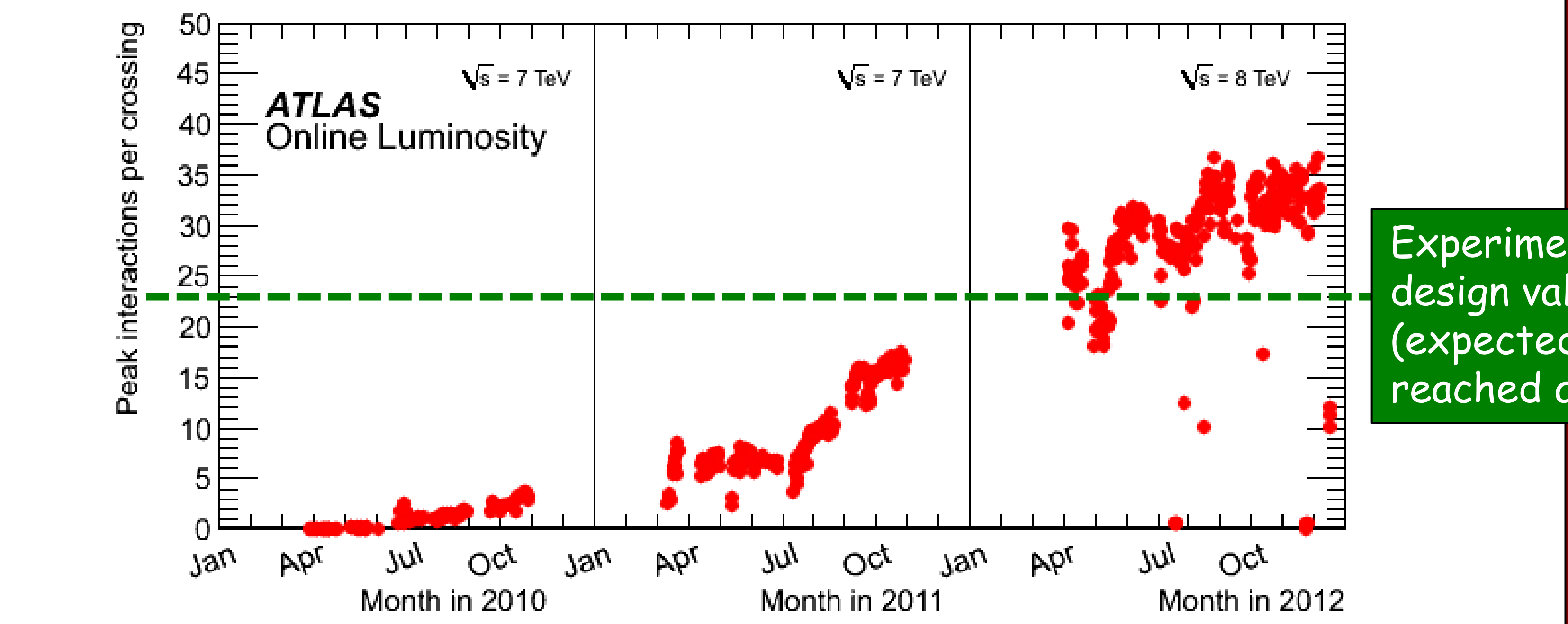
$N = \int L dt \times \sigma(pp \to X)$

$$L = \frac{N^2 k_b f}{4\pi\sigma_x^* \sigma_y^*} F = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

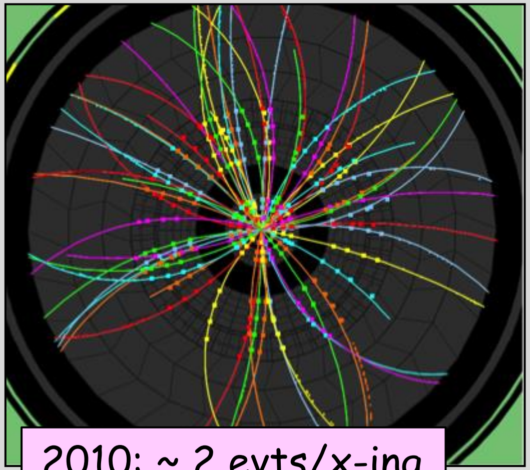
→ See J. Wenninger's talk

ATLAS: very high data-taking efficiency (~ 93.5%) and data-quality (~ 96%)
→ ~ 90% of the delivered luminosity used for physics results
(crucial as e.g. H→ 4l is a rare channel)

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 $L=10^{34}$!)

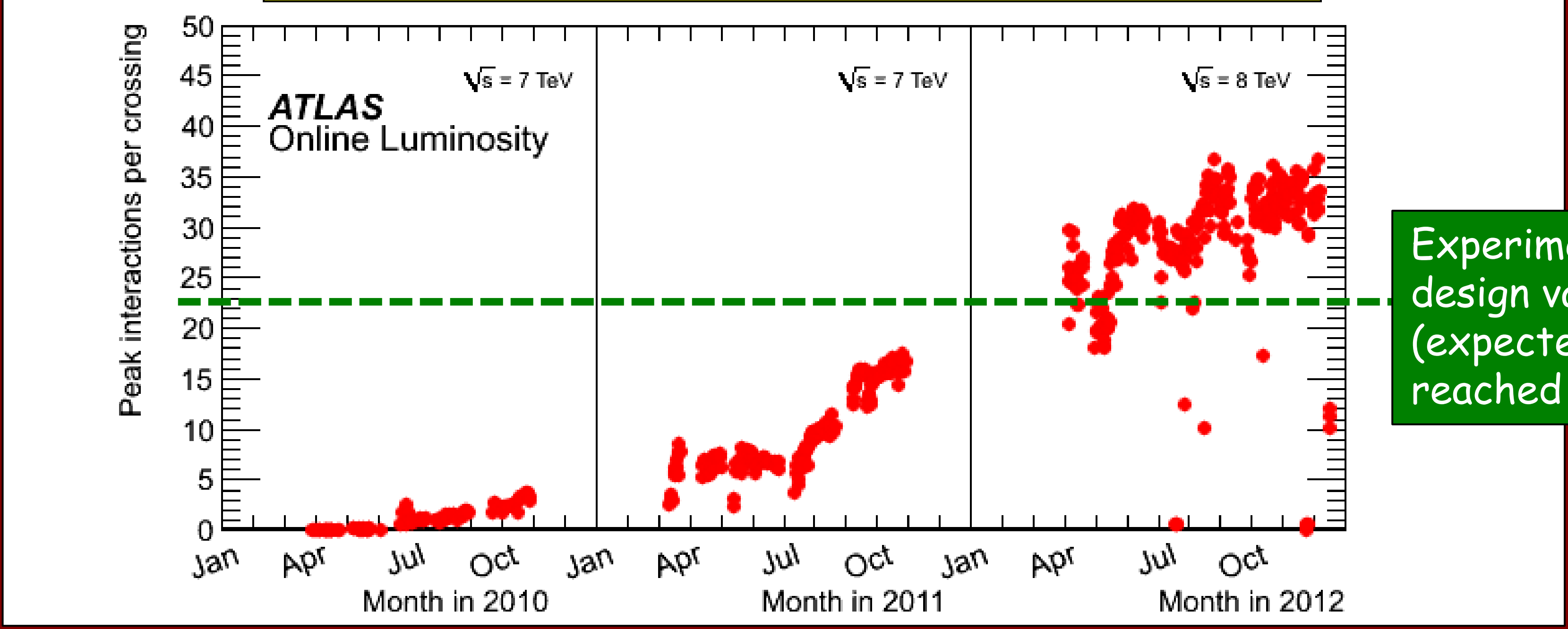


2010: ~ 2 evts/x-ing

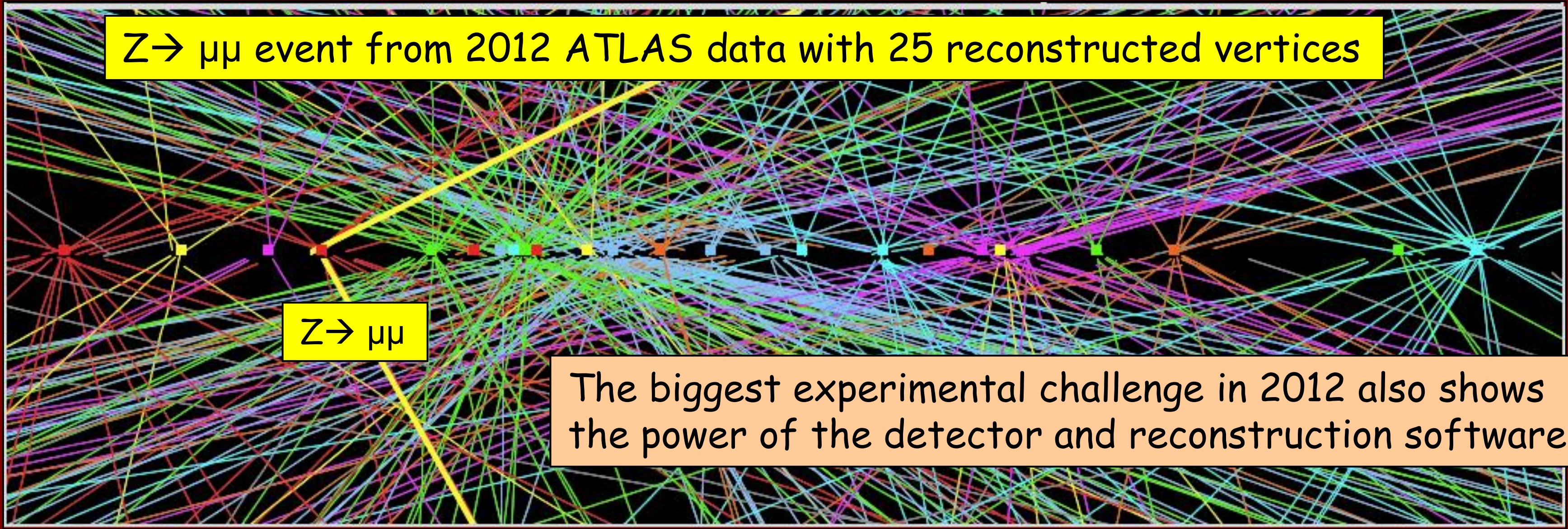
2011: ~ 10 evts/x-ing

2012: ~ 20 evts/x-ing

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



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

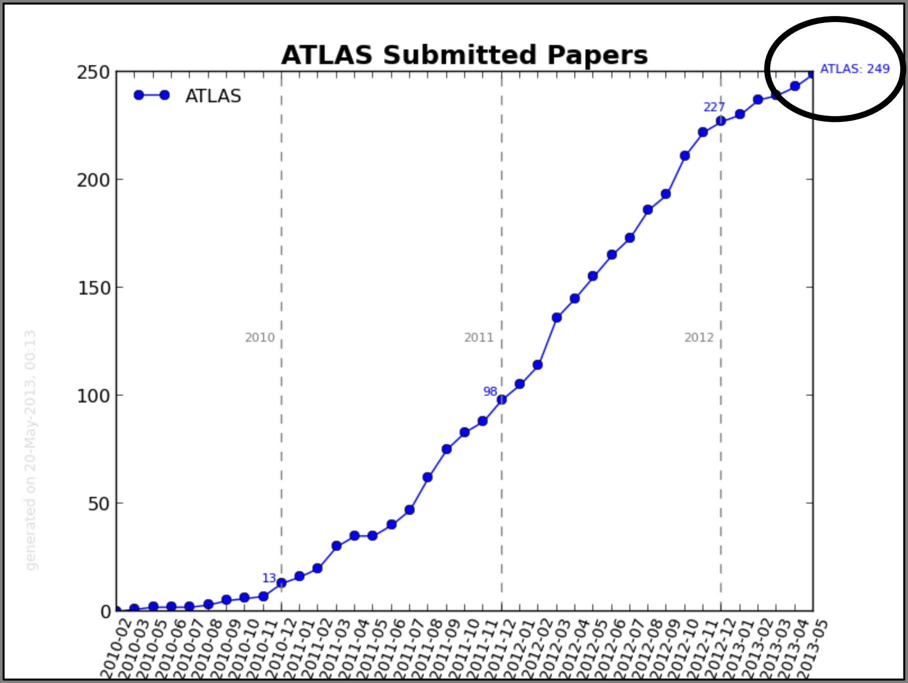


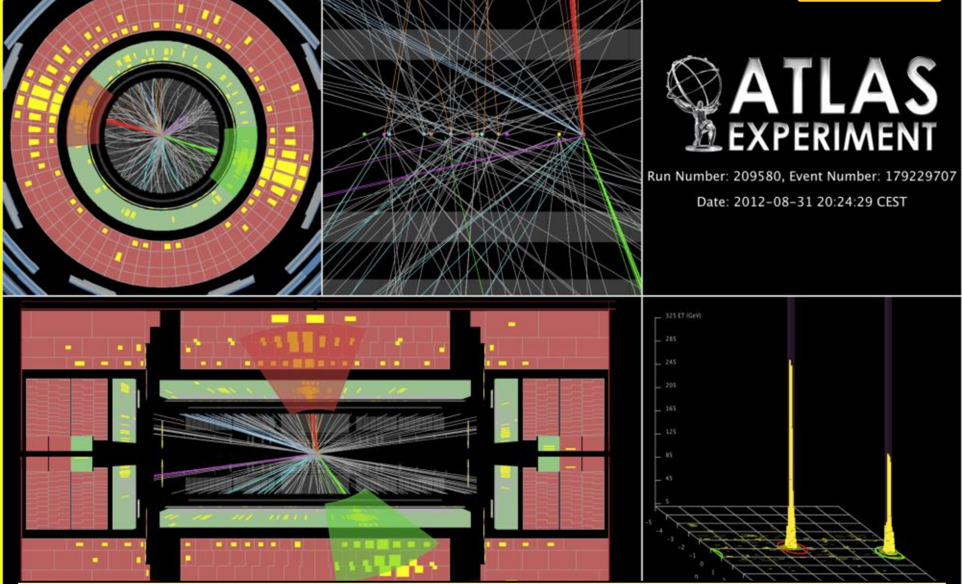
Z→ μμ event from 2012 ATLAS data with 25 reconstructed vertices

Z→ μμ

The biggest experimental challenge in 2012 also shows the power of the detector and reconstruction software

A huge scientific output





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

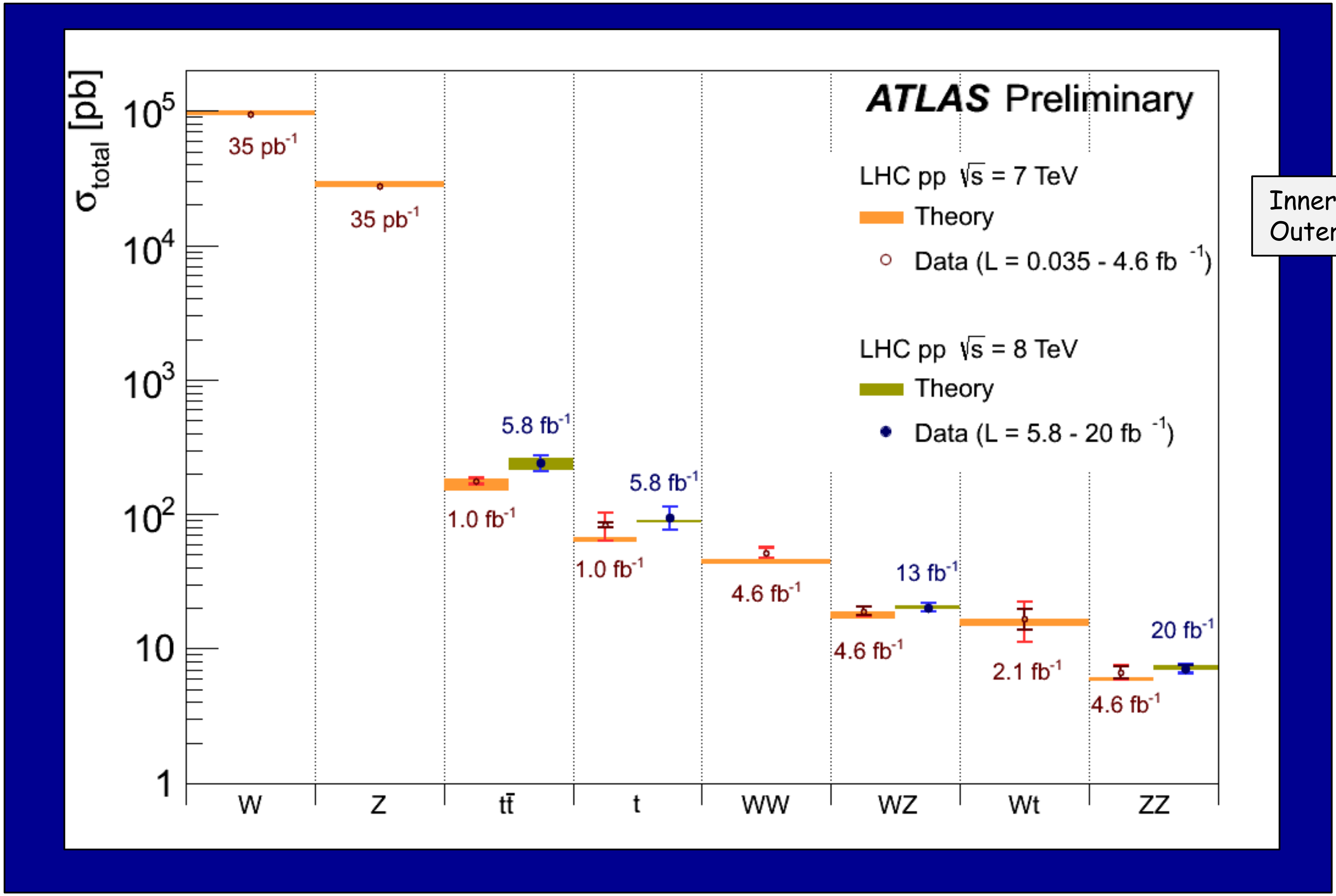
Number of events in the full 2010-2012 ATLAS dataset (~ 25 fb^{-1}) after all selections:

l=e,μ

W → lν ~ 100 M (x50 Tevatron)
Z→ ll ~ 10 M (x50 Tevatron)
tt → l+X ~ 0.4 M (x300 Tevatron)
Higgs candidates ~ 600
Note: ~1 H→ γγ (~1 H→ 4l) produced every 50′ (14h) at 7x 10^{33}

ATLAS in 2012:
the most productive year of any scientific Collaboration ever:
123 papers

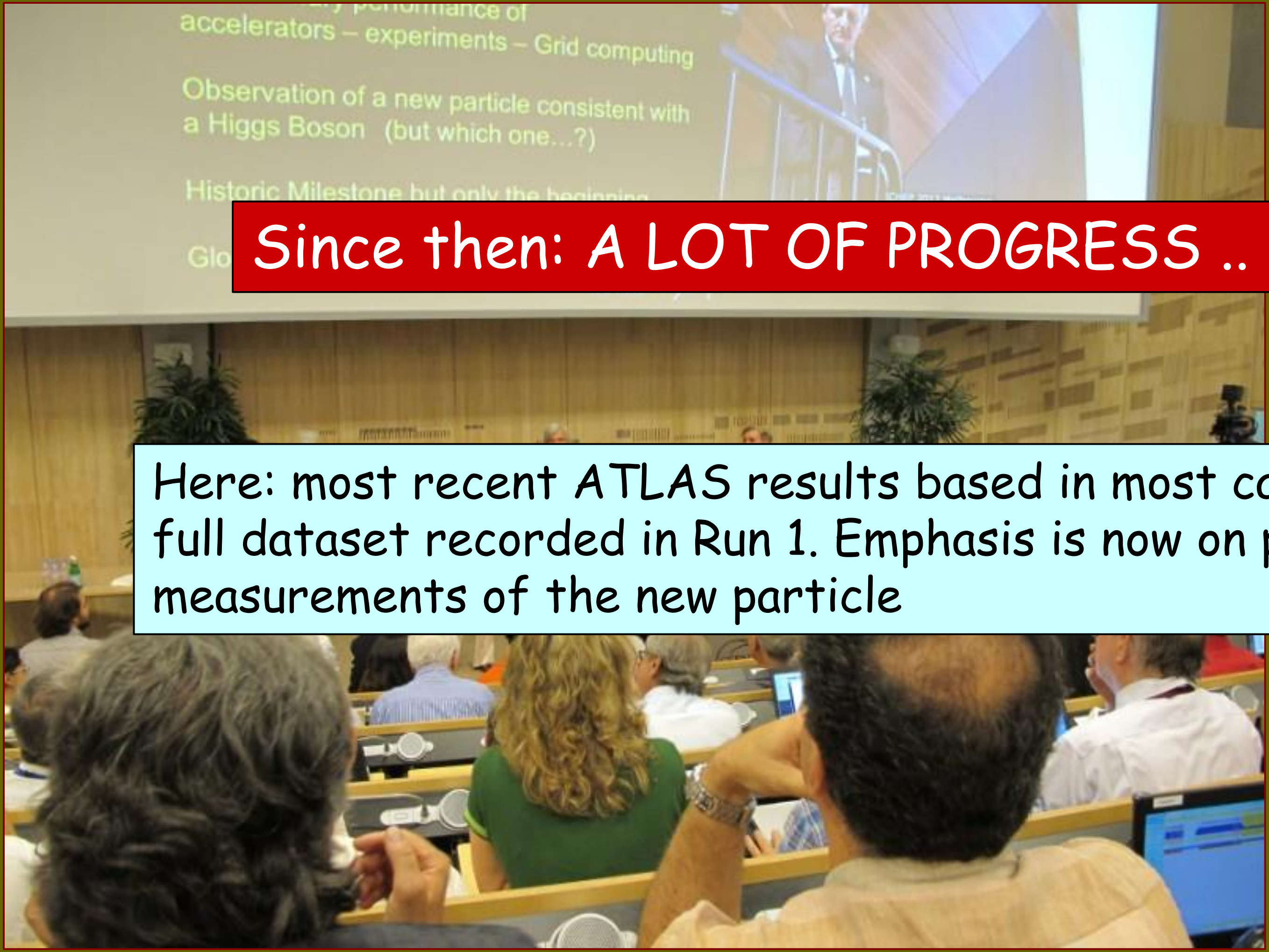
Cross-section measurements of known processes (examples …)



Inner error: statistical
Outer error: total

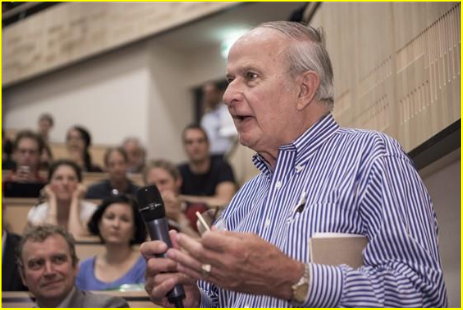
- ☐ Test SM at 7-8 TeV; constrain theory predictions; backgrounds to searches
- ☐ Good agreement with SM expectation
- ☐ Experimental precision starts to challenge theory uncertainty (e.g. tt)

An historical day : 4th July 2012

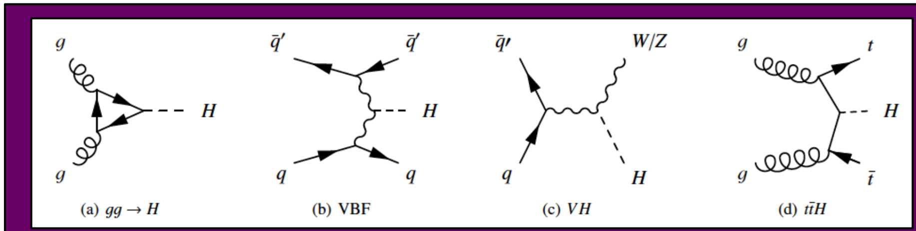


Since then: A LOT OF PROGRESS ..

