The Higgs Hunt with ATLAS at LHC

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For the ATLAS Collaboration

Time and Matter

Venice, Italy

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Prelude

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

Physics Letters B
Volume 716, Issue 1, 17 September 2012, Pages 1–29

ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

Universally Available

"I certainly had no idea it would happen in my lifetime at the beginning, more than 40 years ago.
I think it shows amazing dedication by the young people involved with these colossal collaborations to persist in this way, on what is a really a very difficult task.
I congratulate them."

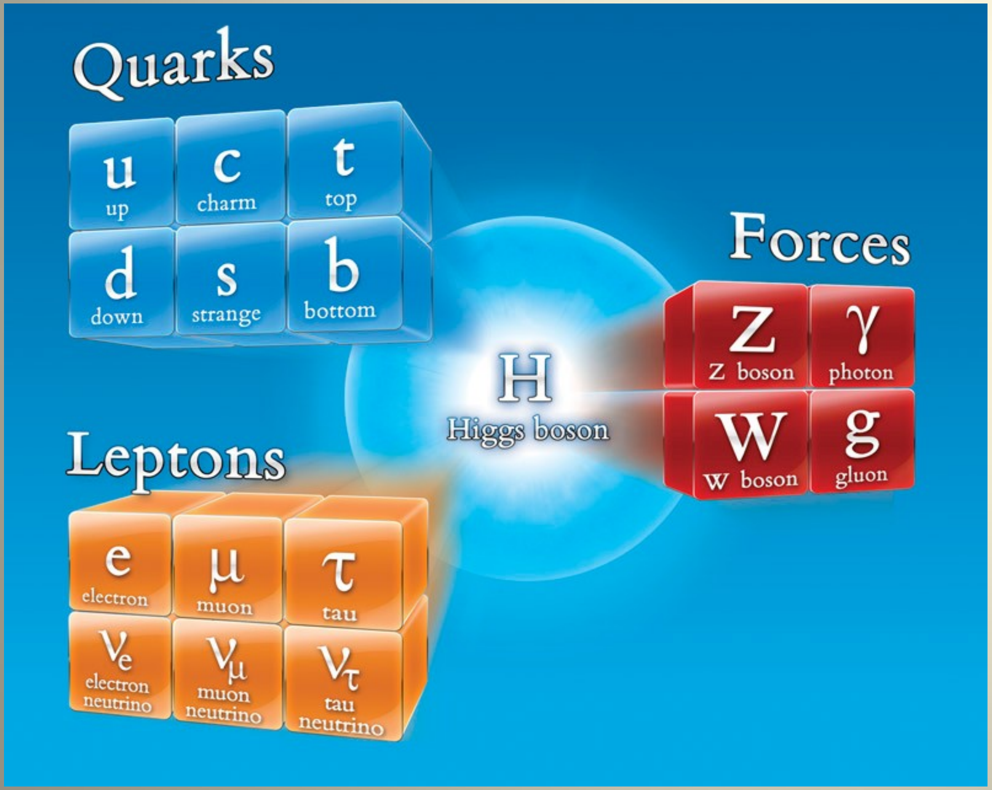
Peter Higgs, July 4th, 2012

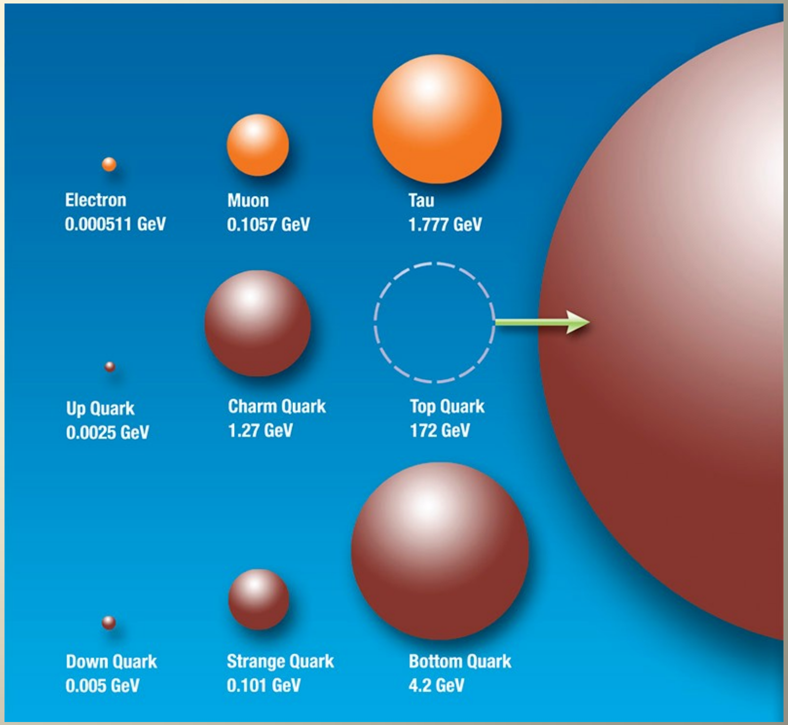
Acknowledgements

- **This presentation rests on the shoulders of over 3000 ATLAS colleagues who built and operate the ATLAS detector, and who tirelessly analyze the data .**
- **The prerequisite for these studies was the seamless and astonishingly ever-improving performance of the Large Hadron Collider in 2011 and 2012.**

Higgs Discovery

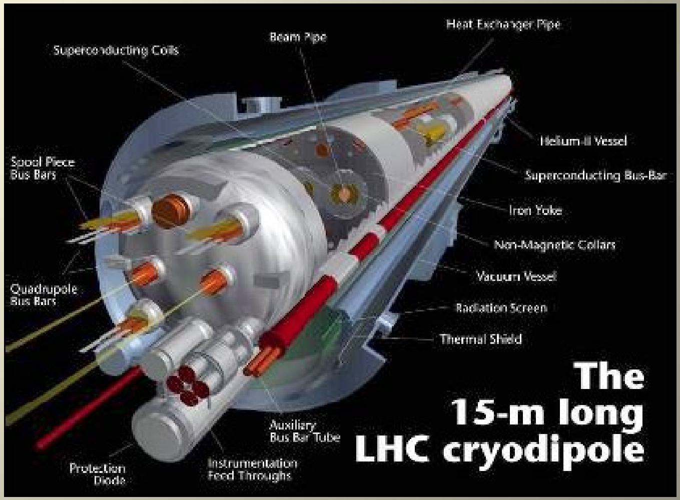
- The discovery of the Higgs particle would wrap up the Standard model in the most elegant and simple way
  - Light Higgs most natural, but opens up the possibility of the “Great Desert” (no new particles) up to the Planck scale – 10^{28} eV – 100 GeV is 10^{11} eV !
  - Measurement of Higgs properties a sensitive tool for probing New Physics





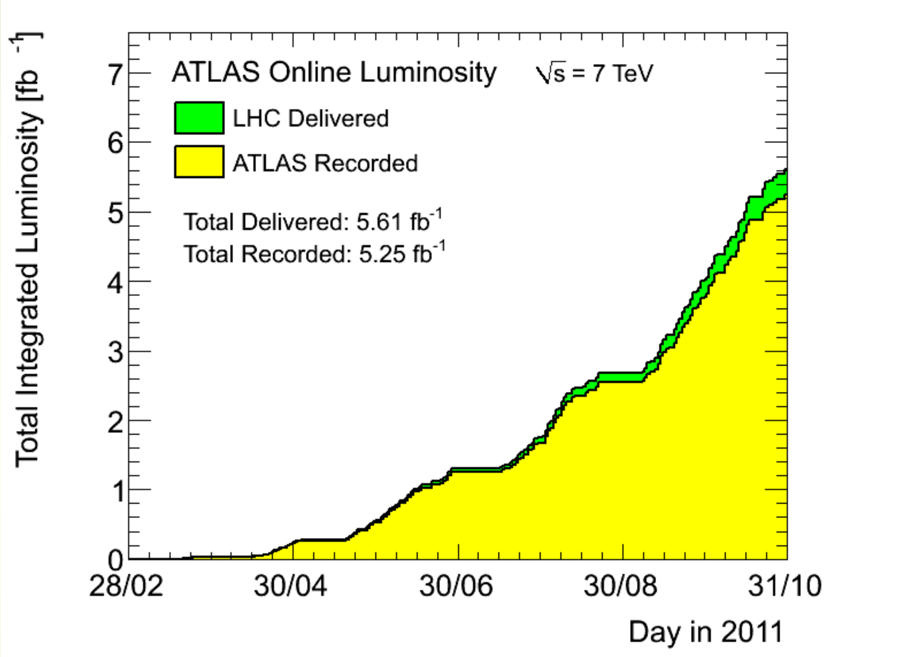
Large Hadron Collider

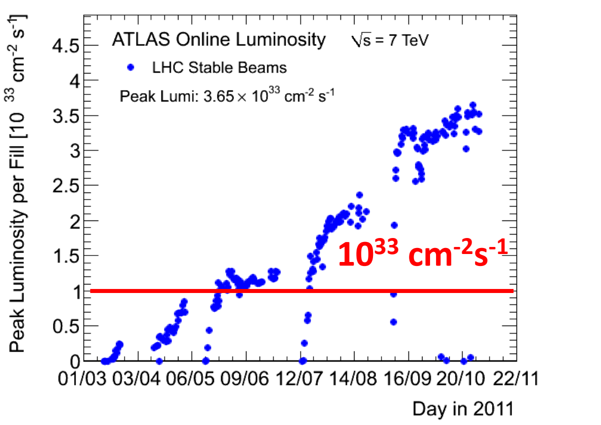
- Large Hadron Collider
  - proton-proton collider
  - Design c.m.s. energy 14 (2x7) TeV, currently at 8 TeV, 7 TeV in 2011
  - Design luminosity 10^{34} cm^{-2}s^{-1}, 7.7×10^{33} achieved so far
- Why 7-8 (2x4) TeV ?
  - LHC in 27 km LEP tunnel (recycling)
  - Energy at r_{LEP} limited by superconducting magnets
    - B_{max} = 8.3 T → E_{max} = 7 TeV
  - Following major incident in Sep’08 damaging ~50 magnets
    - 3.5, then 4 TeV considered safe
- Consolidation to design values during 2013(&14) break



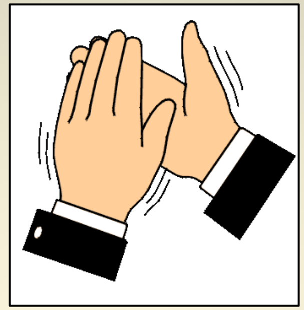
LHC Performance in 2011

- The yearly plan at the Chamonix meeting (Jan'11) was >1 fb^{-1} per experiment
- 50 ns bunch spacing
- Due to increased peak luminosity up to 3.6×10^{33} $cm^{-2}s^{-1}$ the final integrated luminosity surpassed 5 fb^{-1} by end of 2011
- Half of the luminosity (~ 2.5 fb^{-1}) was delivered in the final month of running



