Update on the Search for the Higgs Boson at the LHC

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TRIUMF Seminar
July 5th 2012

Resources

Updates from July 4th CERN seminars

Recorded broadcast:
https://cdsweb.cern.ch/record/1459565

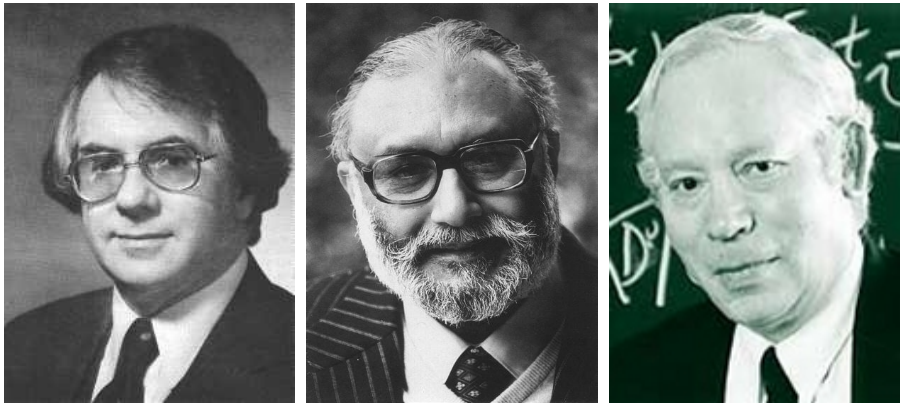
Updates from ATLAS and CMS collaborations
Slides:

http://indico.cern.ch/conferenceDisplay.py?confId=197461

The History of the Standard Model

1979 Nobel Prize-- GLASHOW, SALAM and WEINBERG

the theory of the unified weak and electromagnetic interaction.

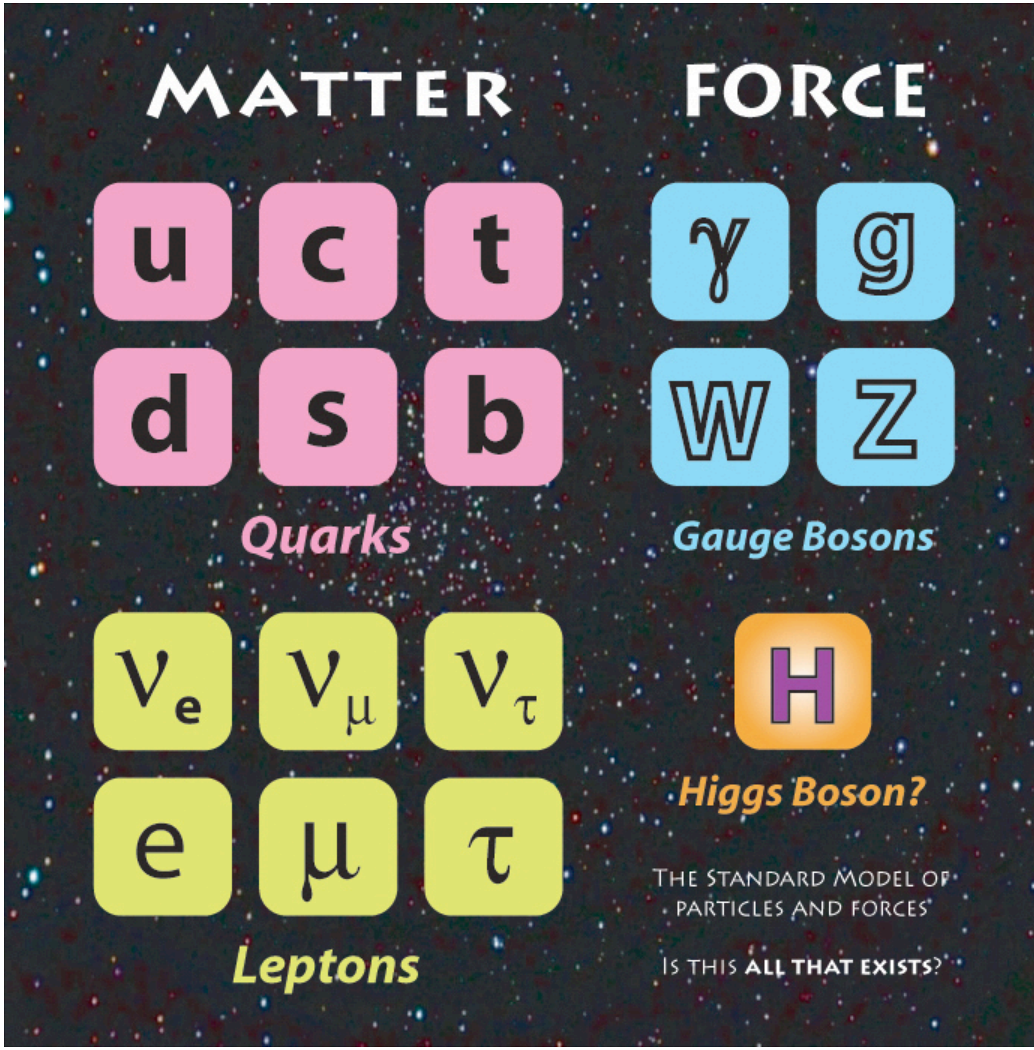


1984 Nobel Prize-- RUBBIA and VAN DER MEER

the discovery of the field particles W and Z, communicators of weak interaction.

The Standard Model of Particles Physics

- The Fundamental Particles:
  - Fermions (6 Quarks)
  - Fermions (6 Leptons)
  - Bosons (Force Carrier)
- For some reason, matter particles appear in three *generations of particles with very different mass!*
- The SM is very successful, tested to very high precision by experiments
- Missing an important piece of the theory, the Higgs boson



The Higgs Boson

What is Mass?

- Newton, definition #1 of Principia:

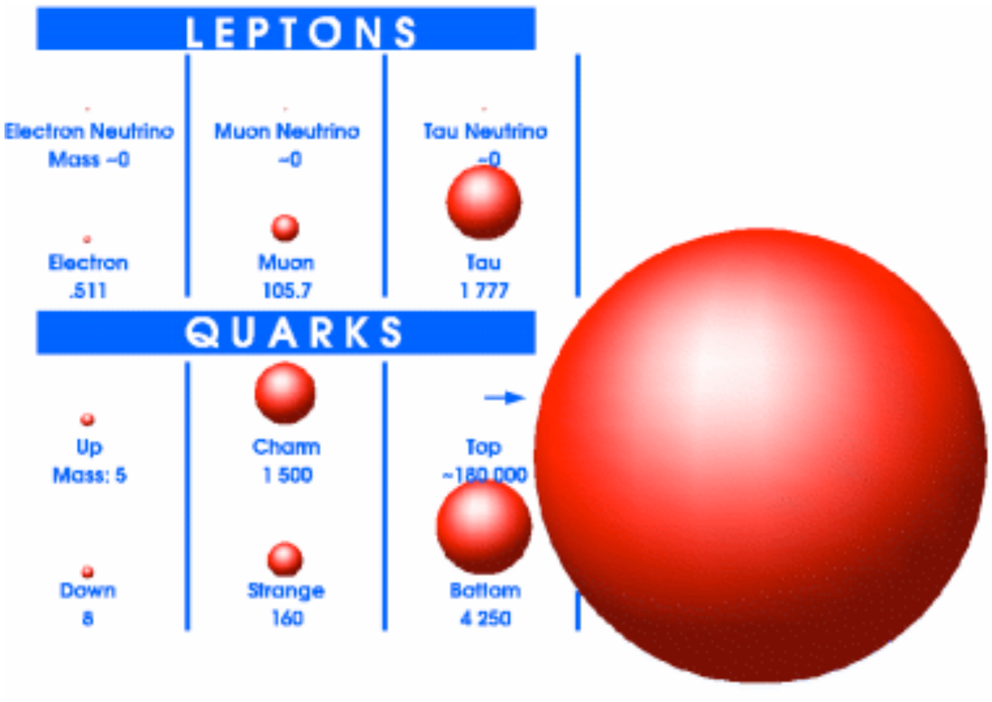
  "the quantity of matter is the measure of the same, arising from its density and its bulk conjointly."
  I think it means: *($m = \rho V$)*

- Merriam-Webster dictionary:

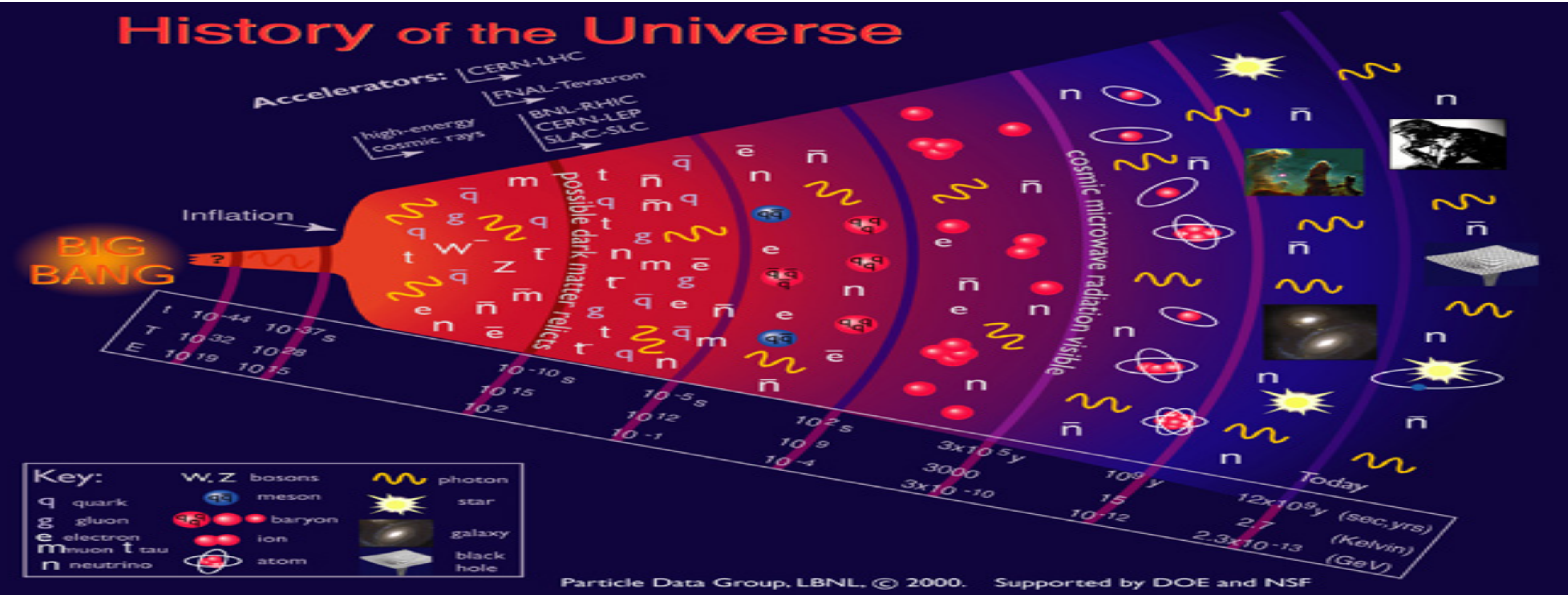
  "the property of a body that is a measure of its inertia and that is commonly taken as a measure of the amount of material it contains and causes it to have weight in a gravitational field"

Particle Masses

- Standard Model does not say anything about the values of the particle masses … have to be measured by experiment
- Underlying quantum field theories are one of the greatest theoretical accomplishments but do not include the mechanism to introduce mass
- *Standard Model introduces Higgs Mechanism to do that job*



Generation of Mass in the Standard Model



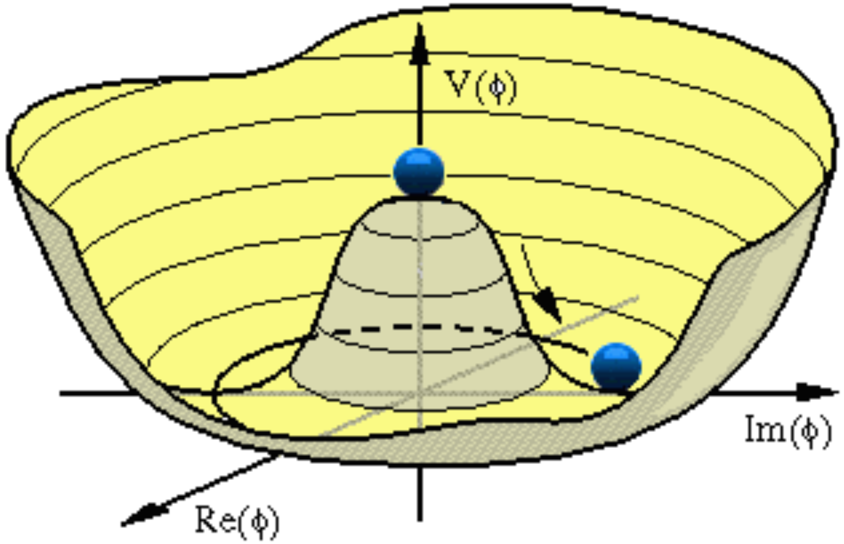
- According to the Standard Model of particle physics, particles acquired mass during a phase transition when the Universe was ~10^{-12} seconds old and cooling rapidly
- During this phase transition, a scalar field (the Higgs field) acquired a non-zero expectation value
  - the vacuum is not empty but is filled by Higgs field ("jelly") that "slows down" anything that interacts with it.
  - Temperature (energy) of universe at transition: ~few 100 GeV
  - The mass of a particle depends on how strongly it interacts with the Higgs field

Higgs Mechanism

The Higgs Mechanism:

- introduce a scalar field
- break symmetry of ground state
- Interactions with scalar field generate mass terms

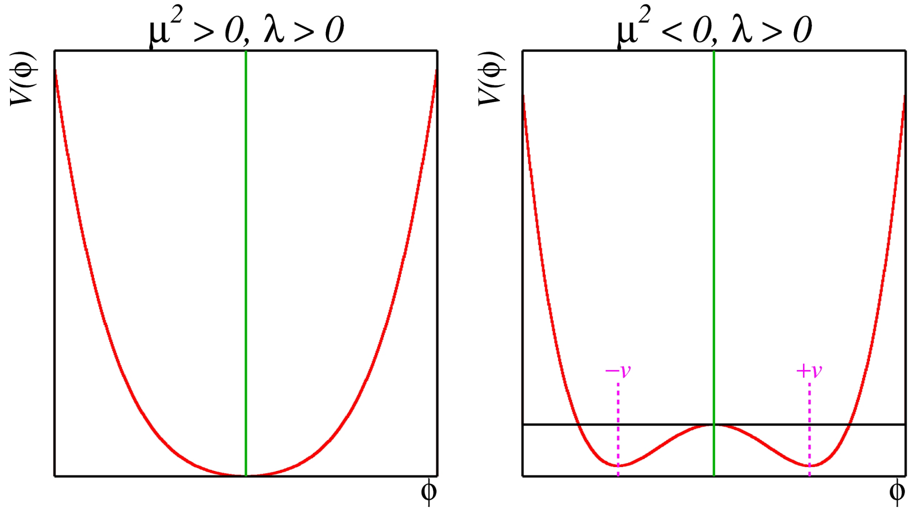
- How strongly a particle interacts with Higgs field determines how massive it is

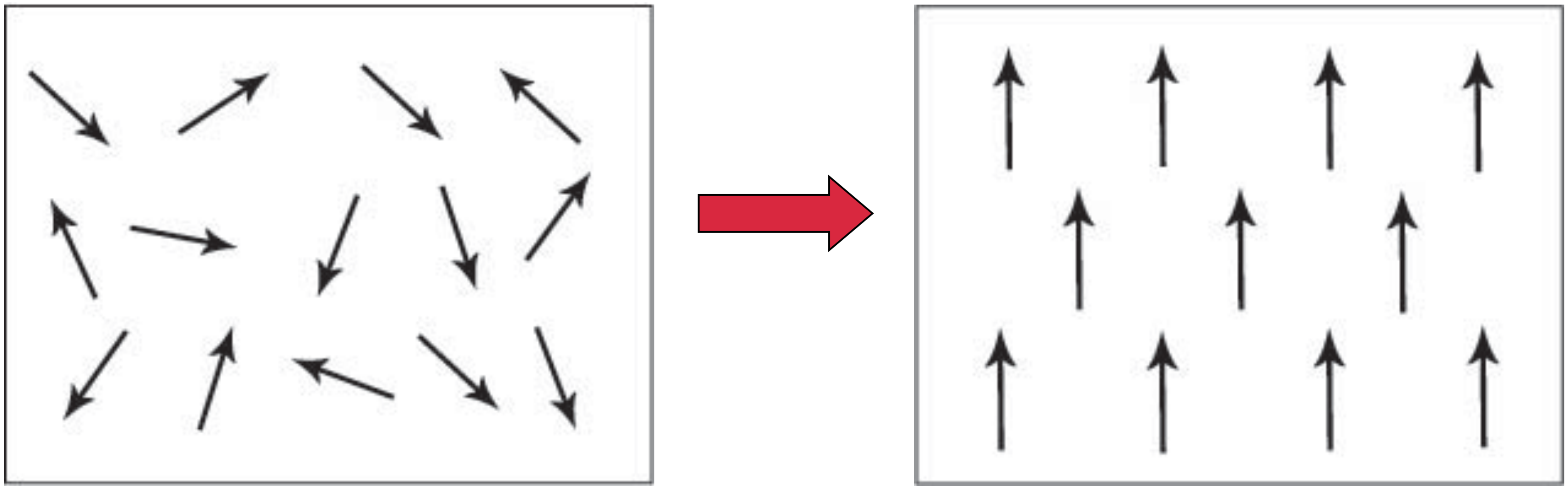


Spontaneous Symmetry Breaking

Example:

What happens to a ferromagnet when cooled below the critical Curie temperature





Higgs Mechanism in the SM

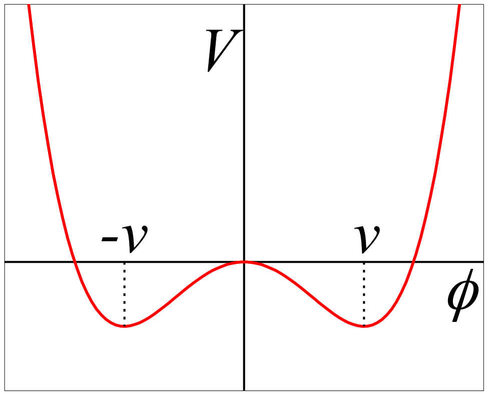
Massless electroweak bosons

$$\begin{pmatrix} B \\ W^-, W^0, W^+ \end{pmatrix}$$

Complex spin 0
Higgs doublet

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

Massless bosons acquire mass



Break symmetry of ground state

$$\begin{pmatrix} & \gamma & \\ W^- & & W^+ \\ & Z^0 & \end{pmatrix}$$

Physical bosons

+ *Higgs boson*

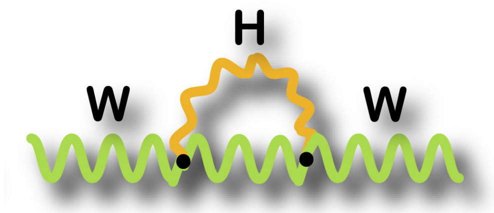
Searching for the Higgs

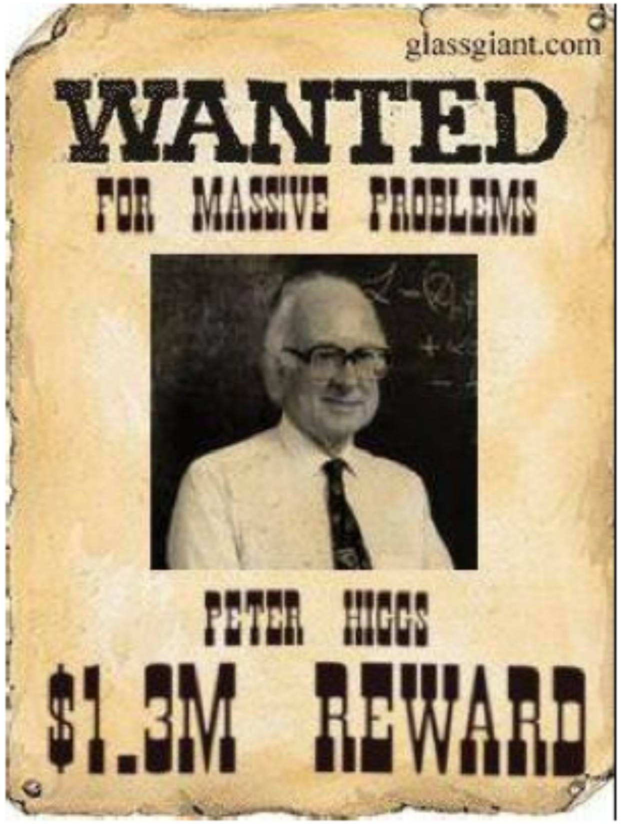
Sounds good, but how do we know it's true?

- Excite the Higgs field make Higgs particles !!!