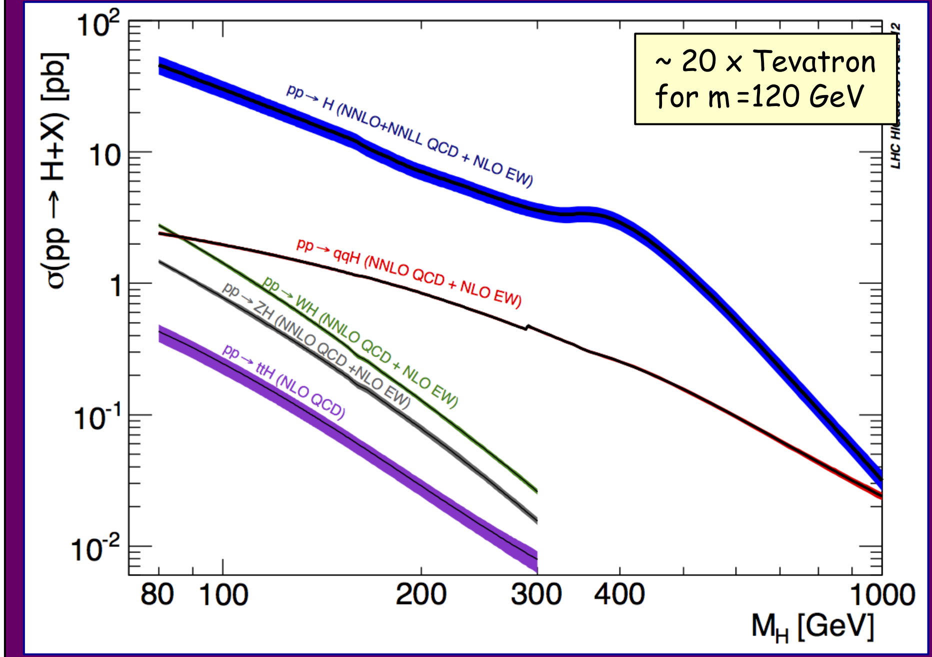
Here: most recent ATLAS results based in most cases on full dataset recorded in Run 1. Emphasis is now on property measurements of the new particle



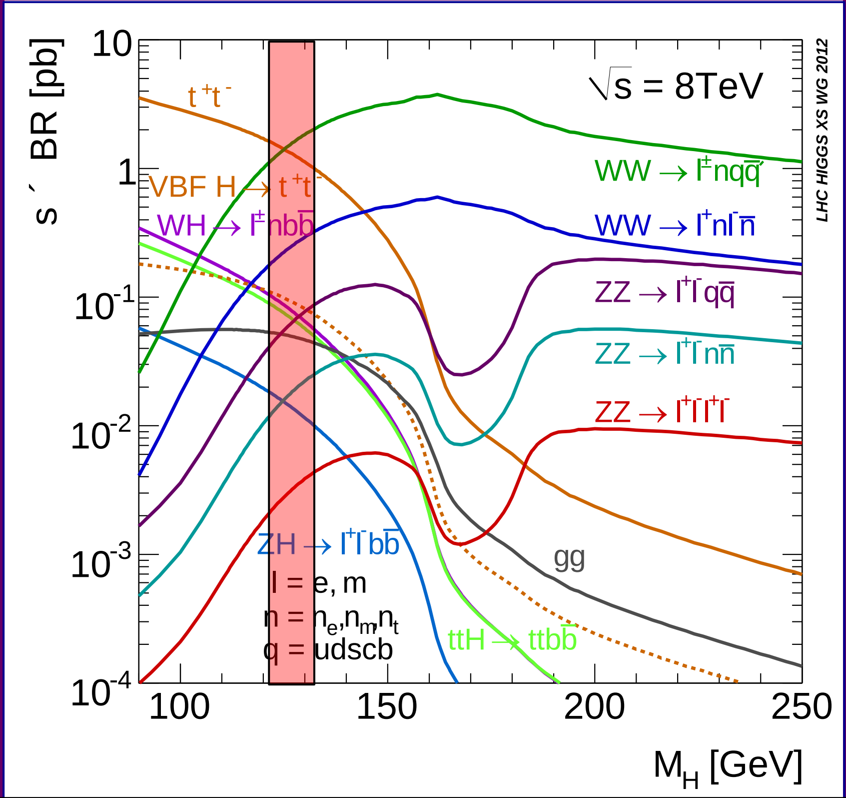
SM Higgs production cross-section and decay modes



(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$



~ 20 x Tevatron
for m =120 GeV



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

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

H→ ZZ*→ 4l, H→ γγ, H→ WW*→ lνlν

H→ ττ

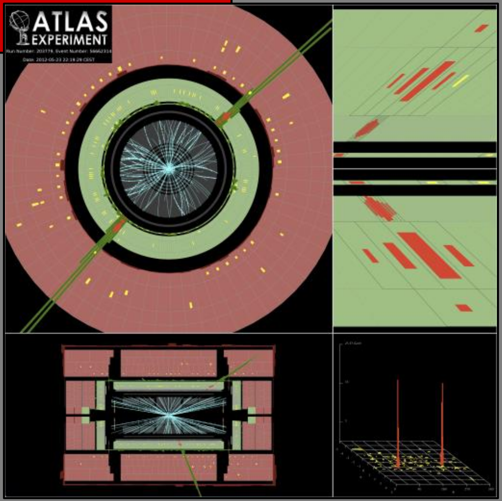
W/ZH→ W/Z bb

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

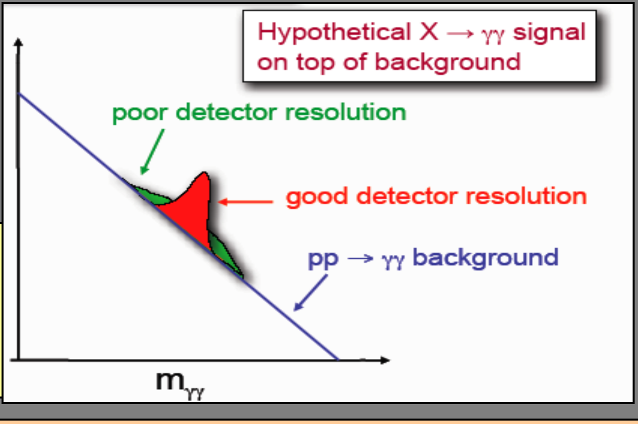
$H \to \gamma\gamma$

$\sigma \times BR \sim 50$ 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%)



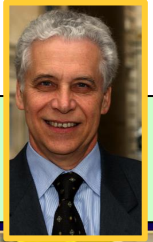
Most crucial experimental issue: excellent $\gamma\gamma$ mass resolution (electromagnetic calorimeter) to observe narrow signal peak above background



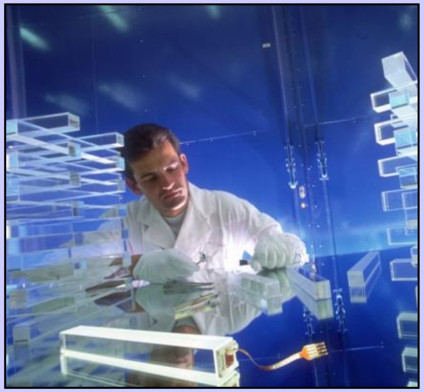
After all selections, expect ($m_H \sim 126$ GeV):
~ 400 signal events
~ 16000 background events in mass window

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.

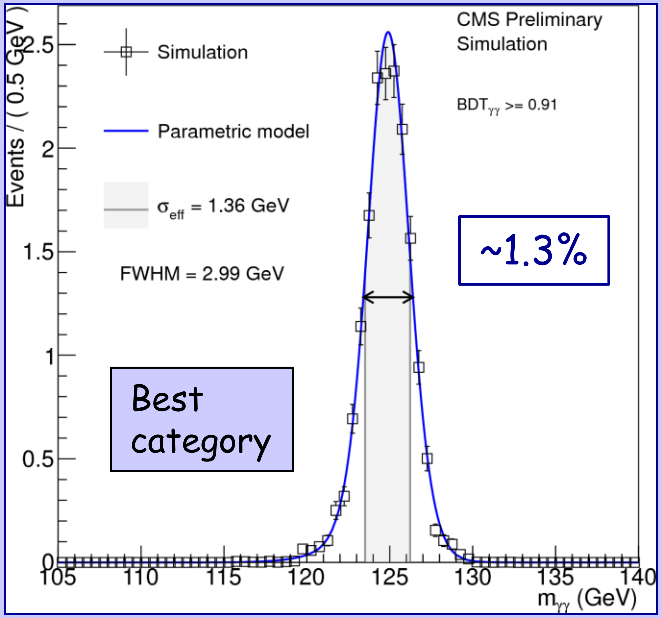
ATLAS and CMS calorimetry: the complementarity



CMS



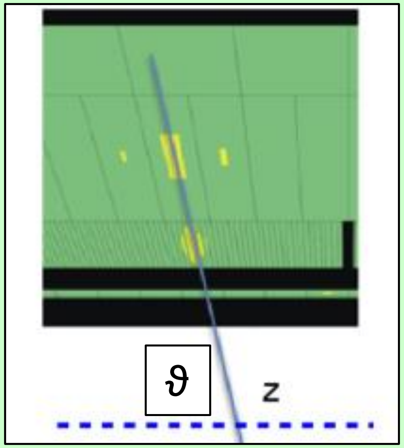
Lead-tungstate crystals (homogeneous):
- excellent E-resolution: 2-5%/√E
- no longitudinal segmentation → event vertex from tracks (more sensitive to pile-up)

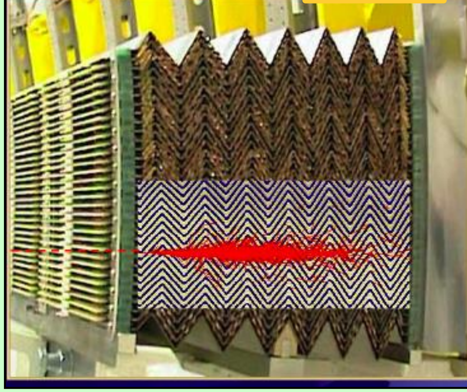


~1.3%

Best category

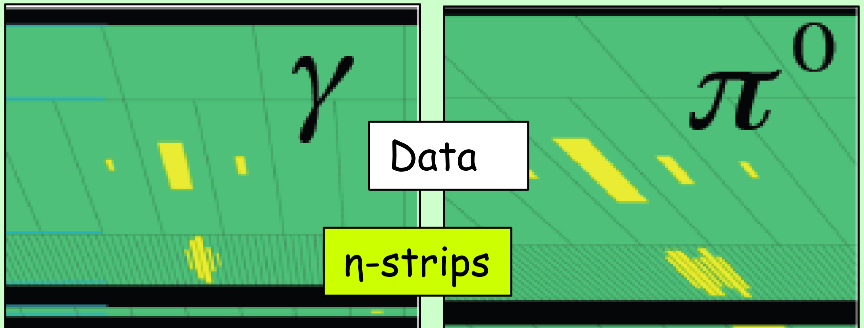
ATLAS

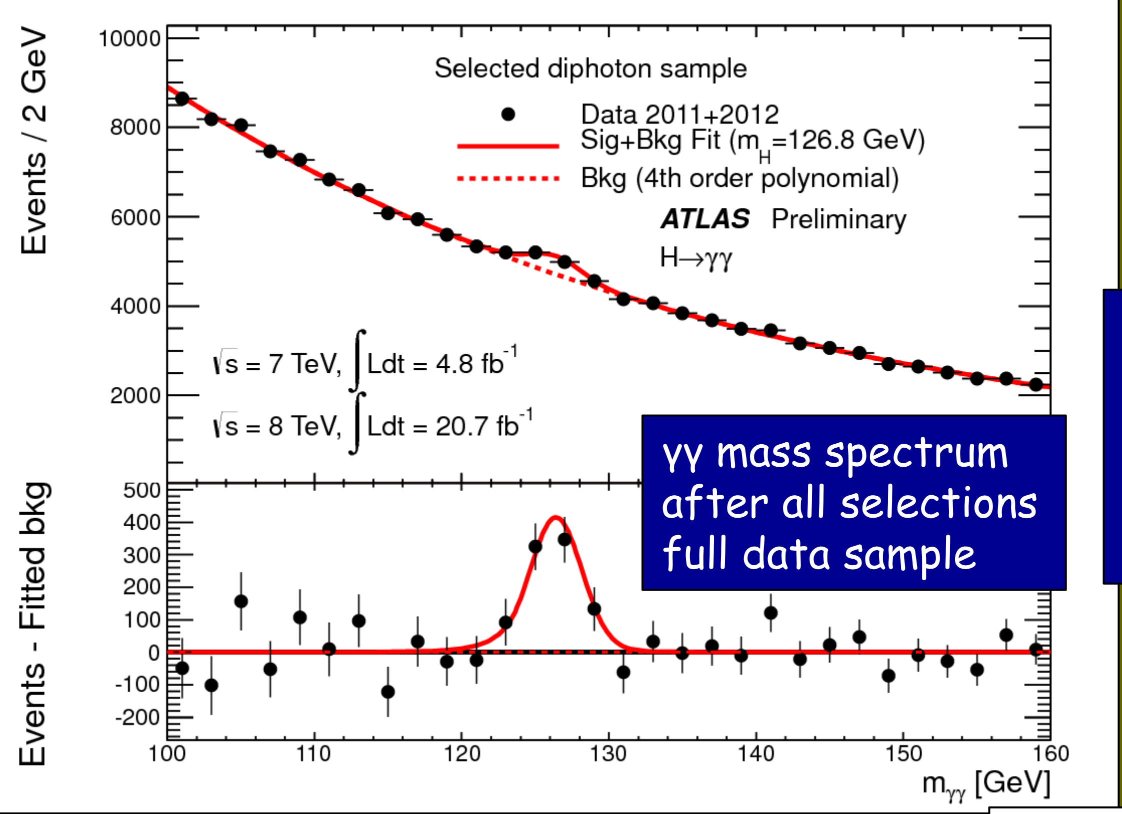




Lead/liquid-argon (sampling):
- good E-resolution: ~10%/√E
- longitudinal segmentation → primary vertex from γ direction → maintains good mass resolution in high pile-up conditions

Fine lateral segmentation
→ γ/π^0 separation (background rejection)

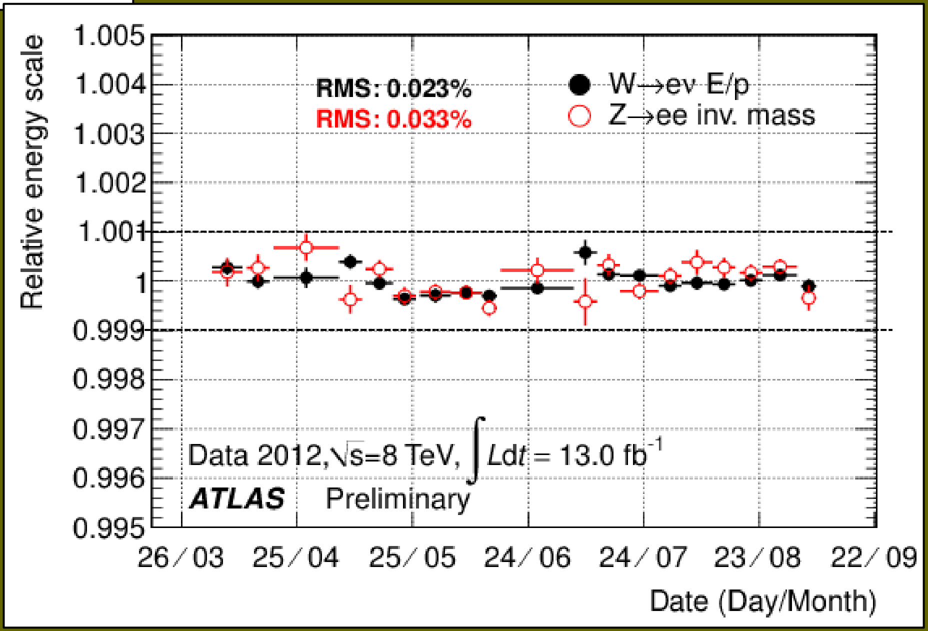




γγ mass spectrum after all selections full data sample

- ☐ 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)

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

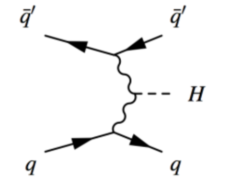


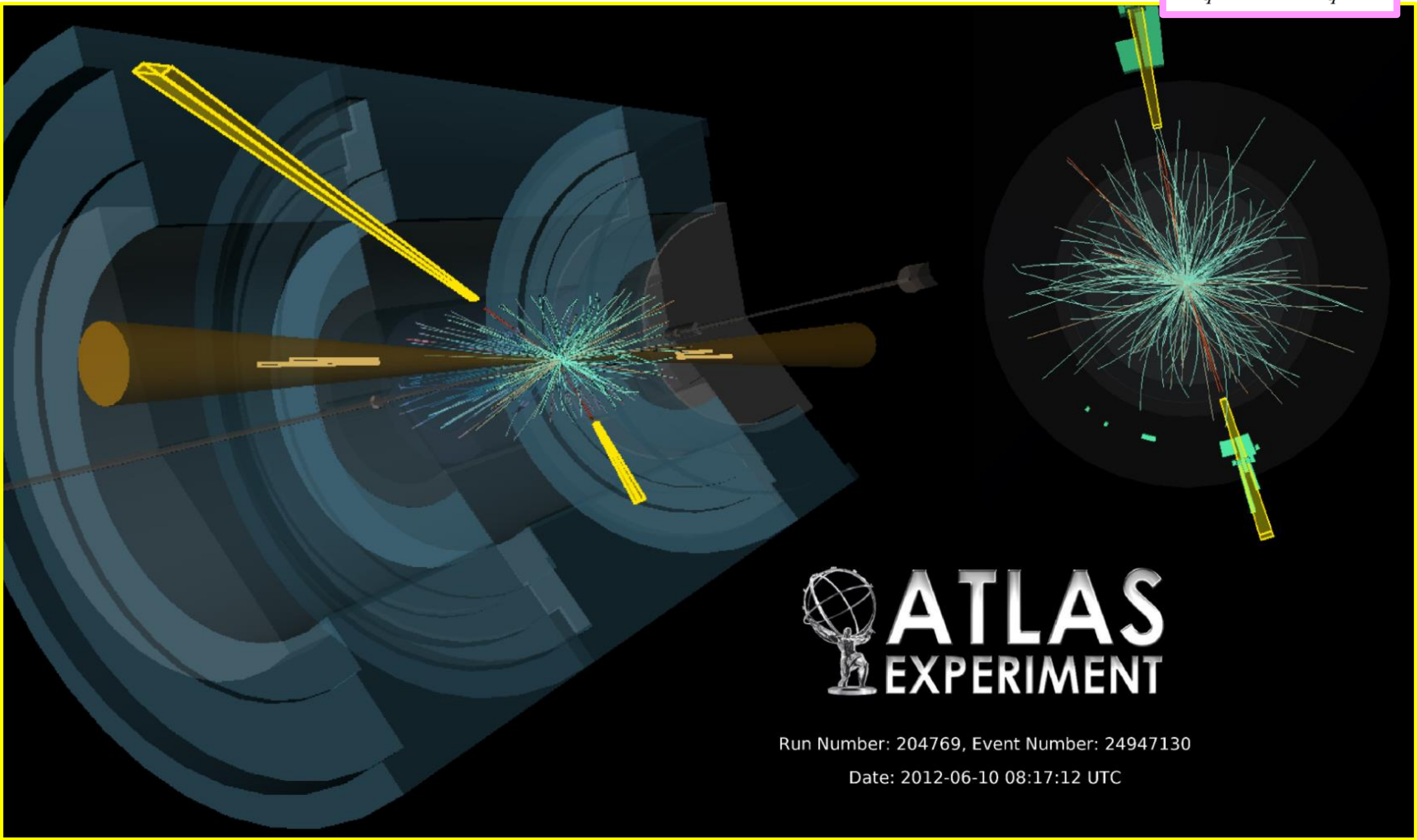
$H \to \gamma\gamma$ candidate with $m_{\gamma\gamma}$= 126.9 GeV