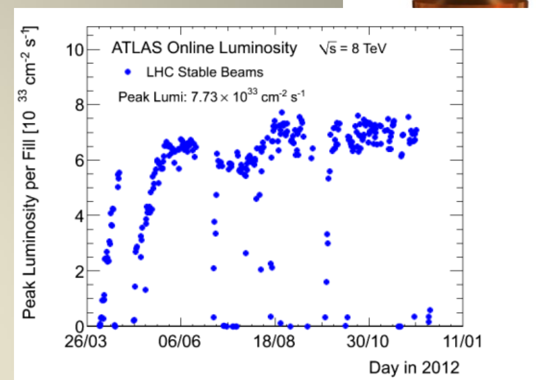


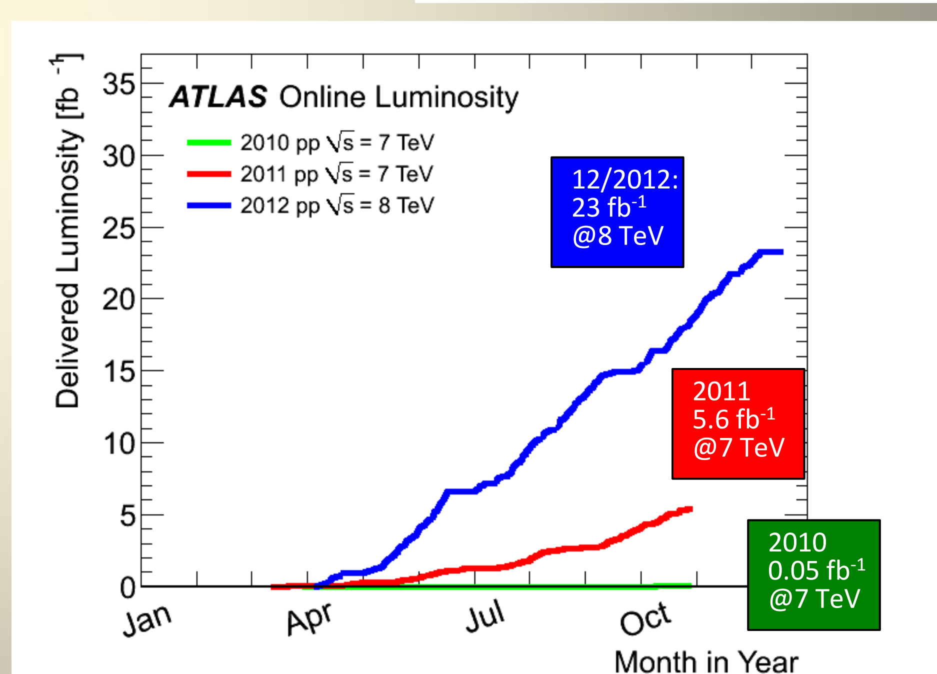
LHC Performance in 2012



- The yearly plan was
  - >5 fb^{-1} by end June
  - ~15 fb^{-1} by end of 2012

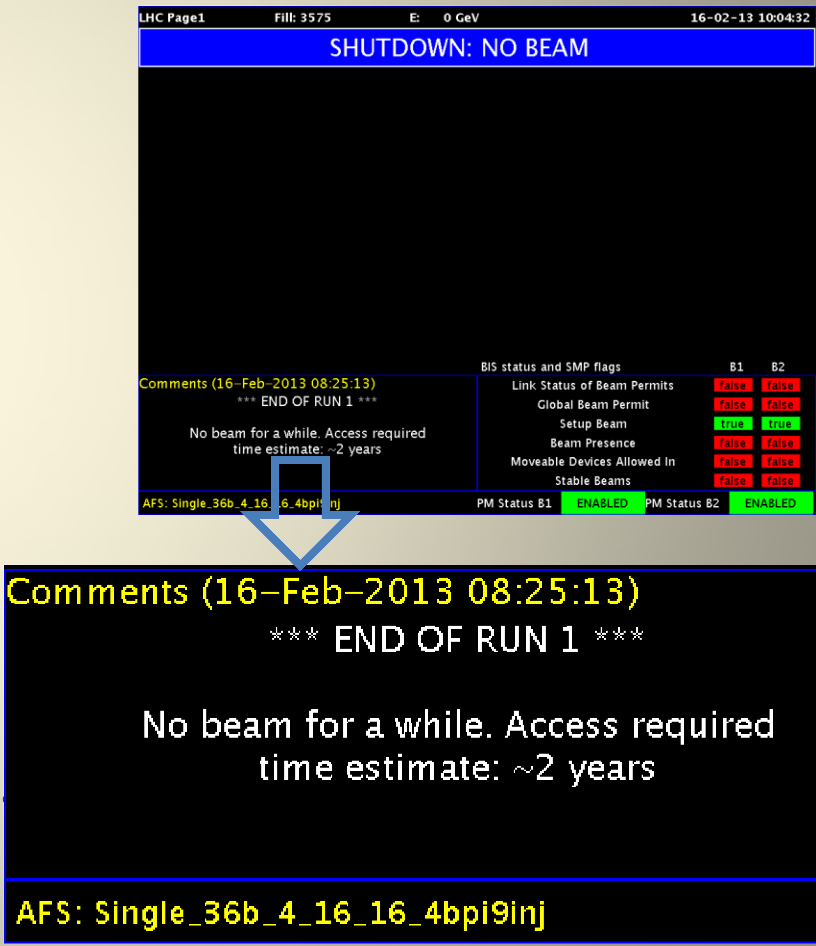
  per experiment
- Peak luminosity increased up to 7.73×10^{33} $cm^{-2}s^{-1}$
- ~6 fb^{-1} by end of June
  - ~1.5 fb^{-1} delivered in the final week – still the record
- 23.3 fb^{-1} total delivered
  - 21.7 fb^{-1} recorded by ATLAS



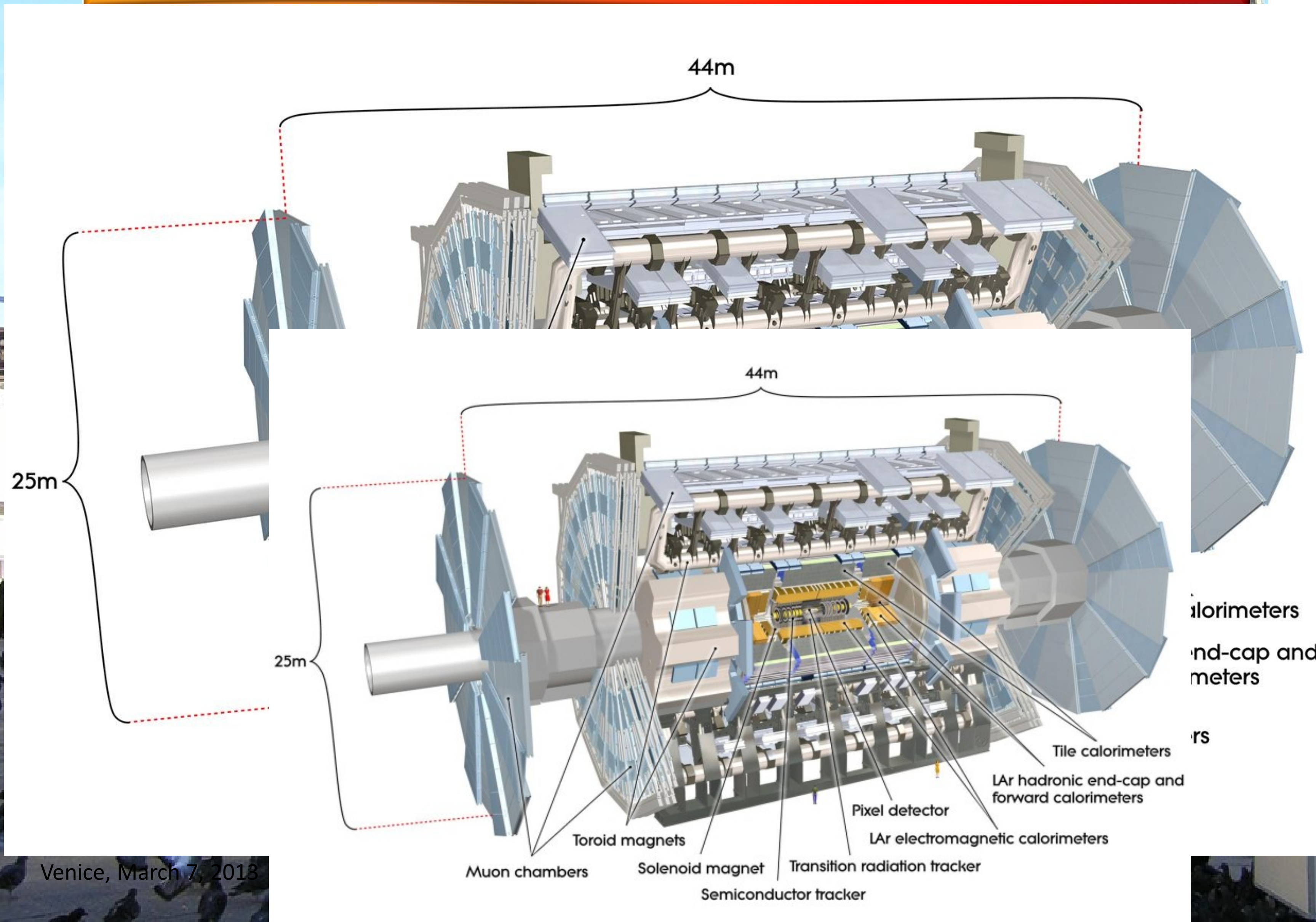


LHC Performance in 2013/14

- Heavy ion run until Feb 16 8:25
- End of LHC Run 1
- Entering consolidation shutdown for ~2 years
  - Change inter-magnet splices to allow running at 13-14 TeV
  - Upgrade collimation system
- Achieve design luminosity of 10^{34} cm^{-2}s^{-1}
- 25 ns bunch spacing
- Accumulate 50-100 fb^{-1} in 201
18



ATLAS Detector

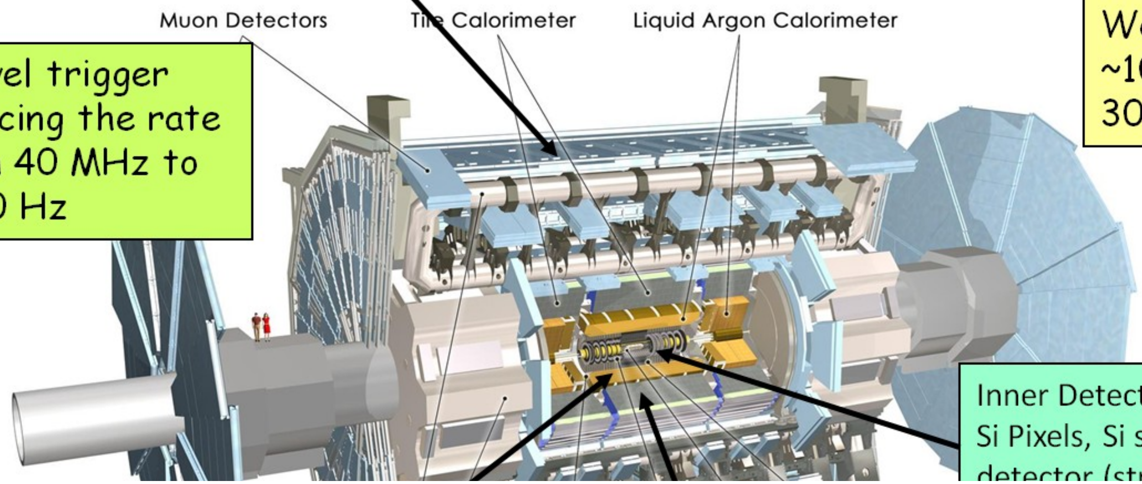


The Real Thing

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

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



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)

EM calori
e/γ trigge
E-resoluti

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

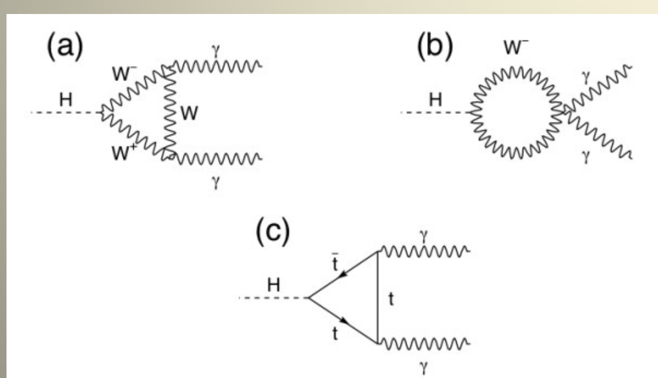
ATLAS Collaboration

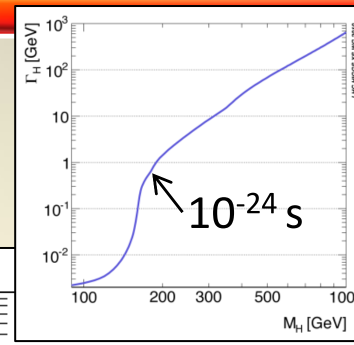
Higgs Production @ LHC

Which haystack is the needle in ?