- Need to collide particles with enough energy to create the mass of the Higgs: $E=mc^2$

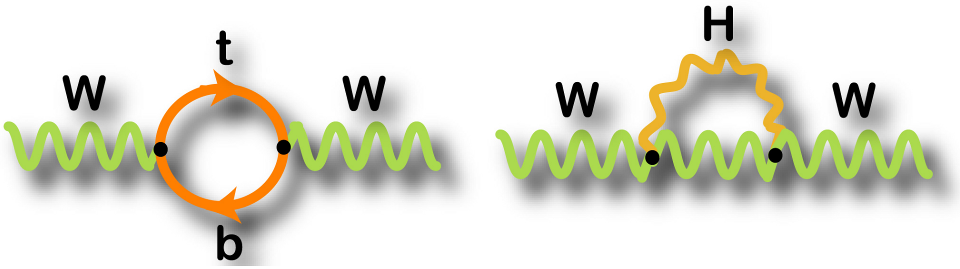
- Or look for its quantum effects

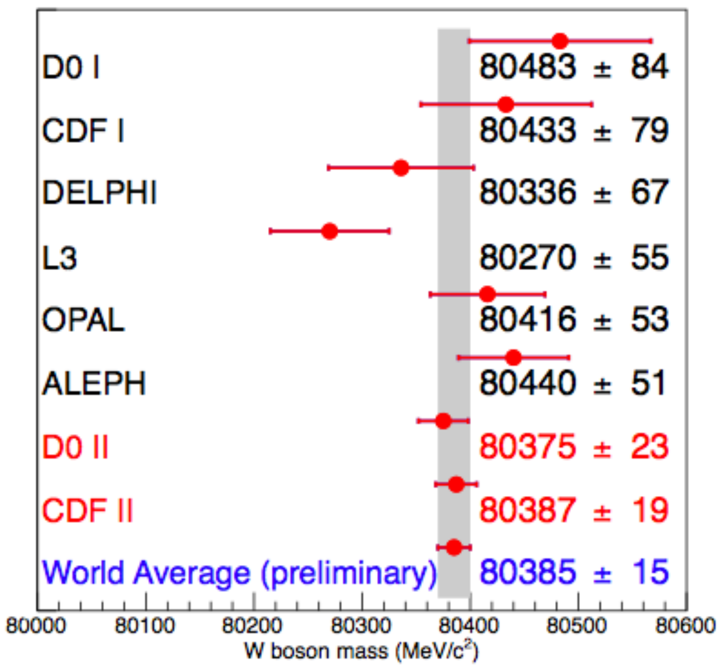


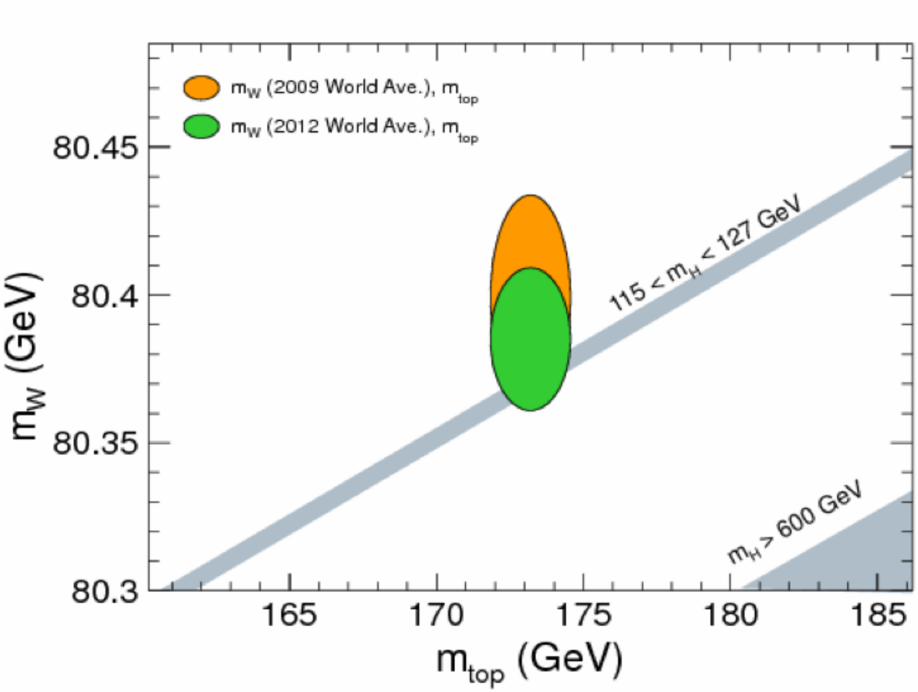


W Boson Mass Precision Constraints

- Derive W mass from precisely measured electroweak quantities
- Radiative corrections Δr dominated by top quark and Higgs loop
  ⇒allows constraint on Higgs mass

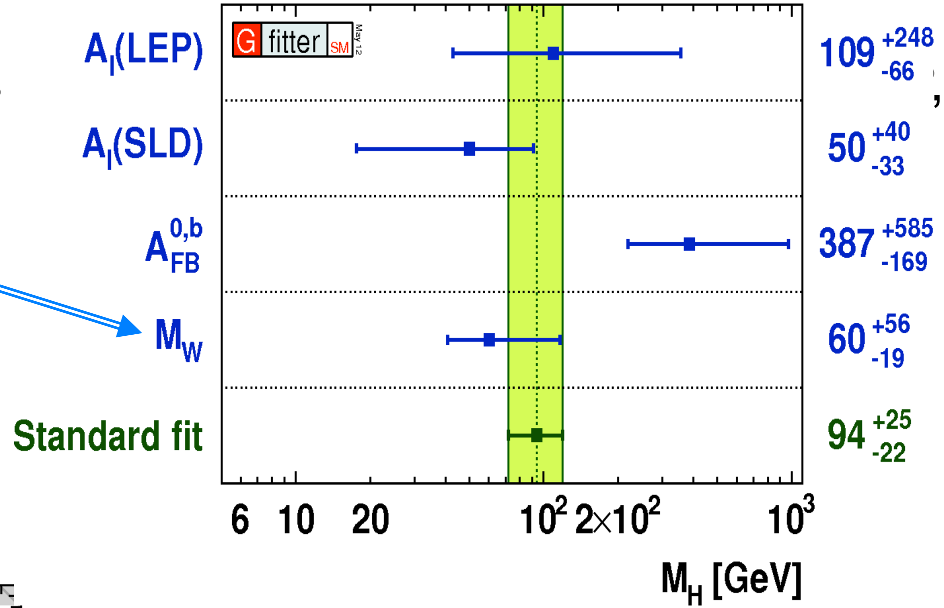


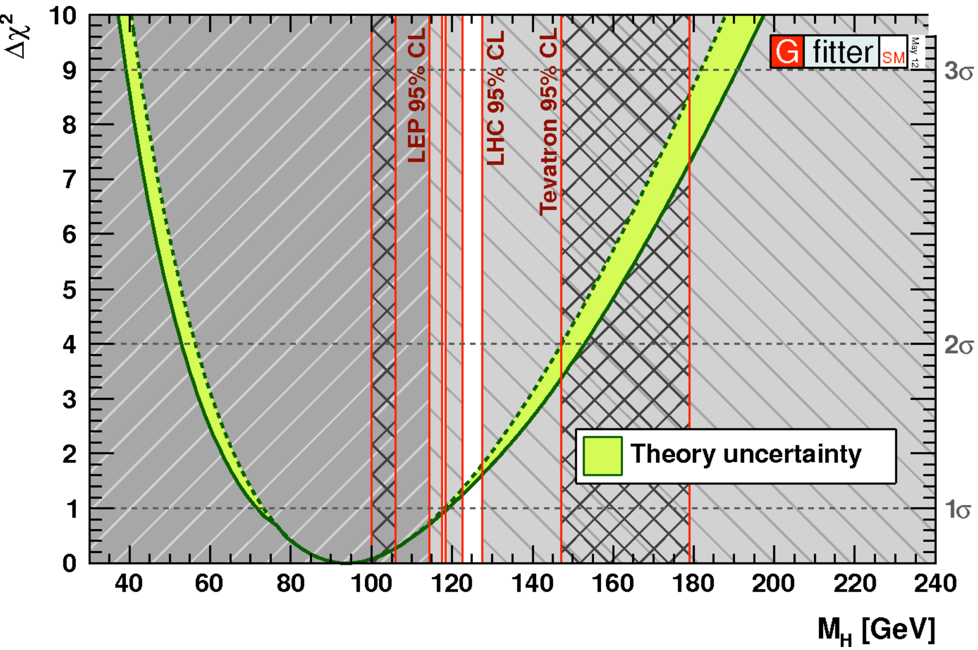




Electroweak Precision Constraints

- 20 years of precision measurements at LEP, SLC, Tevatron, sensitive to Higgs boson mass
- New W boson mass constraint
- Fit for minimum Higgs mass