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

σ_{SM} (VBF) ~7%





Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

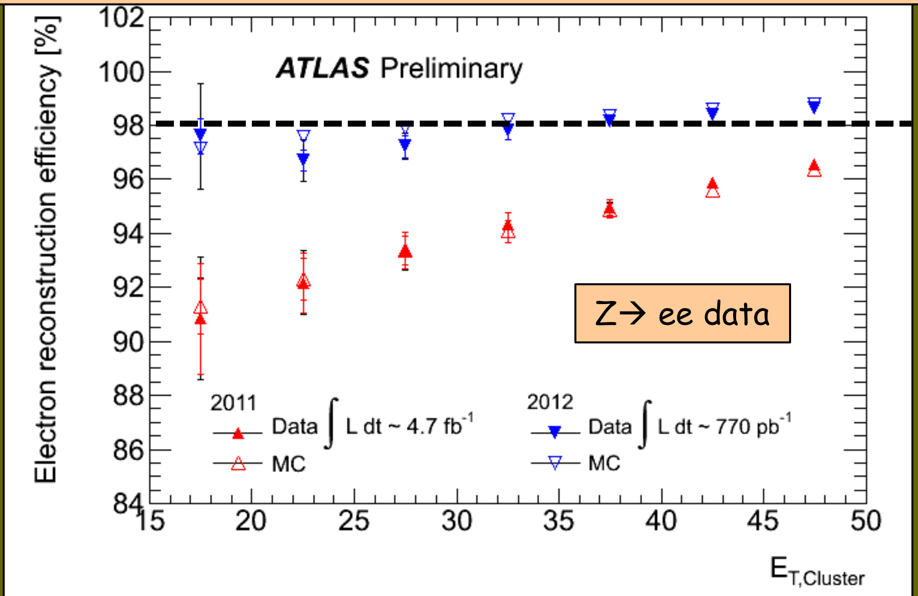
$H \rightarrow ZZ^* \rightarrow 4l$ ($4e$, 4μ, $2e2\mu$)

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

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

Crucial experimental aspect: high lepton acceptance, reconstruction and identification efficiency down to lowest p_T to capture as much as possible of the (tiny) signal

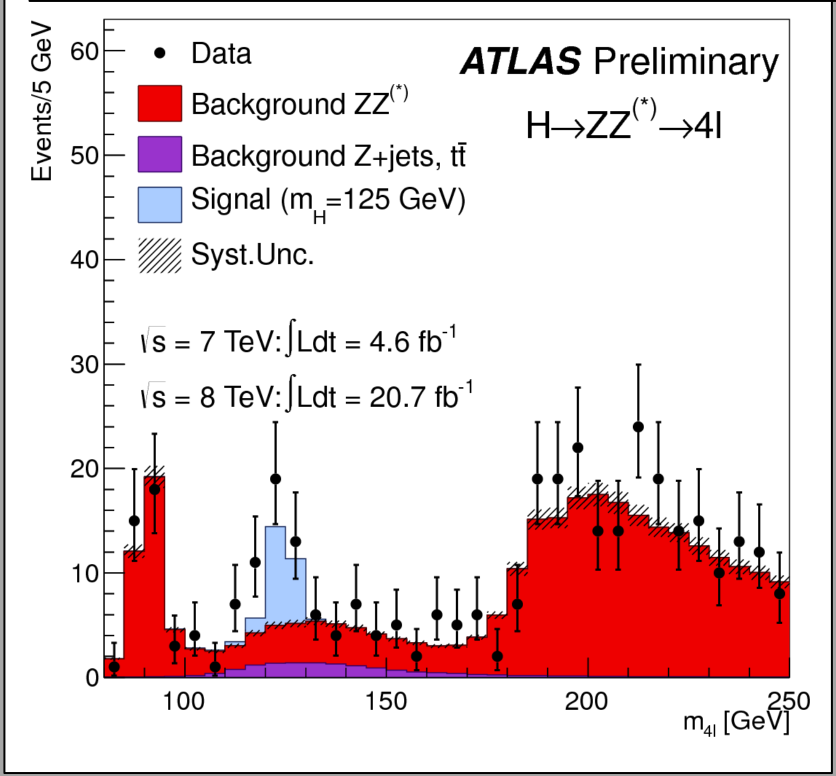
Improved $e^{\pm}$ reconstruction to recover Brem losses



Z→ ee data

Huge efforts made on 2012 to improve $e^{\pm}$ reconstruction and identification efficiency at low p_T and pile-up robustness paid dividends
→ crucial ingredient for fast discovery

4l mass spectrum after all selections; full data sample



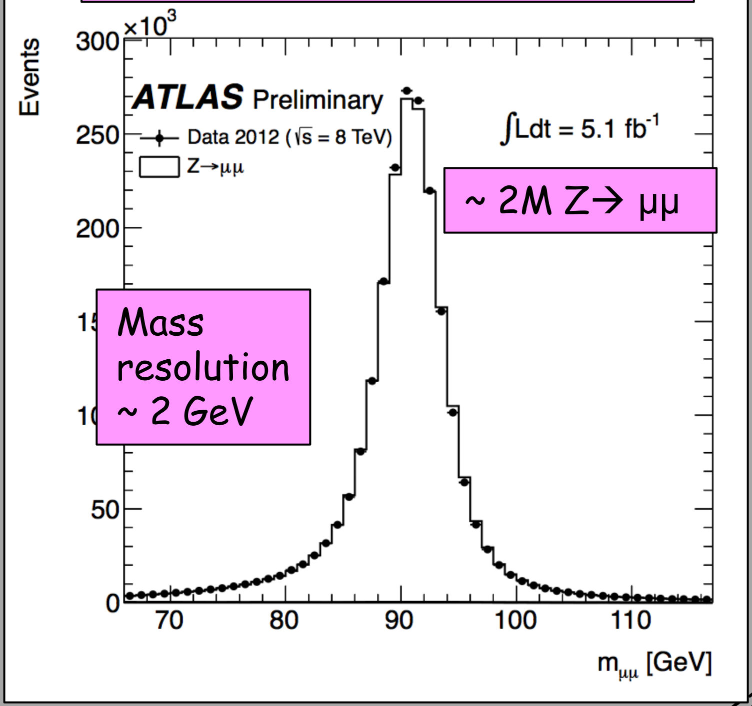
In the region 125 ± 5 GeV

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%

- Clear peak at m_H ~ 124.5 GeV
- Probability it comes from background fluctuation: ~ 10^{-10} → 6.6 σ signal significance (4.4 σ expected from SM H)

2012 Z→ μμ mass spectrum

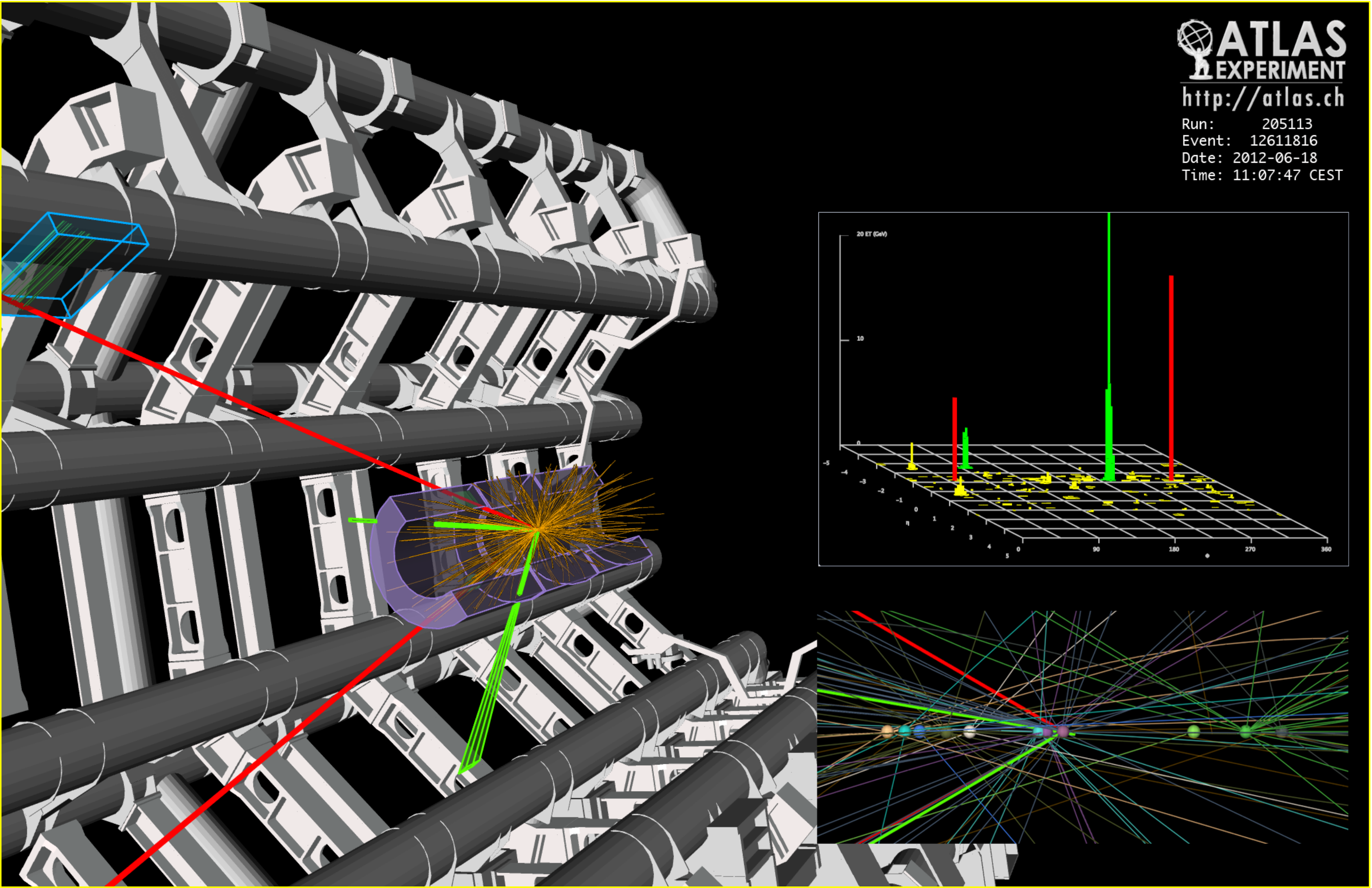


~ 2M Z→ μμ

Mass resolution ~ 2 GeV

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

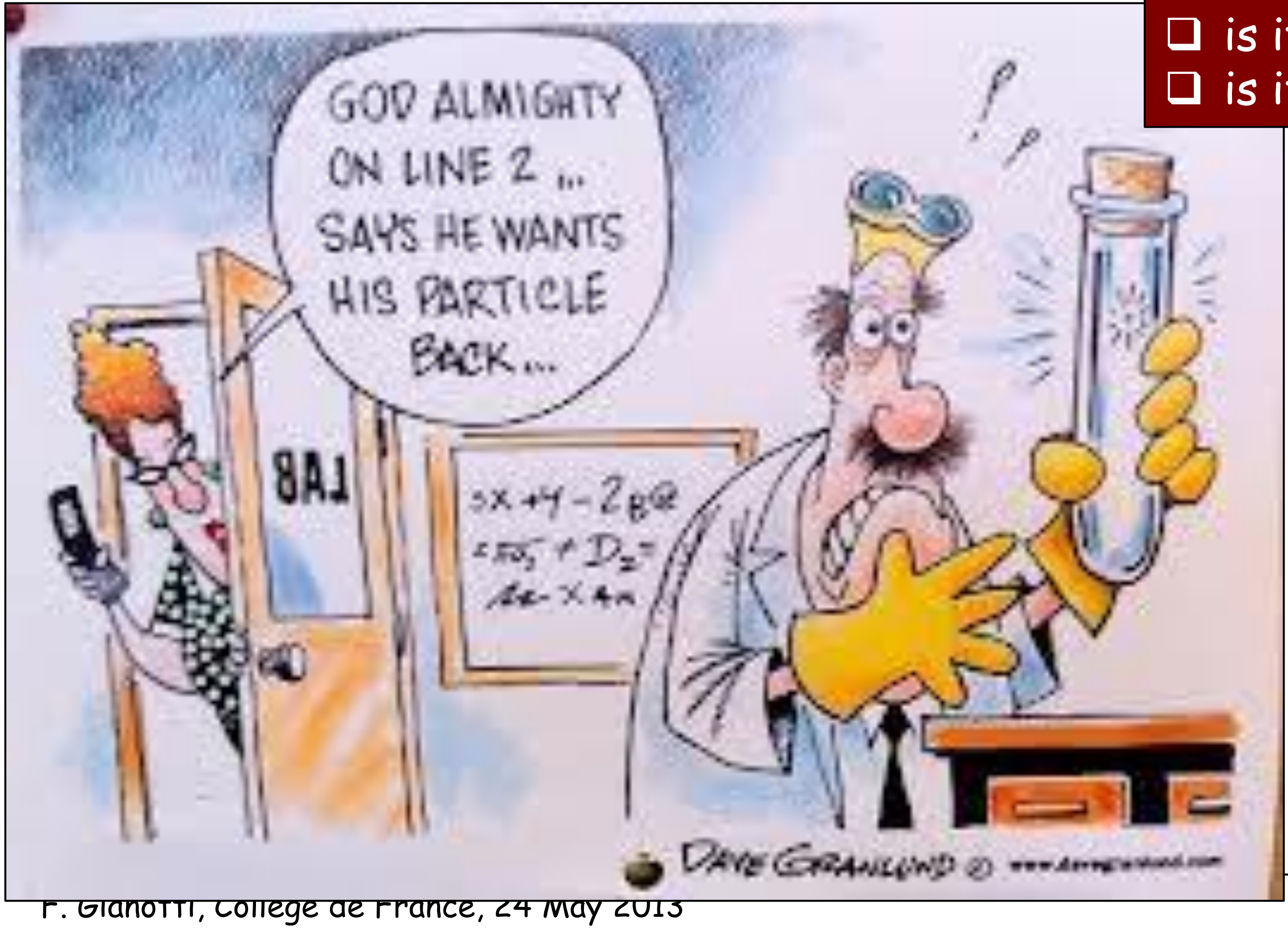


Putting all channels together: 10 σ significance or probability that what ATLAS observes comes from background fluctuation: 10^{-24} !

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 ?

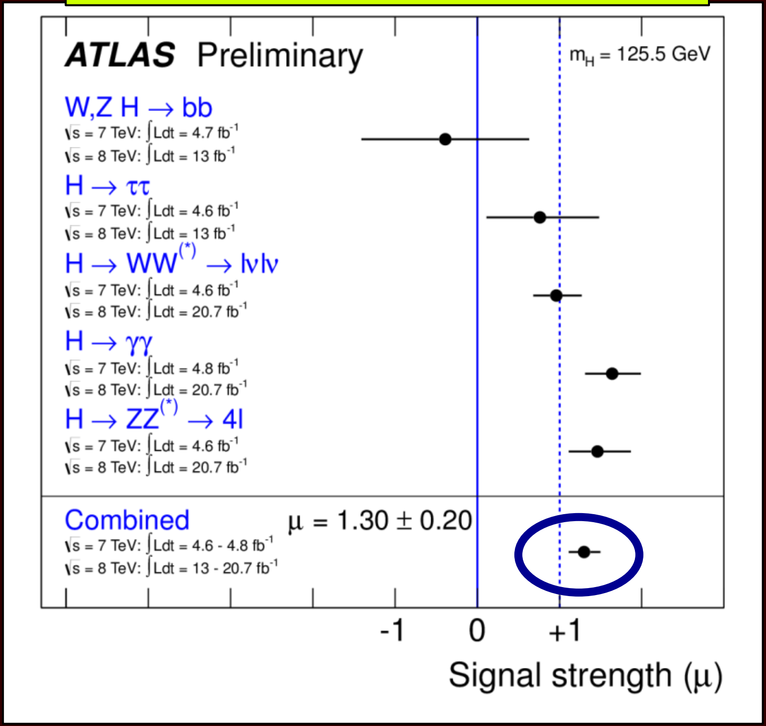


Mass measurement

From high-resolution
H→ γγ and H→ 4l channels

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

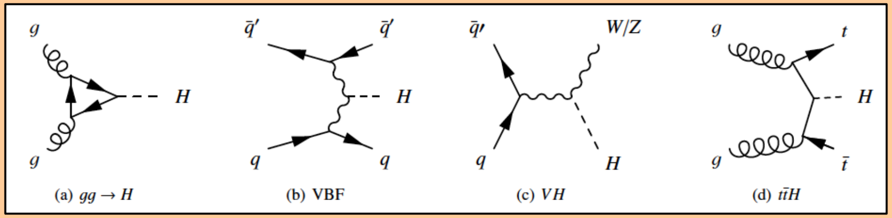
Signal production strength



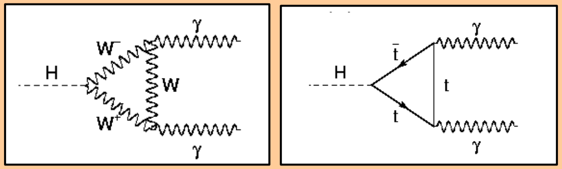
μ = measured signal production rate normalized to SM Higgs expectation at m_H = 125.5 GeV

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

Constraining production modes and couplings (examples …)

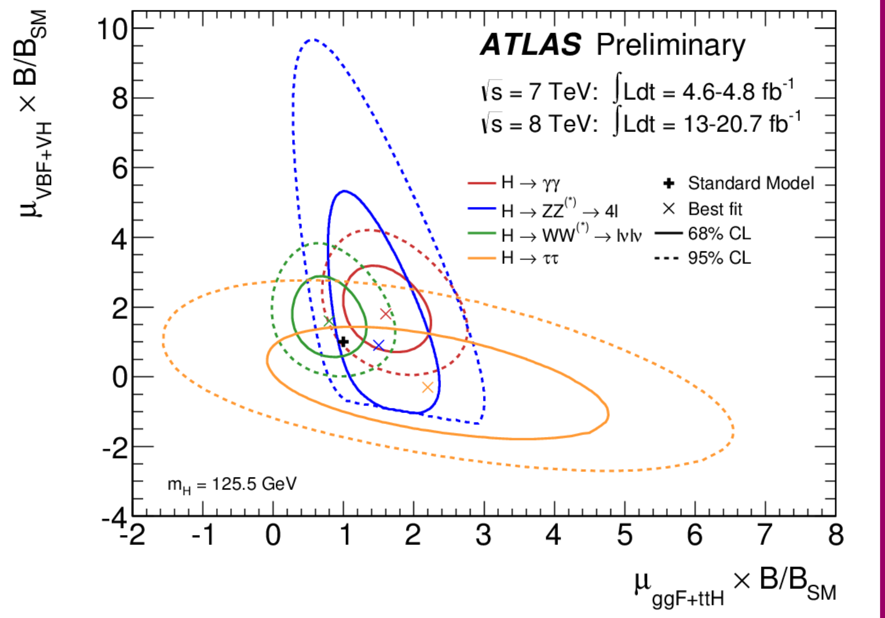


(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

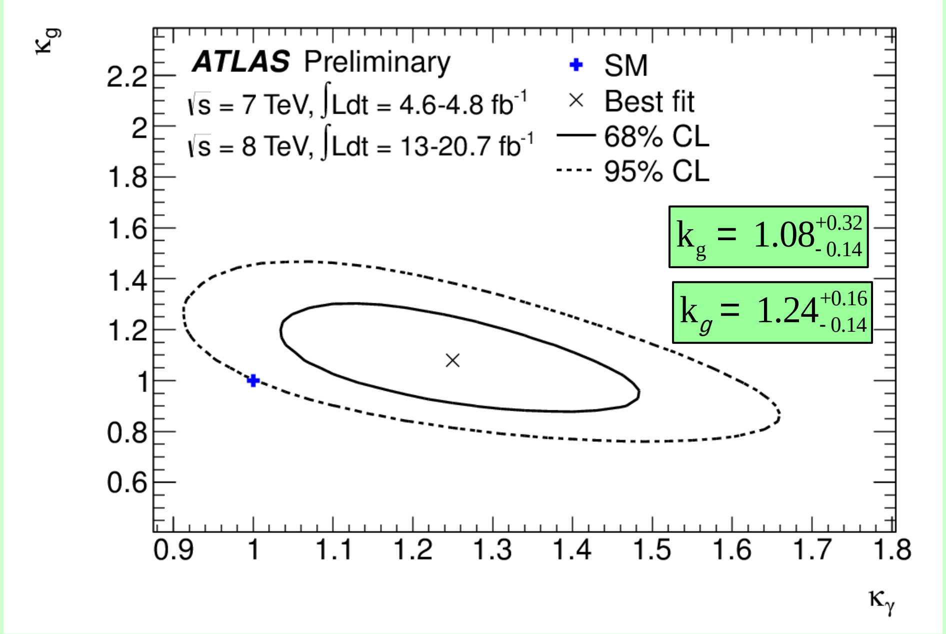


$$k_i^2 = \frac{G_i^{data}}{G_i^{SM}}$$

Vector-boson (VBH, VH) vs top-quark (ggF, ttH) induced processes



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



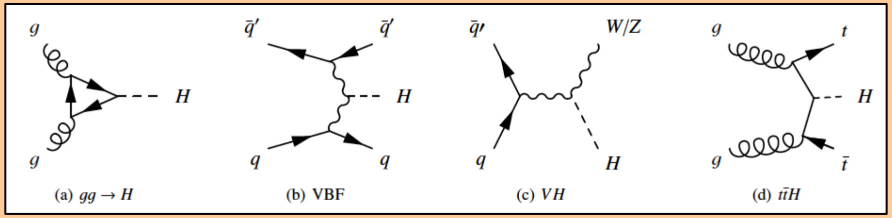
$k_g = 1.08^{+0.32}_{-0.14}$

$k_g = 1.24^{+0.16}_{-0.14}$

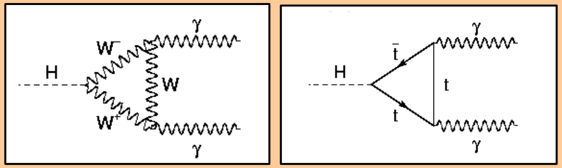
- ☐ 3σ significance for non-vanishing VBF production fraction
- ☐ evidence that the new particle couples to W and Z as expected