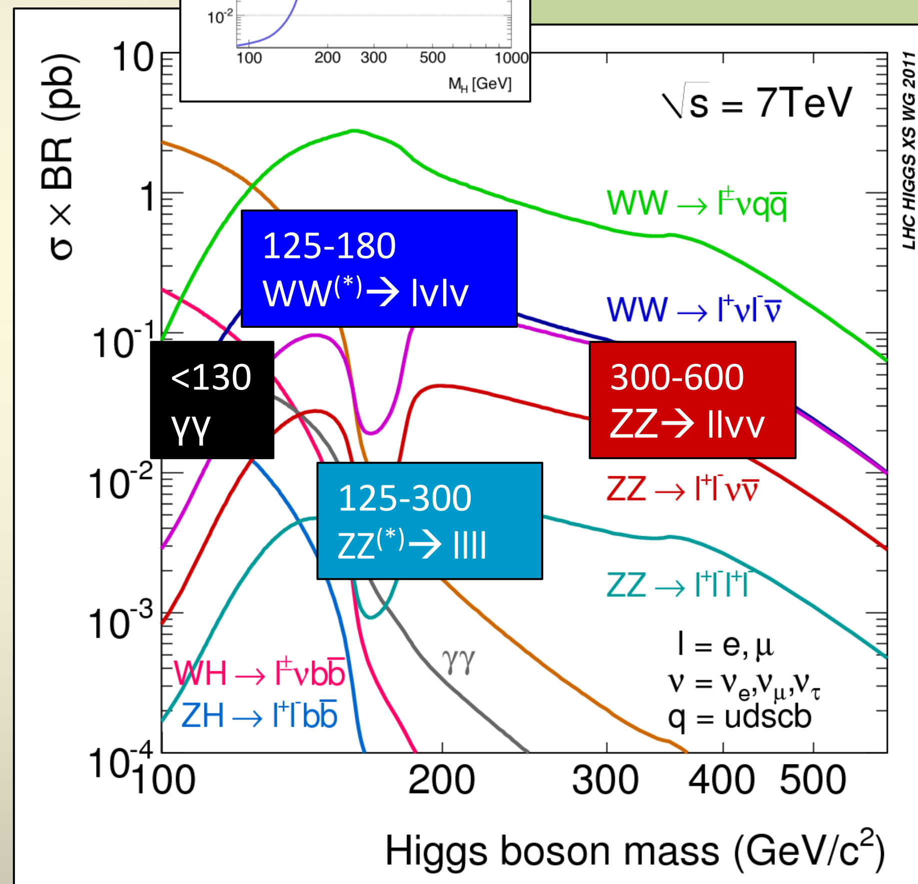
Higgs Decays

- Higgs decays determined by mass couplings
  - Decays to W, Z weak bosons dominate if kinematically allowed
    - One of the bosons can be virtual
  - For low masses two-photon, b-quark and tau decays
    - Two photons via loops



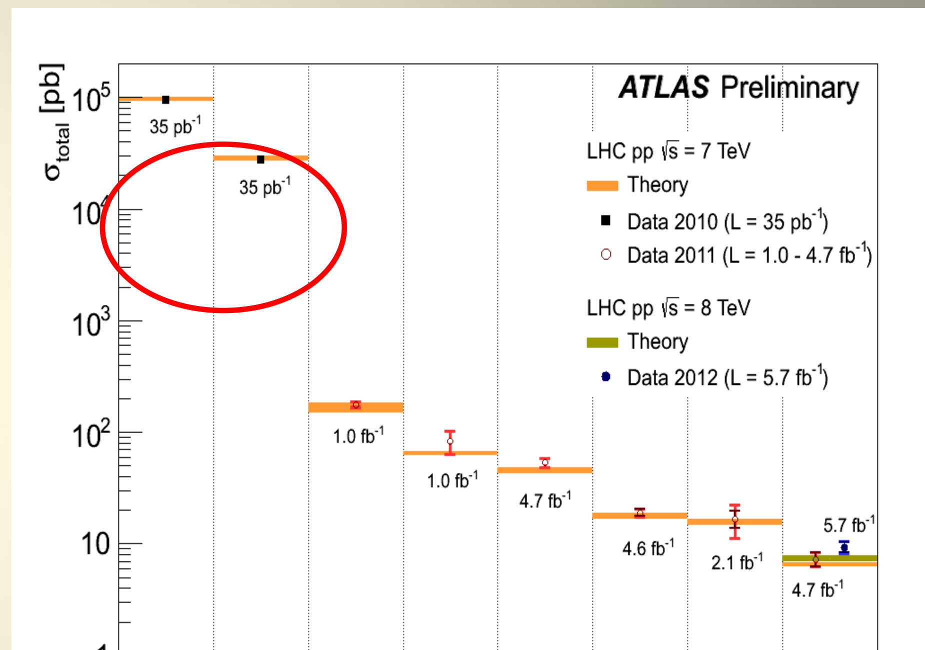


The faster it decays the less precise its mass (Heisenberg)



Higgs Detection @ LHC

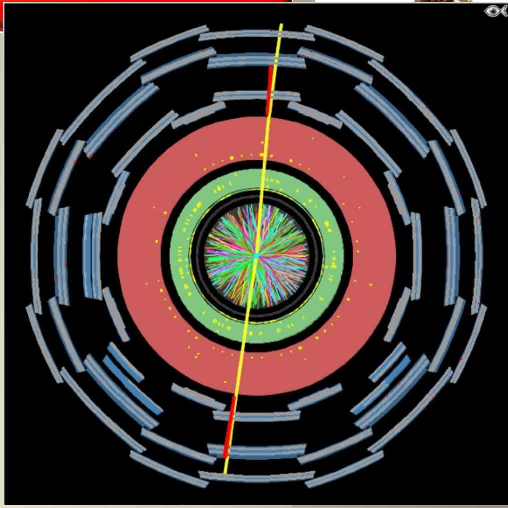
- Rare process
  - Production only $\mathcal{O}(10^{-10})$ of total cross section
  - Further suppression by decay branching ratio
- Huge backgrounds
  - Need distinct event features
    - Leptons (e, μ) from W, Z
    - Energetic gamma rays
    - "Golden" channel: H→ZZ → 4l
    - H→ZZ → 4l and H→γγ can be fully reconstructed: H invariant mass, but $\sigma x BR$ $\mathcal{O}(10\text{ fb})$
    - H→WW → lν lν has two missing ν's, $\sigma x BR$ $\mathcal{O}(100\text{ fb})$
  - Need to understand how to model backgrounds
    - From data and Monte Carlo simulations

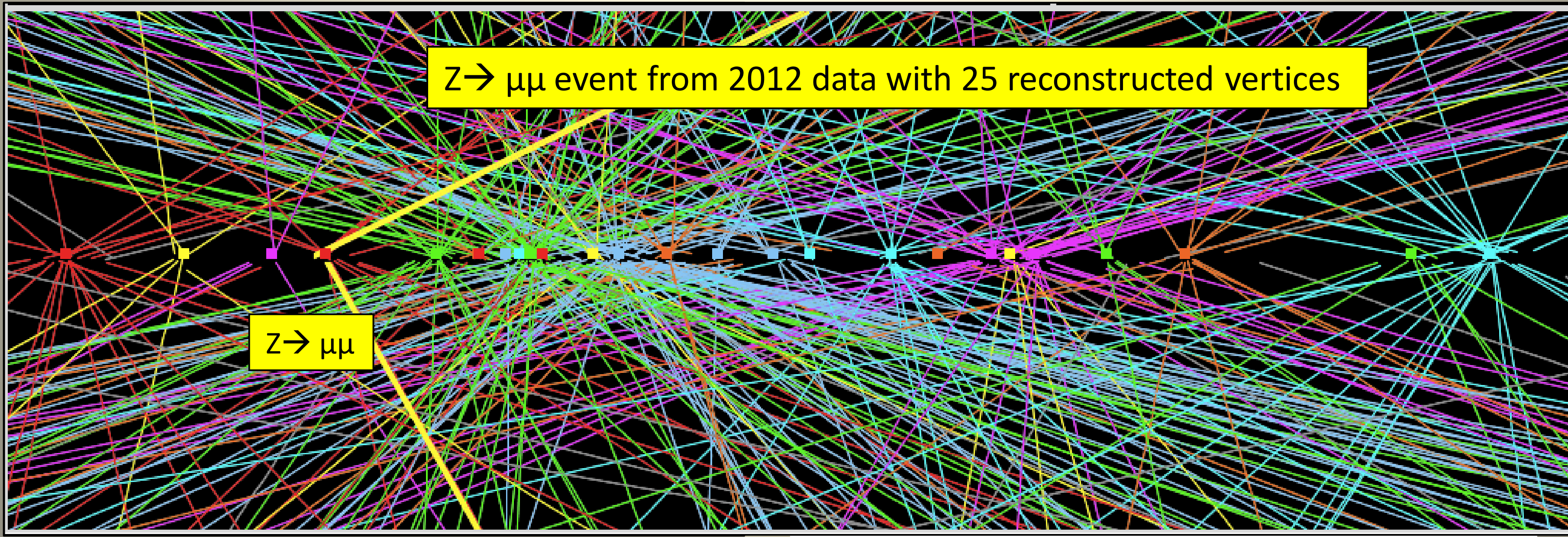


Yesterday's signals are today's backgrounds ! (100M W, 10M Z on tape)

Additional Burden – Pile-Up

- LHC still operates with 50 ns bunch spacing
  - ~1 collision per bunch crossing @ L~2×10^{32} $cm^{-2}s^{-1}$
  - Up to >40 overlaid collisions at highest luminosity
  - Challenging environment - $\mathcal{O}(1000)$ tracks – demonstrating marvelous tracker performance
    - E.g. loose primary vertex constraint for $H \to \gamma\gamma$
    - Backgrounds even harder to control