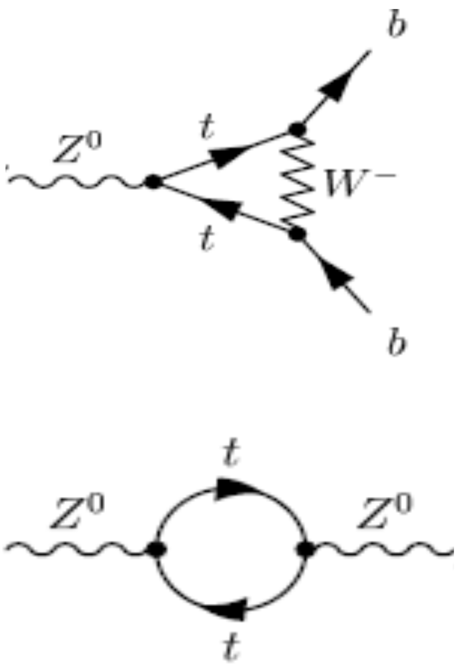


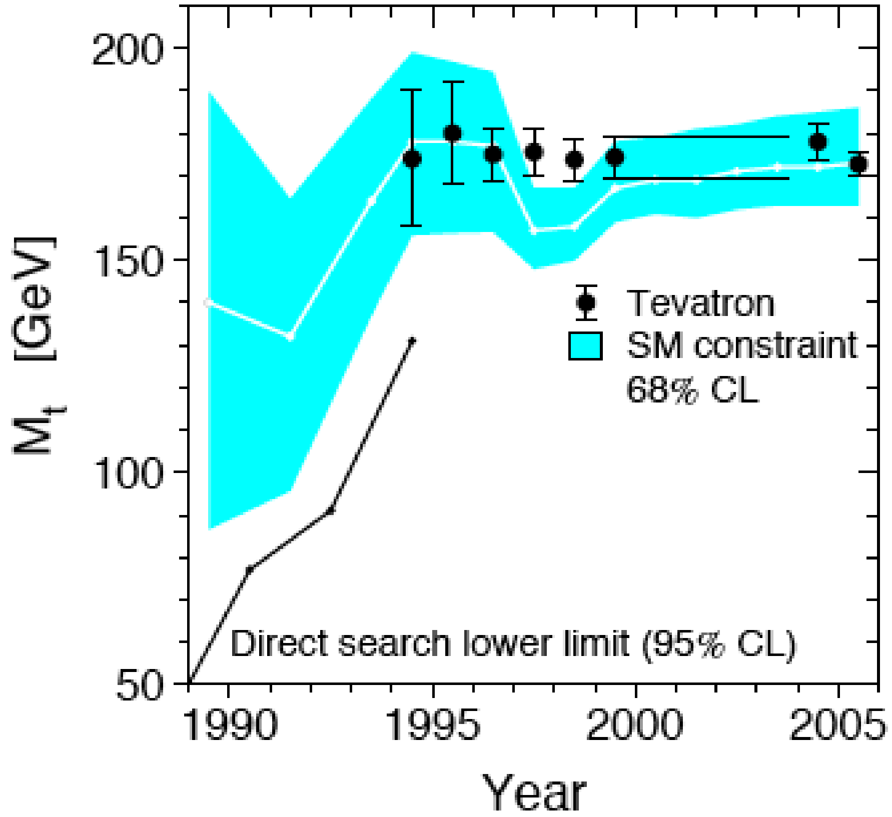
$M_{Higgs}=94^{+25}_{-22}$ GeV

Example from the Past

From precision measurements from LEP and SLC on the Z boson pole

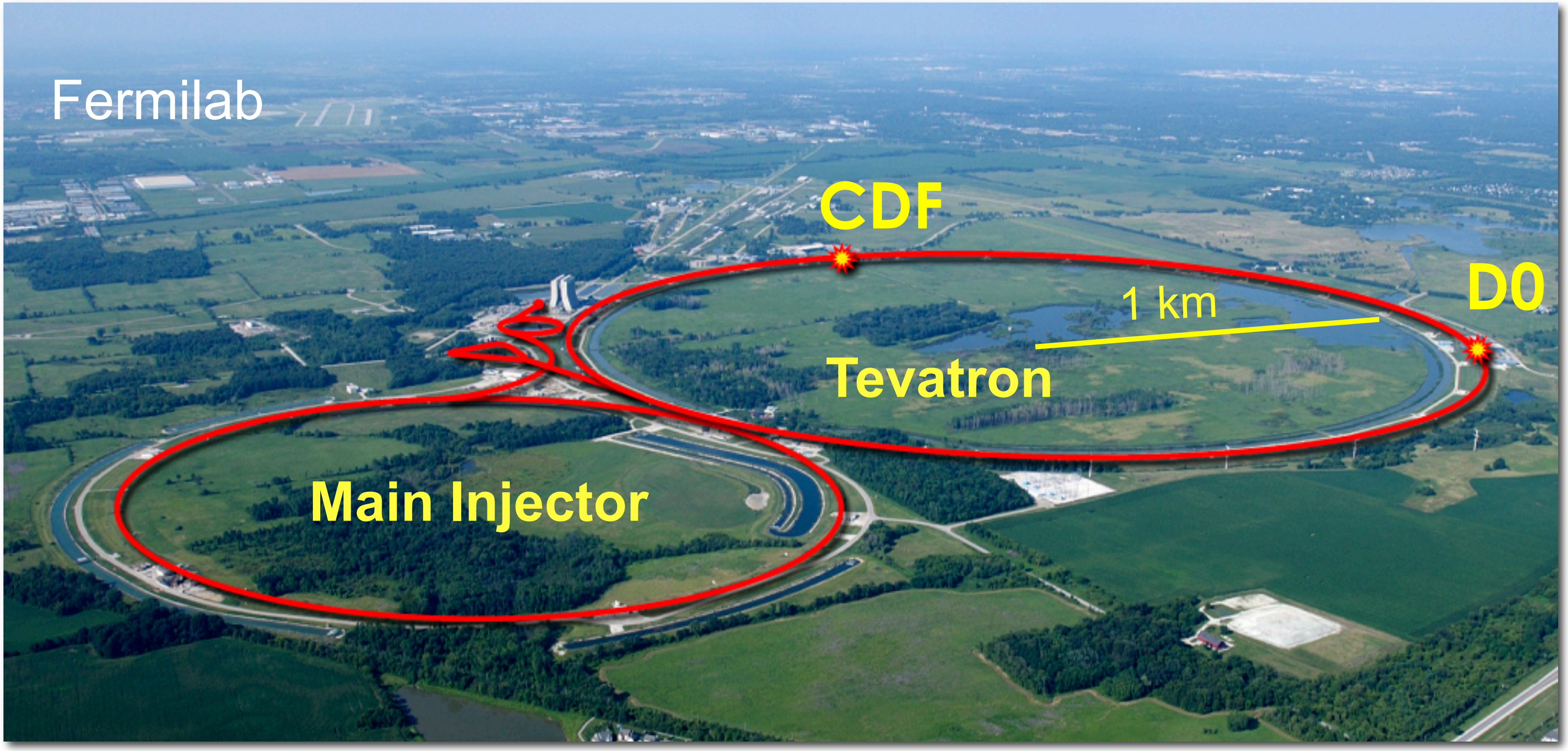
- top quark loops in Z^0





Precision measurements on Z pole constraint top quark mass before its discovery

Tevatron Run II

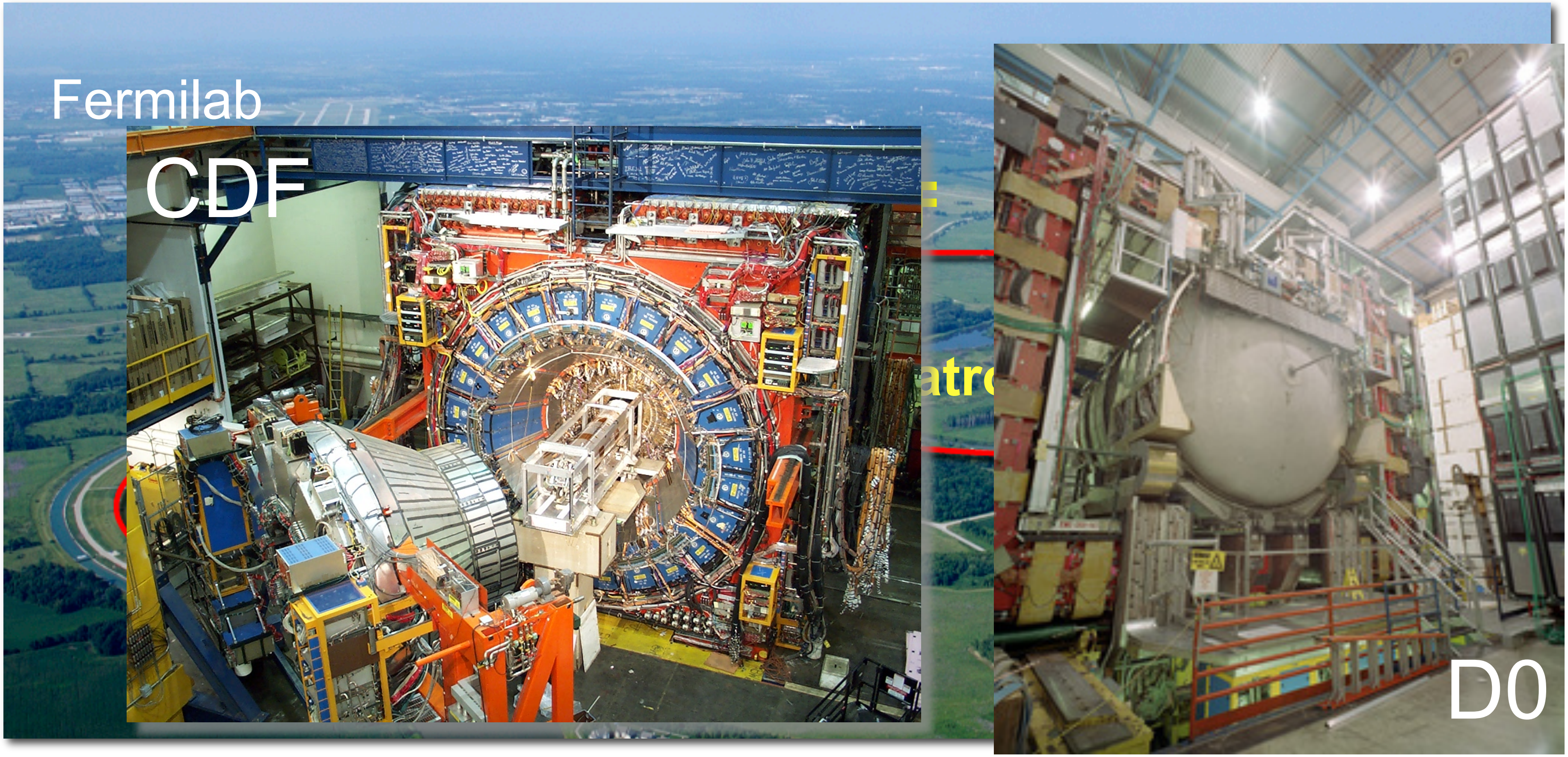


Fermilab's Tevatron Run II pp collider at 1.96 TeV 2001-2011

12 fb^{-1} delivered by Tevatron

10 fb^{-1} recorded by CDF & D0

Tevatron Run II

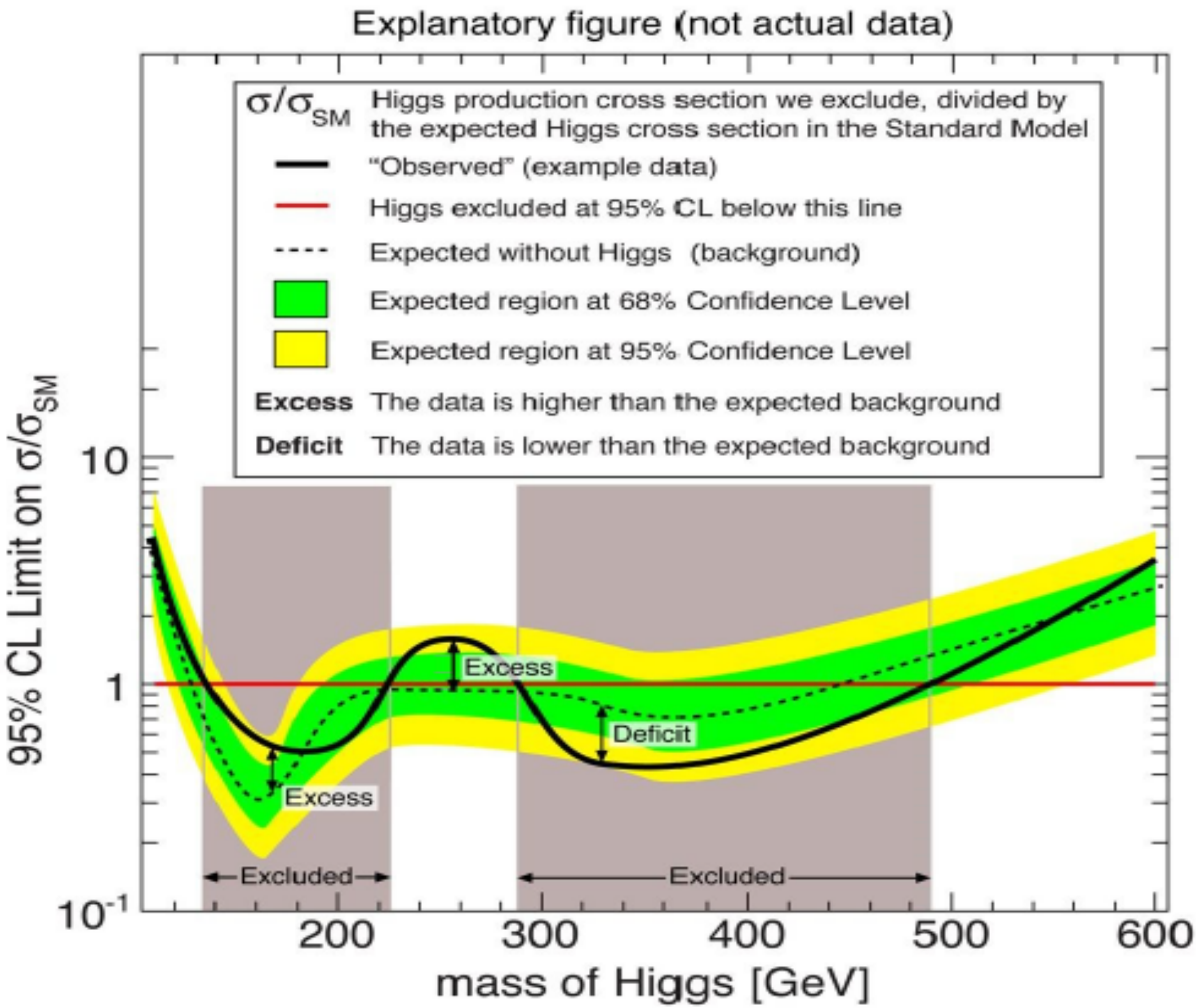


Fermilab's Tevatron Run II pp collider at 1.96 TeV 2001-2011

12 fb^{-1} delivered by Tevatron

10 fb^{-1} recorded by CDF & D0

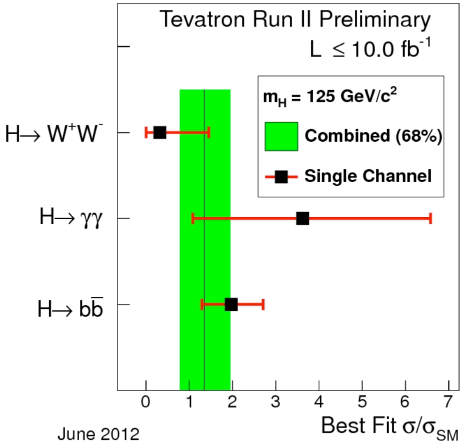
Blue Band, Green Band Illustration



For Discovery use "P-value":

Probability, that the observed excess originates from a background fluctuation

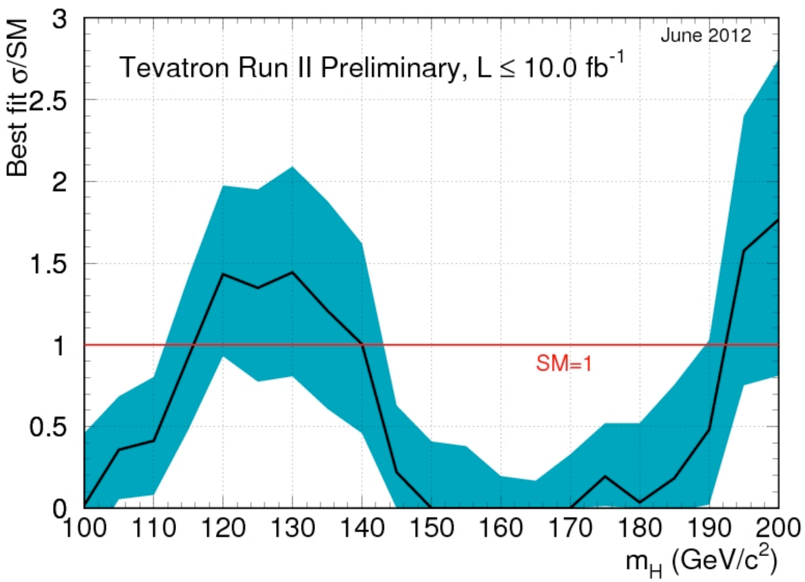
Long history for Higgs search, complementary to LHC, since associated production, WH, ZH, where H->bb contributes at low mass

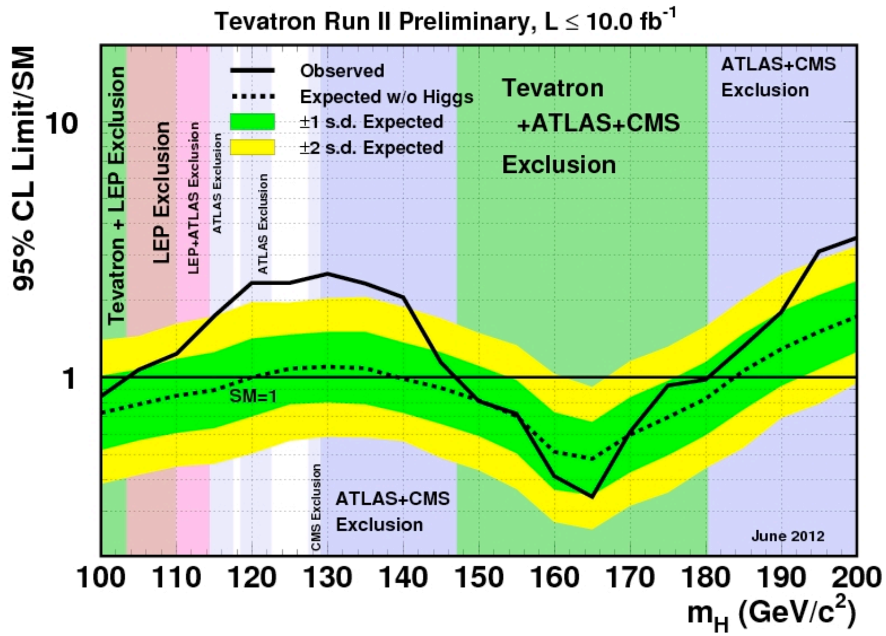


– The data appear to be incompatible with the background, with a global p-value of:

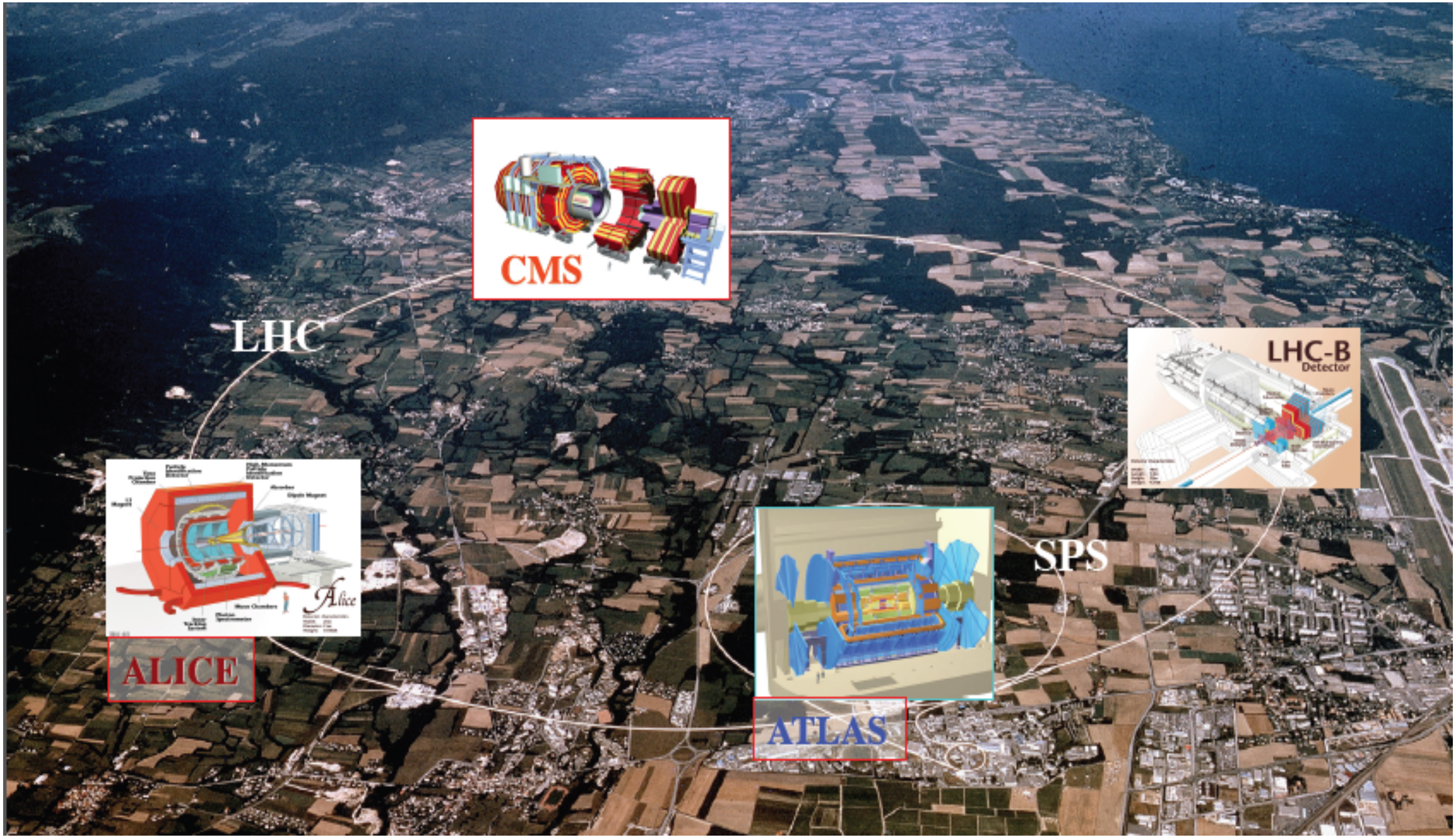
2.5 s.d. (3.0 local)

$H \to bb$ only: 2.9 s.d. (3.2 local)





The LHC



CERN's LHC pp collider at 8 (7) TeV (design 14 TeV)

2011: 5.6 fb^{-1} delivered by LHC, 5.2 fb^{-1} recorded by ATLAS and CMS experiments

2012: 6.6 fb^{-1} delivered, 6.3 fb^{-1} recorded, Goal: 15-20 fb^{-1}

Updated ATLAS Results

Updated results on SM Higgs searches based on the data recorded in 2011 at $\sqrt{s}$=7 TeV (~4.9 fb^{-1}) and 2012 at $\sqrt{s}$=8 TeV (~5.9 fb^{-1})

2012 data recorded until 2 weeks ago

H → γγ and H→ ZZ (4l):

- high-sensitivity at low-m_H
- high mass-resolution
- pile-up robust

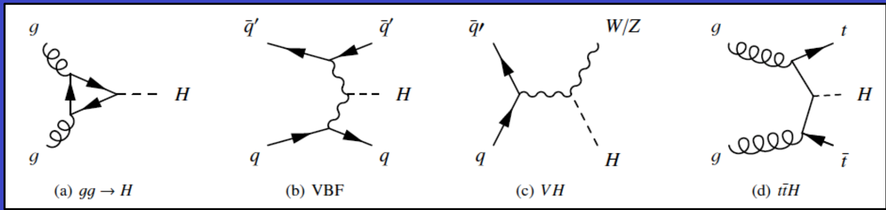
❑ analyses improved to increase sensitivity → new results from 2011 data
❑ all the data recorded so far in 2012 have been analyzed

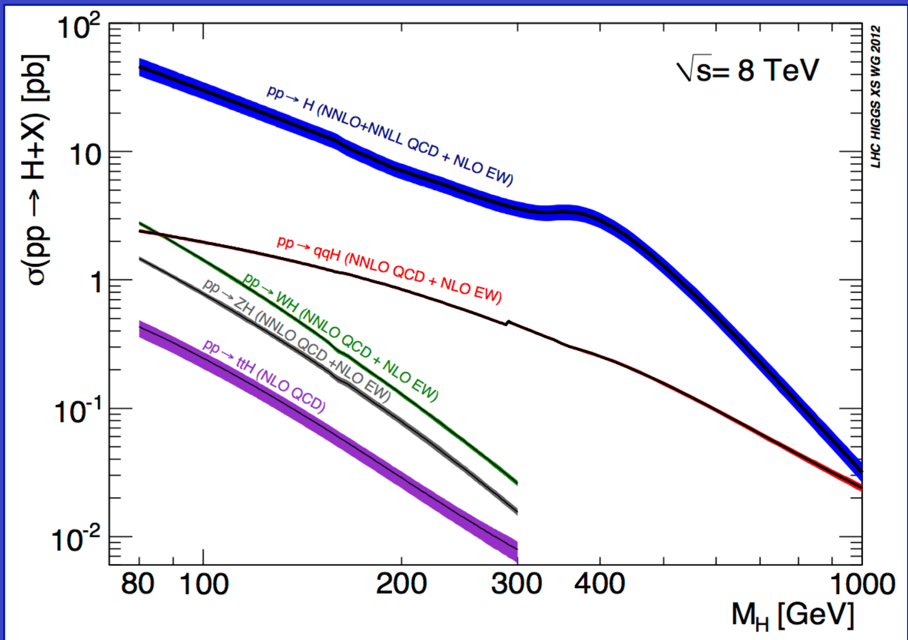
Other low-mass channels: H→ $WW^{(*)}$→ lνlν, H→ ττ, W/ZH→ W/Z bb:

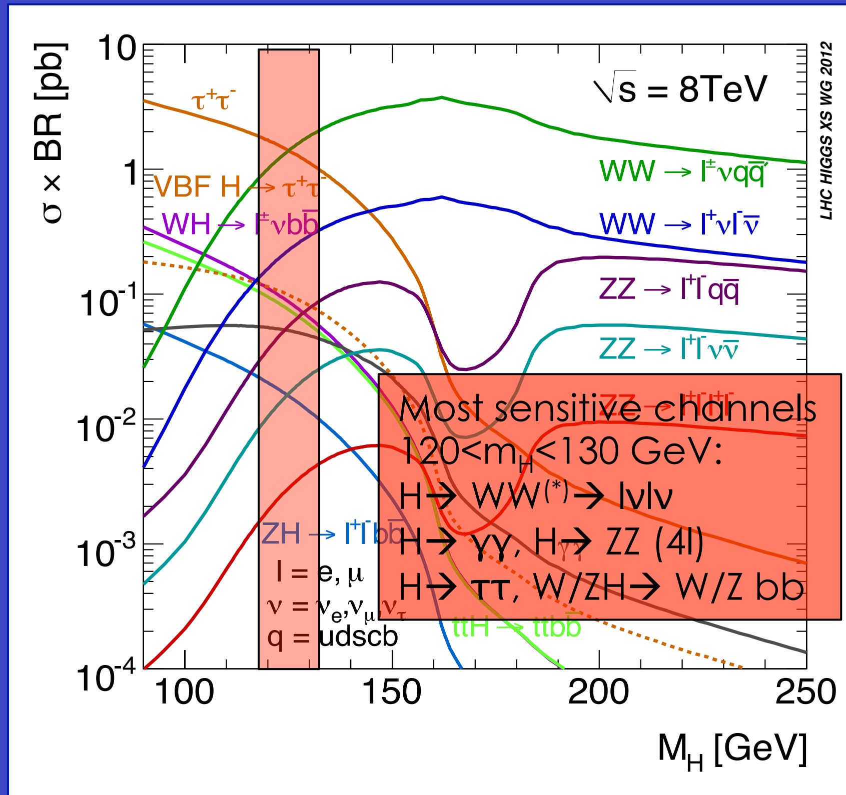
- E_T^{miss} in final state → less robust to pile-up
- No signal "peak" in some cases
- Understanding of the detector performance and backgrounds in 2012 well advanced,
- 2012 results coming soon

→ 2011 results used here for these channels for the overall combination

Standard Model Higgs Searches at the LHC







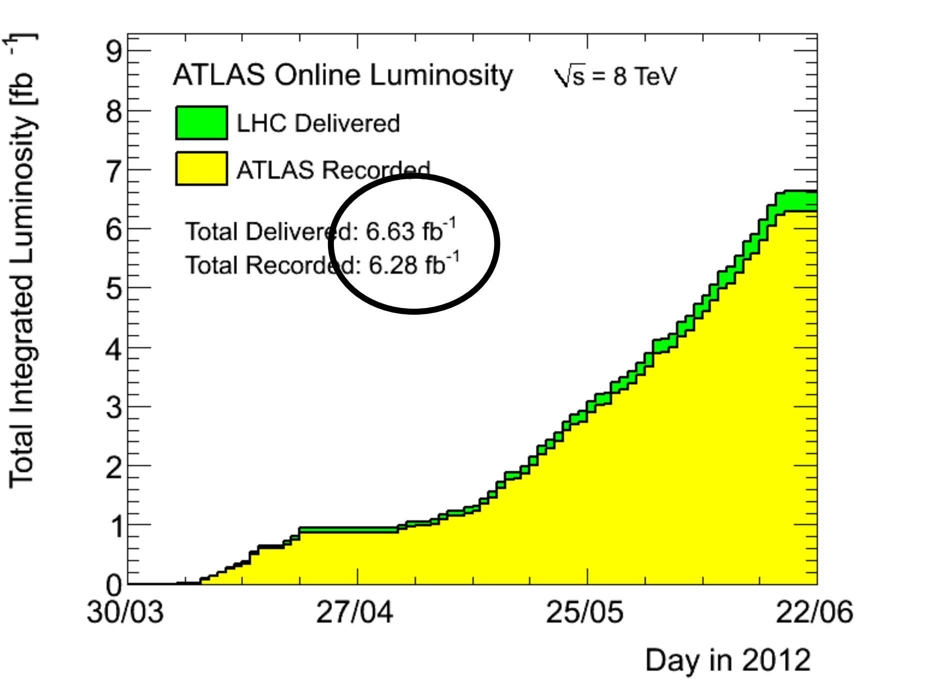
$\sqrt{s}$=7 → 8 TeV:

- ❑ Higgs cross-section increases by ~ 1.3 for m_H ~ 125 GeV
- ❑ Similar increase for several irreducible backgrounds: e.g. 1.2-1.25 for γγ, di-bosons
- ❑ Reducible backgrounds increase more: e.g. 1.3-1.4 for tt, Zbb