→ first "fingerprint" of a Higgs boson (to accomplish its job → EWSB/Higgs mechanism)

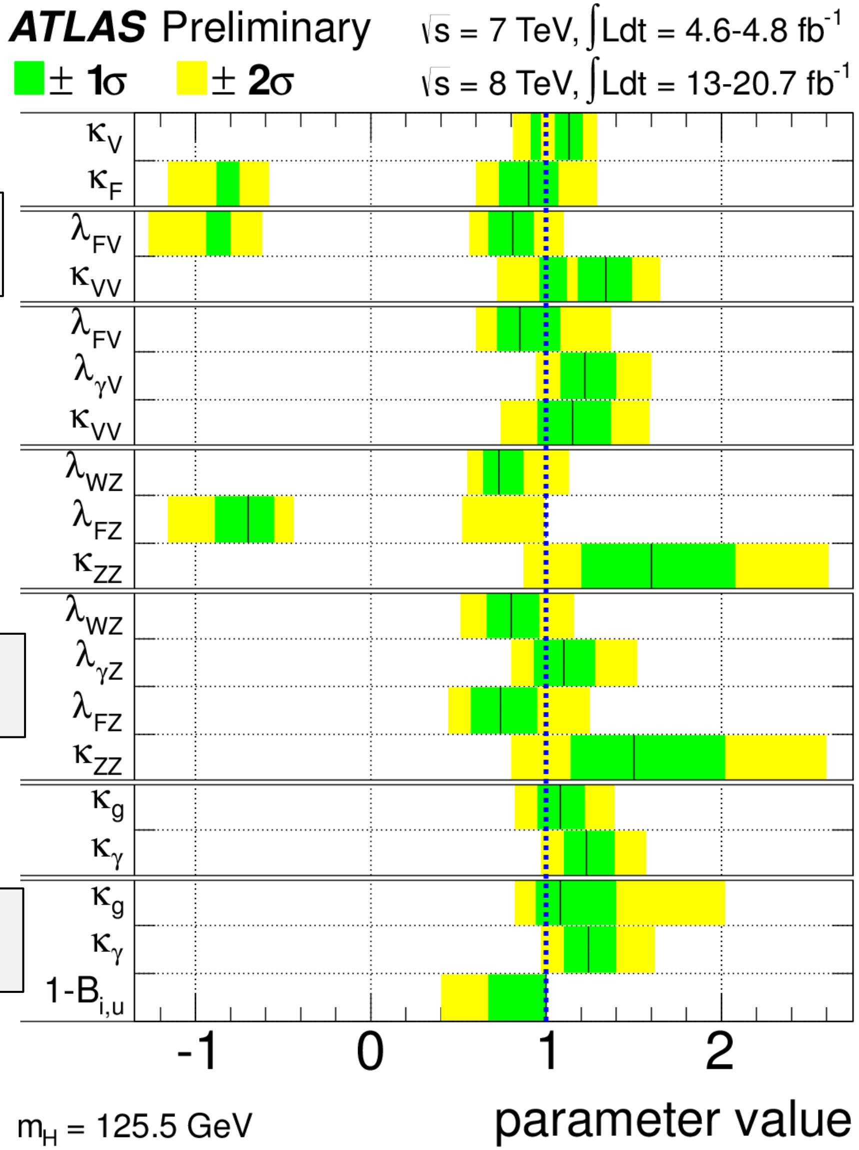
- ☐ No significant New Physics contributions observed (within present uncertainty)



(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$



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



No assumption on Γ_H

No assumption on Γ_H, k_γ

No assumption on k_γ

No assumption on Γ_H

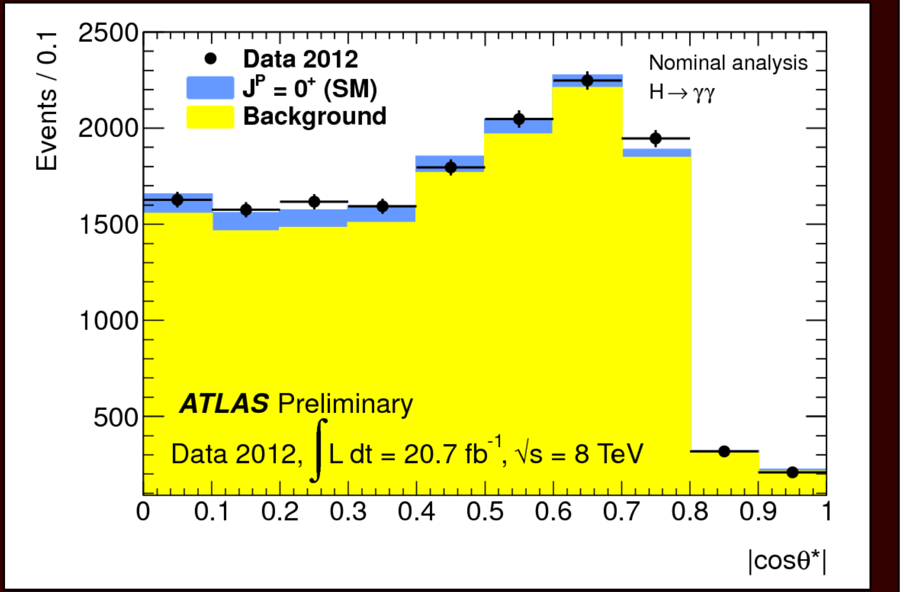
2nd "fingerprint" of a Higgs boson: it has spin zero

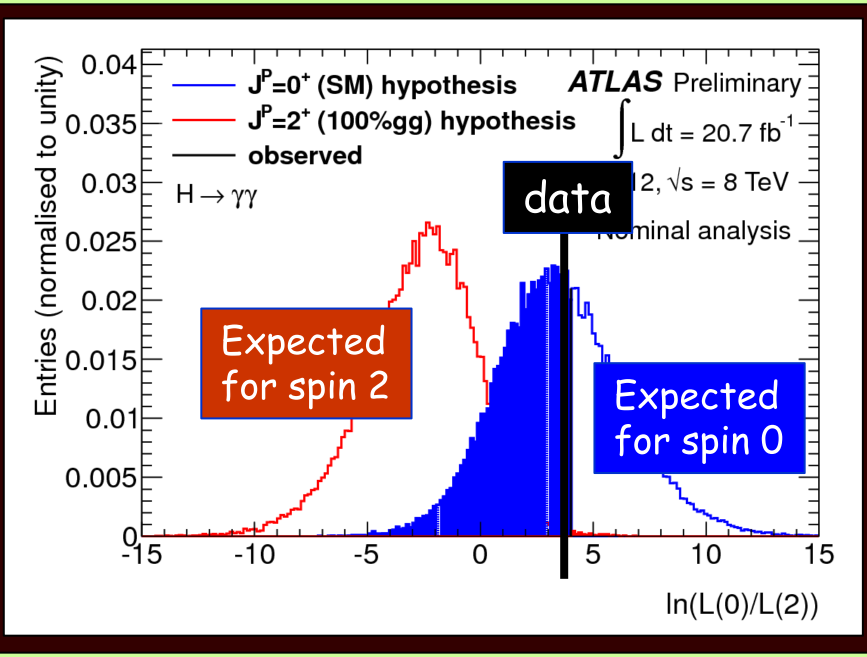
H→ γγ

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

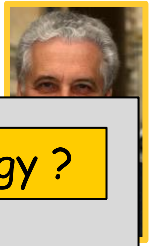
Expected for spin 2

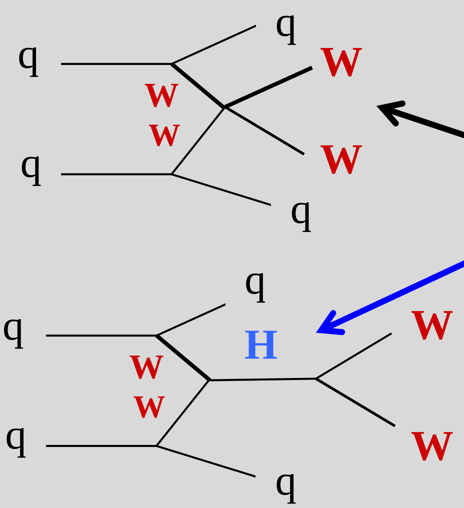
Expected for spin 0

Combining all channels: 2^+ hypothesis rejected at > 99.9% CL
(0^- hypothesis rejected at 99.6% CL from H → 4l)

If this is the first elementary scalar, consequences also for Universe evolution (inflation triggered by a scalar field)

Two additional questions





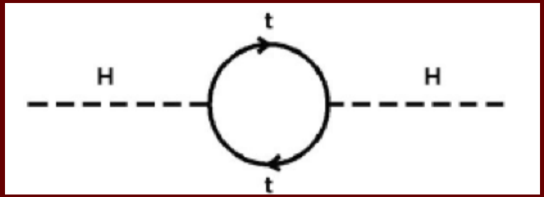
Does this new particle fix the SM problems at high energy ?

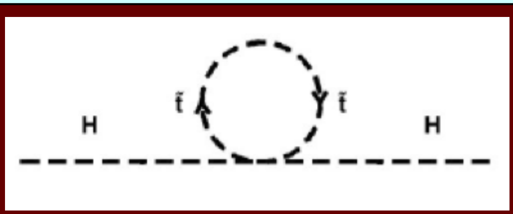
This process violates unitarity: $\sigma \sim E^2$ at $m_{WW} \sim$ TeV
(divergent cross section → unphysical)
if this process does not exist

→ Important to verify that the new particle accomplishes this task → a "closure test" of the SM
→ Need $\sqrt{s} \sim 14$ TeV and ~3000 fb^{-1}

Why is the Higgs so light ?

Is m_H stabilized by ~TeV scale new physics (e.g. SUSY) or is it fine-tuned ?





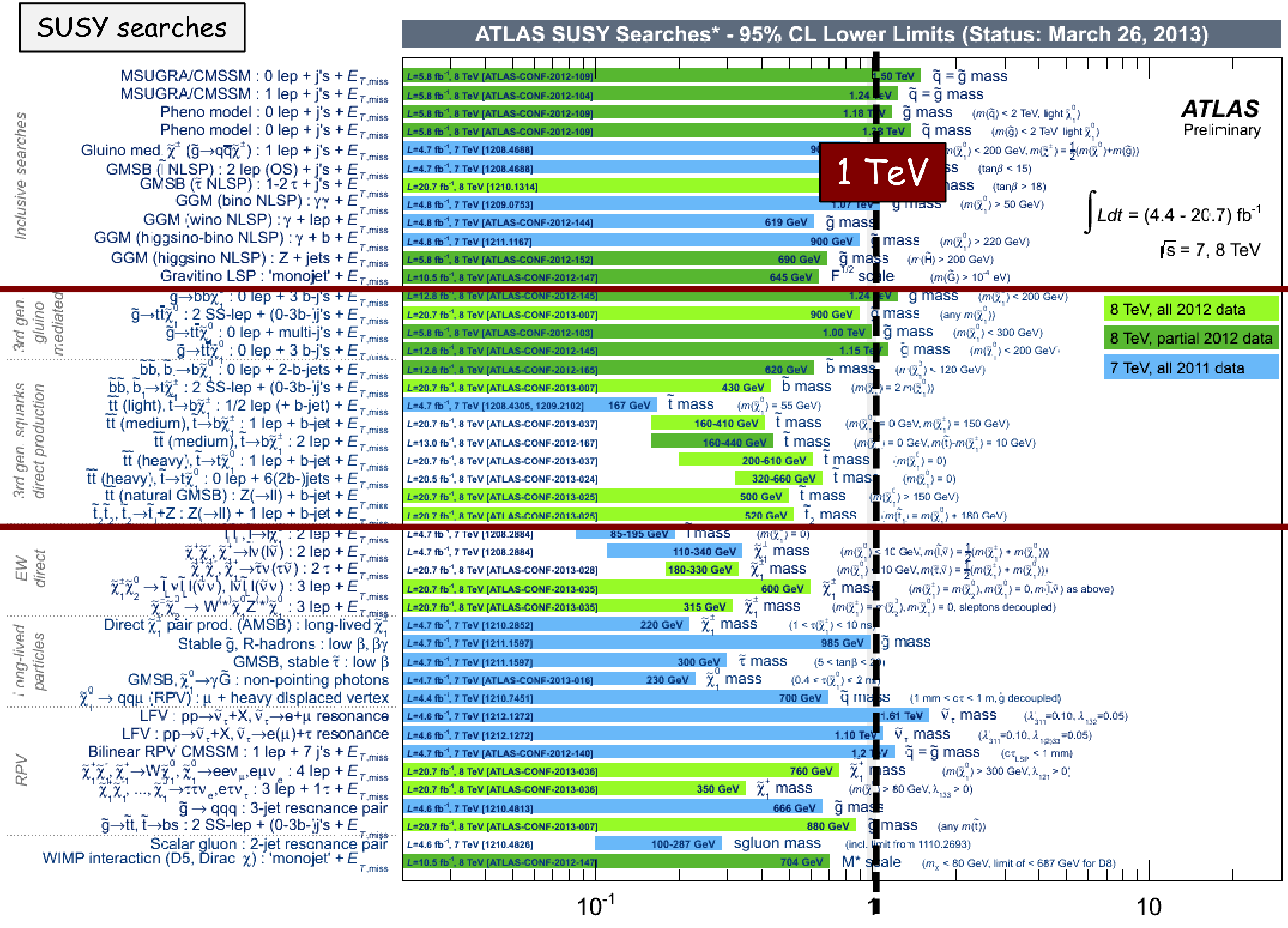
In the SM, top-loop corrections to m_H diverge as ~ Λ^2 (energy scale up to which the SM is valid)

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

Searches for physics beyond the SM

Huge number of models and topologies investigated

SUSY searches

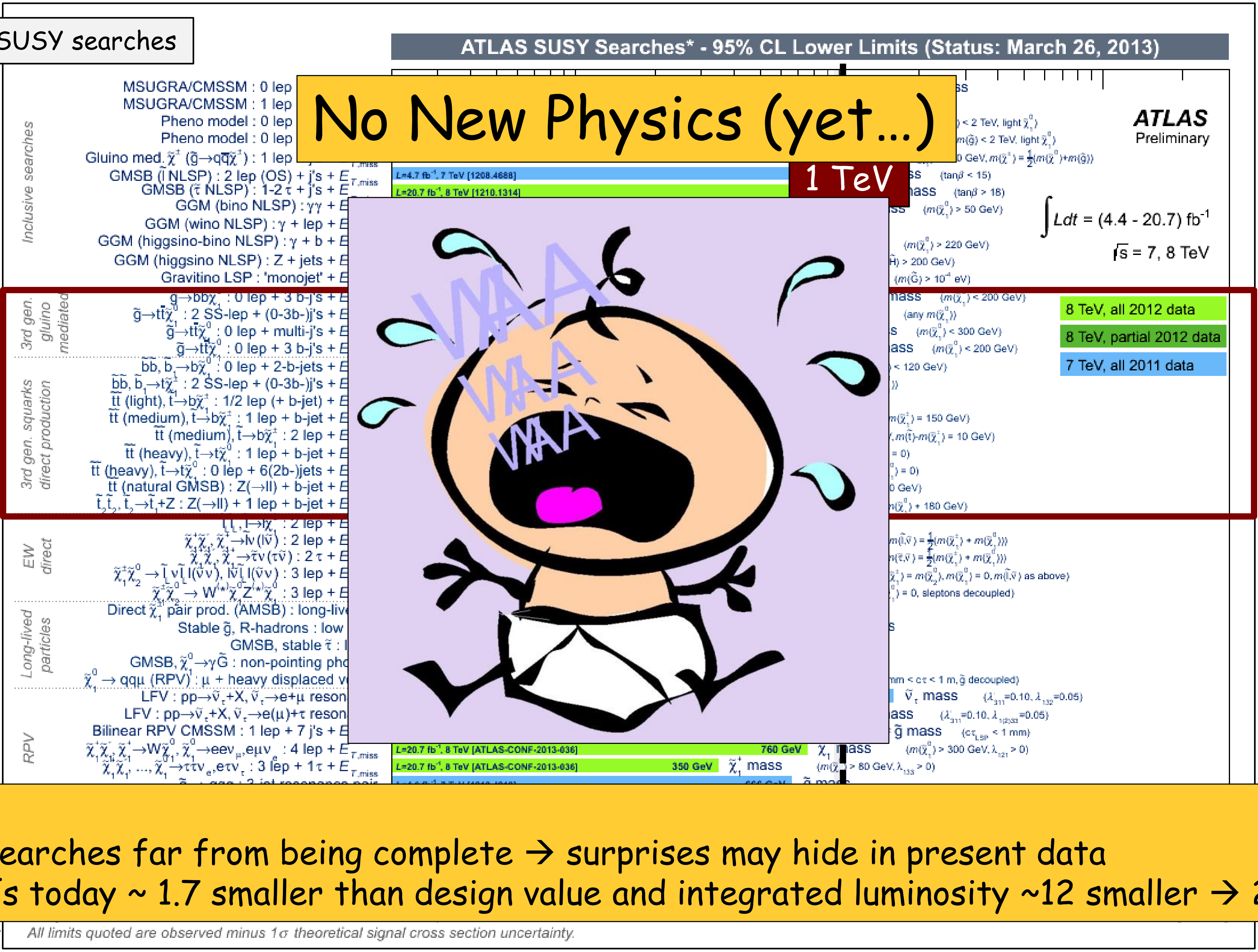


*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Searches for physics beyond the SM

Huge number of models and topologies investigated

SUSY searches



No New Physics (yet…)

1 TeV

But
- ❑ searches far from being complete → surprises may hide in present data
- ❑ √s today ~ 1.7 smaller than design value and integrated luminosity ~12 smaller → 2015++

The next steps …

With the data recorded in "Run 1" (~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 at 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):

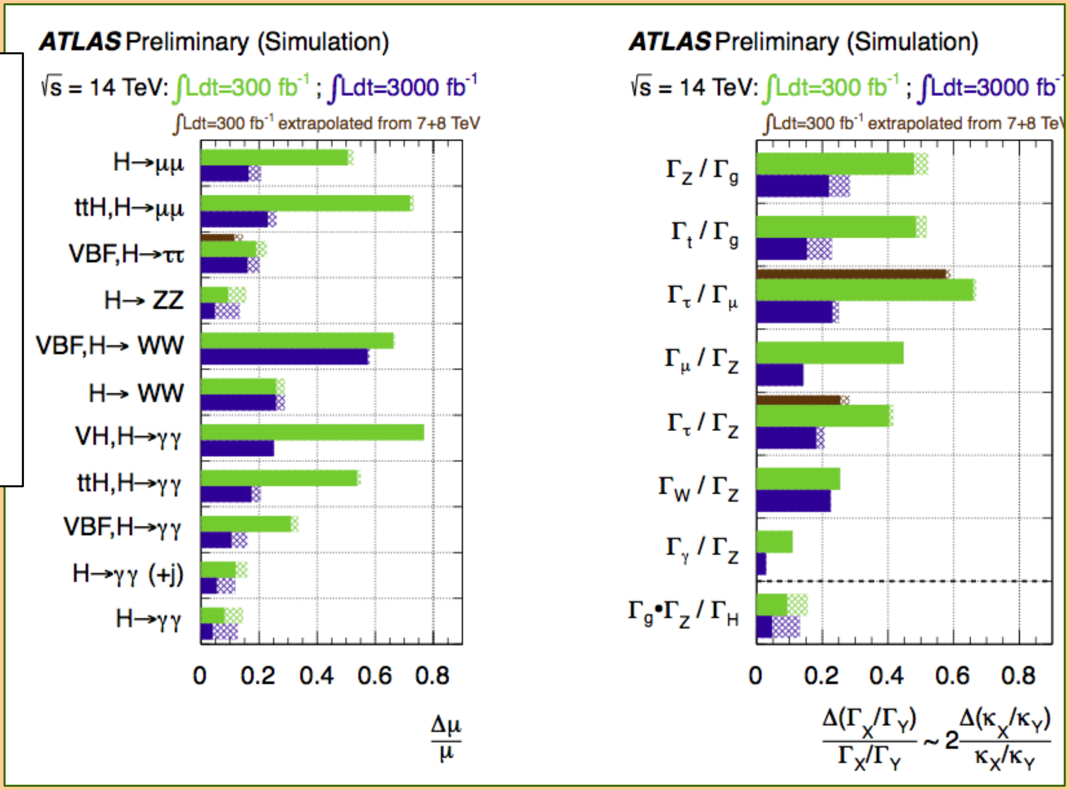
2013-2014: shut-down (LS1)
2015-2017: √s ~ 14 TeV, L ~ 10^{34}, ~ 100 fb^{-1}
2018: shut-down (LS2)
2019-2021: √s ~ 14 TeV, L ~ 2×10^{34}, ~ 300 fb^{-1}
2022-2023: shut-down (LS3)
2023- 2030 ?: √s ~ 14 TeV, L ~ 5×10^{34} , ~ 3000 fb^{-1} (HL-LHC)