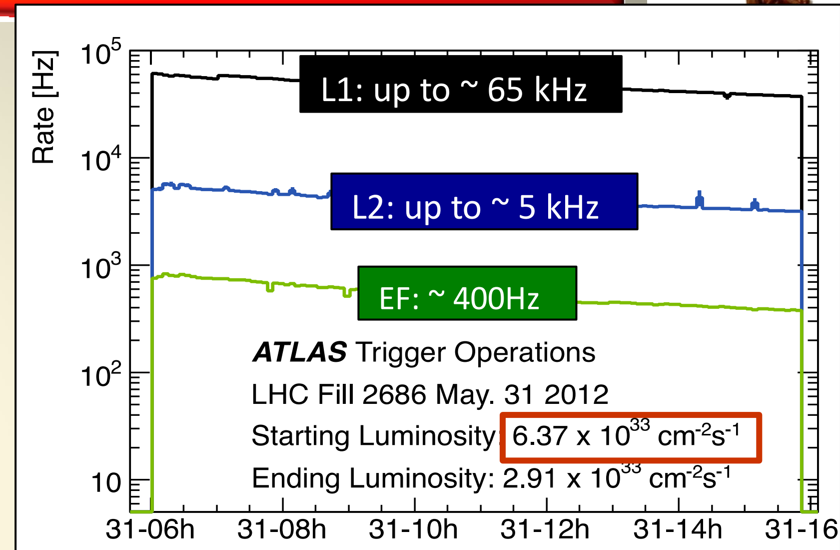
Signal in Presence of Background

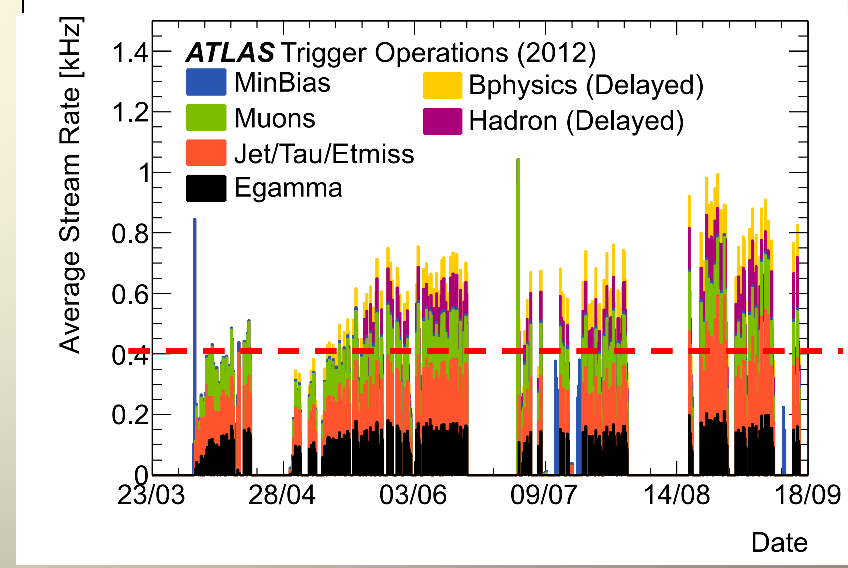
- Most powerful detection channels at low masses
  - $H \to WW^{(*)} \to l\nu\ l\nu$ (counting excess events)
  - $H \to ZZ^{(*)} \to 4l$ (H mass)
  - $H \to \gamma\gamma$ (H mass)

  } The Big Three
- All suffer from presence of background
  - Leptons from W, Z decays, QCD background
- Small *σxBR* results in small event samples
  - Downward fluctuation of signal can prevent detection
    - False negative (signal interpreted as background)
  - Upward fluctuation of background can mimic signal
    - False positive (background interpreted as signal)
- Need careful, unbiased statistical treatment to assess

Sample Selection

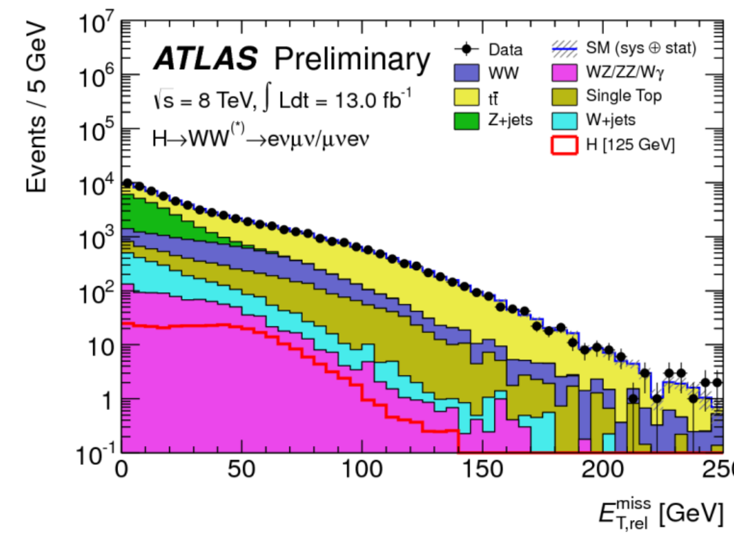
- Initial event rate 20 MHz, (multiple) collisions every bunch crossing
- Three level trigger reduces this to 300-600 Hz of recorded events
  - Trigger focuses on energetic jets, leptons and photons thus efficiency high for relevant Higgs decays
  - Trigger composition changed on the fly during fill to match decreasing luminosity
- Offline sample selection
  - Based on identification of characteristic objects: electrons, muons, photons
  - Large and sometimes not well-known backgrounds estimated mostly with data-driven techniques using signal-free control regions

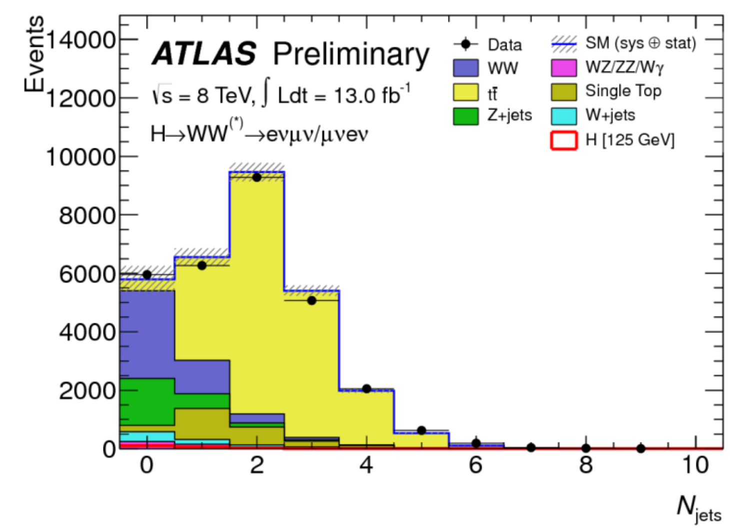




H → WW$^{(*)}$ → lνlν

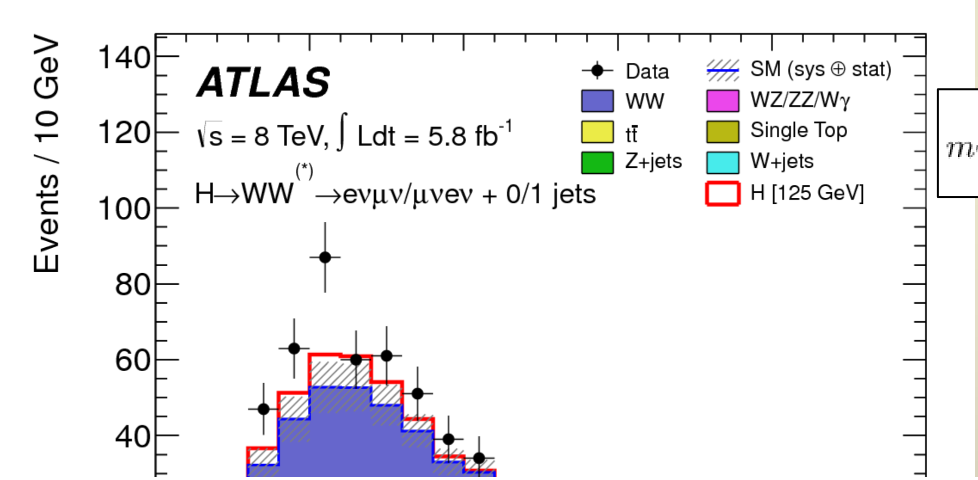
- Most sensitive channel ~ 125-180 GeV (σ ~ 200 fb)
  - Challenging: two missing ν → no mass reconstruction/peak → "counting channel"
  - 2 isolated opposite-sign leptons, large E_{Tmiss}
  - Main backgrounds: WW, top, Z+jets, W+jets
    - ➢ $m_{ll} \neq m_Z$, b-jet veto, …
    - ➢ topological cuts against "irreducible" WW background: pT_{ll}, m_{ll}, $\Delta\phi_{ll}$ (smaller for scalar Higgs), m_T (ll, E_{Tmiss})
- Worse pile-up in 2012
  - Main work-horse WW → eνμν
    - Less background from Z, γ^* → l^+l^-
    - Contributes 93% of WW sensitivity
- Counting → crucial to understand background
  - Understanding of E_T^{miss} (genuine and fake)
    - Sensitive to pile-up !
  - Excellent understanding of background in signal region → use signal-free control regions in data to constrain MC → use MC to extrapolate to the signal region





H → WW(*) 2012 Sample

- No significant excess above expected background observed in 2011 WW → lνlν data (Phys. Lett. B 716 (2012) 62-81)
- Final control plot of 2012 WW → eνμν data up to Oct12 (HCP set)
  - m_T used as control variable
  - Expected S/B in final 8 TeV sample still ~1:10 only
- Excess observed in 2012 data, consistent with a ~125 GeV Higgs

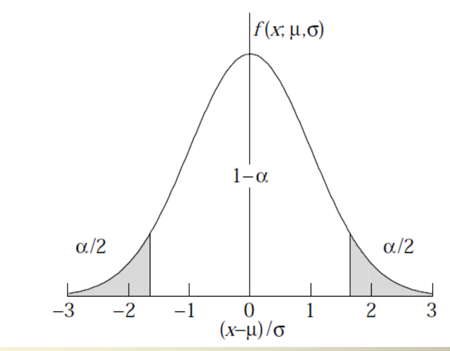


$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
$H+$ 0-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
$H+$ 1-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

Background Fluctuations

- Background is a random process, N_{bg} often well described by Poisson (Gauss) pdf
- The *N-σ* significance refers to probabilities of an excursion from the mean of relevant pdf
- For exclusion of signal presence, ~2 σ downward fluctuation of expected S+B is taken, allowing for 5 % false negatives
- For detection of particles two landmarks on upward background fluctuation are agreed
  - 3 σ: evidence, 0.13 % false positives
  - 5 σ: discovery, <3x10^{-7} false positives
- To bring background fluctuations into perspective
  - For a fair dice in a ludo game ⇒ background only
    - 1 σ effect: ~six in first trial
    - 2 σ effect: ~2 consecutive sixes in a row
    - 3 σ evidence: ~4 consecutive sixes in 2 trials
    - 5 σ discovery: ~8 consecutive sixes in a row
- **When would you start suspecting someone is cheating ?**

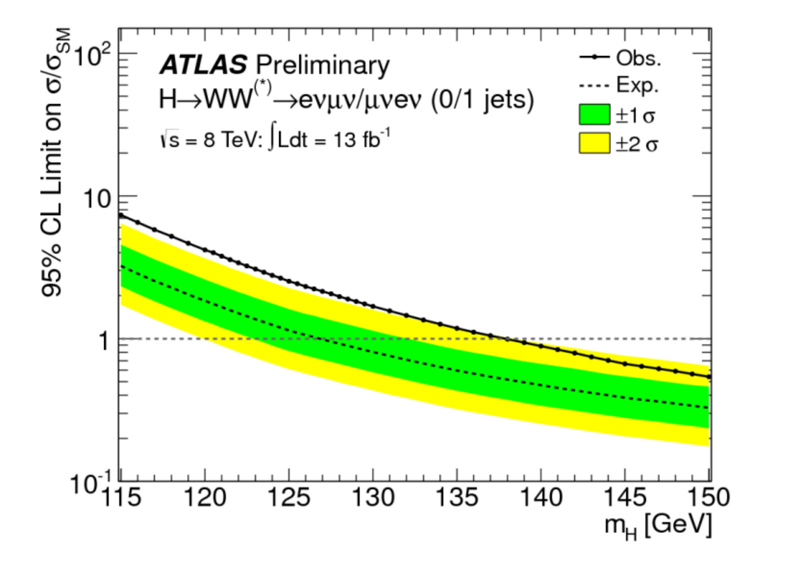


α	δ
0.3173	1σ
4.55×10^{-2}	2σ
2.7×10^{-3}	3σ
6.3×10^{-5}	4σ
5.7×10^{-7}	5σ
2.0×10^{-9}	6σ