→ Expected increase in Higgs sensitivity: 10 - 15%

2012 Data

2012 data-taking so far …



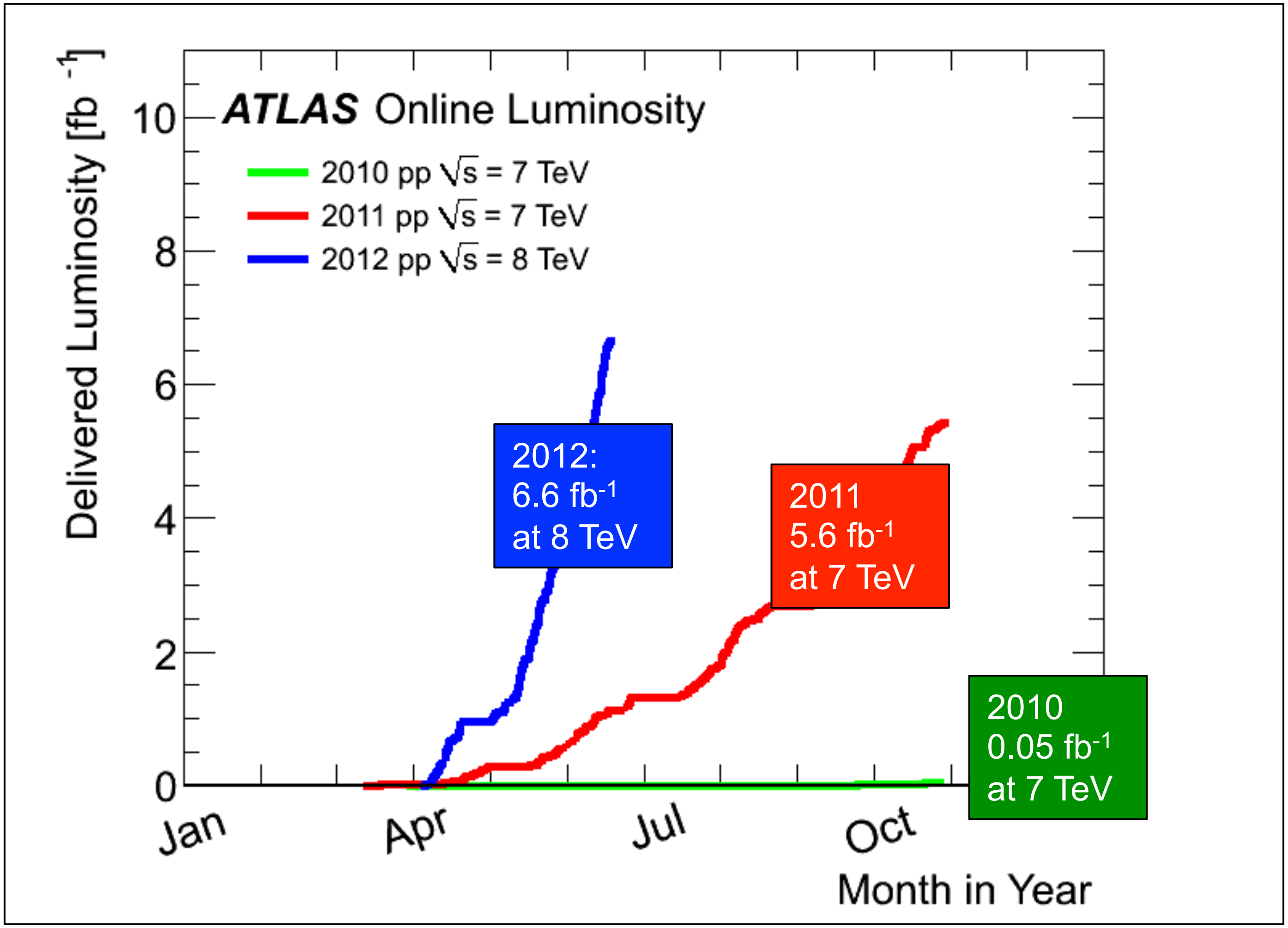
Peak luminosity in 2012:
~ 6.8 x10^{33} cm^{-2} s^{-1}

Fraction of non-operational detector channels: few permil (most cases)

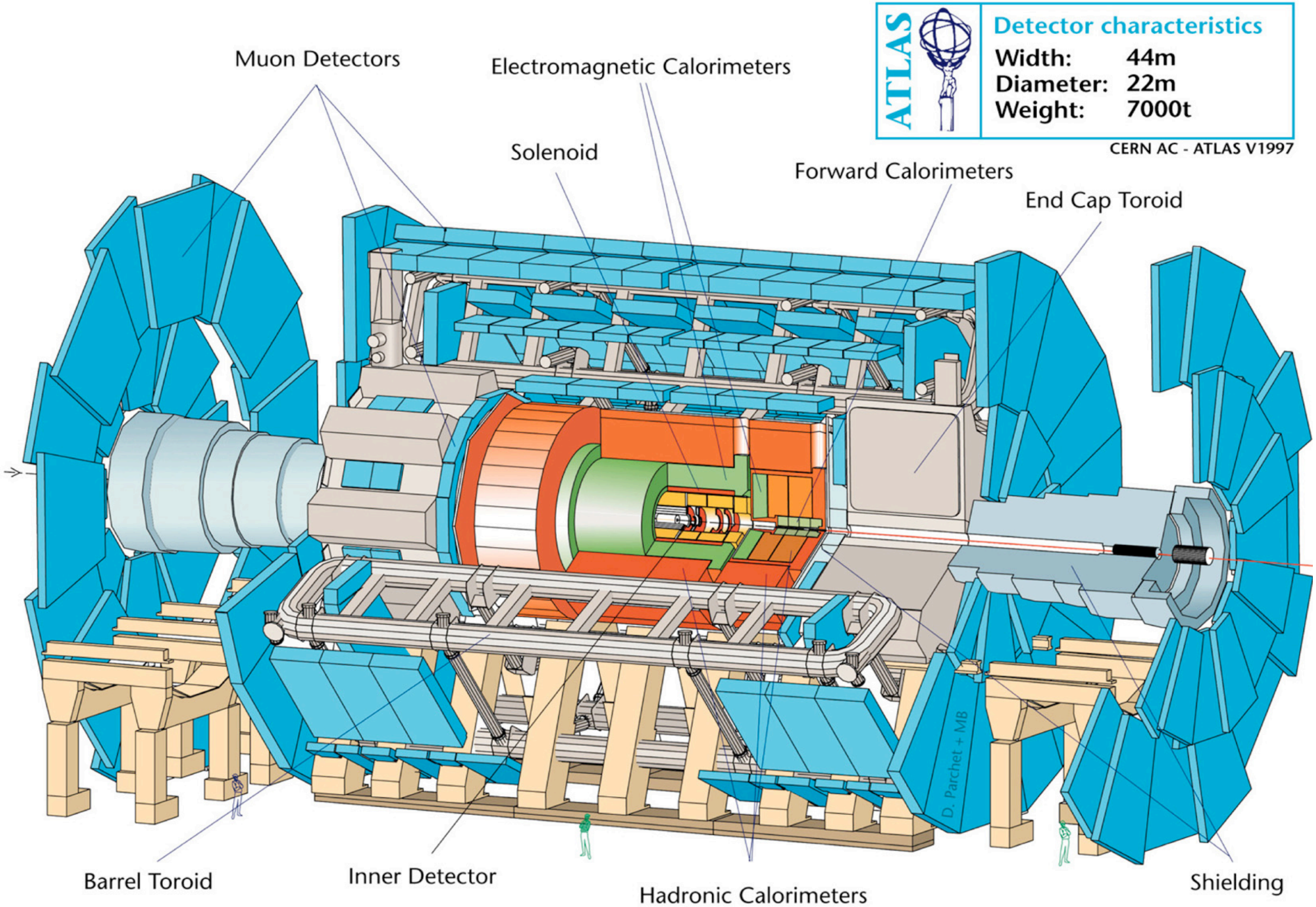
Data-taking efficiency = (recorded lumi)/(delivered lumi): ~ 94.6%

Good-quality data fraction, used for analysis :
(will increase further with data reprocessing) ~ 93.6%

All Luminosity Delivered to ATLAS



ATLAS

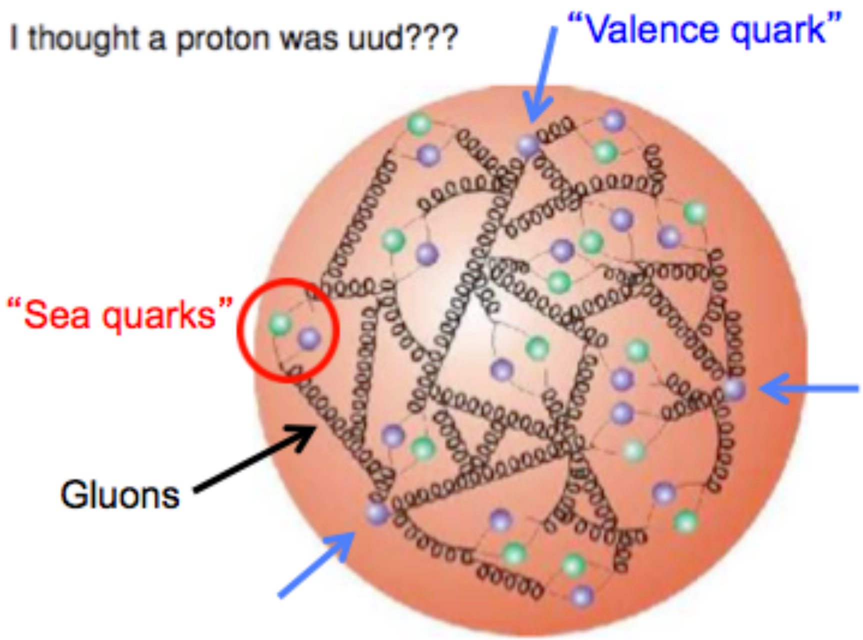

Muon Detectors
Electromagnetic Calorimeters
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Solenoid
Forward Calorimeters
End Cap Toroid
D. Parchet + MB
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

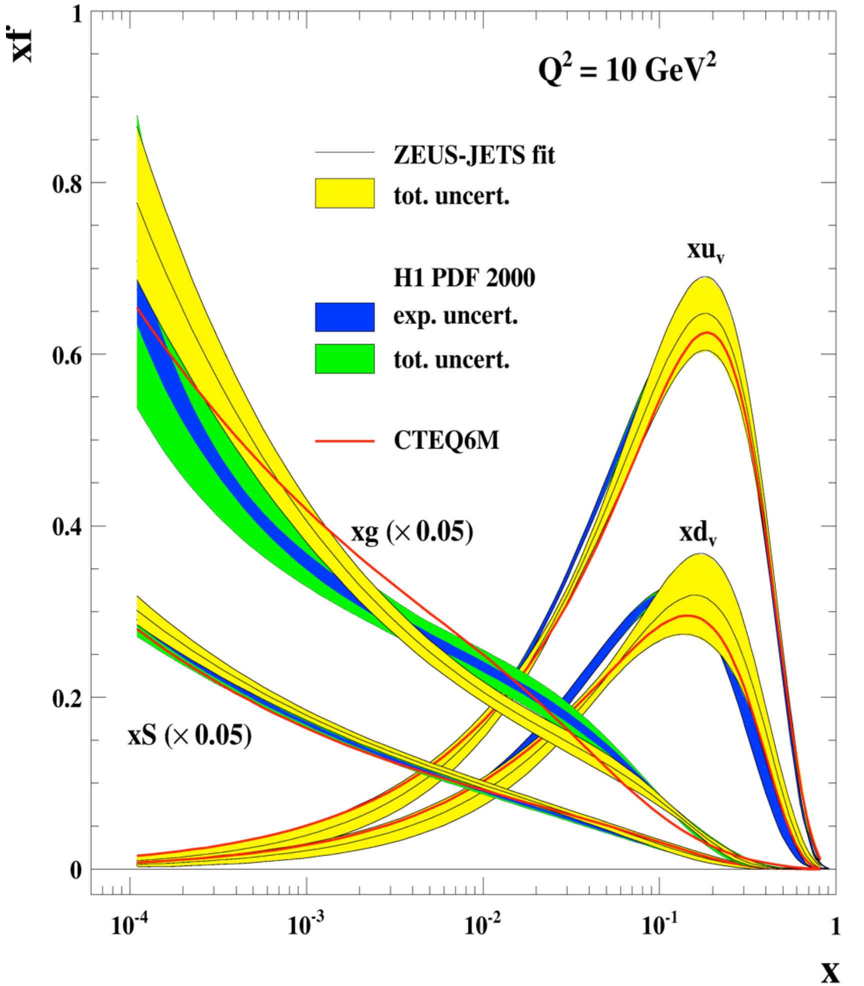
Creating massive fundamental particles

$$E_a + E_b = m_X c^2$$

R. Goscinny, U. Uderzo
Asterix and the Big Fight

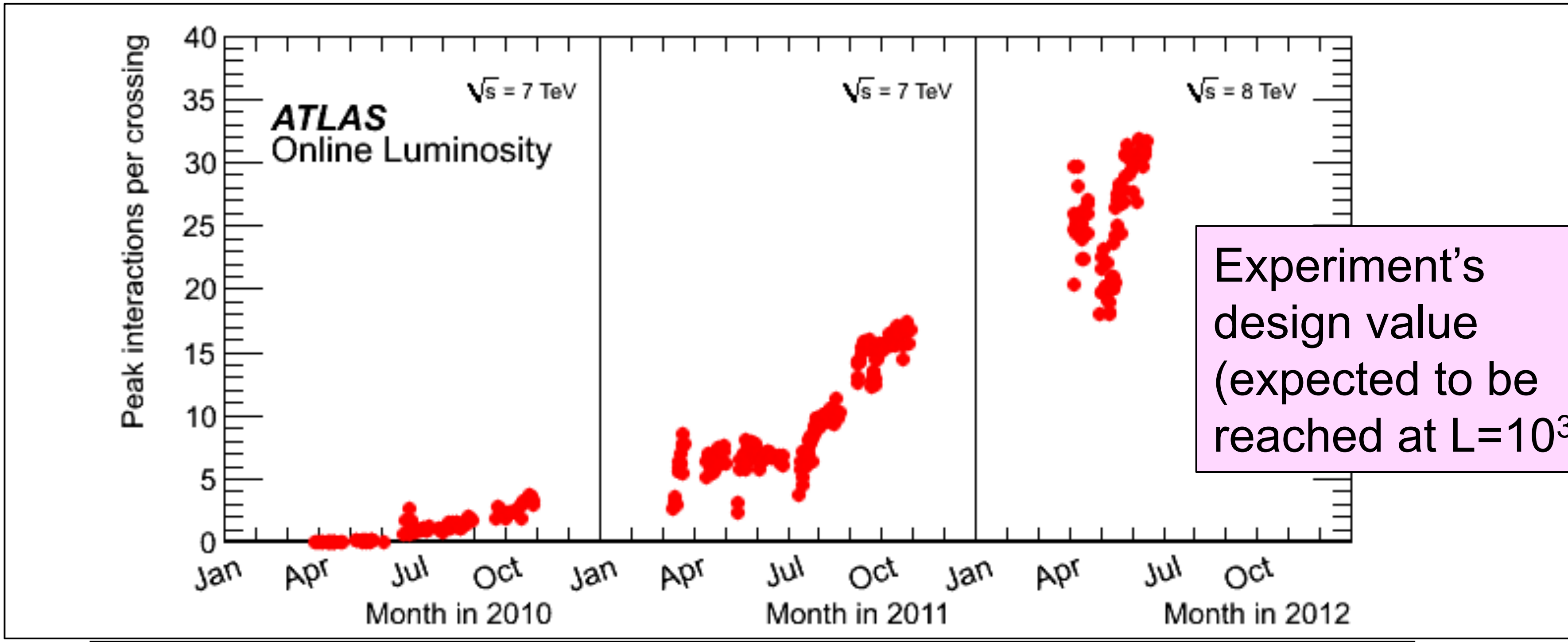
Inside the Proton





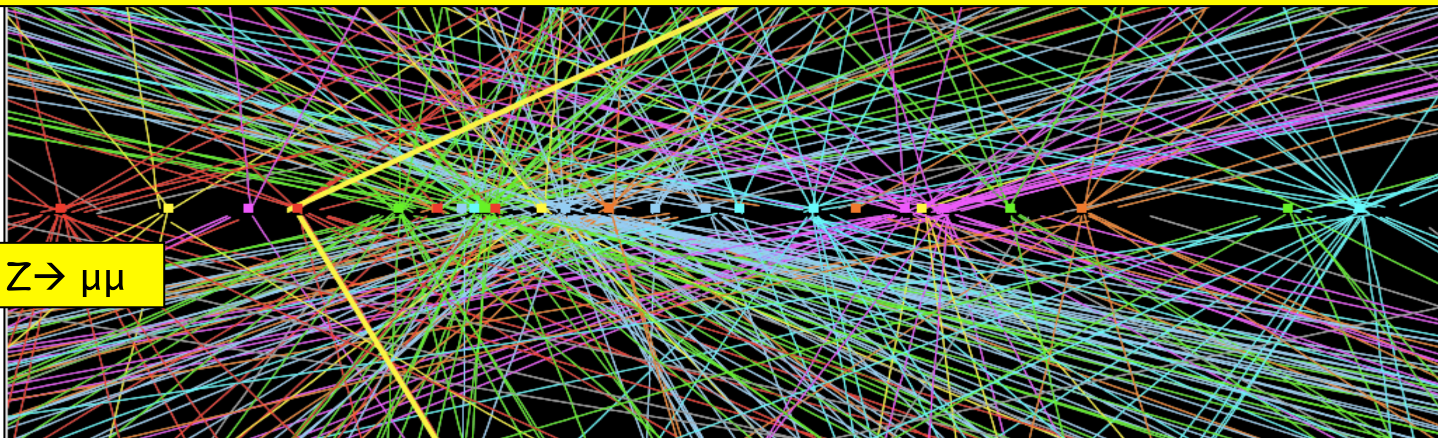
$$E \approx 2\sqrt{x_1 x_2}\,E_{beam}$$

Pile Up Challenge



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

Z→ μμ event from 2012 data with 25 reconstructed vertices



Pile Up Challenge

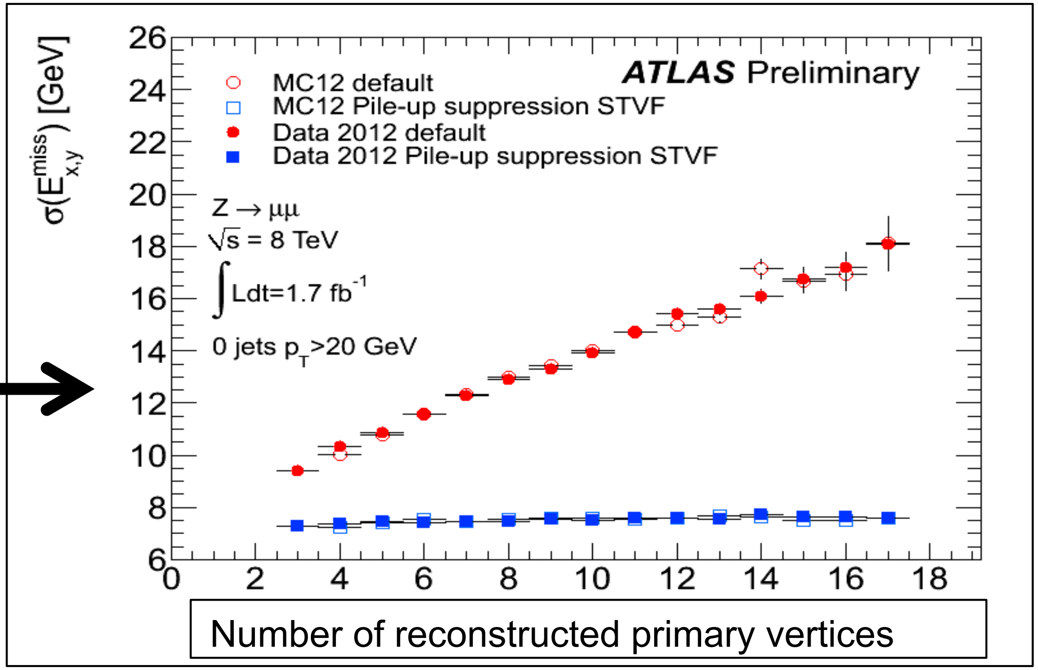
Huge efforts over last months to prepare for 2012 conditions and mitigate impact of pile-up on trigger, reconstruction of physics objects (in particular E_T^{miss}, soft jets, ..), computing resources (CPU, event size)

Reconstruction and identification of physics objects (e, γ, μ, τ, jet, E_T^{miss}) optimised to be ~independent of pile-up → similar (better in some cases!) performance as in 2011 data

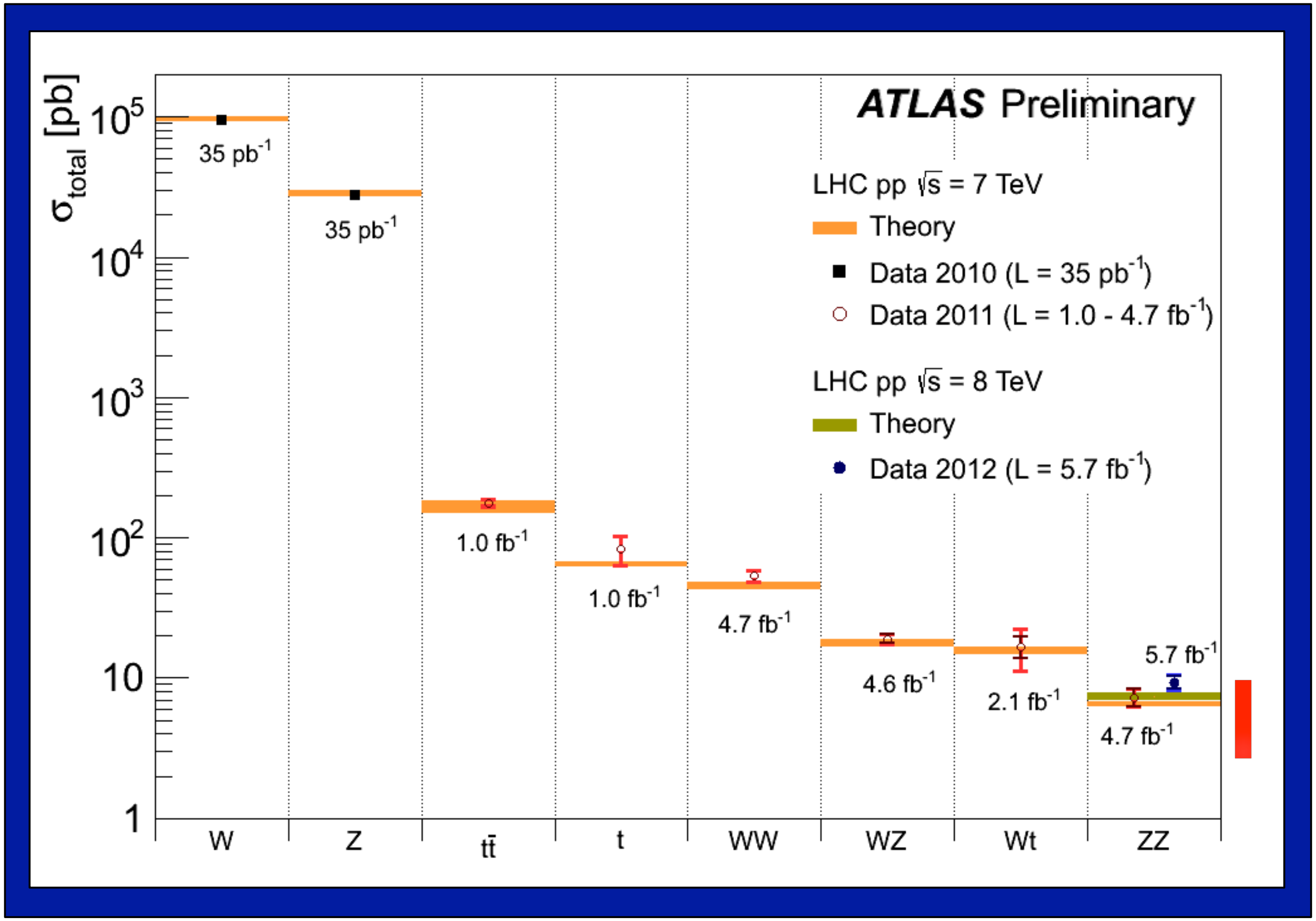
Precise modeling of in-time and out-of-time pile-up in simulation