LHC upgrade:
300 fb^{-1} at 14 TeV by ~2020 and 3000 fb^{-1} by ~2030
→ significant improvements on Higgs measurements and searches for New Physics

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}

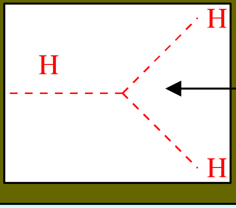
per experiment.
Down to few % in some cases if less conservative systematics (e.g. theory error halved)



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

Summary of the big questions …

- ☐ Is it A Higgs boson:
  - -- does it couple to W/Z as expected ? yes
  - -- does it have spin zero ($J^P=0^+$) ? data strongly favour 0^+

- ☐ Is it THE SM Higgs boson ? looks like … but too early to conclude as present experimental + theoretical precision limited to ~20%
  - -- is it elementary (the first elementary scalar ever !) or composite ? no significant deviations from the SM expectation so far
  - -- are there New Physics contributions to the gg-fusion or H → γγ loops ? compatible with SM within present precision (ATLAS H → γγ at 2.3 σ)
  - -- does it decay to invisible particles ? BR (H→ BSM) < 60% at 95% CL
  - -- is it alone ? looking …

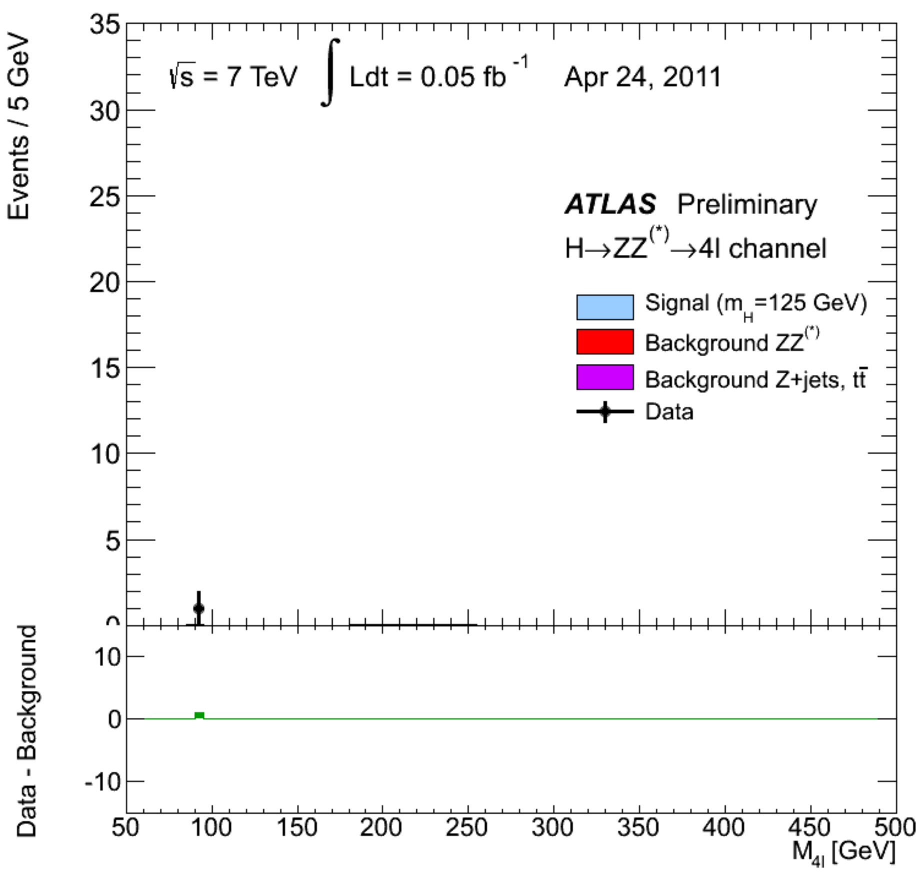
- ☐ Is its mass stabilized by New Physics (e.g. SUSY) ? → nothing found yet … searches will continue at 14 TeV

- ☐ Does it fix the SM unitarity problems in WW scattering at high mass ? need LHC upgrade to address this

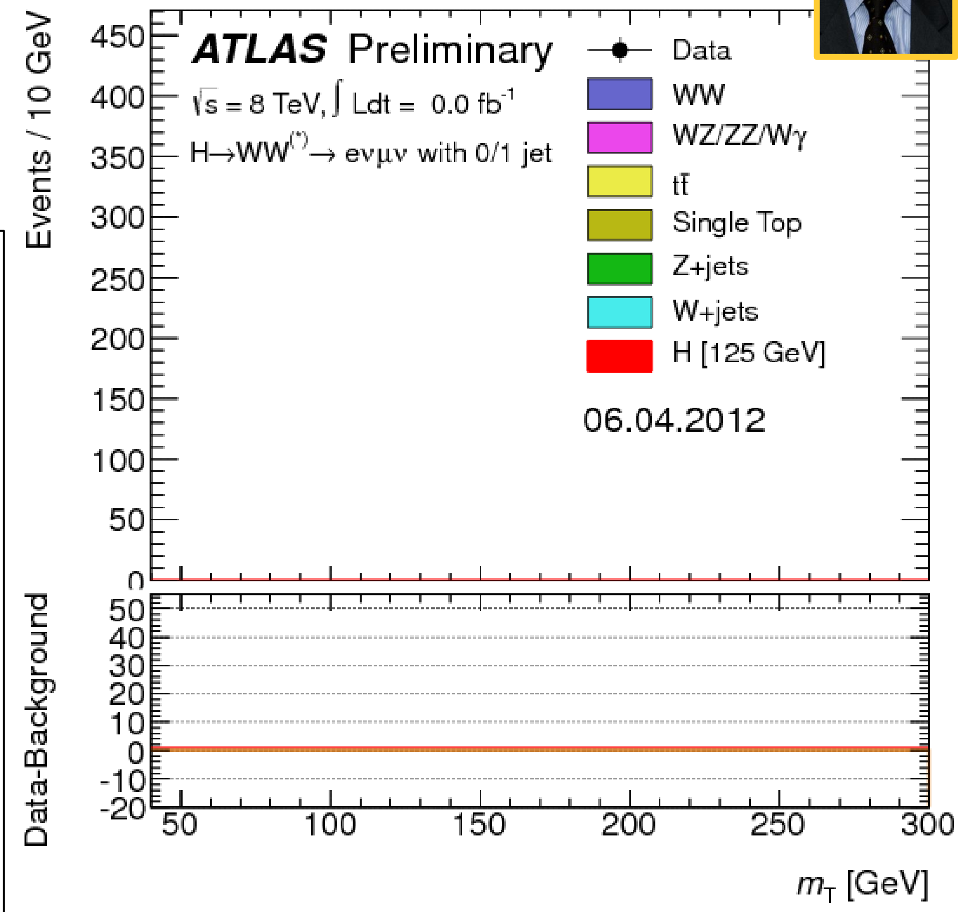
- ☐ What are its self-couplings ? need LHC upgrade to address this

Birth and evolution of a signal

H→ ZZ*→ 4l



H→ WW*→ lνlν



Conclusions

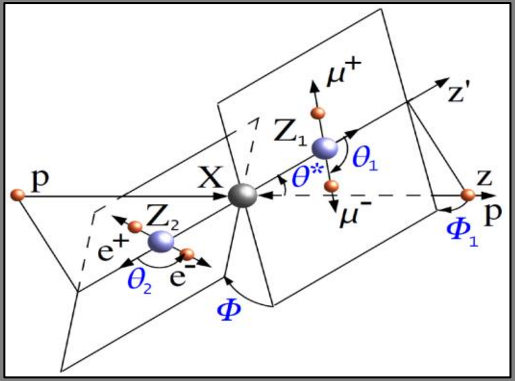
The first LHC proton run (2010-2012) has been EXTRAORDINARY !
Accelerator, experiments, computing (and people !) have performed beyond "design specifications" during three demanding but very exciting years.

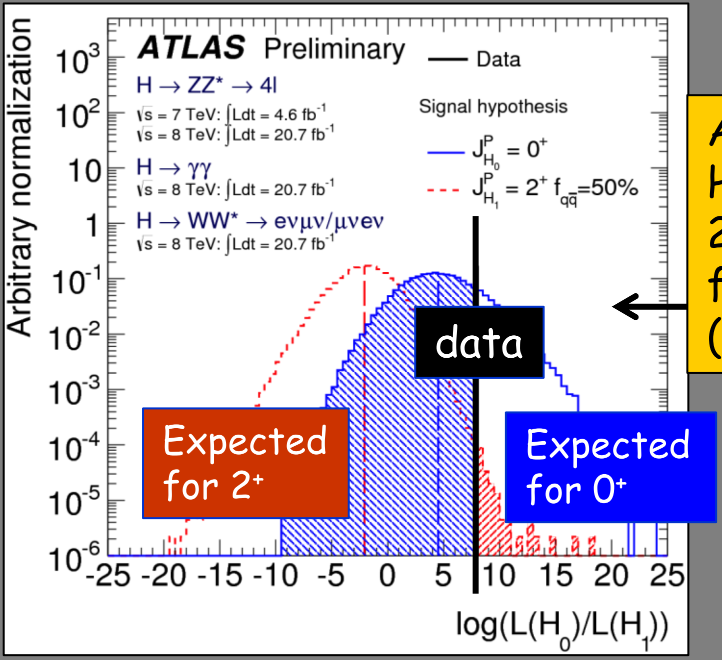
Among the achievements is the crucial discovery of a very special particle, which looks pretty much like the Standard Model scalar.
The era of precise measurements of our new friend has started.

These accomplishments are the result of more than 20 years of talented work and extreme dedication of those involved in the LHC project.
More in general, they are the result of the ingenuity, vision, tenacity, painstaking work of the full HEP community (accelerator, instrumentation, computing, experimental physics, theory)

Thank you Gabriele for being among those who have inspired and given us the courage to undertake such a challenging and exciting adventure !

SPARES



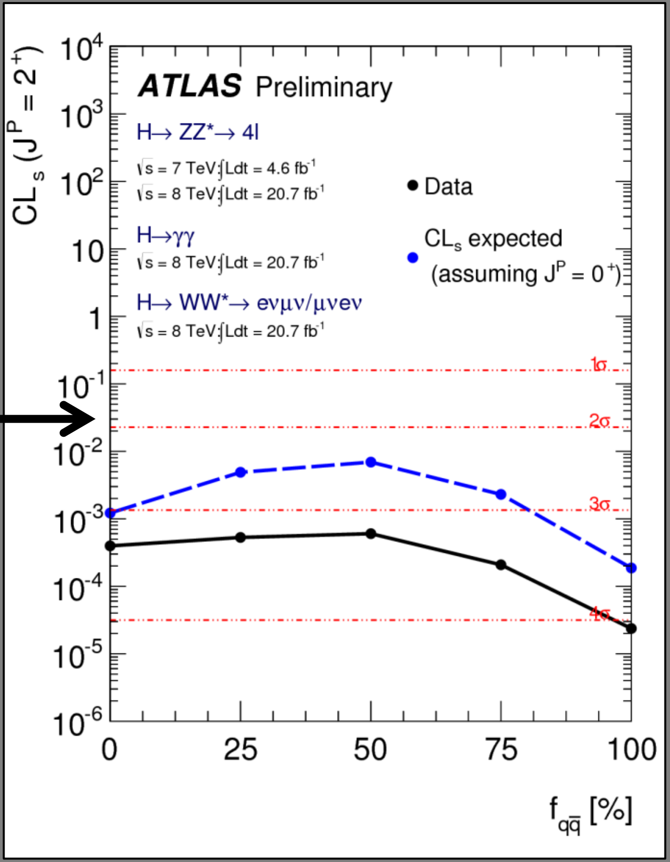


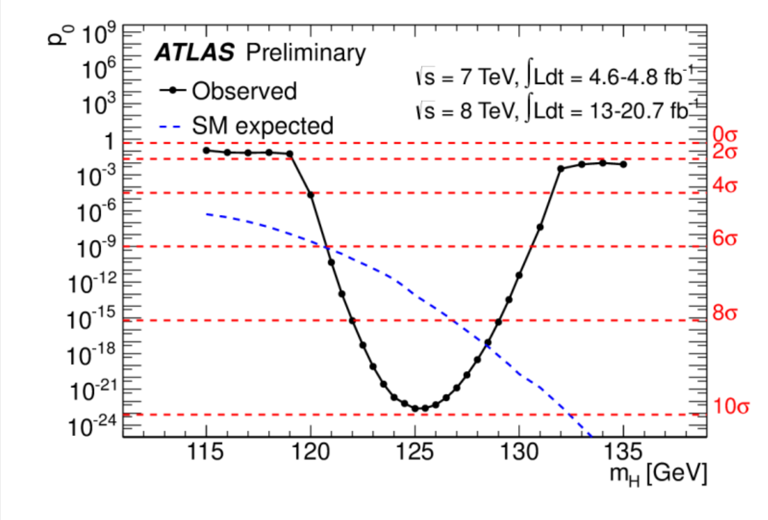
data

Expected for 2^+

Expected for 0^+

ATLAS: combining
$H \rightarrow \gamma\gamma$, $H \rightarrow 4l$, $H \rightarrow l\nu l\nu$:
2^+ disfavoured at 3-4 σ
for any production mode
(qq or gg)





Mass measurement

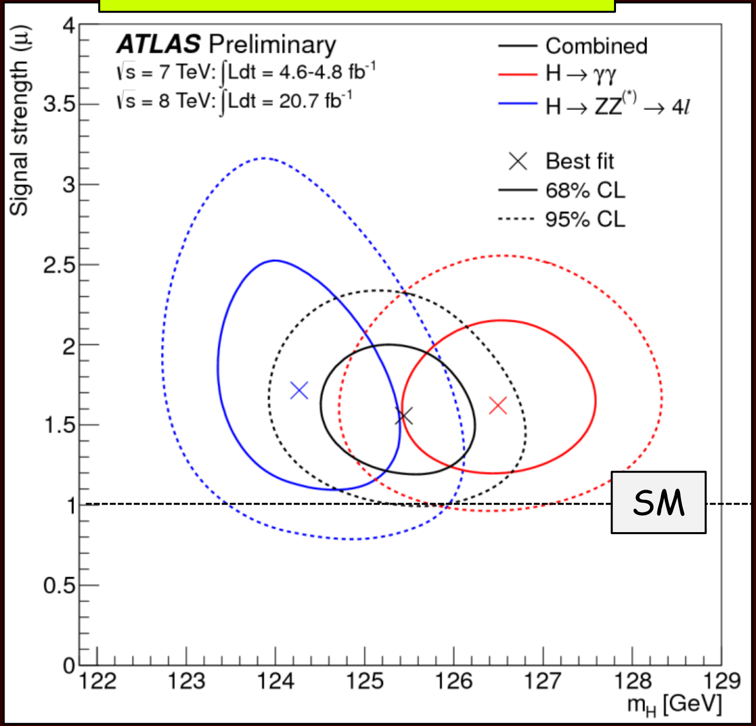
Estimated mass from high-resolution H→ γγ and H→ 4l channels:

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

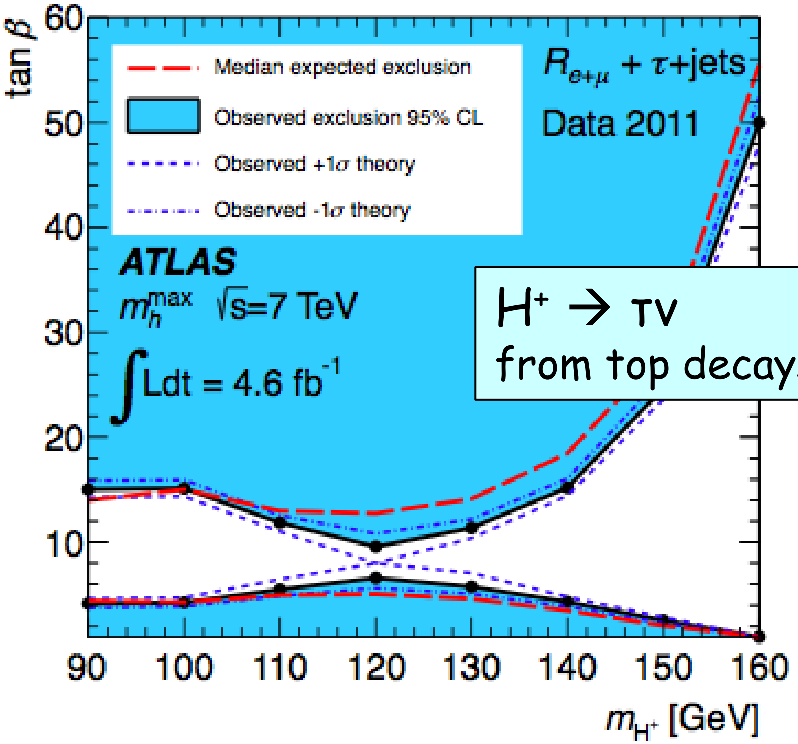
m_H (4l) = 124.3 GeV $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV

Probability for same particle: 1.5-8%

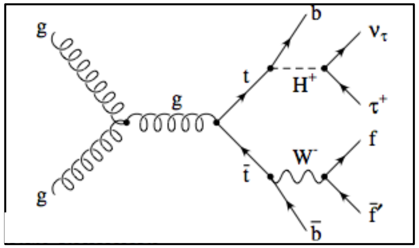


SM

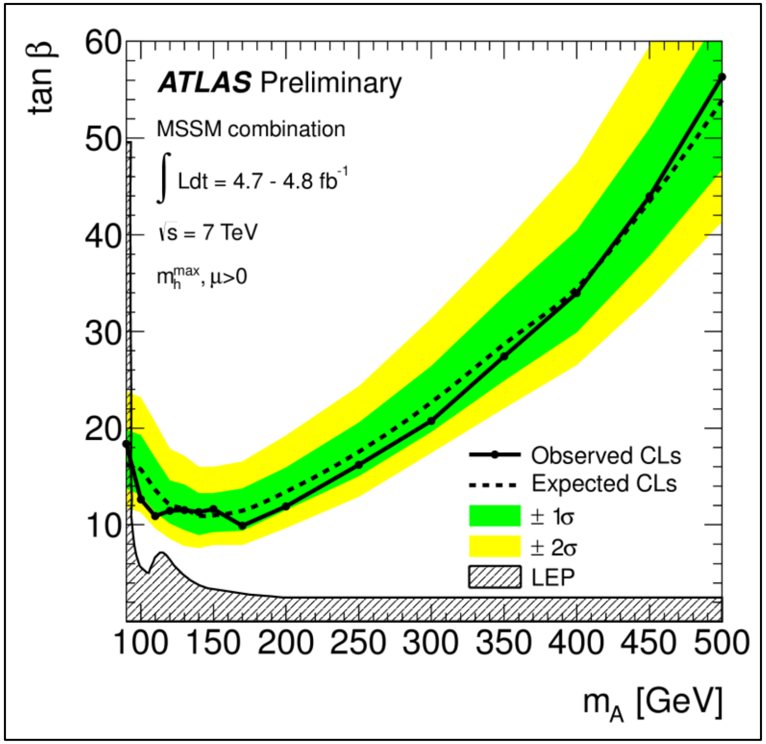
Searches for MSSM Higgs bosons



$H^+ \rightarrow \tau\nu$
from top decays



$A/H \rightarrow \tau\tau, \mu\mu$



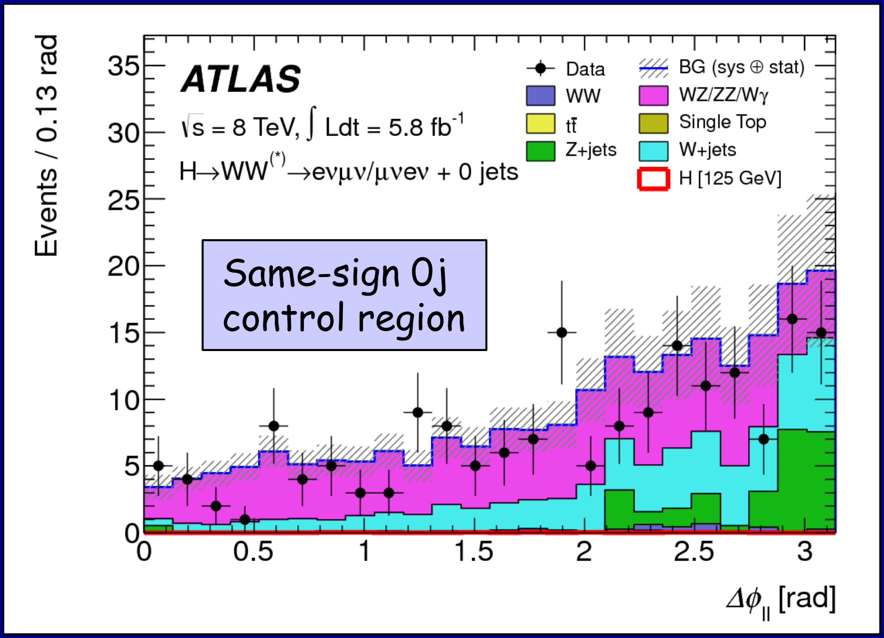
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ ($e\nu e\nu$, $\mu\nu\mu\nu$, $e\nu\mu\nu$)