$H \rightarrow WW^{(*)}$ Results

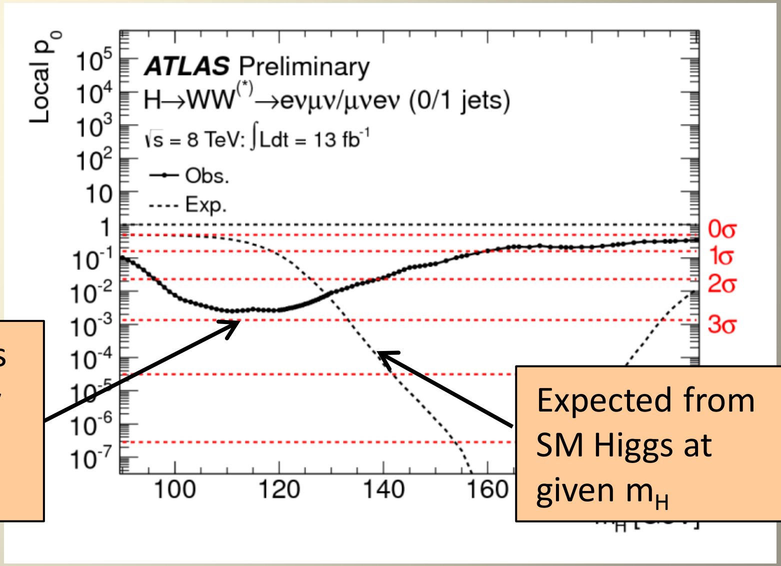
- 13 fb^{-1} of 2012 data up to Oct

Exclusion of Higgs signal contents in units of σ_{SM} at 95 % C.L.



p_0 - consistency of data with background-only expectation

Poor mass sensitivity broadens range



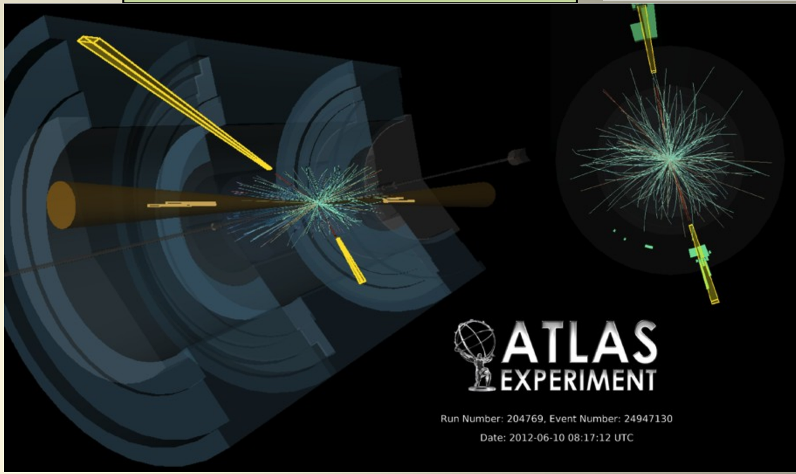
Expected from SM Higgs at given m_H

- Excluded (95% CL): **139 GeV< m_H** (expected: **127 GeV !**)
- Excess 2.8σ (1.9 expected) over a broad range of **m_H ~ 125 GeV** (poor **m_H** resolution)

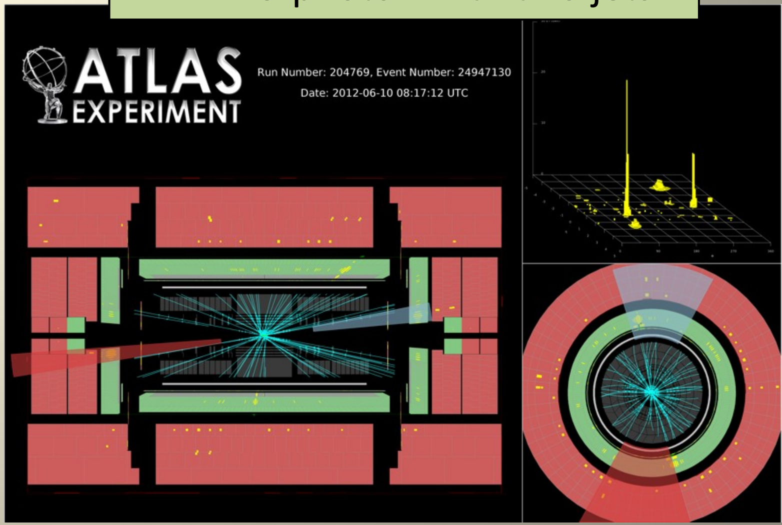
H→γγ

- Small cross-section: σ ~ 40 fb
- Simple final state: 2 high-p_T isolated photons
  - E_T (γ1, γ2) > 40, 30 GeV (20/20 for 7 TeV)
  - Main background: γγ continuum
    - irreducible, smooth, ..
- Events divided into 14 categories
  - 9 based on η-photon (e.g. central, rest, …), converted/unconverted, $p_T^{\gamma\gamma}$ perpendicular to γγ thrust axis + VBF(2j) + VH (l, E_{Tmis}, $2j_{lowmass}$)
- Crucial experimental aspects:
  - excellent γγ mass resolution to observe narrow signal peak above irreducible background
  - powerful γ/jet separation to suppress γj and jj background with jet → π^0 faking single γ

Two-photon event



Two-photon with two jets

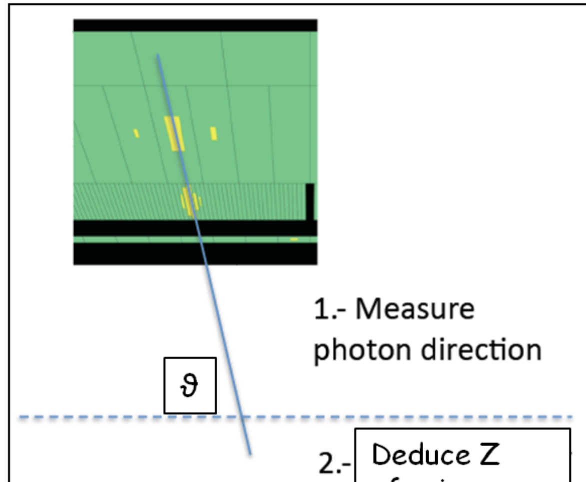


H→γγ Invariant Mass – γγ Angle

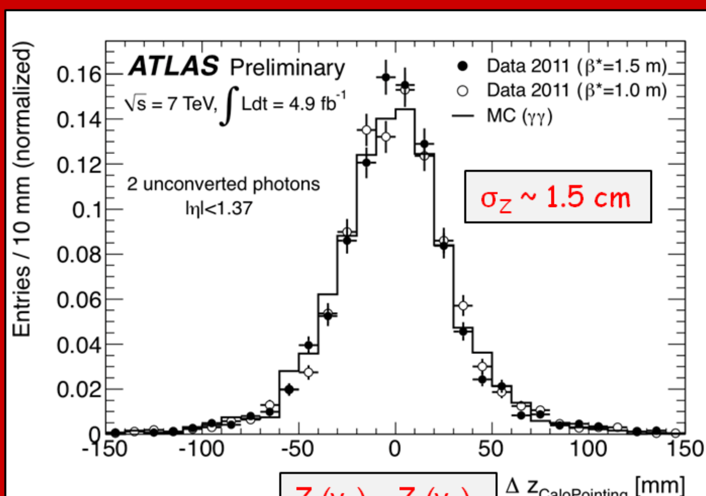
$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

α=opening angle of the two photons

Use longitudinal (and lateral) segmentation of EM calorimeter to measure photon polar angle ϑ crucial at high pile-up: many vertices distributed over σ_Z (LHC beam spot) ~ 5.6 cm → difficult to know which one produced the γγ pair



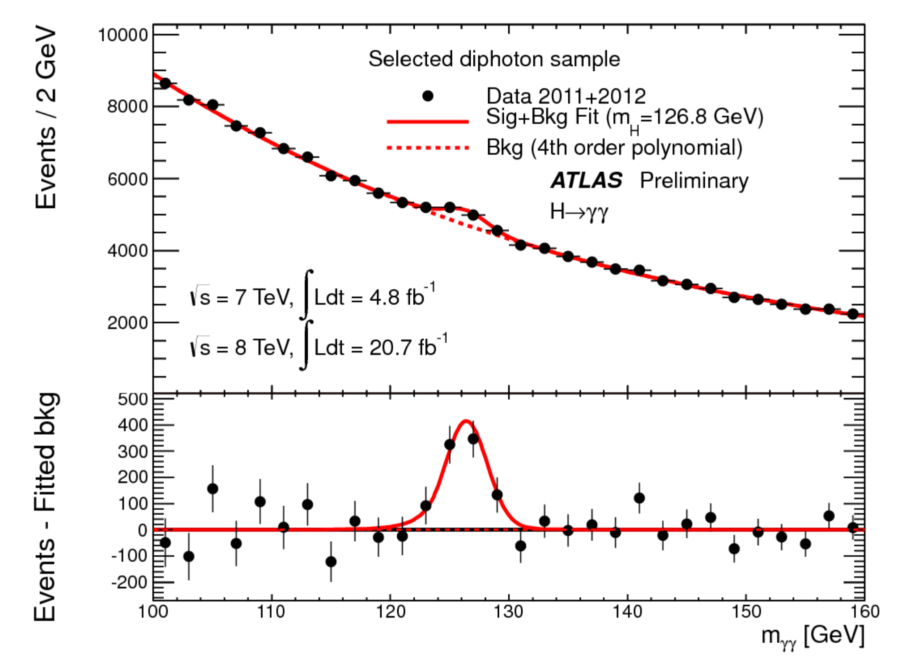
Z-vertex as measured in γγ events after selection from calorimeter "pointing"



- ❑ Calorimeter pointing capability reduces vertex uncertainty from ~ 5.6 cm (LHC beam spot) to ~ 1.5 cm
- → Contribution to mass resolution from angular term is negligible with calo pointing (γ →ee vertex also used)
- ❑ Robust against pile-up

H→γγ Final Sample

- After all selections: kinematic cuts, γ identification and isolation
  - ~145k events with $100 < m_{\gamma\gamma} < 160$ GeV observed in the 2011+2012 data
  - expected signal efficiency: ~ 40% for m_H=125 GeV
- $m_{\gamma\gamma}$ spectrum fit with
  - 4th order polynomial or exponential for background, depending on category
  - plus Crystal Ball + Gaussian for signal,
  - background determined directly from data



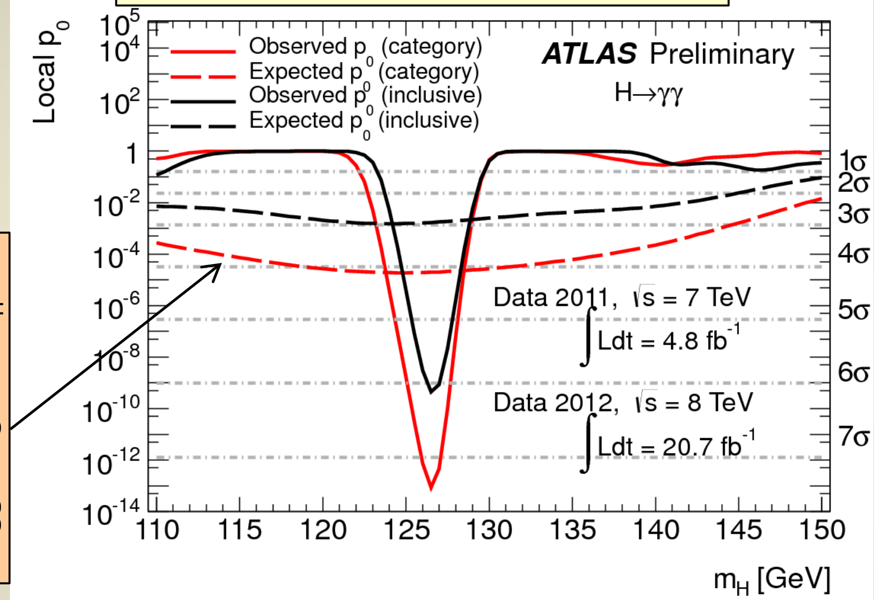
Main systematic uncertainties

Expected signal yield : ~ 8/11%
H→ γγ mass resolution : ~14%
Background modeling : ±0.2-4.6/0.3-6.8 ev. (category, 11/12)