Understanding of E_T^{miss} (most sensitive to pile-up) is crucial for H→ WW$^{(*)}$ → lνlν , W/ZH→W/Zbb, H→ττ

E_T^{miss} resolution vs pile-up in Z→ μμ events **before** and **after** pile-up suppression using tracking information



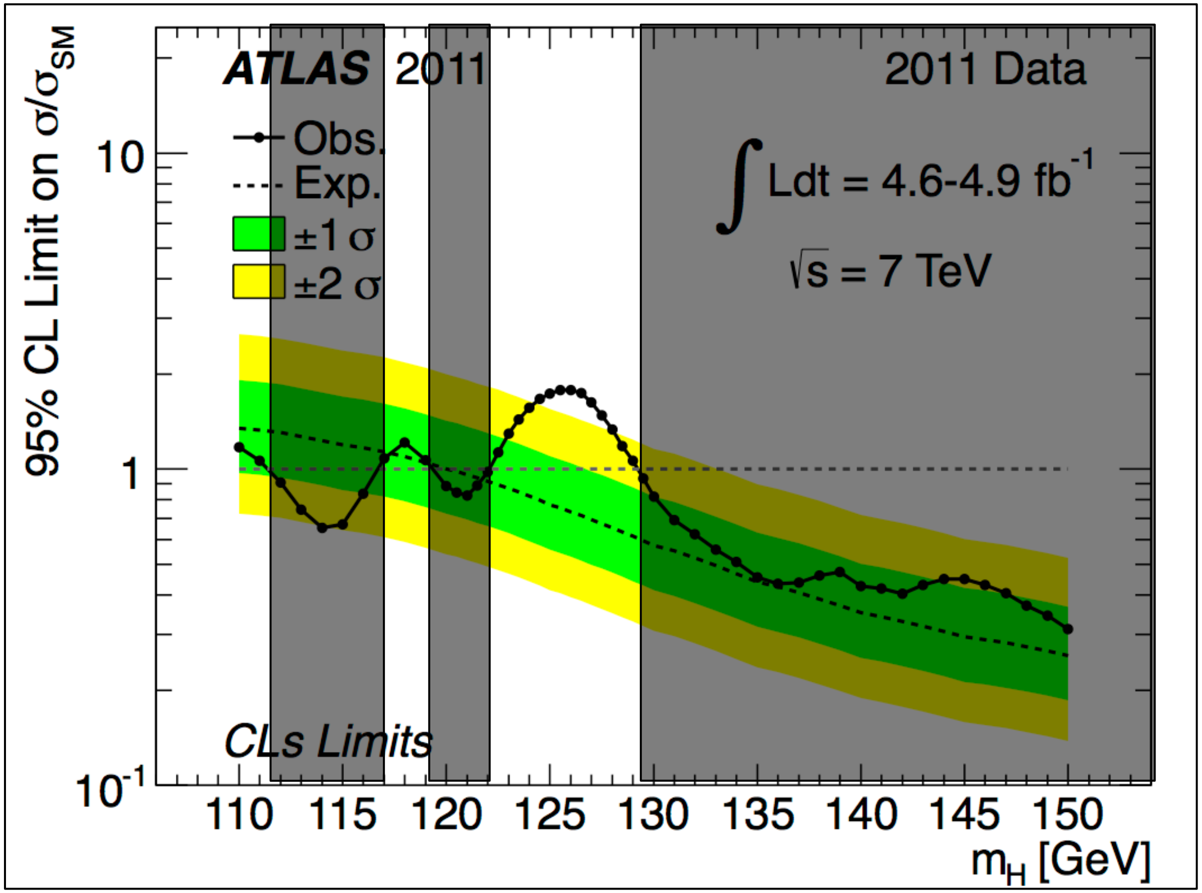
Measuring the Standard Model



Inner error: statistical
Outer error: total

- Important on their own and as foundation for Higgs searches
- Most of these processes are backgrounds to Higgs
- Reconstruction and measurement of challenging processes are good training for Higgs final states

2011 Results



Combination of 12 channels:

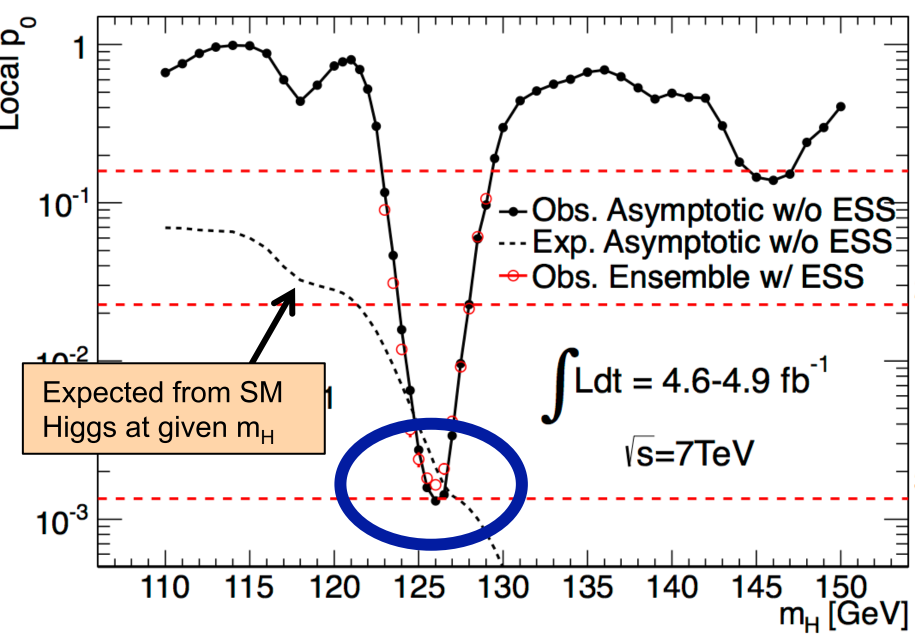
H→ γγ
W/ZH→W/Z bb
H→ ττ
H→ ZZ(*) → 4l
H→ WW(*) → lνlν
H→ ZZ → llqq
H→ ZZ → llνν
H→ WW → lνqq

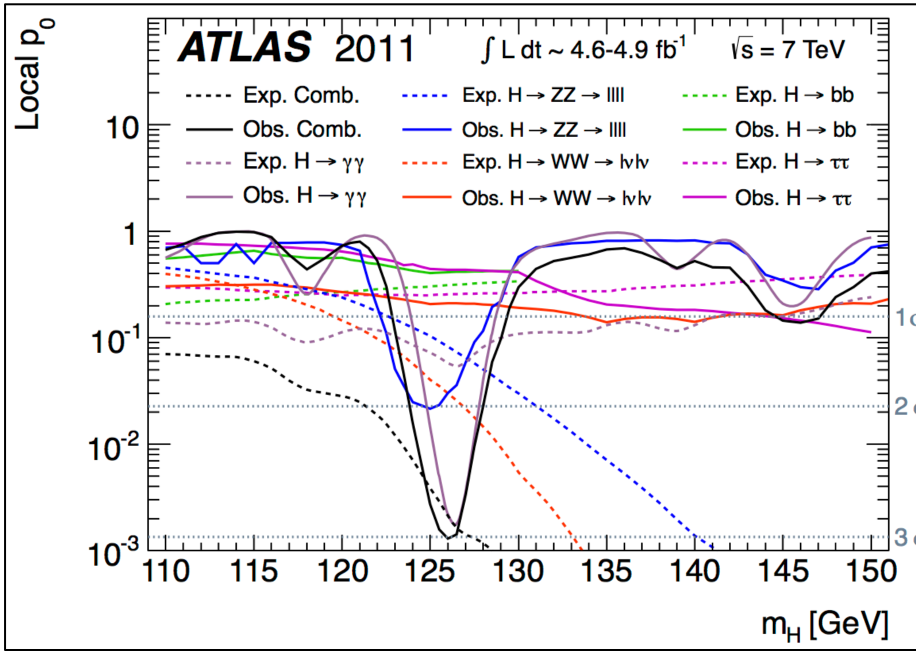
Excluded at 95% CL

111.4 < m_H < 122.1 GeV (except 116.6-119.4)
129.2 < m_H < 541 GeV (expected 120-560 GeV)

2011 Results

Consistency of the data with the background-only expectation (p-value)





2.9 σ excess observed for m_H ~ 126 GeV

Probability to occur anywhere over 110-600 (110-146 GeV): 15% (6%) (trials factor)

Local significance	Observed	Expected from SM Higgs
Total	2.9 σ	2.9 σ
$H\rightarrow\gamma\gamma$	2.8 σ	1.4 σ
H→ 4l	2.1 σ	1.4 σ
H→ lvlv	0.8 σ	1.6 σ

2012 Update

Presented:

- $H \rightarrow \gamma\gamma$

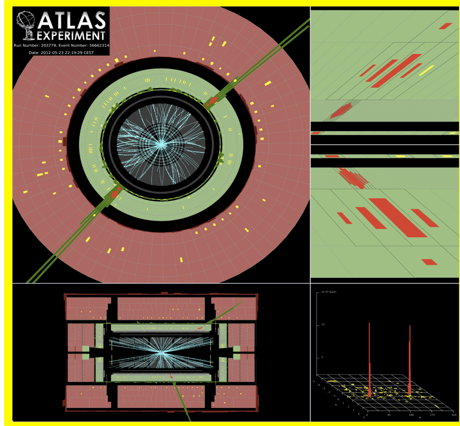
- $H \rightarrow ZZ \rightarrow 4l$ results with full $\sqrt{s}$=7 TeV and $\sqrt{s}$=8 TeV datasets (~10.7 fb^{-1}) and improved analyses

- new overall combination
  (all channels other than $H \rightarrow \gamma\gamma$, ZZ based on 7 TeV data)

$H \rightarrow \gamma\gamma$

- ❑ Topology: two high-p_T isolated photons E_T (γ_1, γ_2) > 40, 30 GeV

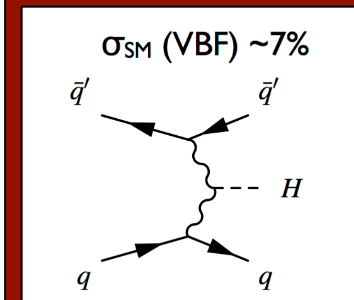
$110 \lesssim m_H \lesssim 150$ GeV



To increase sensitivity, events divided in 10 categories based on location, converted/unconverted γ p_{Tt} ($p_T^{\gamma\gamma}$ perpendicular to γγ thrust axis); 2jets

Main improvements in new analysis:
- ❑ 2jet category introduced → targeting VBF
- ❑ γ identification and isolation

→ Expected gain in sensitivity: + 15%



2 jets with
p_T > 25-30 GeV
$|\eta|$<4.5
$|\Delta\eta|_{jj}$ > 2.8
M_{jj} > 400 GeV
$|\Delta\varphi|$ (γγ-jj) > 2.6

Crucial experimental aspects:
- ❑ excellent γγ mass resolution to observe narrow signal peak above irreducible background
- ❑ powerful γ identification to suppress γj and jj background with jet → π^0 → fake γ

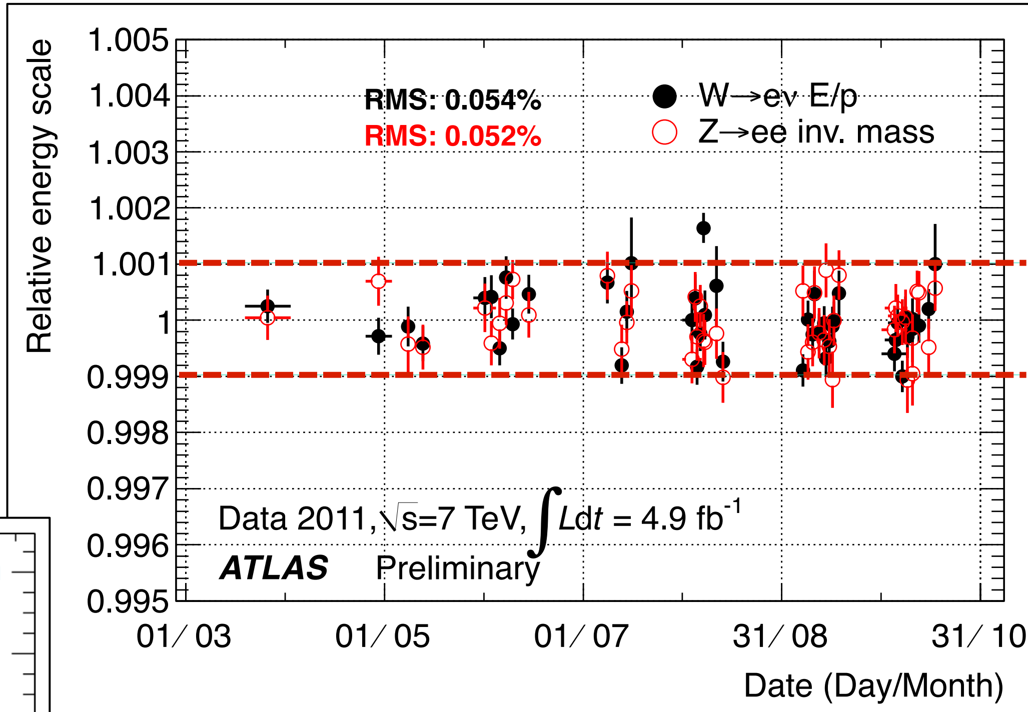
Mass Resolution

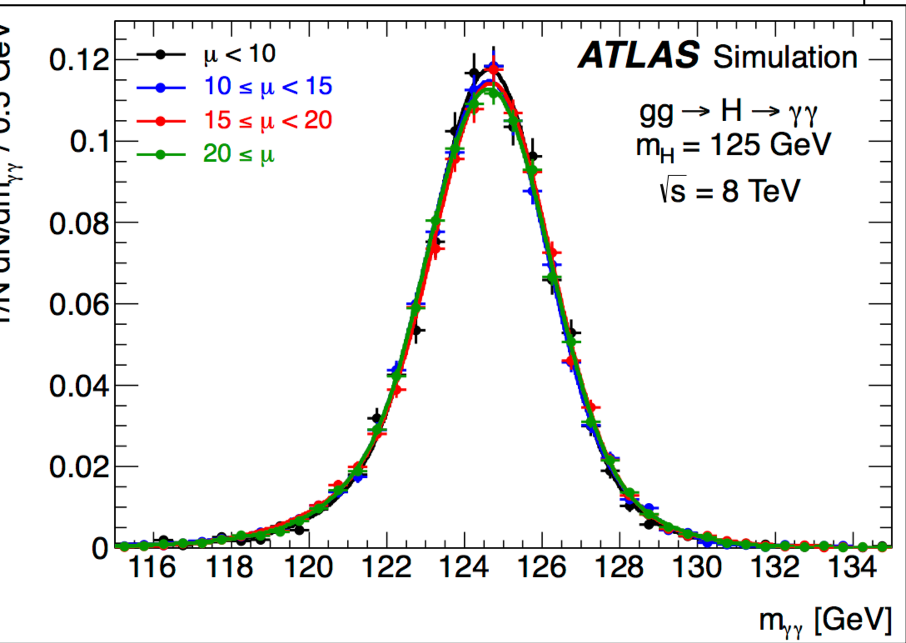
$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

Scale stability during 2011, better than 0.1%

Calorimeter understanding:
E scale (from Z, J/ψ → ee, W→ eν)

constant term of resolution: ~ 1%
(2.5% for 1.37<|η|<1.8)





Electron scale transferred to photons using MC

Mass resolution not affected by pile-up

Mass resolution of inclusive sample: 1.6 GeV

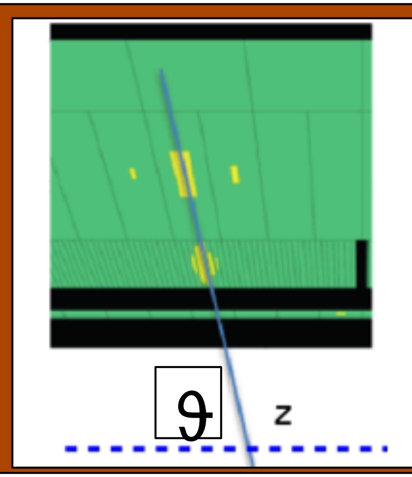
$H \rightarrow \gamma\gamma$

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

α=opening angle of the two photons

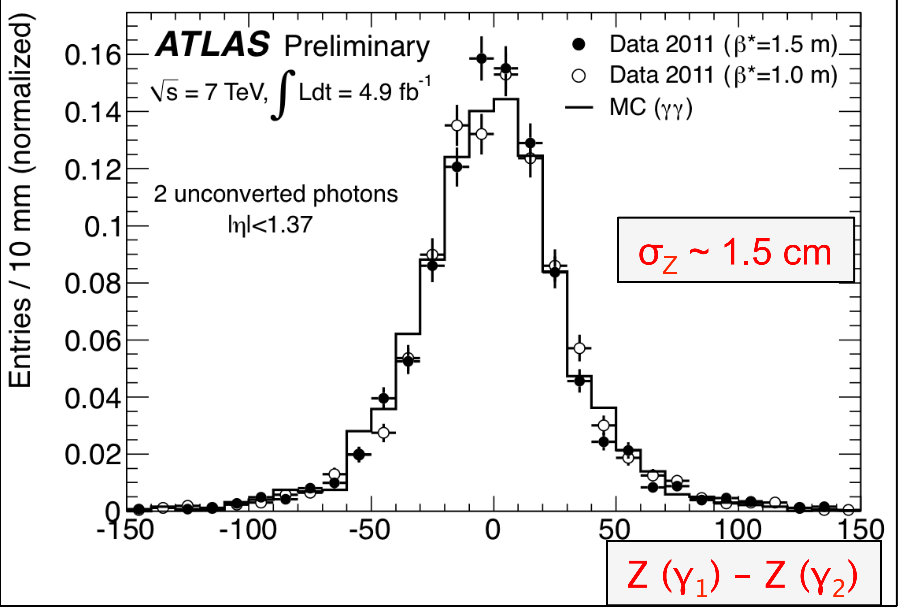
High pile-up: many vertices distributed over σ_Z (LHC beam spot) ~ 5-6 cm

Primary vertex from:
- ❑ EM calorimeter longitudinal segmentation
- ❑ tracks from converted photons