σ x BR ~ 200 fb for m~ 125 GeV

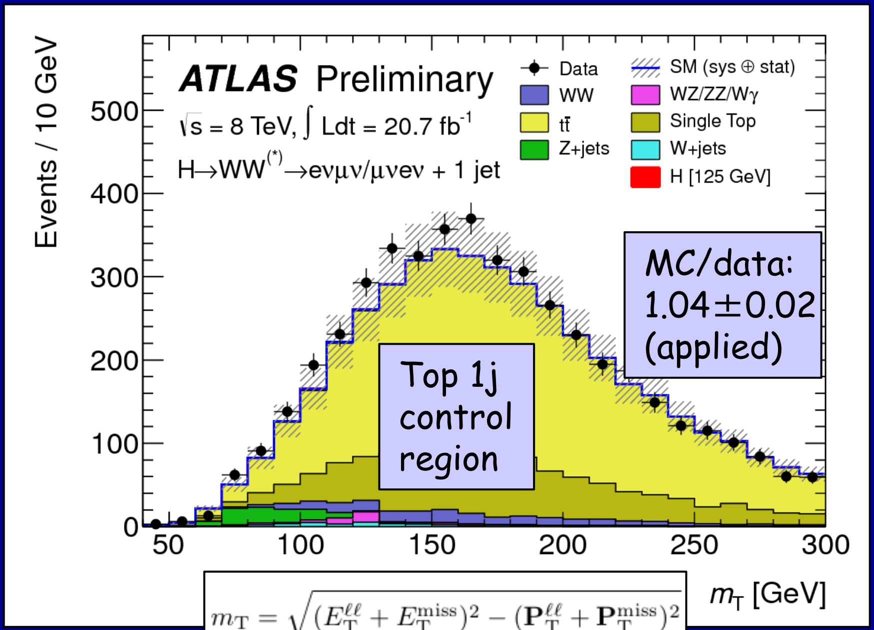
- ☐ Large cross section
- ☐ However: 2ν in final state → mass peak cannot be reconstructed → "counting channel"

- ☐ 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



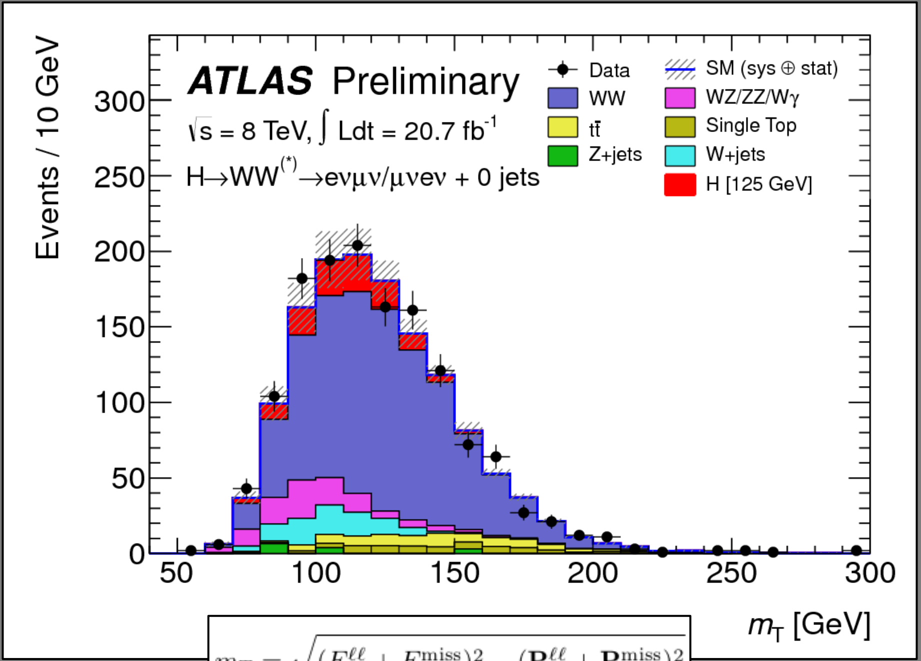
Same-sign 0j control region



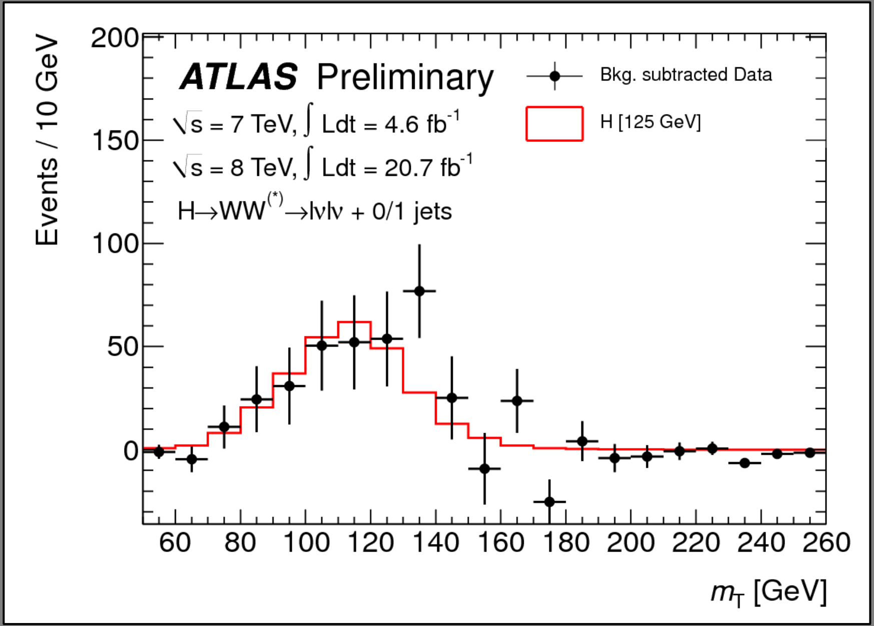
Top 1j control region

MC/data: 1.04±0.02 (applied)

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

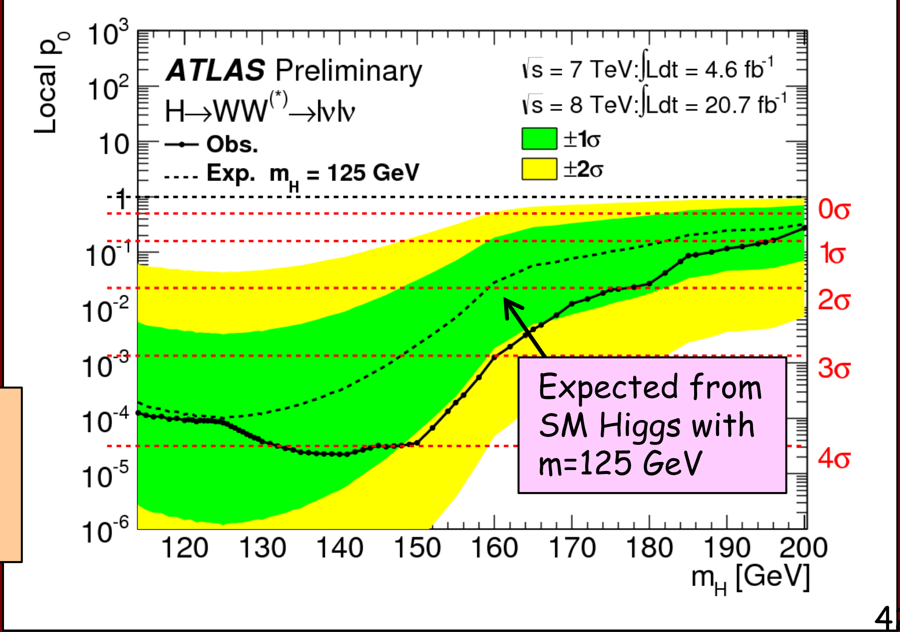


$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$



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)



Expected from SM Higgs with m=125 GeV

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

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

- ❑ Important for coupling measurements
- ❑ Huge backgrounds: $Z \rightarrow \tau\tau$, top, fakes

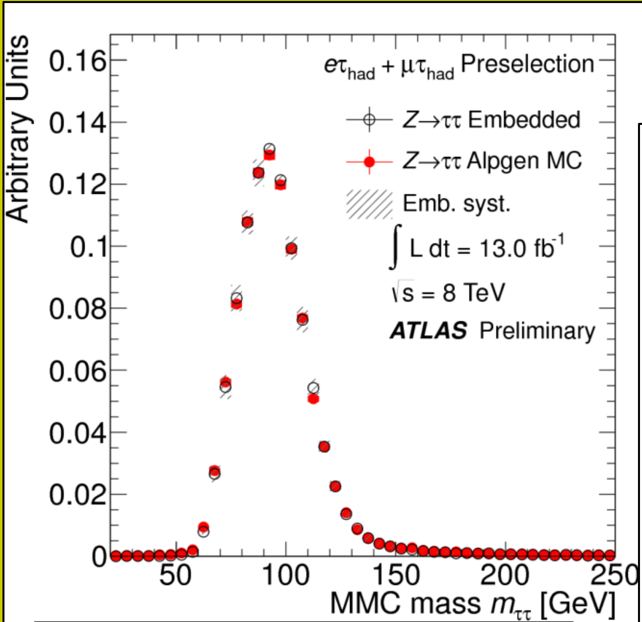
  Dominant/irreducible $Z \rightarrow \tau\tau$ from "embedded" $Z \rightarrow \mu\mu$ data (μ replaced by simulated τ)

  → 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

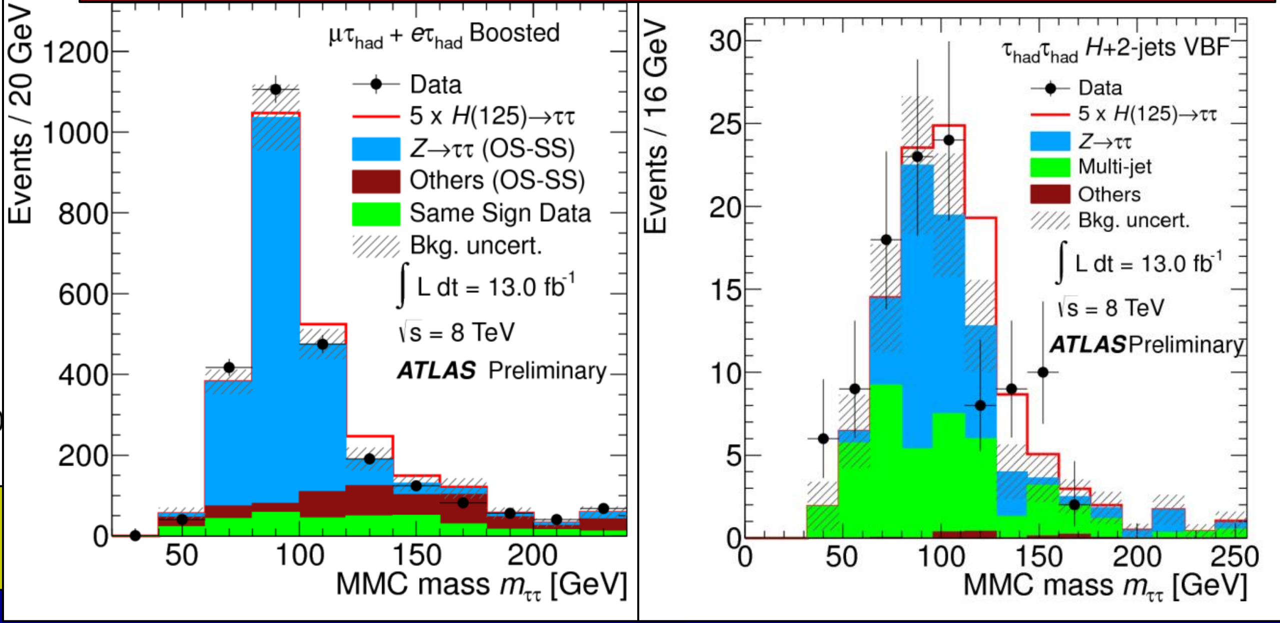
  → $\tau\tau$ mass resolution (13-20%) better for boosted system (→ better Z/H separation)
- ❑ After all cuts: expect ~ 250 events at 8 TeV; S/B ~ 0.5-1% overall (4-10% VBF)

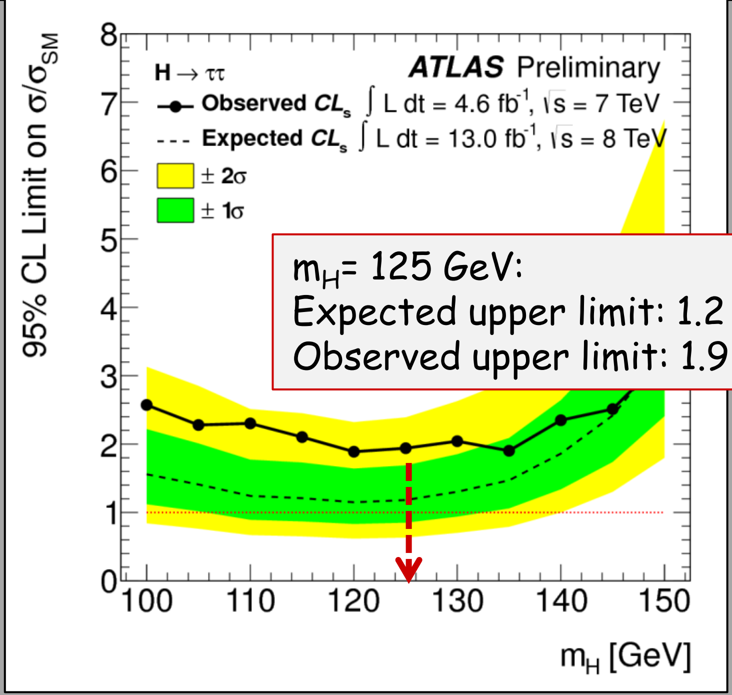


Excellent agreement $Z \rightarrow \tau\tau$ (embedded) data-simulation

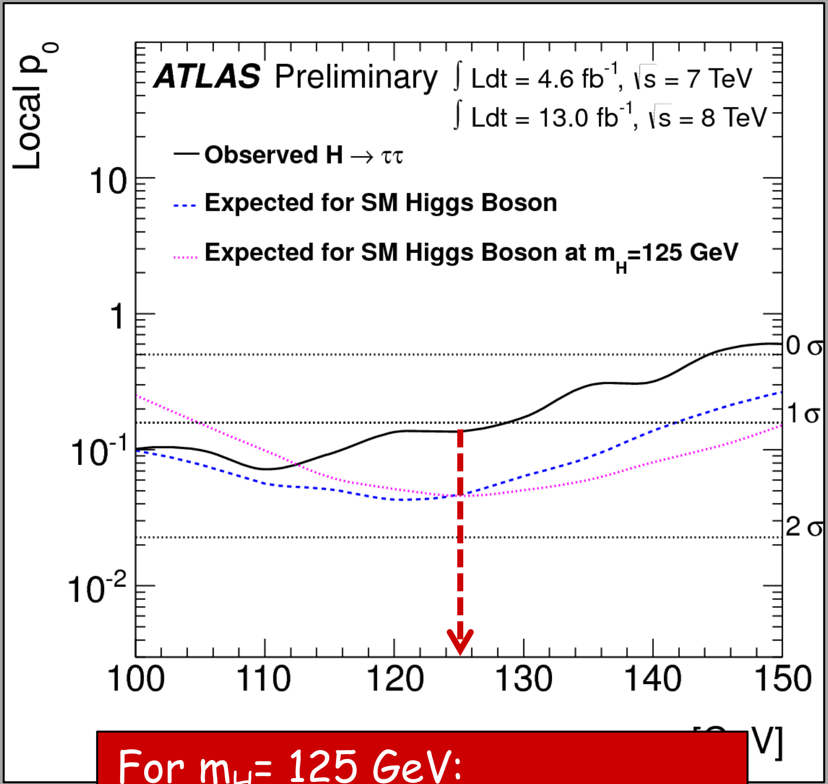
Higgs discrimination based on $\tau\tau$ mass

$m_{\tau\tau}$ distributions after cuts for most sensitive categories

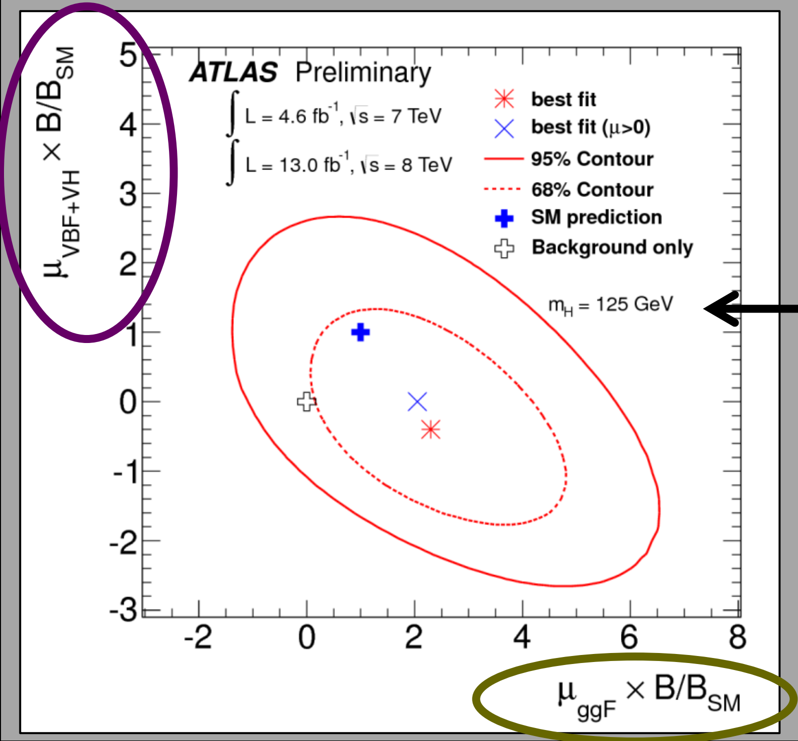




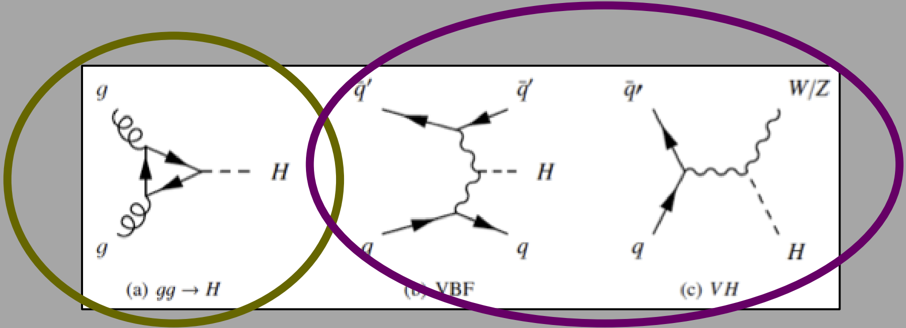
m_H= 125 GeV:
Expected upper limit: 1.2 x SM
Observed upper limit: 1.9 x SM



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)