H→γγ Results

p_0 - consistency of data with background-only expectation

Expected from SM Higgs at given m_H



- Maximum deviation from background-only expectation observed for m_H = 126.5 GeV:
  - Local p_0-value: ~**10^{-13}** or **7.4 σ** at **126.5 GeV**
  - Expected from SM Higgs: ~ **4.1 σ**
- Seeing more signal than expected from SM… upward fluctuation of the signal ?
- Single channel discovery, no big point in quoting exclusion…

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

- σ ~ 2-3 fb only, however:
  - Mass can be fully reconstructed → signal events cluster in a (narrow) peak
  - Pure: S/B ~ 1, narrow peak σ ~2 GeV

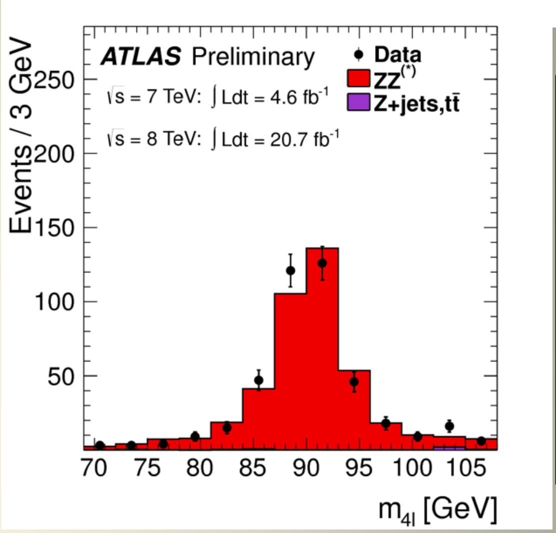
- Select 4 leptons: $p_T^{1,2,3,4}$ > 20, 15, 10, 7/6(e/μ) GeV
  - m_{12} =50-106 GeV; 115 > m_{34} > 12-50 GeV (depending on m_{4l})
- Main backgrounds:
  - $ZZ^{(*)}$ (irreducible)
  - $m_H < 2m_Z$: Zbb, Z+jets, tt with two leptons from b/q-jets → leptons

  → Suppressed with isolation and impact parameter cuts on two softest leptons
- Signal acceptance x efficiency: 15-37 % for m_H~ 125 GeV

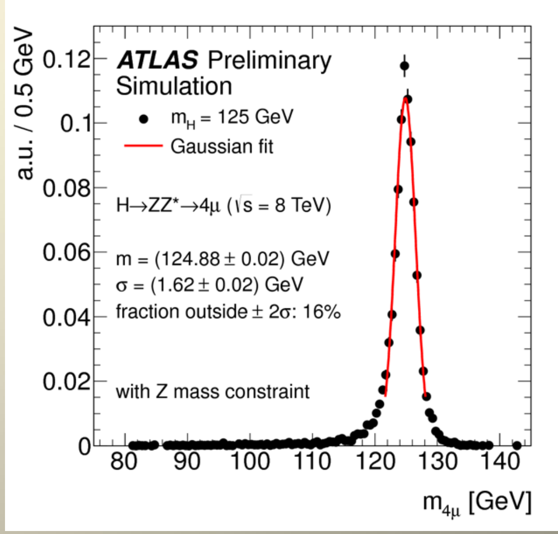
- Crucial experimental aspects:
  - High lepton reconstruction and identification efficiency down to lowest p_T
  - Good lepton energy/momentum resolution
  - Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region:
    - ➢ Cannot rely on MC alone (theoretical uncertainties, b/q-jet → l modeling, ..)
    - ➢ Need to compare MC to data in background-enriched control regions (but: low statistics)

H→ZZ$^{(*)}$ → 4l Performance

- ZZ$^{(*)}$ → 4e, 4μ, 2e2μ
- Electrons
  - Identification efficiency from J/ψ → ee, W → eν, Z→ ee data samples
  - Crucial to understand low-p_T electrons (affected by material) with data
  - H→ 4e mass resolution: 2.5 GeV
    - Event fraction in ±2σ: ~ 80%
- Muons
  - Checked on Z → μμ data sample
  - Muon reconstruction efficiency > 95% over 4 < p < 100 GeV
  - H→ 4μ mass resolution: ~1.6 GeV
    - Event fraction in ±2σ: ~ 85%



pp→ Z→ 4l
4l invariant mass peak



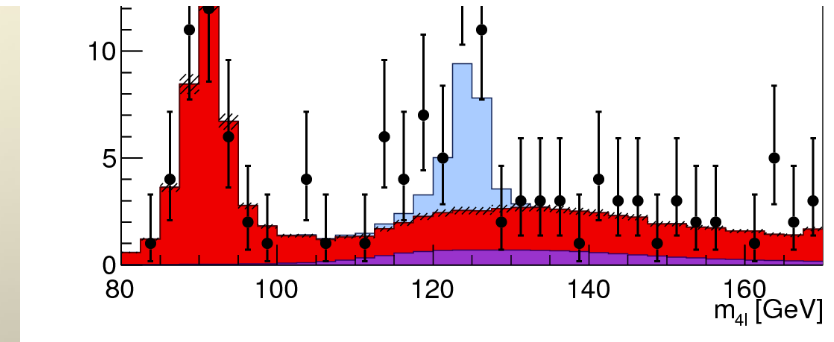
FSR corrected and Z constraint fit

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Final Sample

- After all selections:
  - kinematic cuts, isolation, impact parameter
- Mass range above 160 GeV
  - Observed: 317/59 events (8/7 TeV)
  - 301/53 background events expected
    - mainly from $ZZ^{(*)}$
- m(4l) < 160 GeV
  - Observed: 100/21 events (8/7 TeV)
  - Expected from background: 74/13
  - Significant excess clustered around 125 GeV
- 120 < m(4l) < 130 GeV (containing ~90% of a m_H=125 GeV signal):
  - Similar contributions expected from signal and background: ~ 5 events each
  - S/B 1.9 (4μ), 1.3 (2e2μ), 1.1 (4e)
  - Background dominated by ZZ* (4μ), Z+jets and tt (2μ2e, 4e)
  - 32 events observed, 27 expected from SM S+B

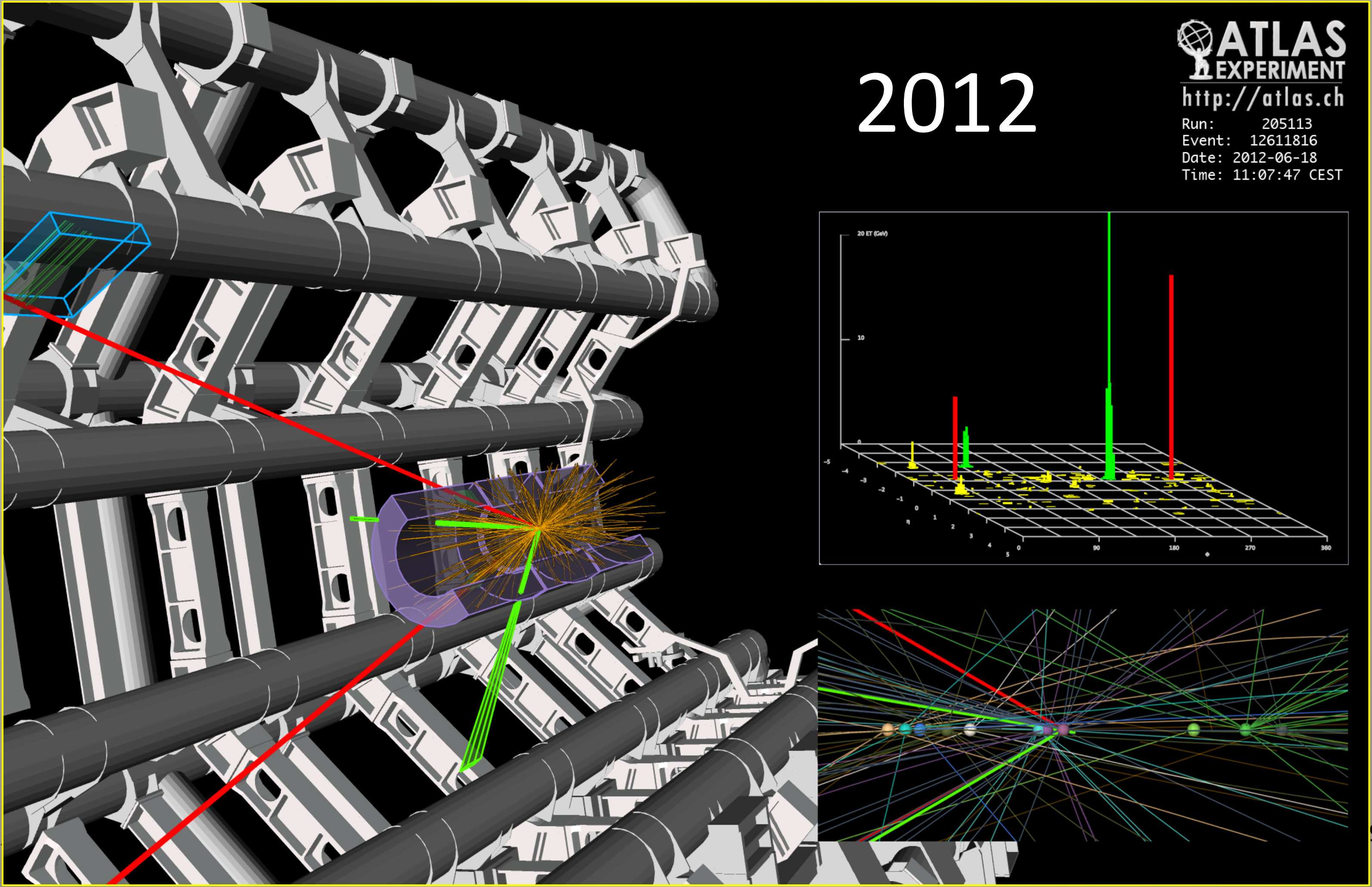
Events in $120 < m_{4l} < 130$ Gev

	total signal full mass range	signal	$ZZ^{(*)}$	$Z+\text{jets}, t\bar{t}$	S/B	expected	observed
$\sqrt{s} = 8$ TeV							
4μ	5.8 ± 0.7	5.3 ± 0.7	2.3 ± 0.1	0.50 ± 0.13	1.9	8.1 ± 0.9	11
$2\mu 2e$	3.0 ± 0.4	2.6 ± 0.4	1.2 ± 0.1	1.01 ± 0.21	1.2	4.8 ± 0.7	4
$2e2\mu$	4.0 ± 0.5	3.4 ± 0.4	1.7 ± 0.1	0.51 ± 0.16	1.5	5.6 ± 0.7	6
$4e$	2.9 ± 0.4	2.3 ± 0.3	1.0 ± 0.1	0.62 ± 0.16	1.4	3.9 ± 0.6	6
total	15.7 ± 2.0	13.7 ± 1.8	6.2 ± 0.4	2.62 ± 0.34	1.6	22.5 ± 2.9	27
$\sqrt{s} = 7$ TeV							
4μ	1.0 ± 0.1	0.97 ± 0.13	0.49 ± 0.02	0.05 ± 0.02	1.8	1.5 ± 0.2	2
$2\mu 2e$	0.4 ± 0.1	0.39 ± 0.05	0.21 ± 0.02	0.55 ± 0.12	0.5	1.2 ± 0.1	1
$2e2\mu$	0.7 ± 0.1	0.57 ± 0.08	0.33 ± 0.02	0.04 ± 0.01	1.5	0.9 ± 0.1	2
$4e$	0.4 ± 0.1	0.29 ± 0.04	0.15 ± 0.01	0.49 ± 0.12	0.5	0.9 ± 0.1	0
total	2.5 ± 0.4	2.2 ± 0.3	1.17 ± 0.07	1.12 ± 0.17	1.0	4.5 ± 0.5	5
$\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV							
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.3 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	15.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32