Measure γ direction with calo
→ get Z of primary vertex

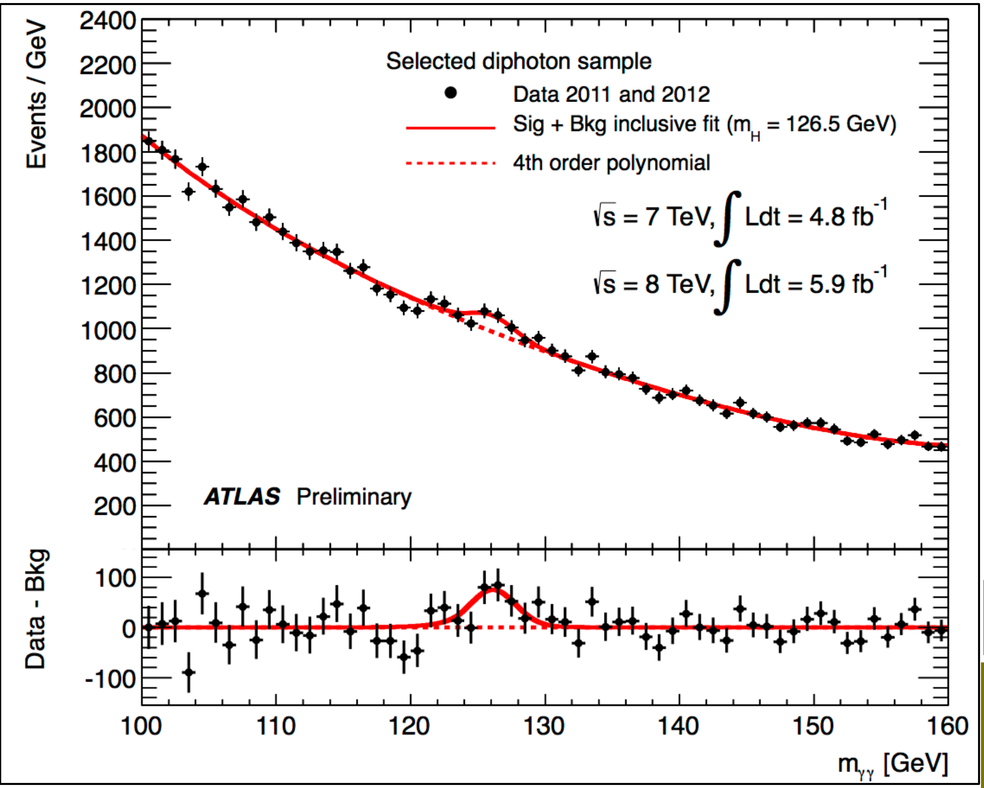
Z-vertex measured in γγ events from calorimeter "pointing"



- ❑ 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

$H \rightarrow \gamma\gamma$



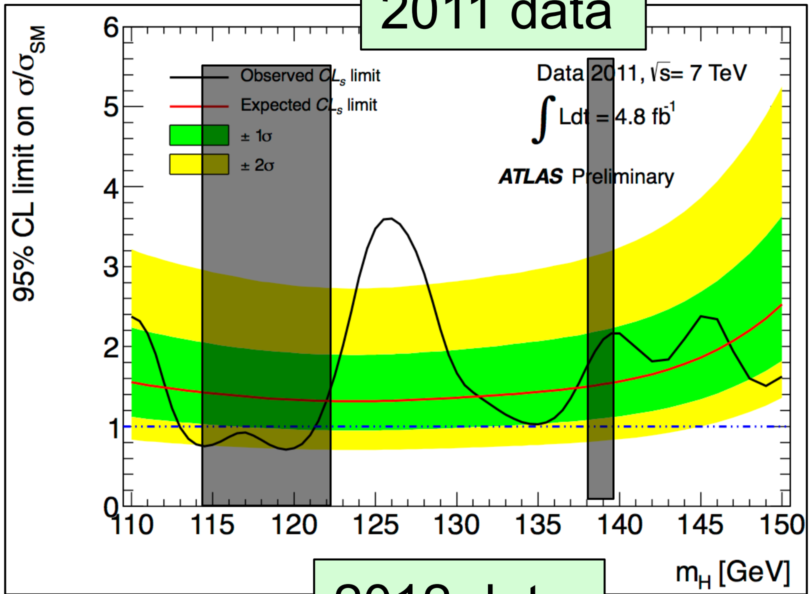
$m_{\gamma\gamma}$ spectrum fit, <u>for each category</u>, with Crystal Ball + Gaussian for signal plus background model optimized (with MC) to minimize biases

Main systematic uncertainties

Signal yield Theory Photon efficiency Background model	 ~ 20% ~ 10% ~ 10%
Categories migration Higgs p_T modeling Conv/unconv γ Jet E-scale Underlying event	 up to ~ 10% up to ~ 6% up to 20% (2j/VBF) up to 30% (2j/VBF)
$H \rightarrow \gamma\gamma$ mass resolution Photon E-scale	~ 14% ~ 0.6%

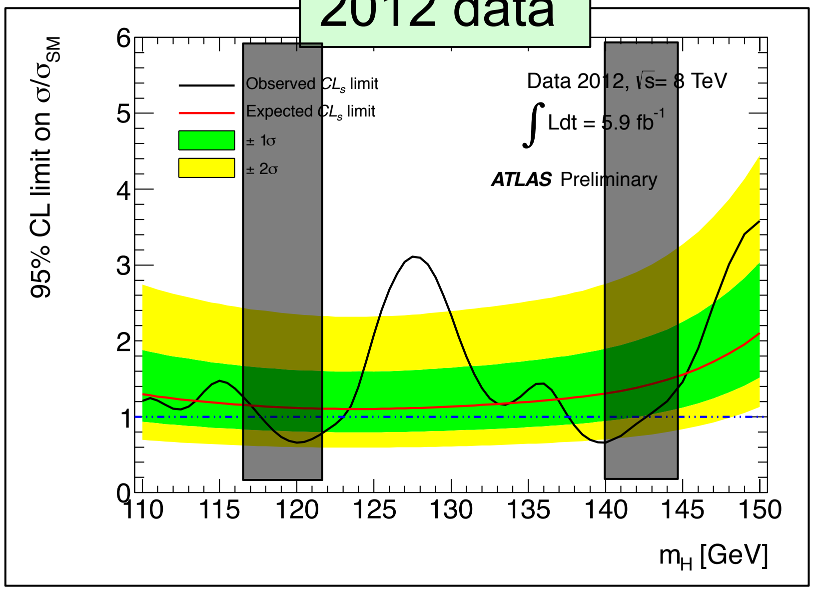
$H \rightarrow \gamma\gamma$

2011 data

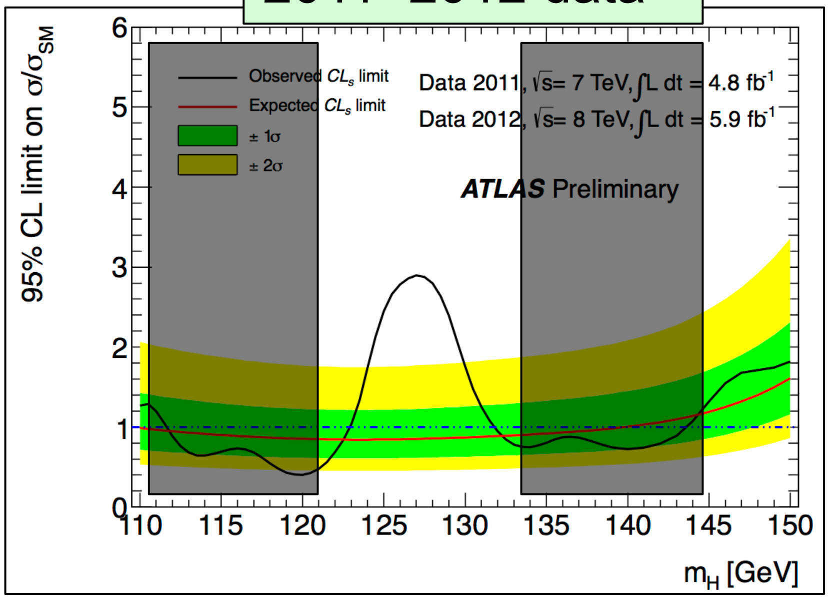


Excluded (95% CL):
112-122.5 GeV, 132-143 GeV
Expected: 110-139.5 GeV

2012 data

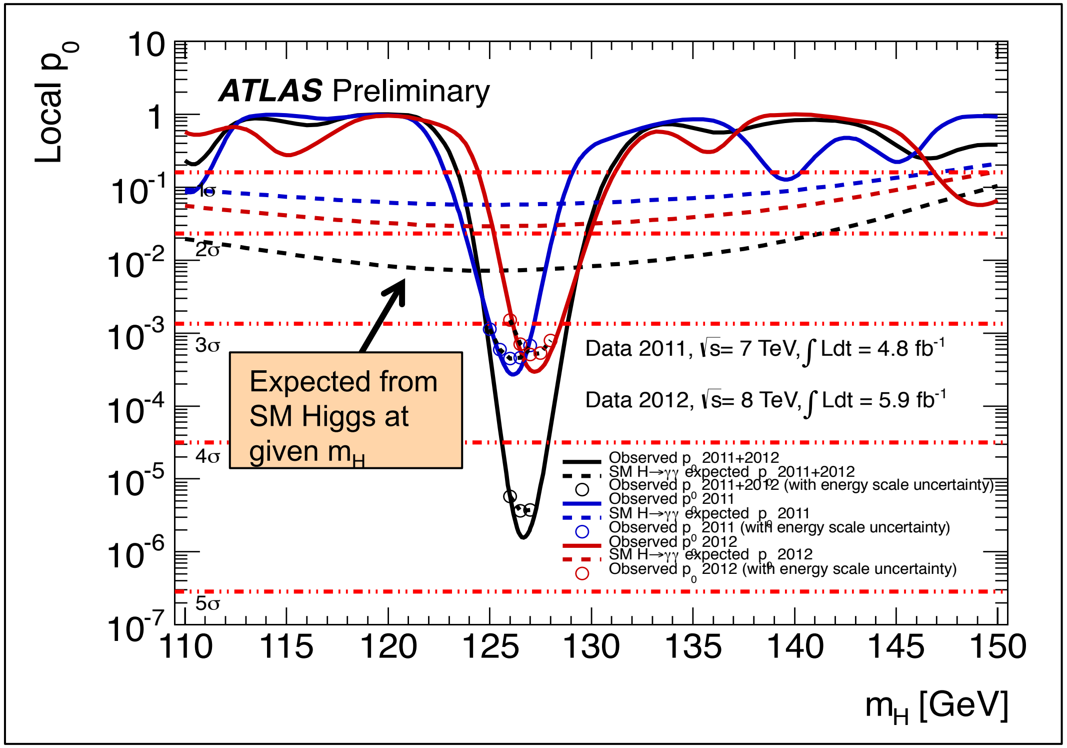


2011+2012 data



$H \rightarrow \gamma\gamma$

Consistency of data with background-only expectation



Data sample	m_H of max deviation	local p-value	local significance	expected from SM Higgs
2011	126 GeV	3×10^{-4}	3.5 σ	1.6 σ
2012	127 GeV	3×10^{-4}	3.4 σ	1.9 σ
2011+2012	126.5 GeV	2×10^{-6}	4.5 σ	2.4 σ

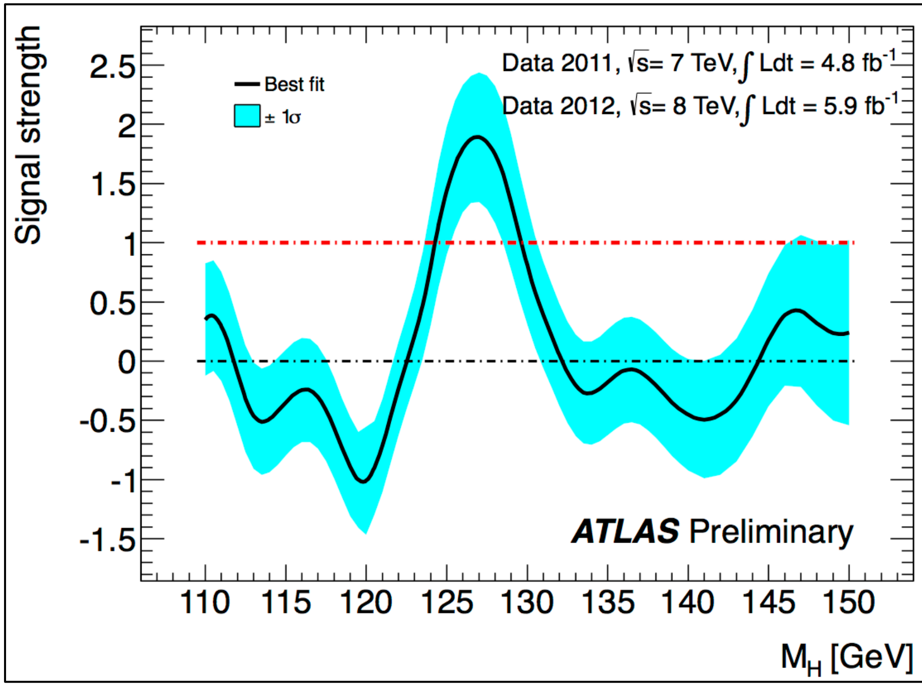
Global 2011+2012 (including trials factor over 110-150 GeV range): 3.6 σ

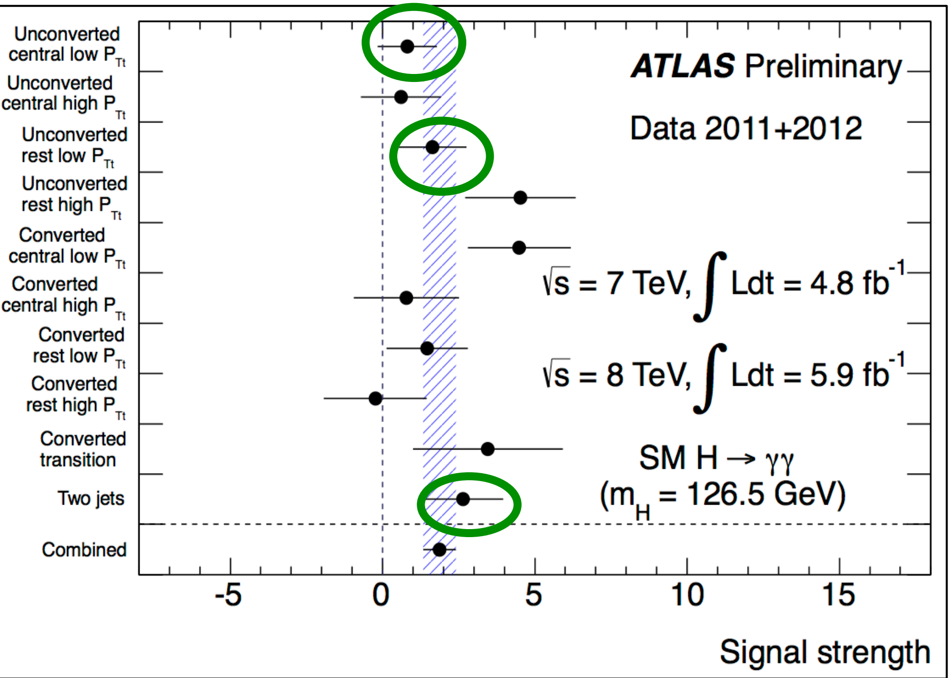
H→ γγ

Fitted signal strength

Normalized to SM Higgs expectation at given m_H (μ)

Best-fit value at 126.5 GeV: μ=1.9 ± 0.5





Consistent results from various categories within uncertainties (most sensitive ones indicated)

$H \rightarrow ZZ \rightarrow llll$

$110 < m_H < 600$ GeV

- Tiny rate, BUT:
  - -- mass can be fully reconstructed
  - -- pure: S/B ~ 1
- 4 leptons: $p_T^{1,2,3,4} > 20,15,10,7\text{-}6$ (e-μ) GeV; $50 < m_{12} < 106$ GeV; $m_{34} > 17.5\text{-}50$ GeV (vs m_H)

Crucial experimental aspects:

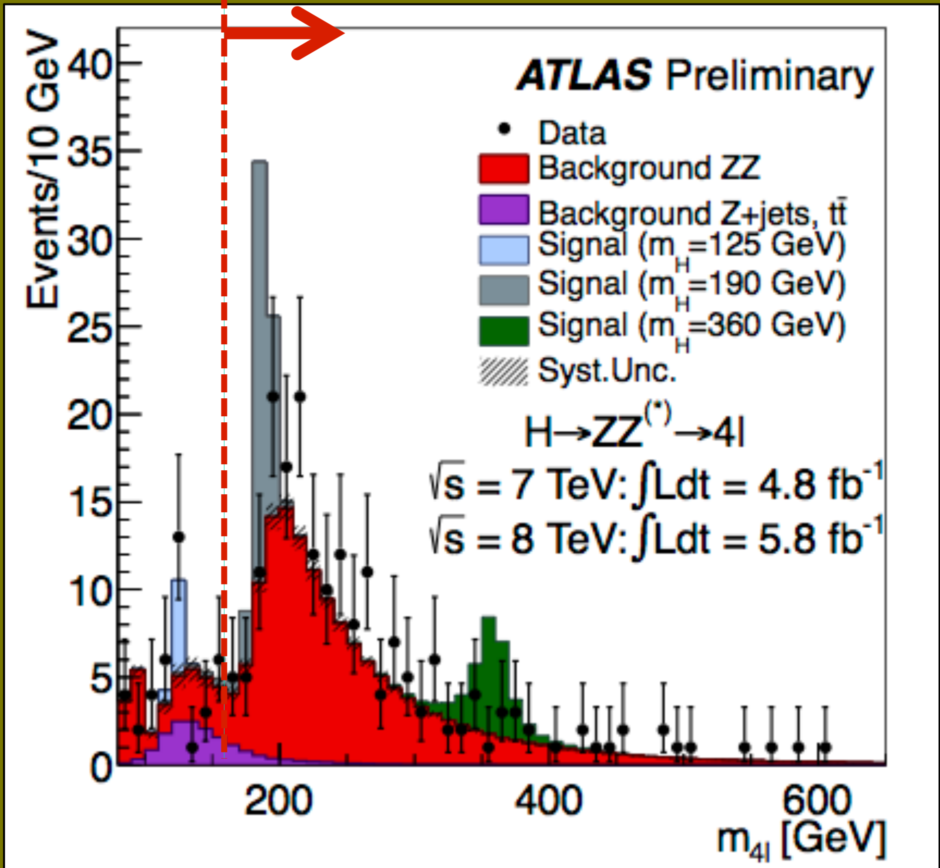
- Good lepton energy/momentum resolution
- Good control of reducible backgrounds

Main improvements in new analysis:

- kinematic cuts (e.g. on m_{12}) optimized/relaxed to increase signal sensitivity at low mass
- increased $e^{\pm}$ reconstruction and identification efficiency at low p_T , increased pile-up robustness, with negligible increase in the reducible backgrounds

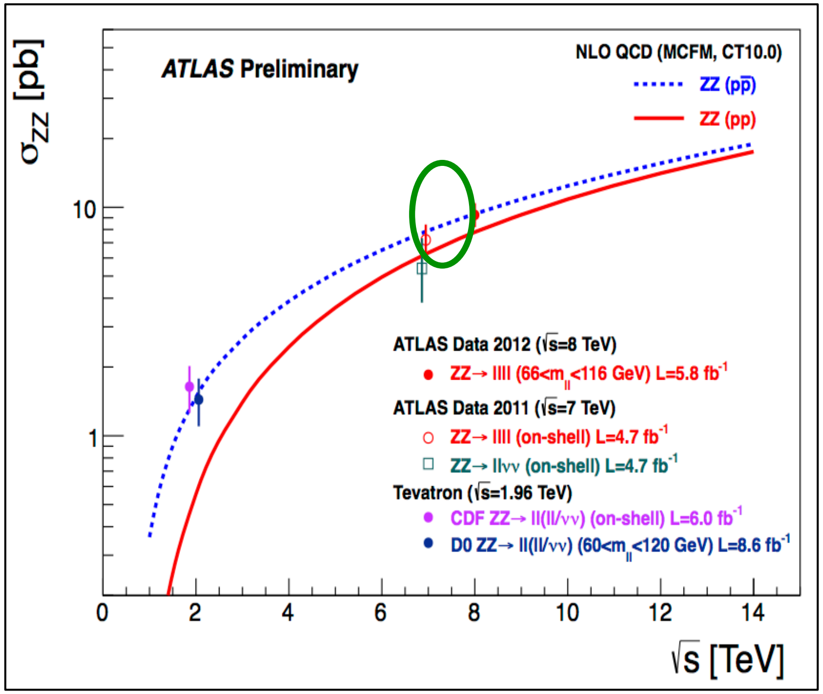
→ Gain 20% (4μ) to 30% (4e) in sensitivity compared to previous analysis

H→ ZZ → llll



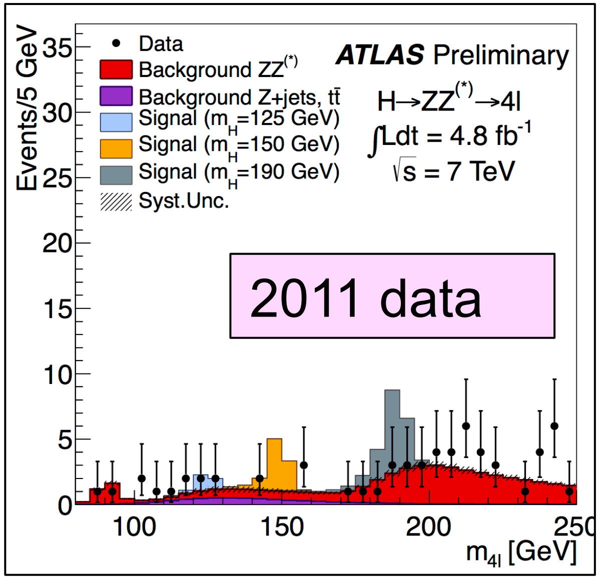
~ 1.3 times more ZZ events in data than SM prediction →in agreement with measured ZZ cross-section in 4l final states at $\sqrt{s}$ = 8 TeV

Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4± 0.4 pb



Discrepancy has negligible impact on the low-mass region < 160 GeV
(no change in results if in the fit ZZ is constrained to its uncertainty or left free)

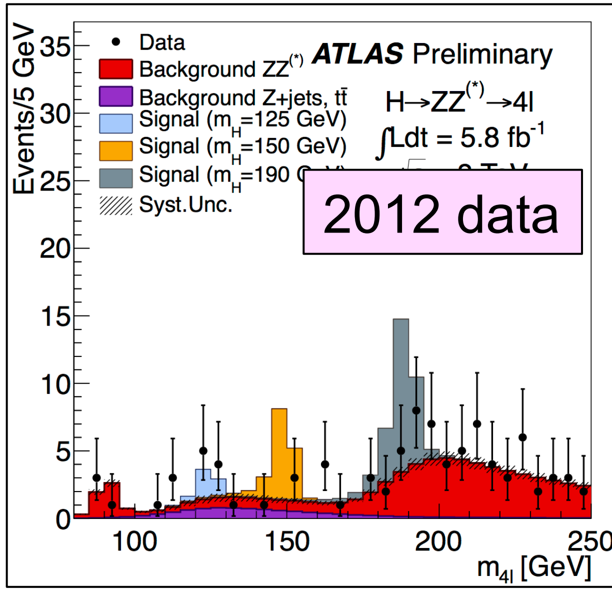
$H \rightarrow ZZ \rightarrow llll$



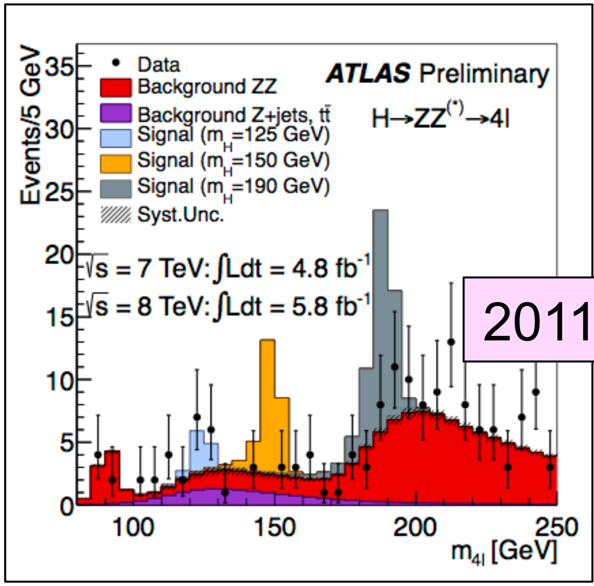
2011 data

The low-mass region

m4l <160 GeV:
Observed: 39
Expected: 34± 3



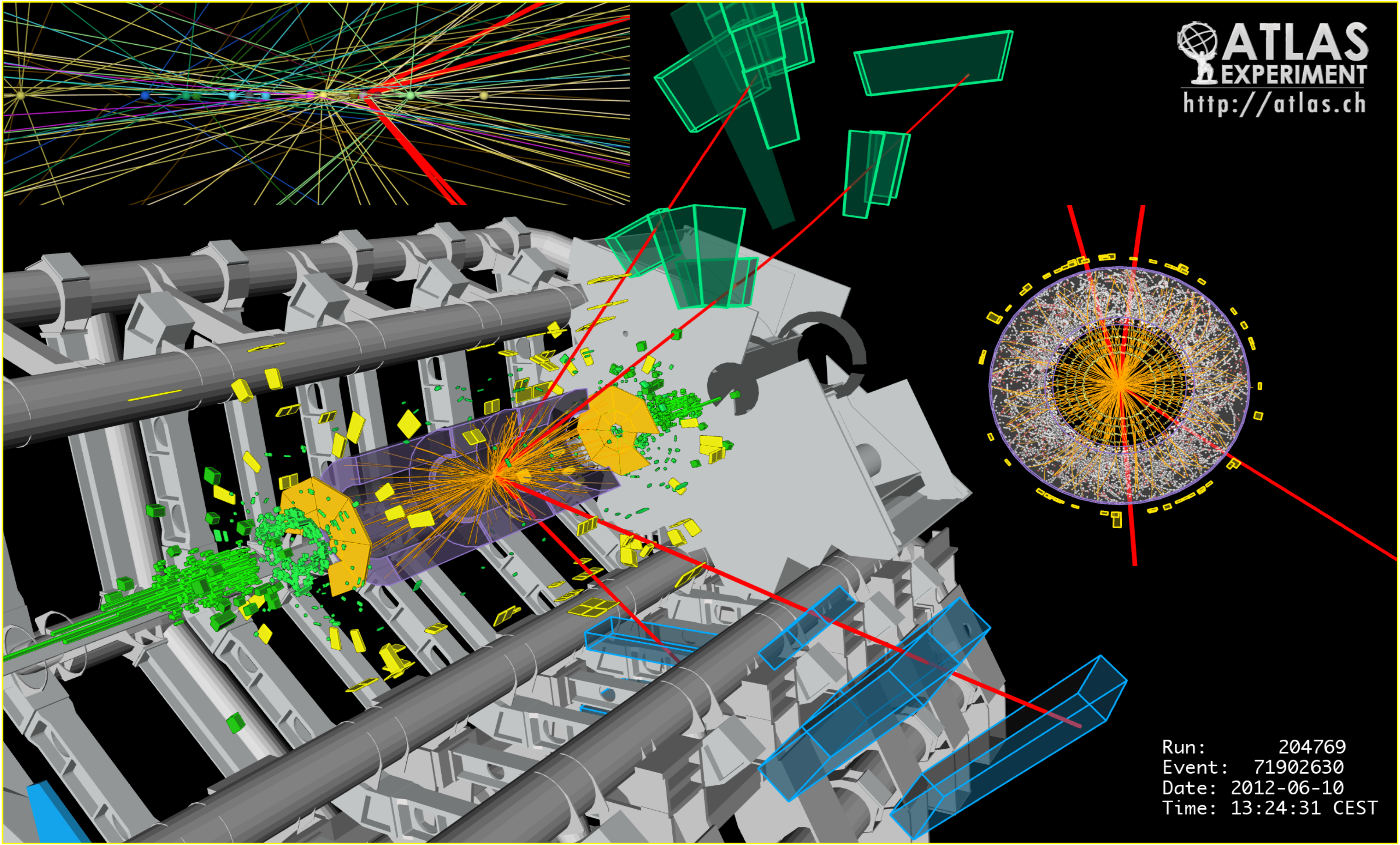
2012 data



2011+2012 data

$H \to ZZ \to llll$

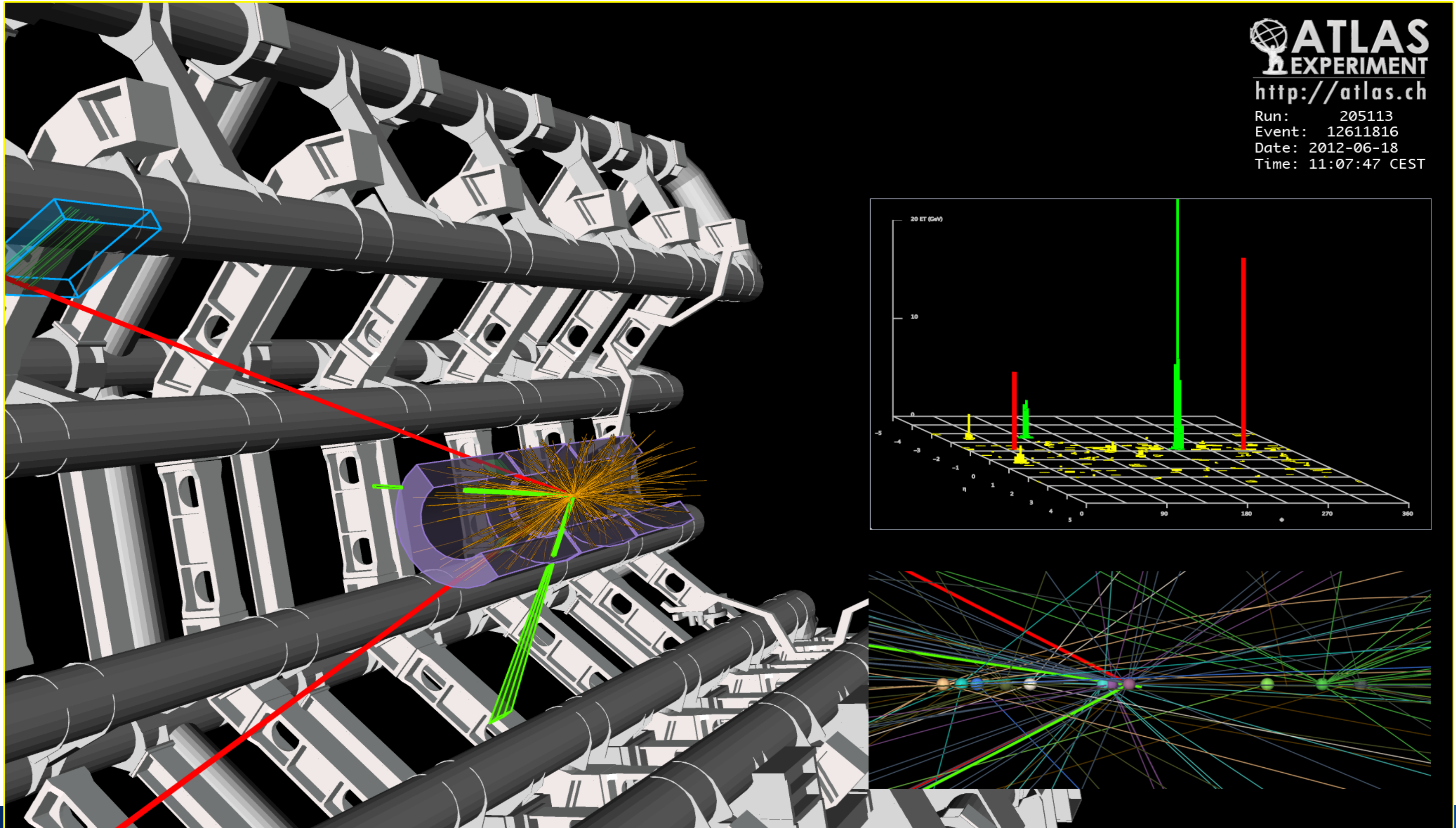
p_T (muons)= 36.1, 47.5, 26.4, 71 .7GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices



$H \rightarrow ZZ \rightarrow llll$

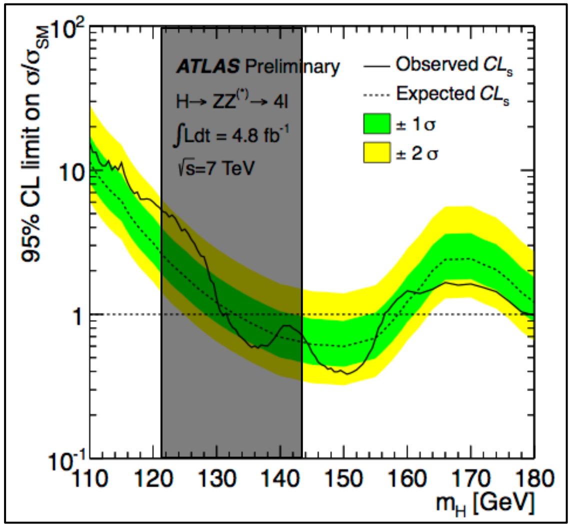
p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m$(\mu^+\mu^-)$ =19.6 GeV
12 reconstructed vertices

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

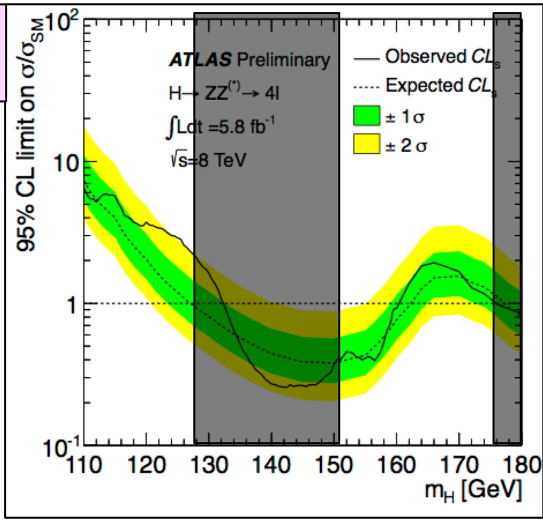


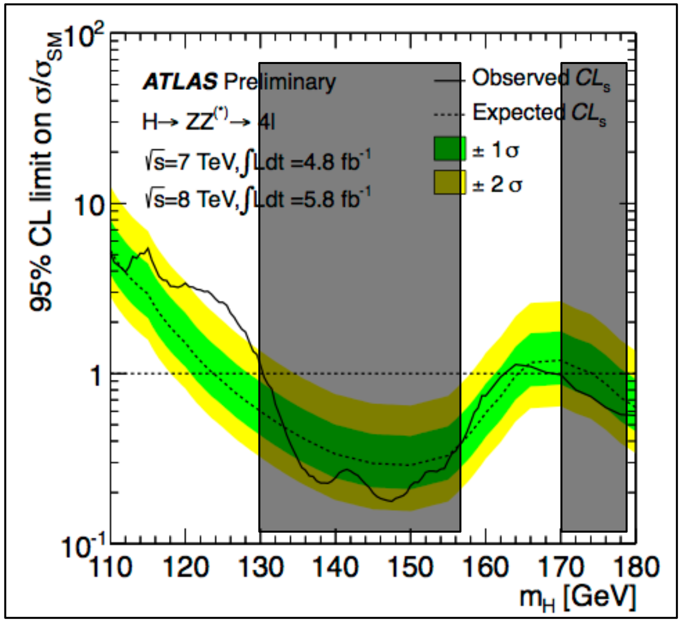
H → ZZ → llll

2011 data



2012 data



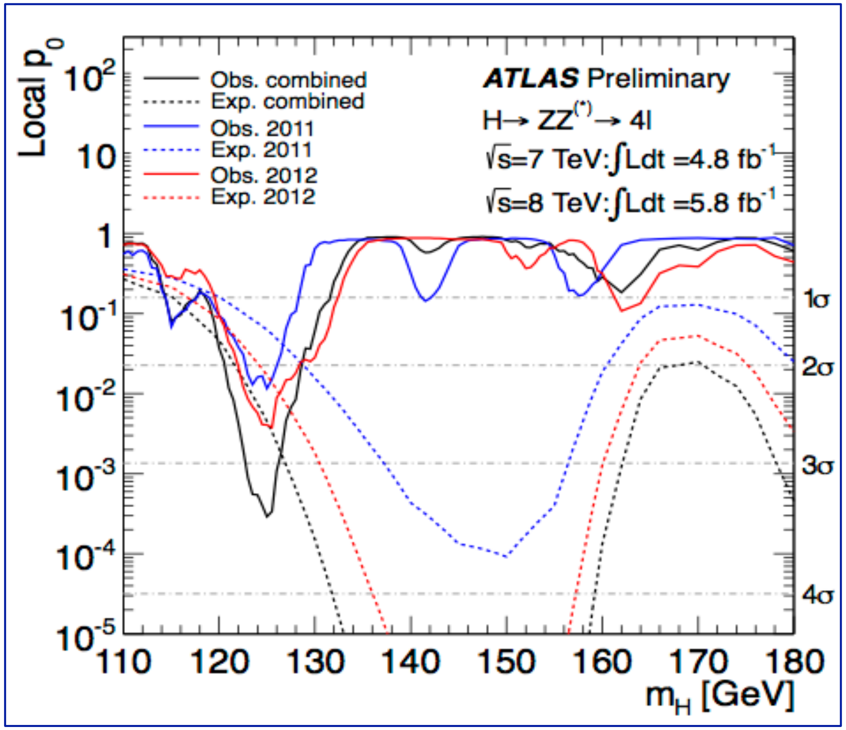


Excluded (95% CL): 131-162, 170-460 GeV
Expected: 124-164, 176-500 GeV

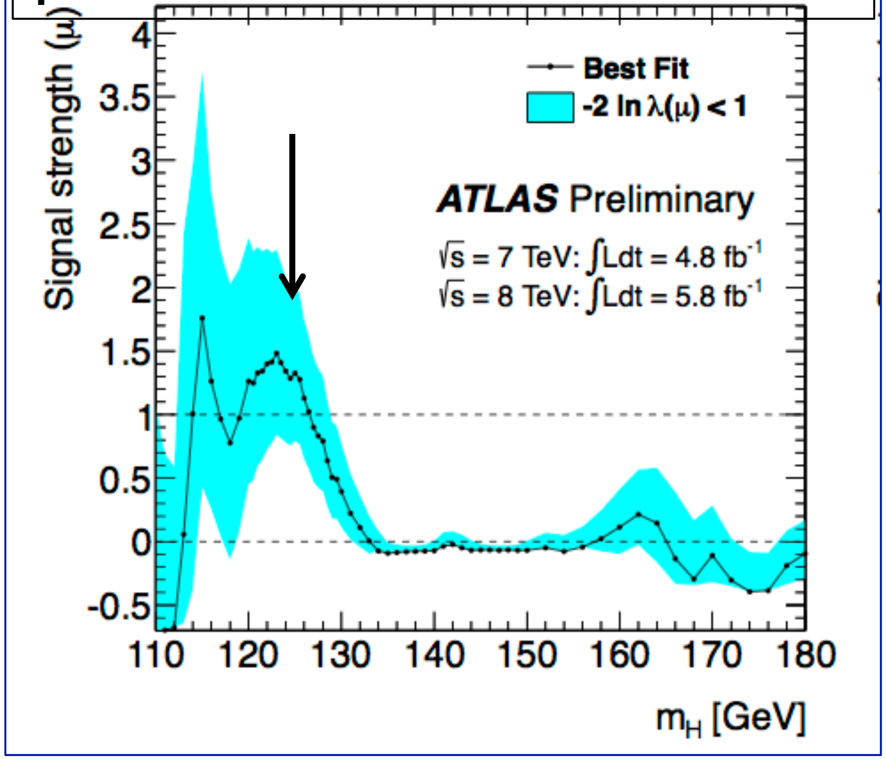
2011+2012 data

Higgs→ZZ → llll

Consistency of the data with
the background-only expectation

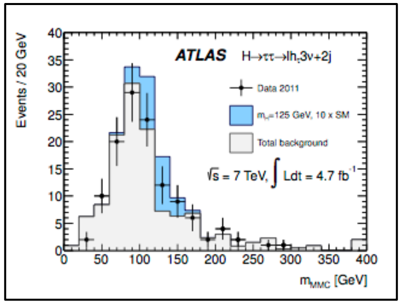


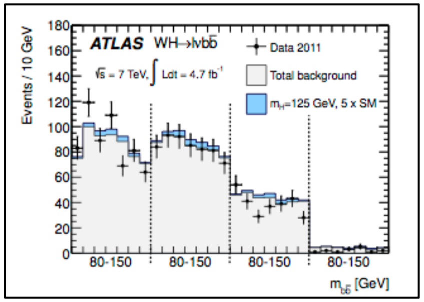
Best-fit value at 125 GeV:
μ=1.3 ± 0.6

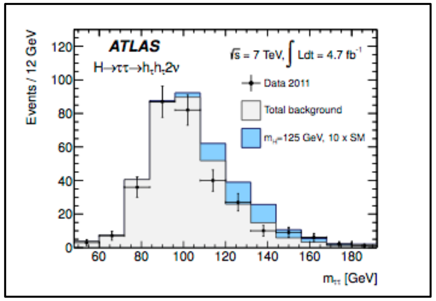


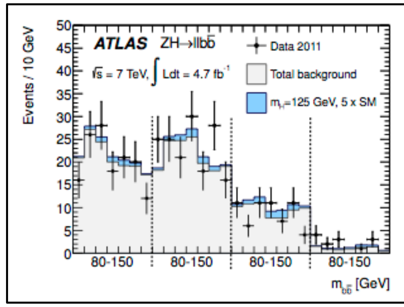
Data sample	m_H of max deviation	local p-value	local significance	expected from SM Higgs
2011	125 GeV	1.1%	2.3 σ	1.5 σ
2012	125.5 GeV	0.4%	2.7 σ	2.1 σ
2011+2012	125 GeV	0.03%	3.4 σ	2.6 σ