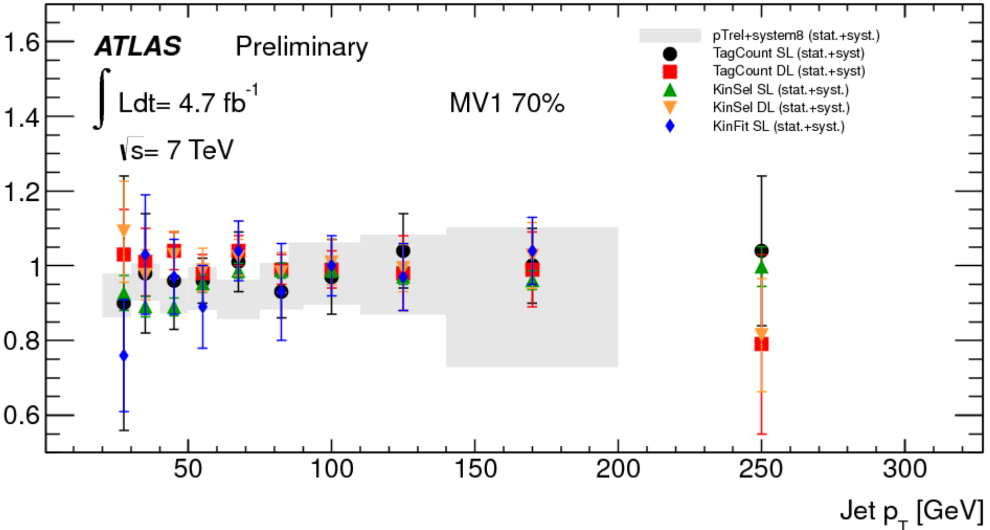
W/ZH → lνbb, llbb, ννbb

σ x BR ~ 150 fb m_H~ 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

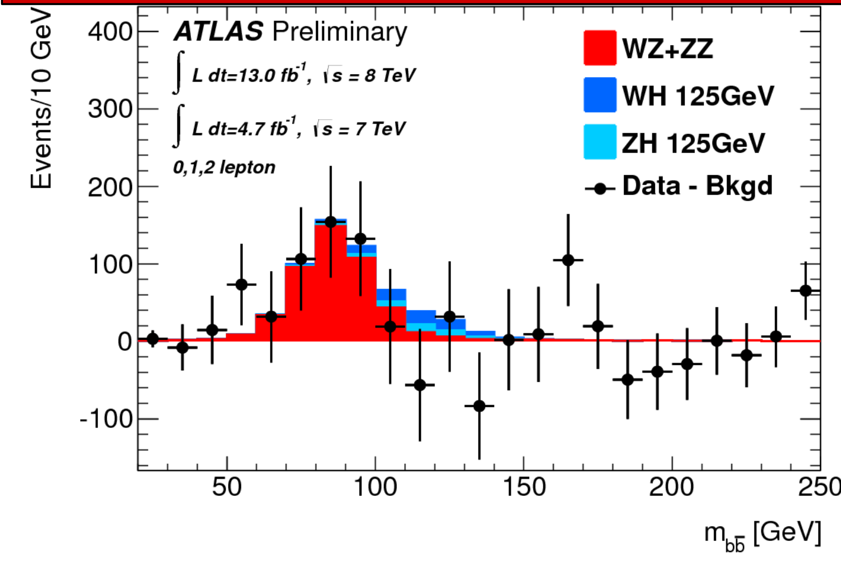
- ❑ Large and complex (flavour composition !) backgrounds from W/Z+jets and top
- ❑ V+q, V+c from pre-tag/1-tag control samples, V+b and top from final fit to 2-tag sample
- ❑ After all cuts: S/B ~ 0.5-5%, increasing with p_T^V / E_T^{miss}
- ❑ Dominant systematic uncertainty from b/c-tagging and Jet/E_T^{miss}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

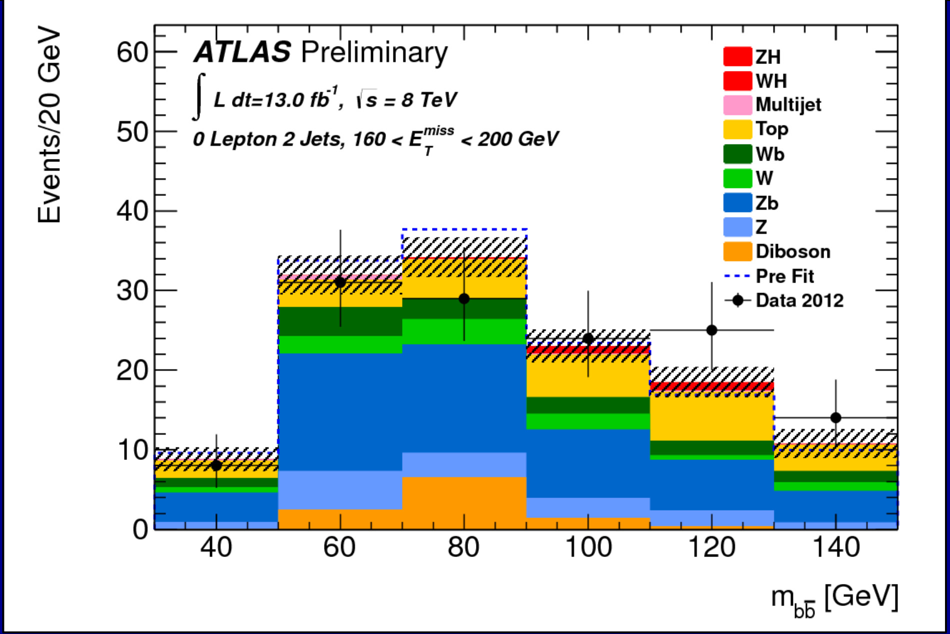
Ratio data/MC for b-tag efficiency from tt events (tt covers high p_T, complementary to other methods)

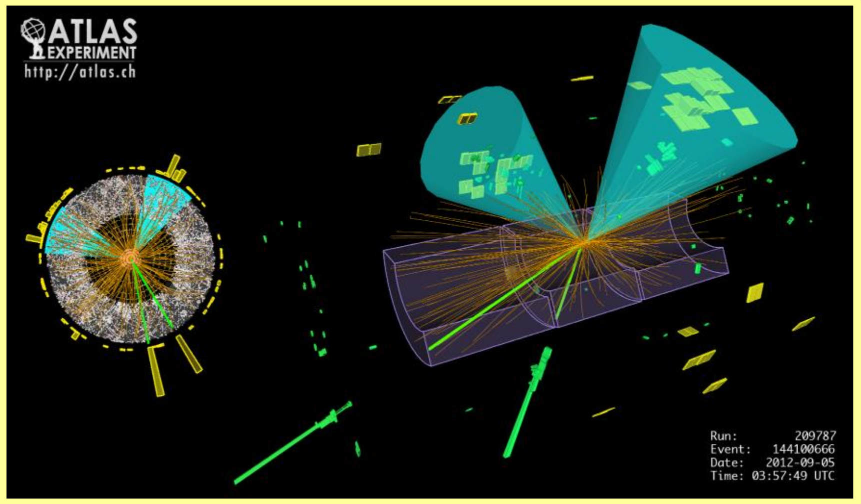


Observation of WZ/ZZ with Z→ bb peak from fit to data after subtraction of all non-di-boson backgrounds

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



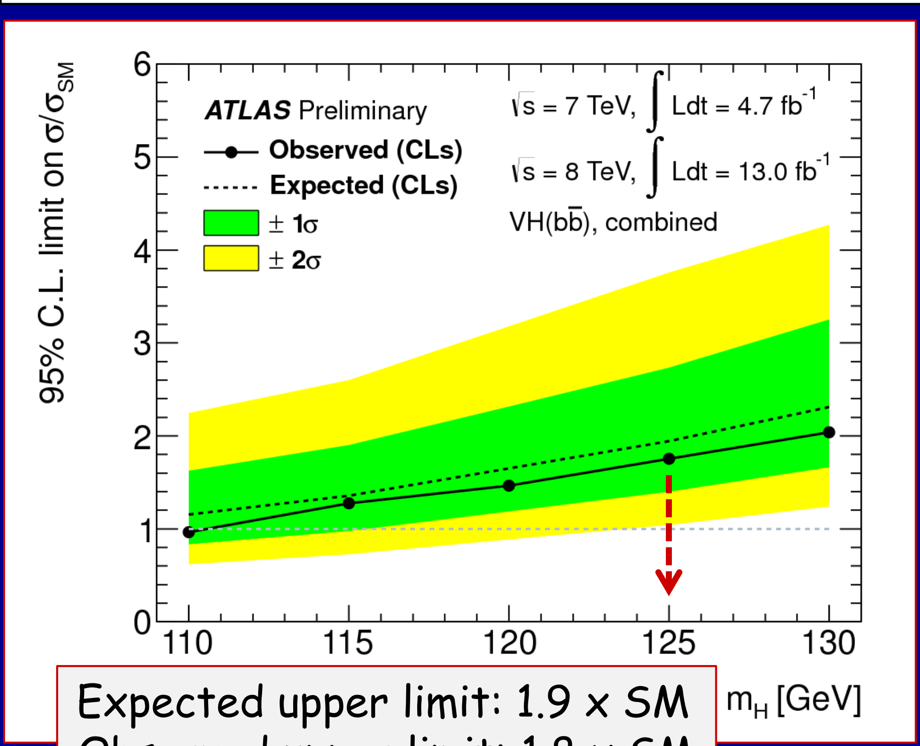




7 TeV data: 2σ deficit compared to background-only expectation

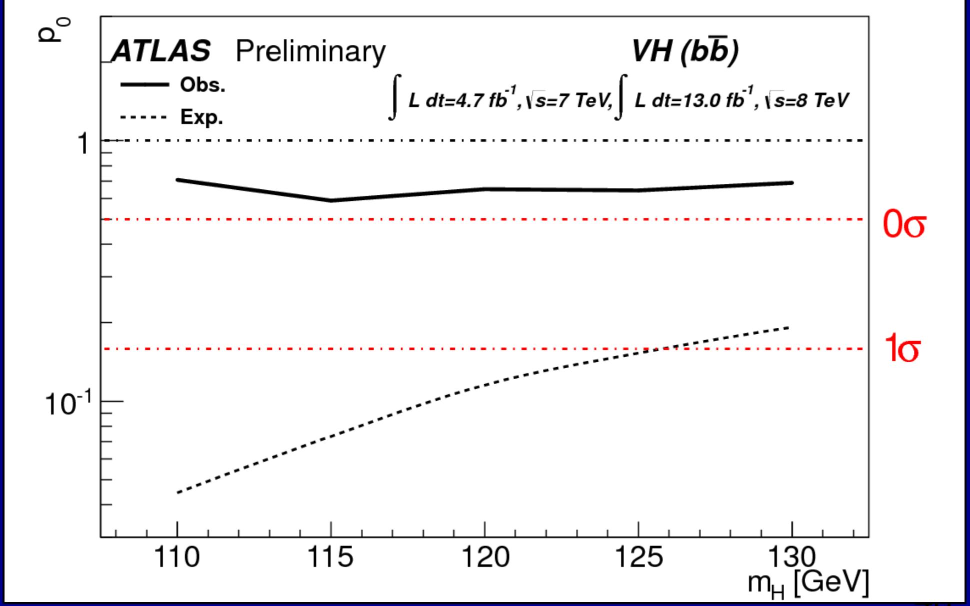
8 TeV data: 1σ excess

→ combined $\mu = -0.4 \pm 0.7$ (stat) $\pm$ 0.7 (syst)

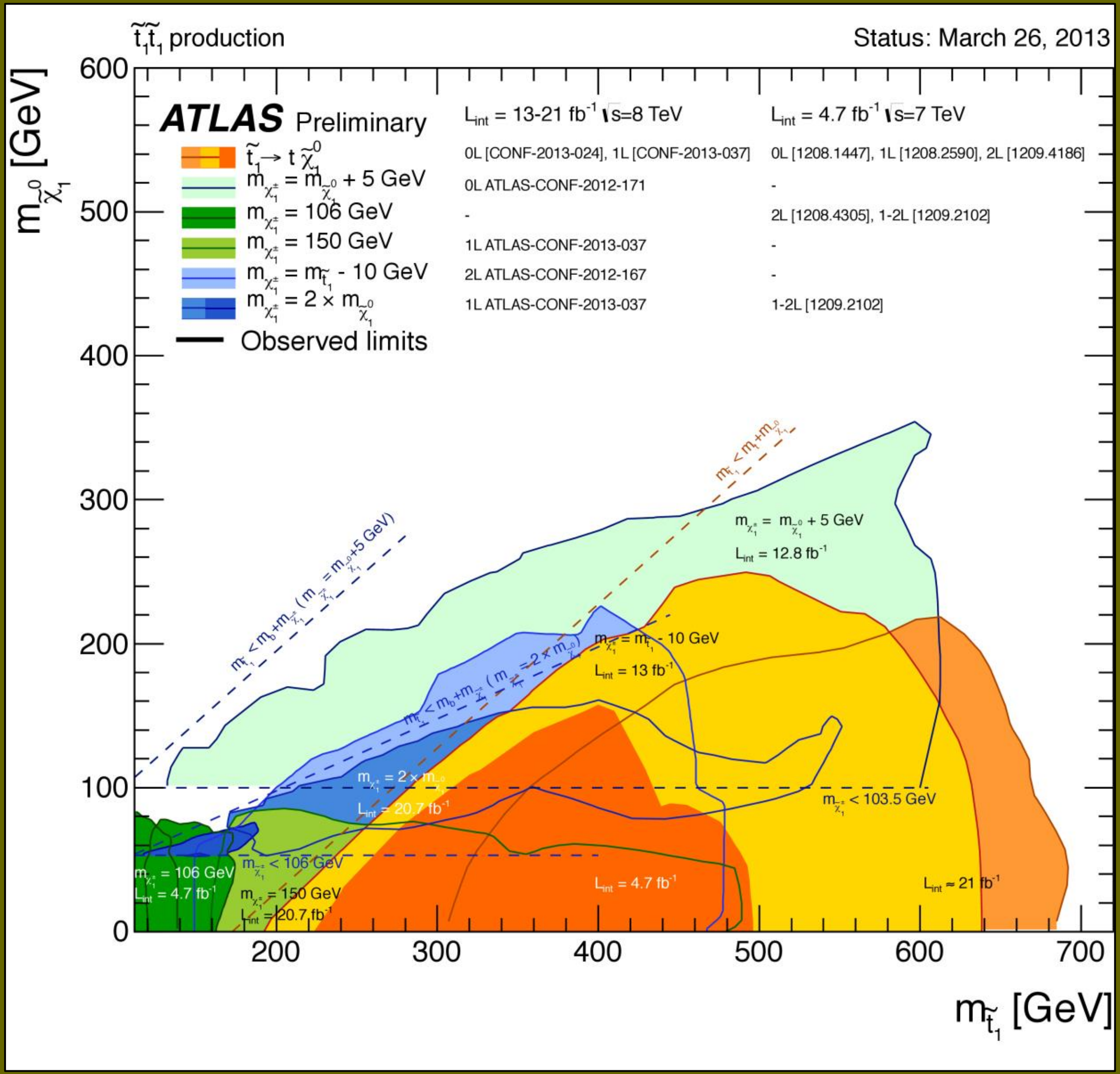


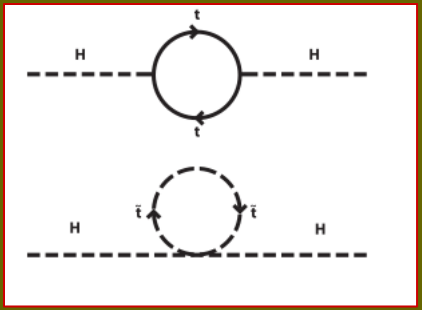
Expected upper limit: 1.9 x SM

Observed upper limit: 1.8 x SM



Is the Higgs mass stabilized by New Physics ?

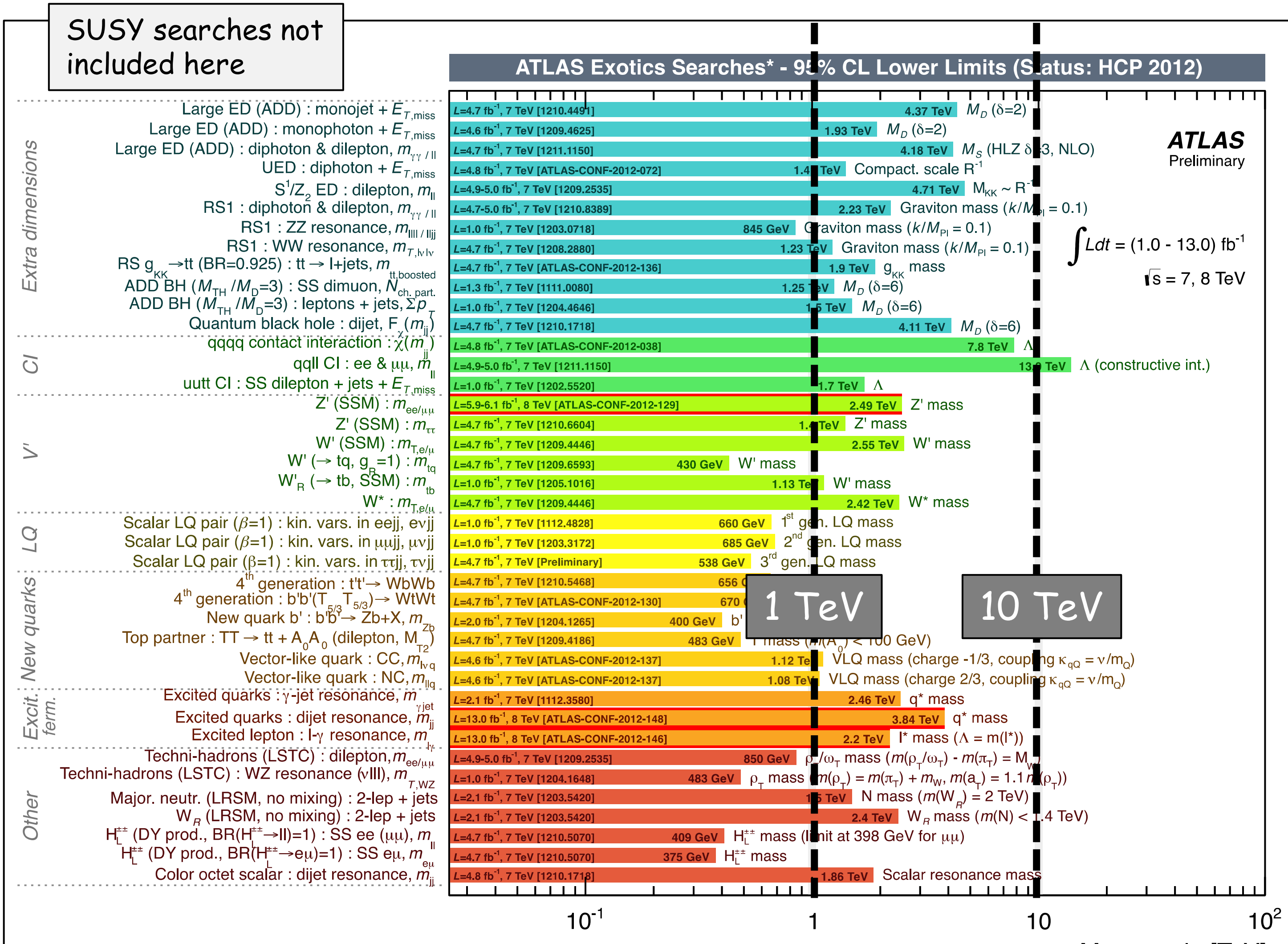




Searches for physics beyond the SM

Huge number of models and topologies investigated

SUSY searches not included here



*Only a selection of the available mass limits on new states or phenomena shown

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)

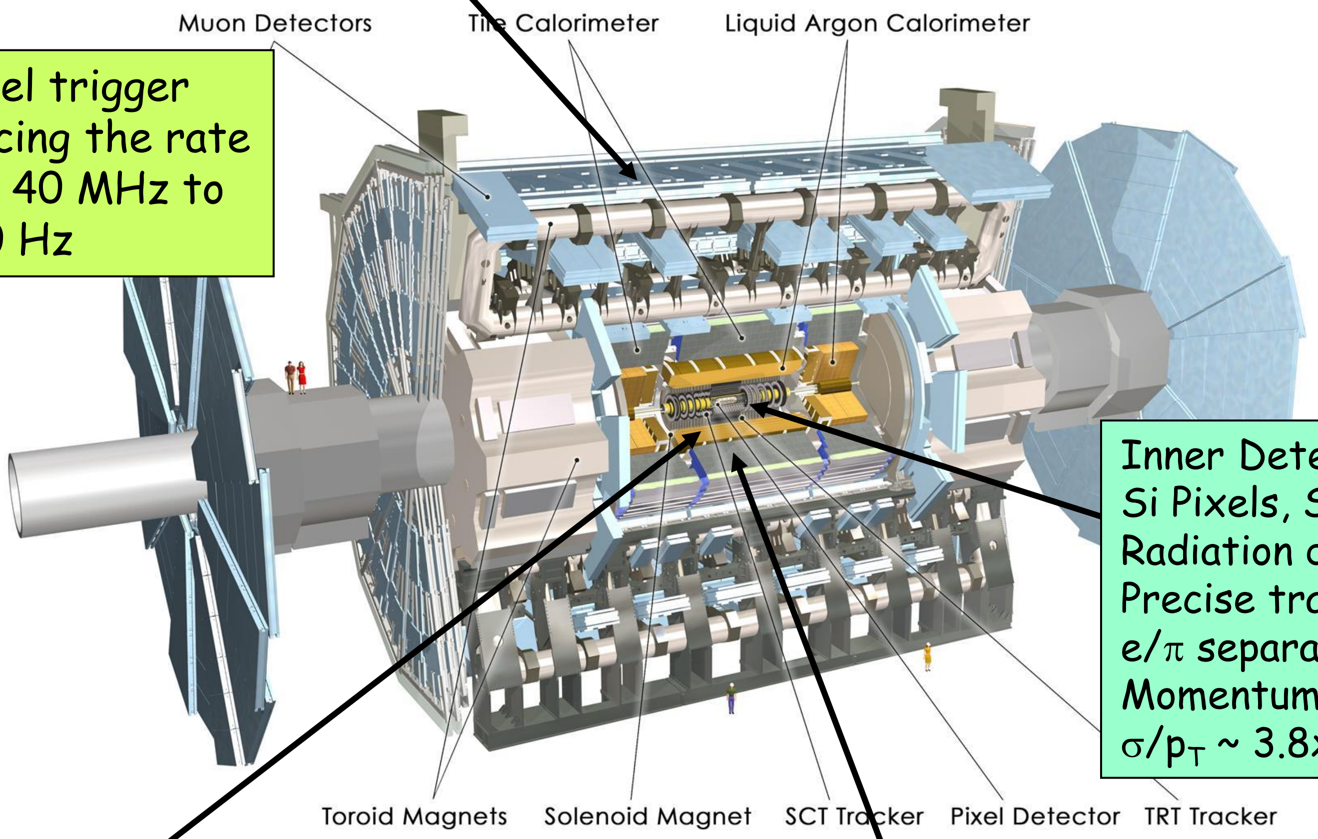
Doubly charged Higgs (
- multi leptons, same sign leptons)

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

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

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



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: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

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.