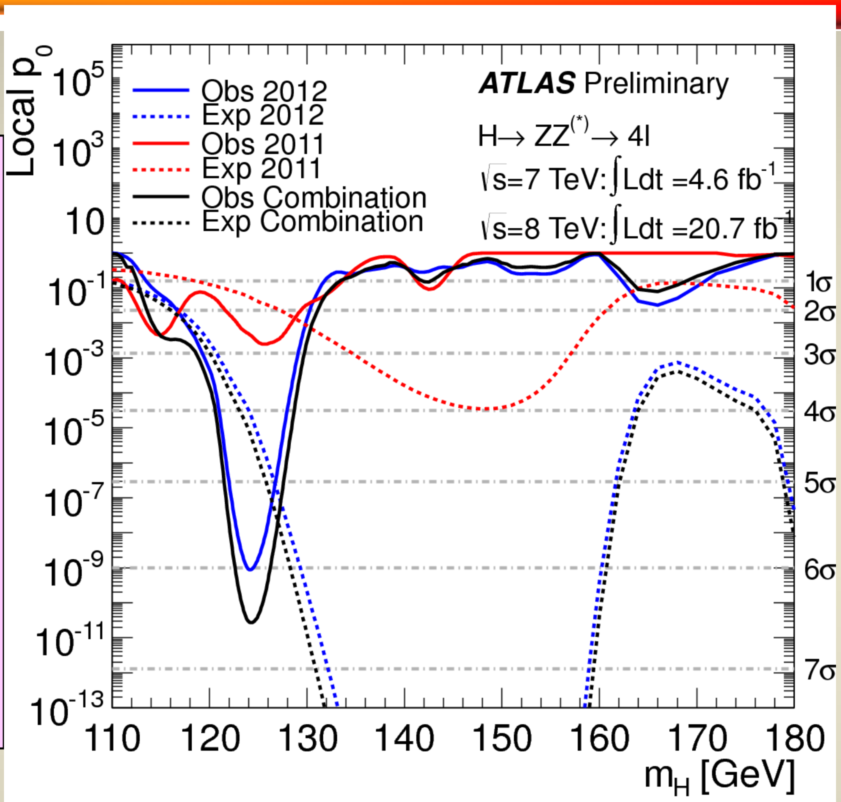
2e2μ Event with $m_{2e2\mu}$ = 123.9 GeV

- 12 reconstructed vertices - ~normal pile up in 2012
- p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m_{ee} = 87.9 GeV, $m_{\mu\mu}$ =19.6 GeV



$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Results

p_0 - consistency of data with background-only expectation



- Maximum deviation from background-only expectation observed for m_H = 124.3 GeV:
  - Local p_0-value: 2.7x$\mathbf{10^{-11}}$ or **6.6 σ**
  - Expected from SM Higgs: ~ **4.4 σ**
- (Another) single channel discovery

Wrapping it up – Combined Results

- Statistically combine data we talked …

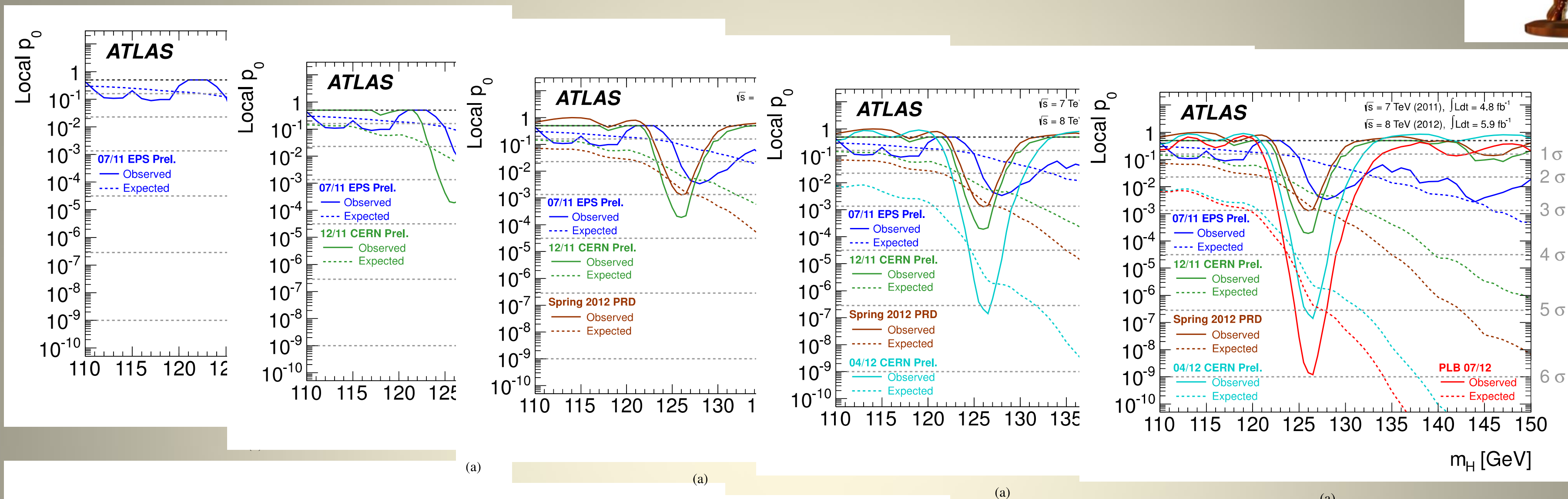
… and did not talk about

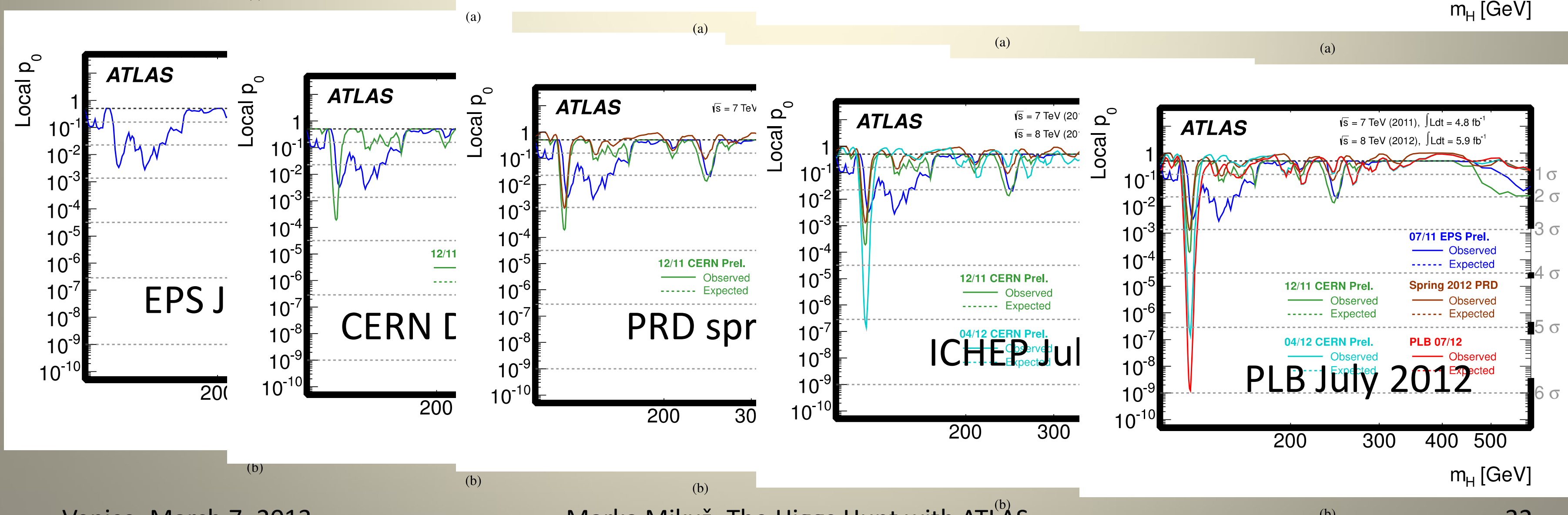
In a nutshell

- $\gamma\gamma$ and 4l for complete 2011/12
  - ~5+21 fb^{-1}
- WW 2012 up to Oct
  - ~13 fb^{-1}
- bb and $\tau\tau$ 2011/Oct12
  - ~5+13 fb^{-1}

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	4.6	[7]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\}$	4.8	[6]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{$0-jet$\} \oplus \{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	4.6	[8]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e,\mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	4.6	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	4.6	[9]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	21	[7]
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH$\}$	21	[6]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{$0-jet, 1-jet$\}$	13	[10]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	13	[8]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e,\mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	13	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	13	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	13	[9]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	

A Bit of History





Entering Precision Higgs Physics

- With discovery well established in two separate channels
  - No need to push limit on SM signal presence

- Explore the newly discovered particle
  - Mass, signal strength
  - Production mechanisms
  - Spin
  - Couplings

Mass Measurement

- The two precision channels yield

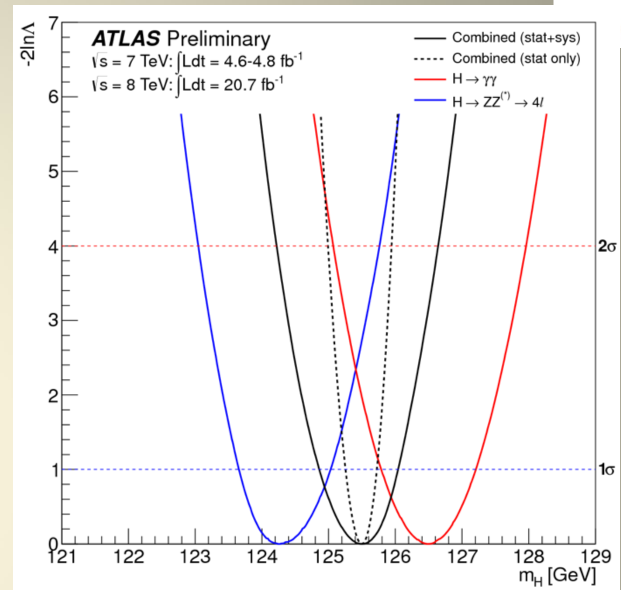
$$m_H = 126.8 \pm 0.2\,(\text{stat}) \pm 0.7\,(\text{sys})\ \text{GeV}$$ H→γγ

$$m_H = 124.3^{+0.6}_{-0.5}\,(\text{stat})\,^{+0.5}_{-0.3}\,(\text{sys})\ \text{GeV}$$ H→4l

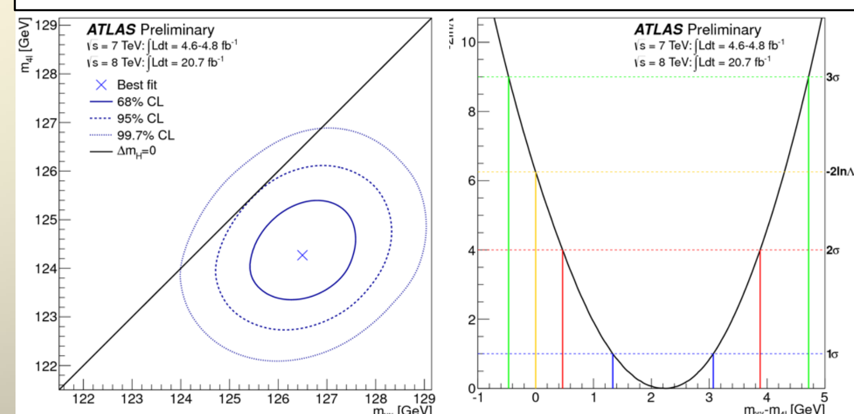
- Best fit value

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

- Results still compatible at ~1% level (~2.5σ)
  - Can depend critically on energy resolution modeling