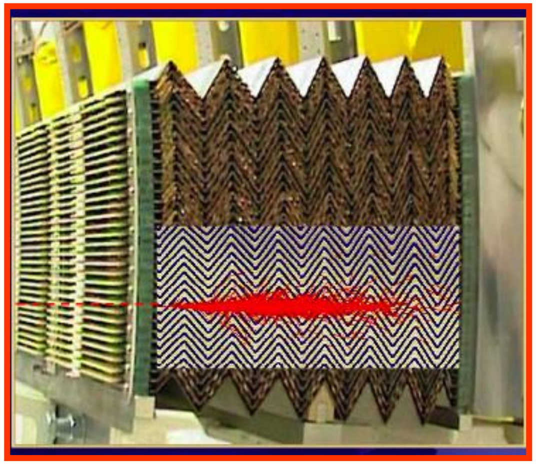
	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5x10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5x10^{-4}\ p_T \oplus 0.005$
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)

ATLAS electromagnetic calorimeter



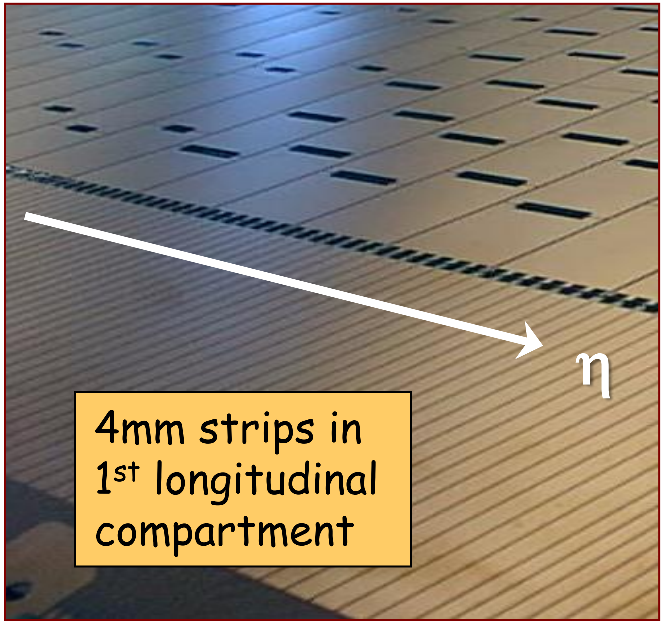
Lead/liquid-argon detector with a novel Accordion geometry (introduced by Daniel Fournier, LAL/Orsay) to achieve a fast response ~ 50 ns

☐ good E-resolution: ~10%/√E

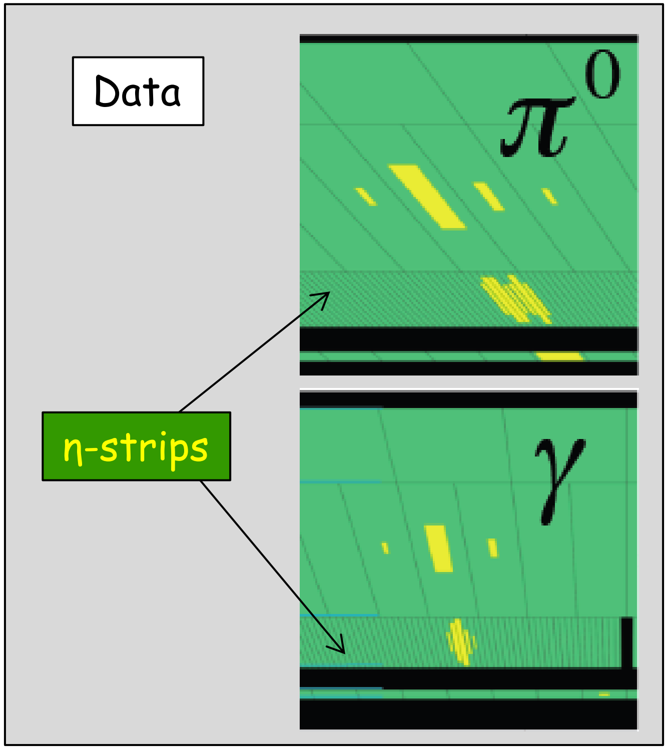
☐ fine longitudinal and lateral segmentation

→ vertex reconstruction (mass resolution)

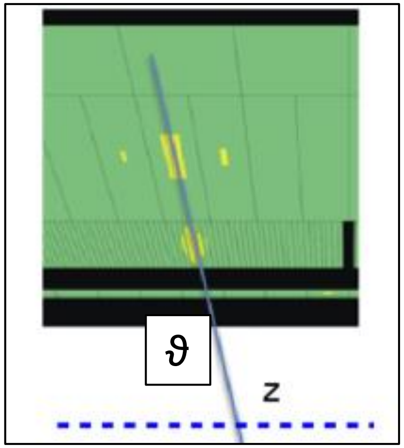
→ γ/π^0 separation (background rejection)



4mm strips in 1st longitudinal compartment

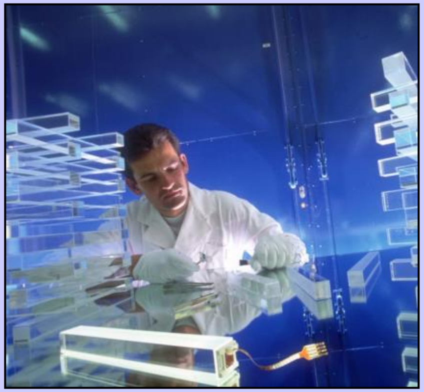


Reconstruction of primary vertex from γ direction → maintains good mass resolution in high pile-up conditions

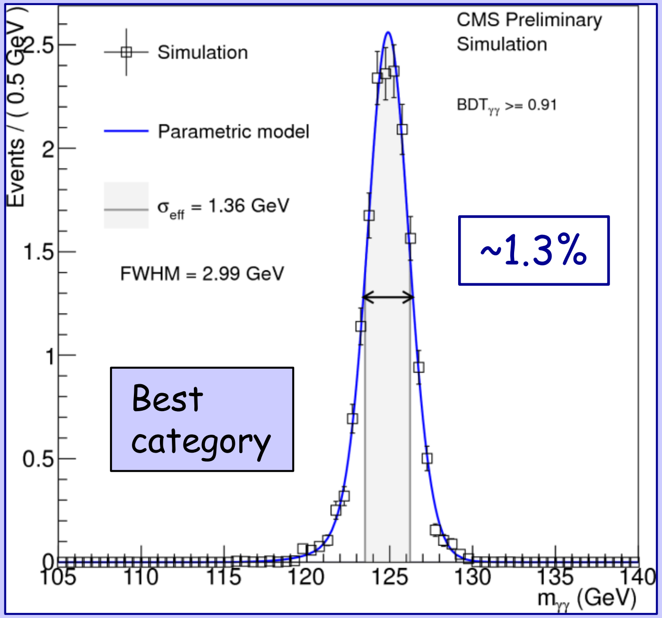


ATLAS and CMS calorimetry: the complementarity

CMS



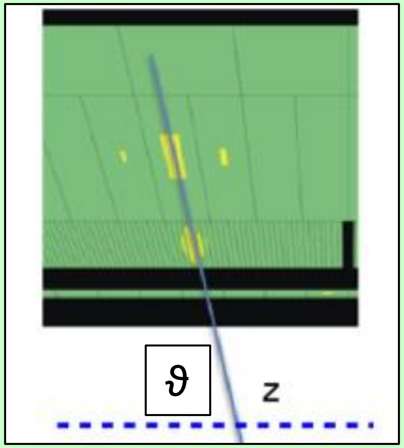
Lead-tungstate crystals (homogeneous):
- ☐ excellent E-resolution: 2-5%/√E
- ☐ no longitudinal segmentation → event vertex from tracks (more sensitive to pile-up)



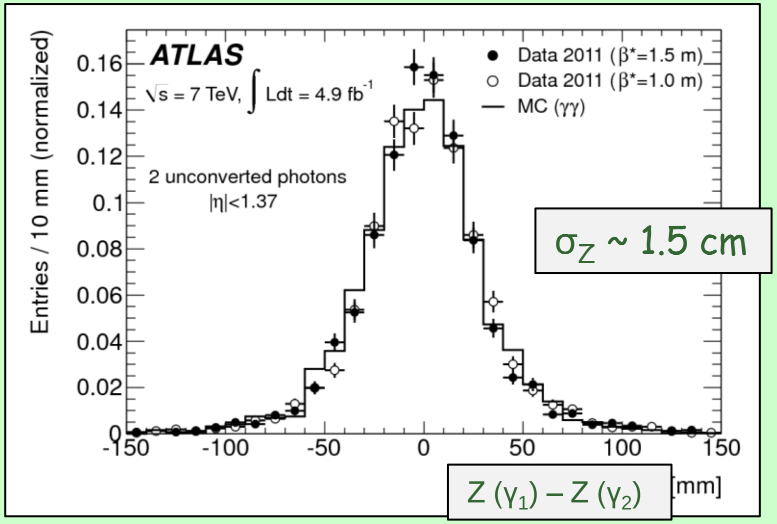
~1.3%

Best category

ATLAS



Lead/liquid-argon (sampling):
- ☐ good E-resolution: ~10%/√E
- ☐ longitudinal segmentation → vertex from photon direction → pile-up robust



σ_Z ~ 1.5 cm

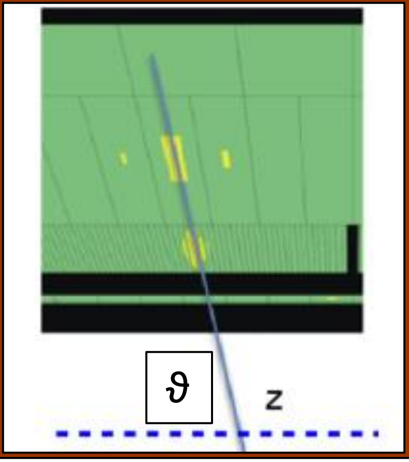
$Z(\gamma_1) - Z(\gamma_2)$

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

α=opening angle of the two photons

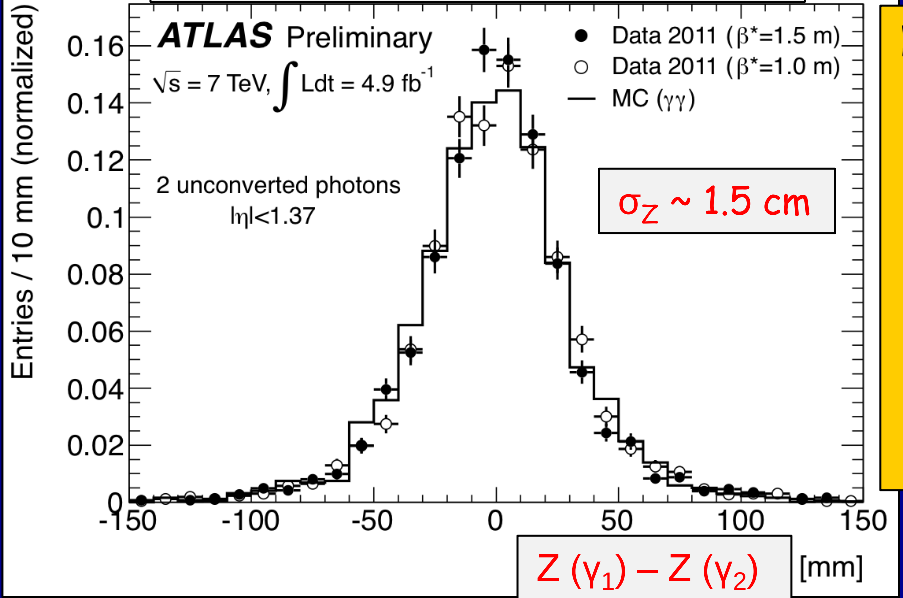
High pile-up: many vertices distributed over σ_Z (LHC beam spot) ~ 5-6 cm
→ difficult to know which one has produced the γγ pair

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"

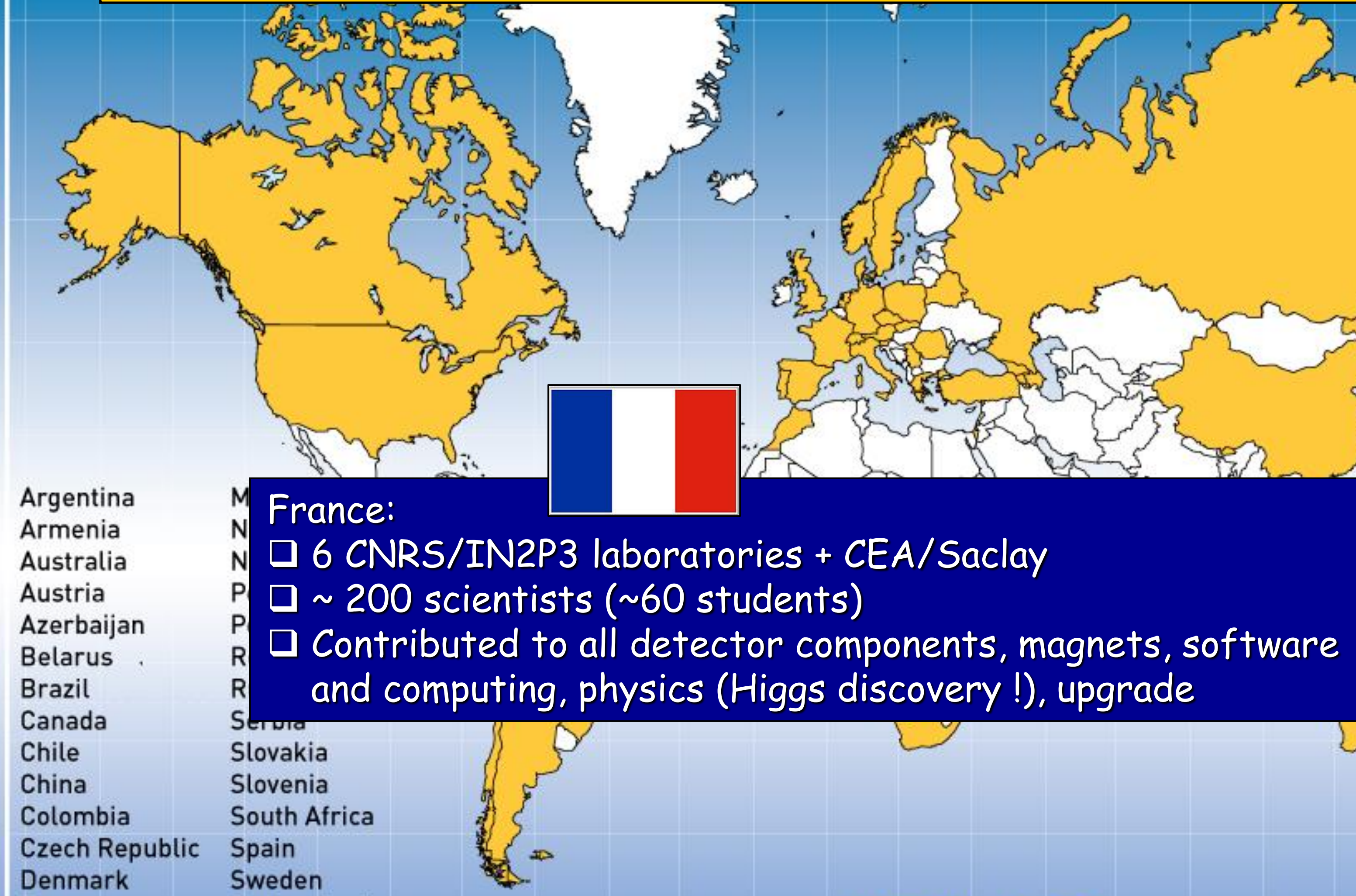


σ_Z ~ 1.5 cm

$Z(\gamma_1) - Z(\gamma_2)$ [mm]

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

~ 3000 scientists from 177 Institutions from 38 Countries



France:
- ❑ 6 CNRS/IN2P3 laboratories + CEA/Saclay
- ❑ ~ 200 scientists (~60 students)
- ❑ Contributed to all detector components, magnets, software and computing, physics (Higgs discovery !), upgrade

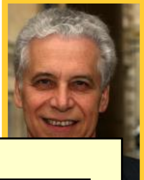
Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan

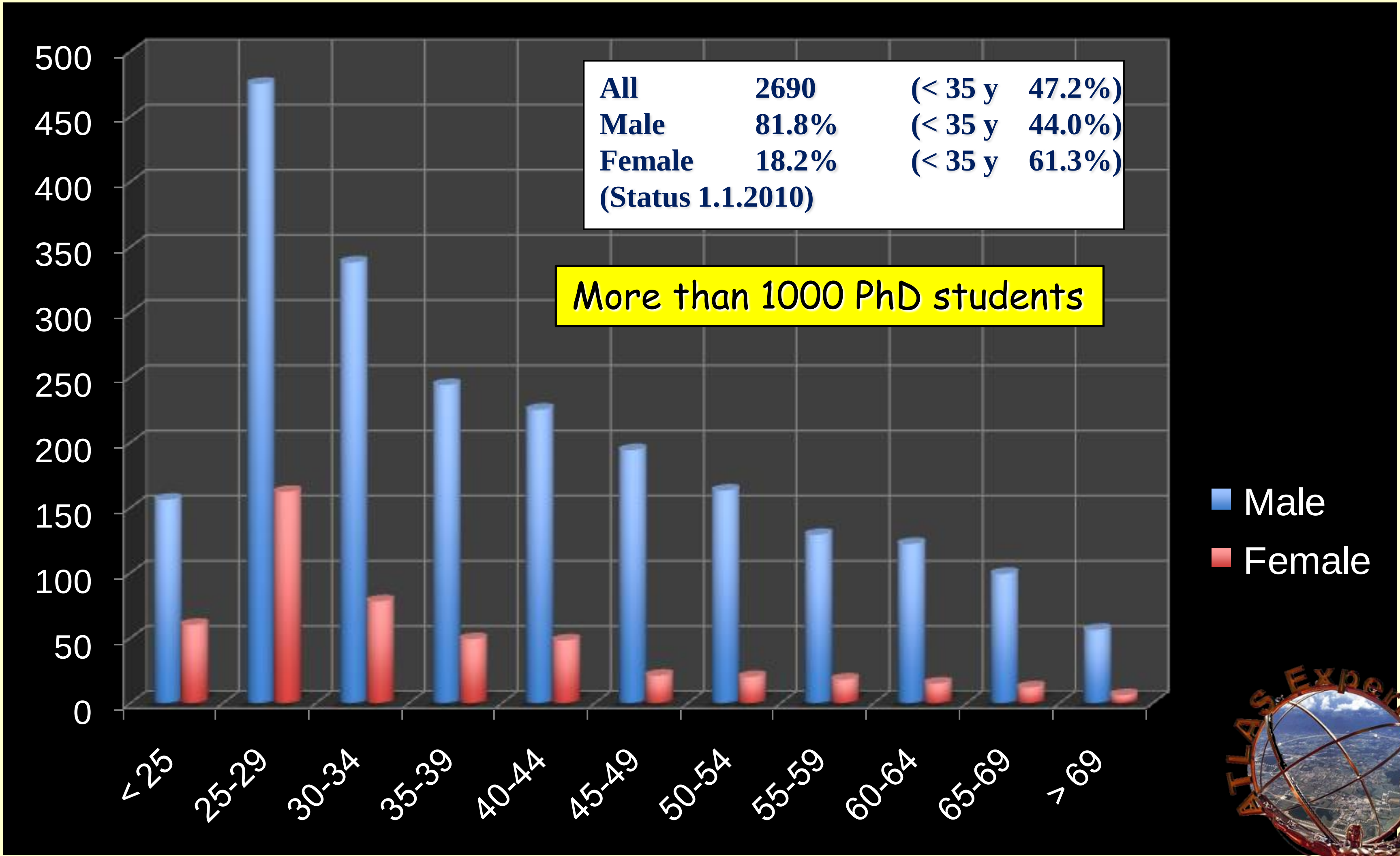
M
N
N
P
P
R
R
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR

ATLAS Collaboration

ATLAS Experiment

Age distribution of the ATLAS population





All	**2690**	**(< 35 y**	**47.2%)**
Male	**81.8%**	**(< 35 y**	**44.0%)**
Female	**18.2%**	**(< 35 y**	**61.3%)**

(Status 1.1.2010)

More than 1000 PhD students

THANK YOU !


caglecartoons.com
ELEMENTARY PARTICLE RESPONSIBLE FOR MASS
CERN
AMERICAN OBESITY
See! IT'S NOT MY FAULT- I WAS BORN WITH TOO MANY HIGGS BOSONS.
MikeKeefe INTOON.COM 7·6·12