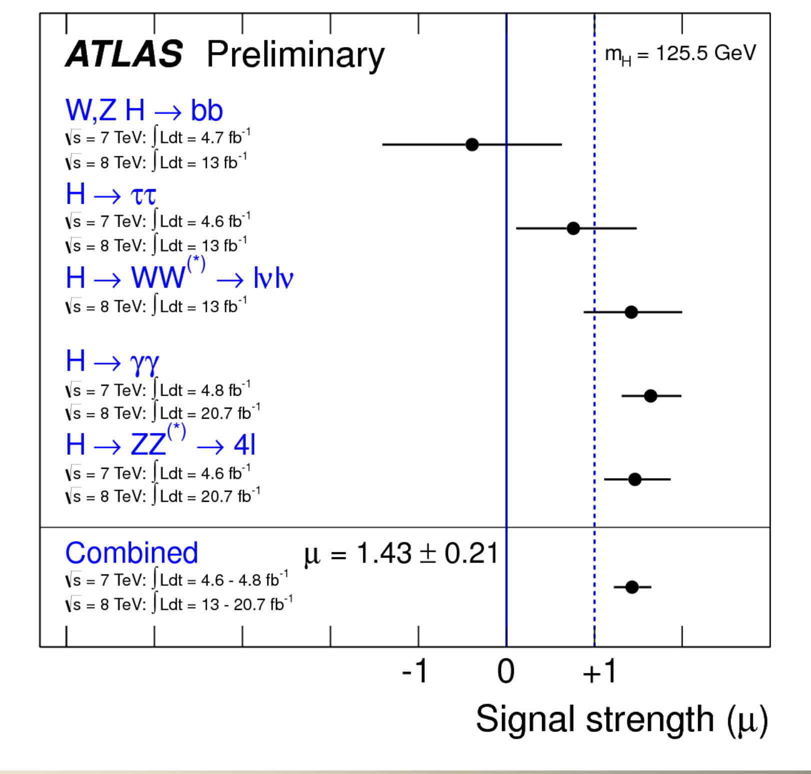
$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$



Signal Strength

- All strengths relative to SM prediction
  - Evaluated at m_H =125.5 GeV

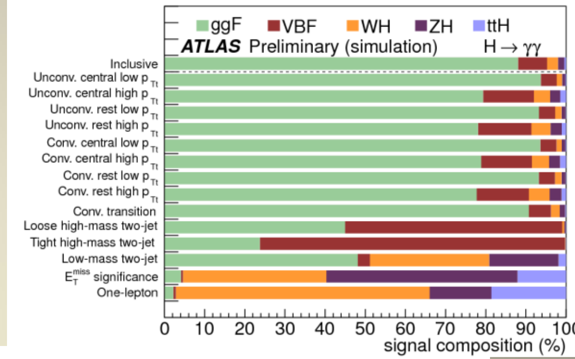
Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \rightarrow Vbb$	-0.4 ± 1.0
$H \rightarrow \tau\tau$	0.8 ± 0.7
$H \rightarrow WW^{(*)}$	1.4 ± 0.6
$H \rightarrow \gamma\gamma$	1.6 ± 0.3
$H \rightarrow ZZ^{(*)}$	1.5 ± 0.4
Combined	1.43 ± 0.21

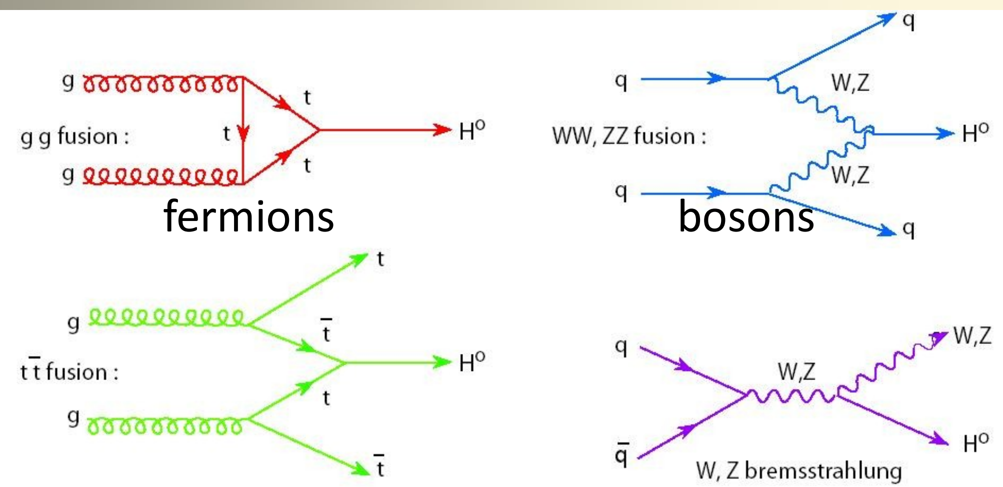


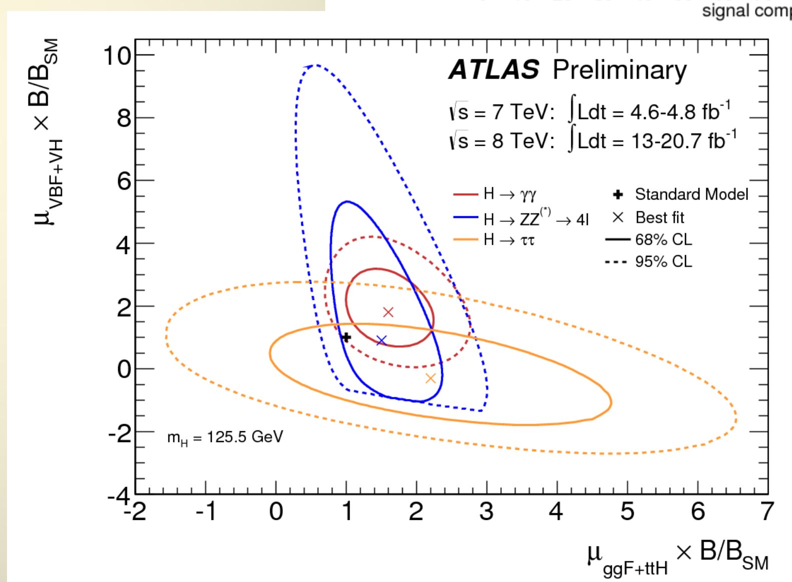
  - 2 σ excess w.r.t. SM expectation
    - Need more statistics before any claims can be made…
  - No firm hint of coupling to fermions yet

Production Mechanism

- Dominant Higgs production mechanisms at LHC well defined in Standard Model
  - Results from H→γγ, 4l, ττ
  - Combine H couplings to fermions/bosons:
    - ggF+ttH; VBF+VH





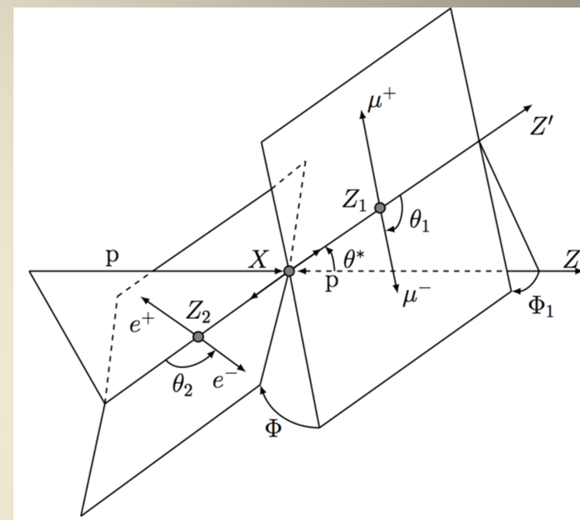


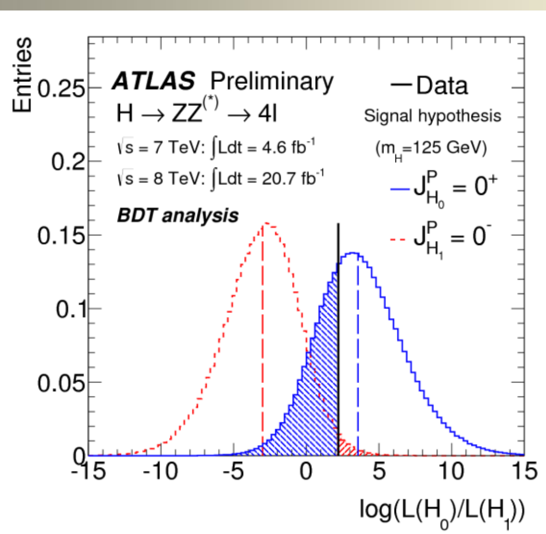
Production relative to SM

- Result consistent with (high side of) SM predictions

Spin

- From decays the new particle is clearly a boson,
  - H→γγ forbids J=1
- First measurements in H→γγ and H→4l
  - H→γγ: photon angle relative to Higgs direction
    - Not yet approved for complete 2012 data-set
  - H→4l: Multivatiate analysis: BDT, MELA
    - Problem: J=2 (graviton) model dependent





H→4l

		BDT analysis				J^P-MELA analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S	tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022	0.0011	0.0022	0.40	0.004
1^+	p_0	0.0016	0.001	0.55	0.002	0.0031	0.0028	0.51	0.006
1^-	p_0	0.0038	0.051	0.15	0.060	0.0010	0.027	0.11	0.031
2^+_m	p_0	0.092	0.079	0.53	0.168	0.064	0.11	0.38	0.182
2^-	p_0	0.0053	0.25	0.034	0.258	0.0032	0.11	0.08	0.116

- SM value $J^P=0^+$ favoured over others, but exclusion level still small

The New Boson – What is it ?

a) The Higgs boson (the One, SM) ?
b) A Higgs boson (one of many, e.g. MSSM) ?
c) An impostor (sth else) ?

- The Standard Model Higgs boson has a rich and well-defined associated phenomenology
  - Cross section, branching ratios
  - Spin, parity, couplings, self coupling
- All this needs to be explored in detail before providing a definite answer
- We have just started to enter the exploration regime for this new particle
  - The quest has just begun with remarkable results already available
  - LHC will deliver at least 10x if not 100x more data in its lifetime
- Exploring the new discovery in detail will take time, resources, and might require a new (linear ?) collider

Summary

- We have analysed up to 4.9 fb^{-1} of 7 TeV and up to 21 fb^{-1} of 8 TeV pp collision data for presence of SM Higgs boson
  - Across the 110-600 GeV mass region
  - In many distinct decay channels (3 most relevant for 2012 data)
- We observe an excess of events centred at **m_H~ 125 GeV**:
  - Excess comfortably exceeds discovery limit in two distinct, high-precision channels: H→ γγ (**7.5 σ**) and H→ ZZ* → 4l (**6.3 σ**)
    - SM Higgs expectation: **4.1/4.2 σ**
  - Best mass value: **+125.4 ± 0.6 GeV**
  - Signal strength relative to SM: **1.45 ± 0.22**
- We are entering precision Higgs physics
  - Started on spin and production mechanisms

No matter whether this particle turns out the Higgs, a Higgs or something exotic, we have set an important milestone in unveiling the very secrets of Nature

Backup

H→γγ Backgrounds

- Potentially huge background from γj and jj production with jets fragmenting into a single hard π^0 and the π^0 faking single photon
  - Suppressed by fine lateral segmentation (4mm η-strips) of the first compartment of ATLAS EM calorimeter
  - Need suppression of $\mathcal{O}(10^{-4})$ to get to level of irreducible γγ background
- After all cuts: ~120k events with $100 < m_{\gamma\gamma} < 160$ GeV observed in the 2012 data
- Sample composition estimated from data using control samples
  - ✓ γj + jj << γγ irreducible (purity 75%)