Combination

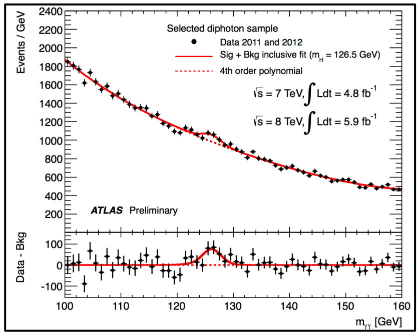


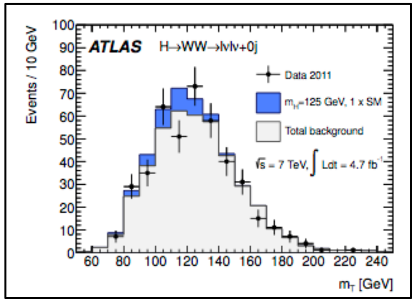


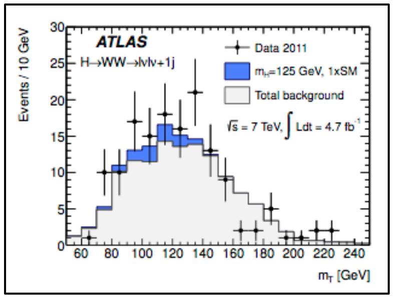


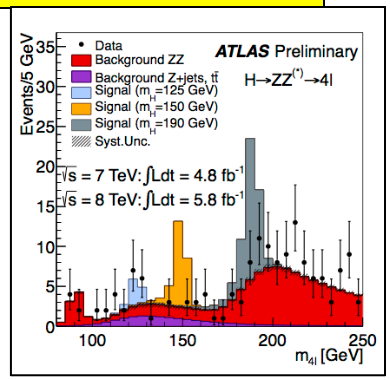


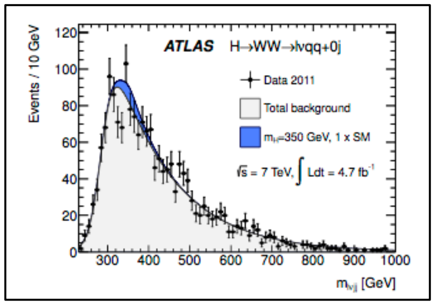
- H→ γγ, 4l: full 2011 and 2012 datasets (~ 10.7 fb^{-1}) and improved analyses
- all other channels (H→ $WW^{(*)}$→ lνlν, H→ ττ, WH→ lνbb, ZH→ llbb, ZH→ ννbb, ZZ → llνν, H→ ZZ → llqq; H→ WW→lνqq): full 2011 dataset (up to 4.9 fb^{-1})

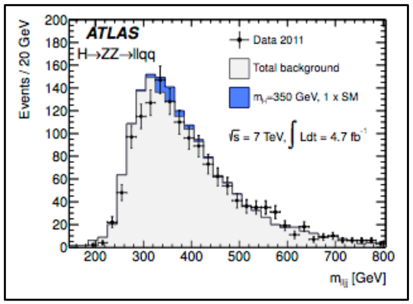


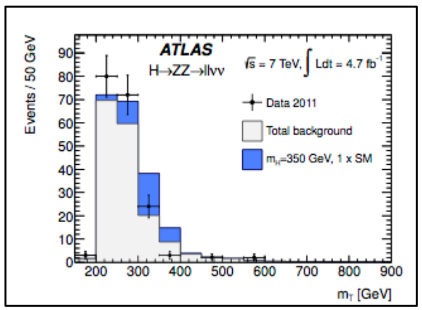


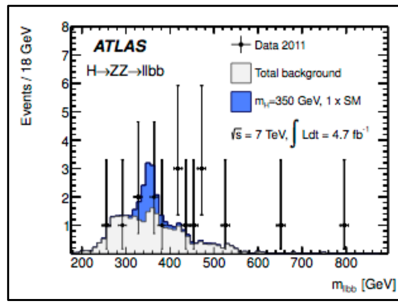








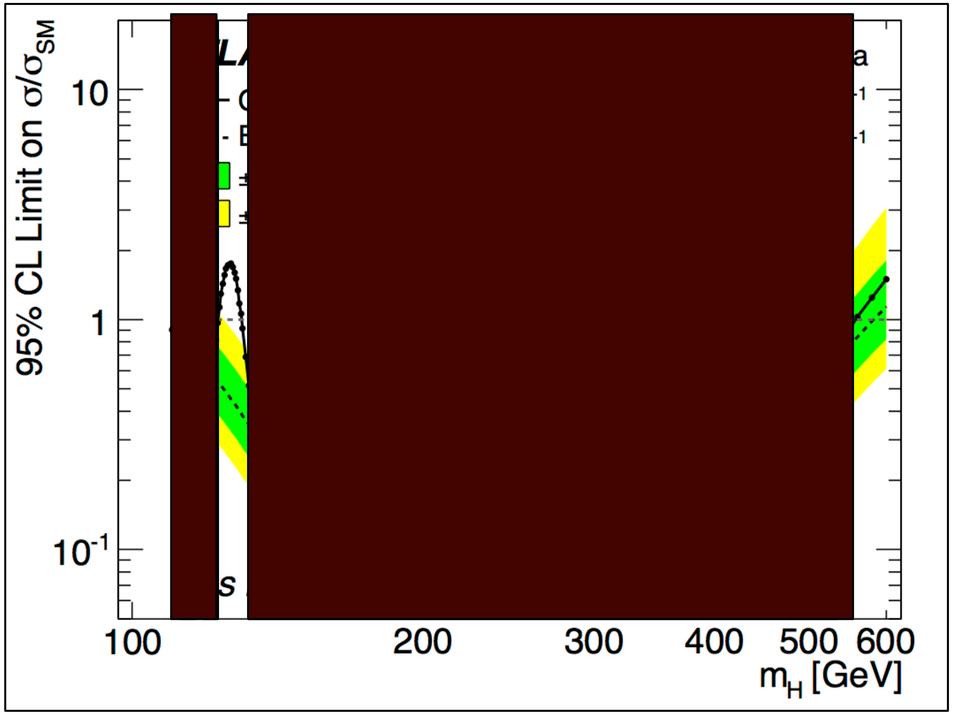


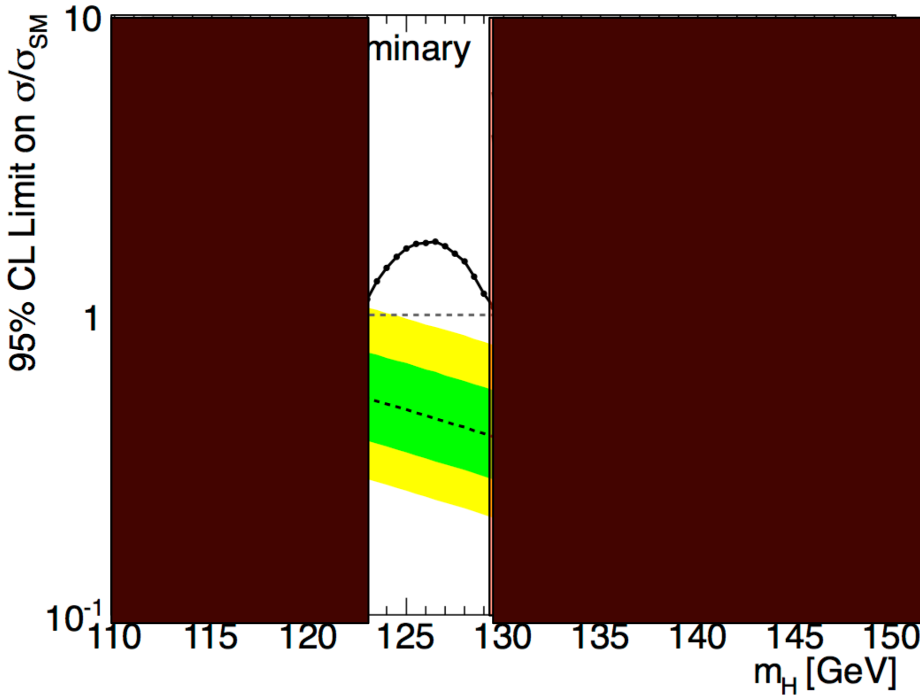


Combination

ATLAS now

Previous ATLAS results





Excluded at 95% CL

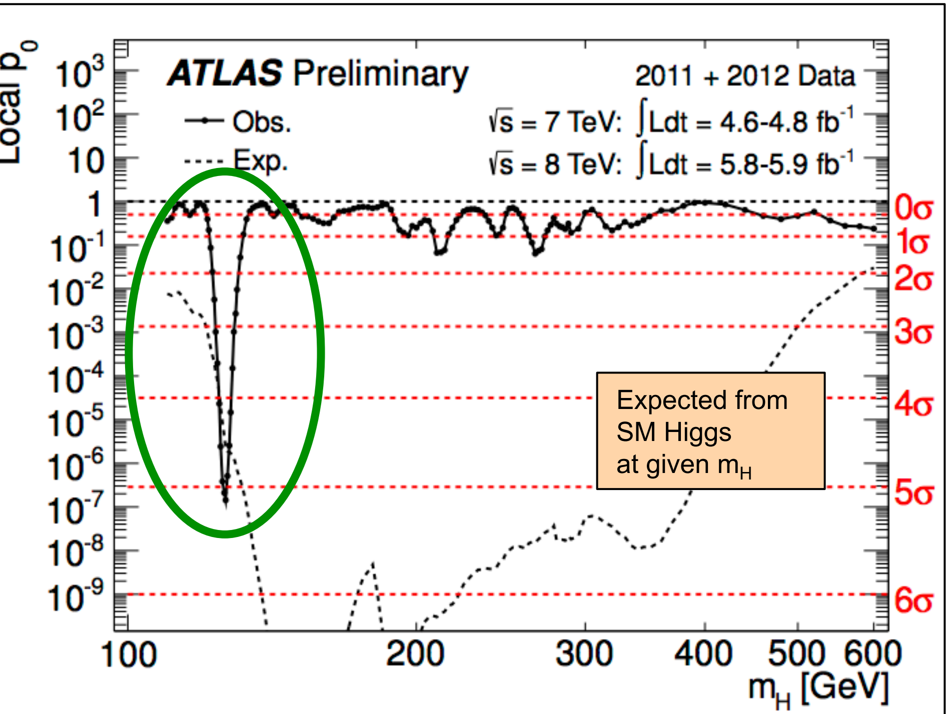
110-122.6   129.7-558 GeV

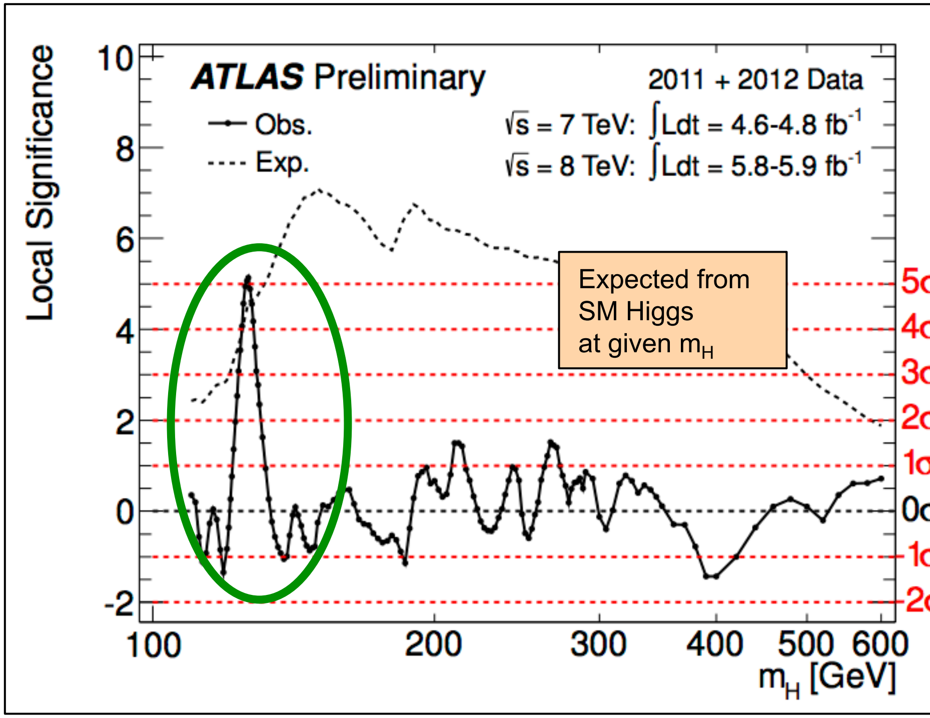
Expected at 95% CL

110-582 GeV

Combination

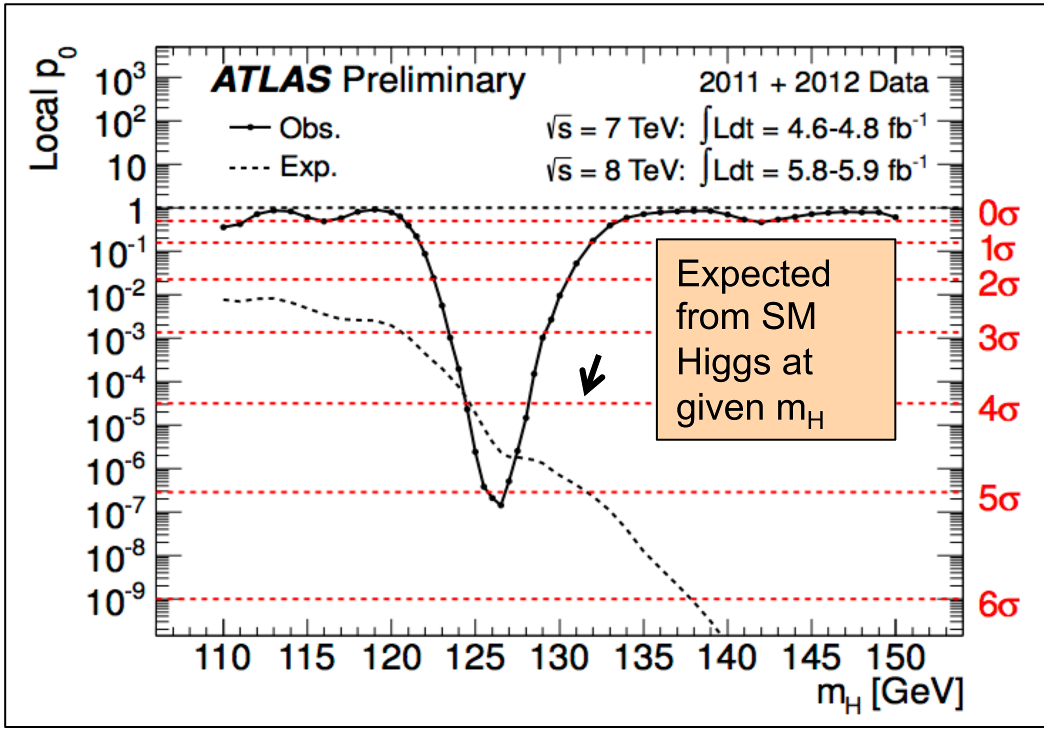
Combined results: consistency of the data with the background-only expectation and significance of the excess





Excellent consistency (better than 2σ !) of the data with the background-only hypothesis over full mass spectrum except in one region

Combination: The Excess



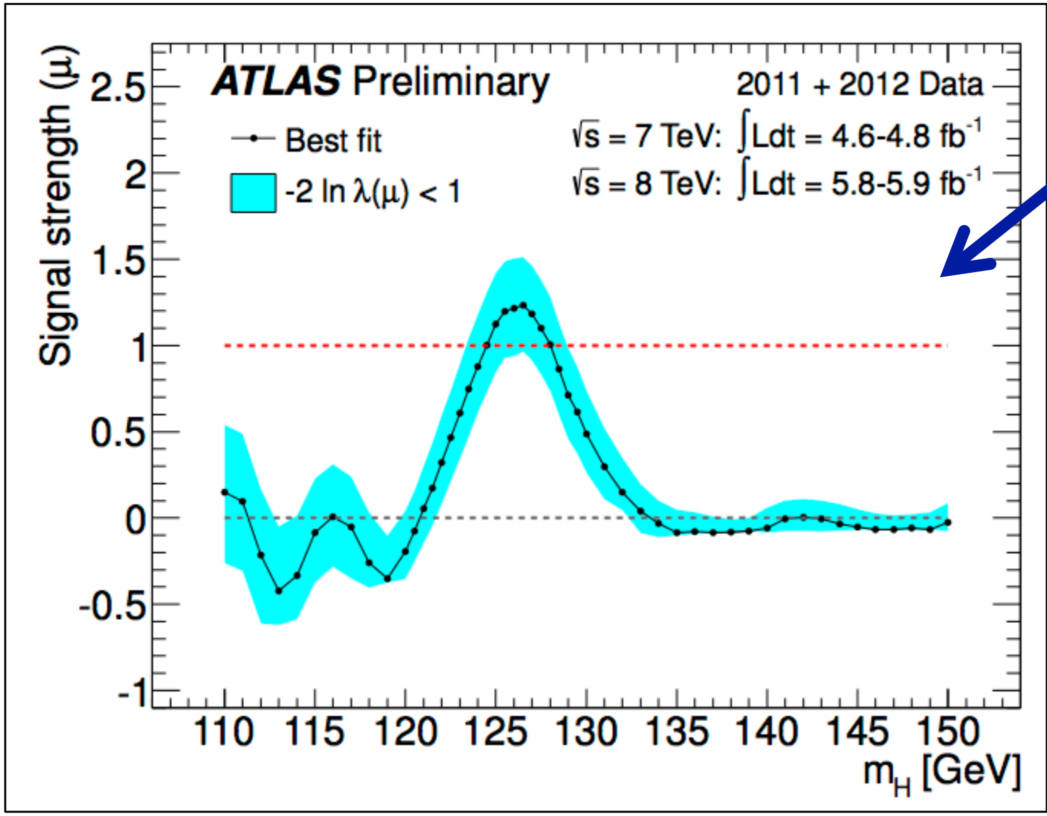
5σ

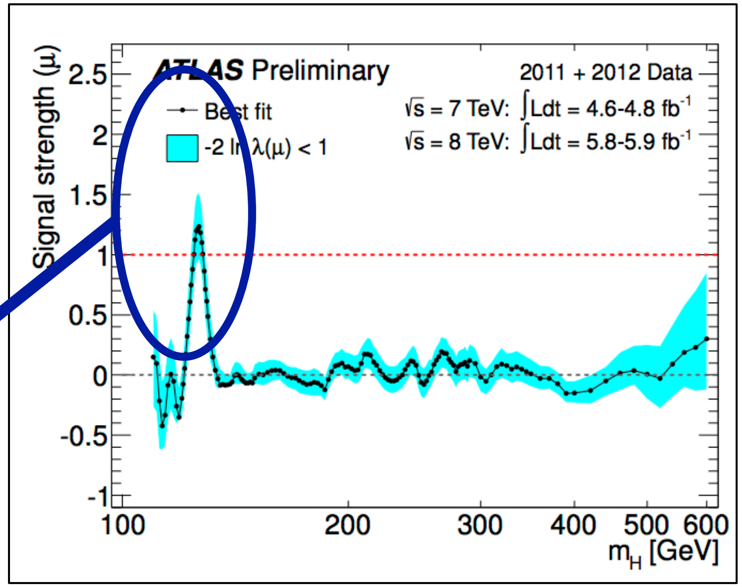
Maximum excess observed at	m_H = 126.5 GeV
Local significance	5.0 σ
Probability of background up-fluctuation	3 x 10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (with trials factor over 110-600 or 110-150 GeV)

Combination: Signal Strength

Normalized to SM Higgs expectation at given m_H (μ)





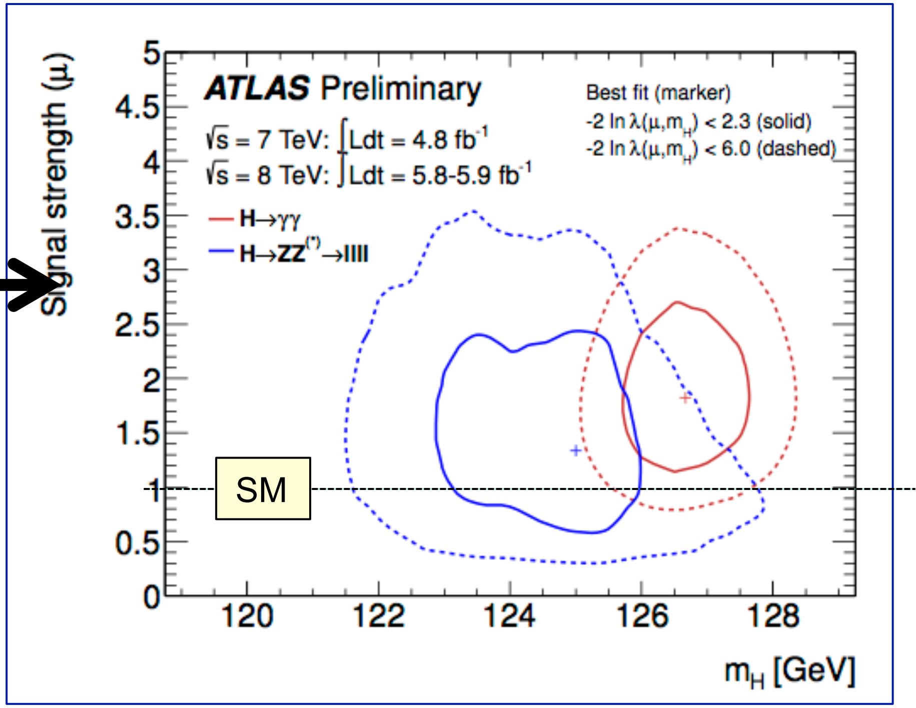
Best-fit value at 126.5 GeV:
$\mu = 1.2 \pm 0.3$

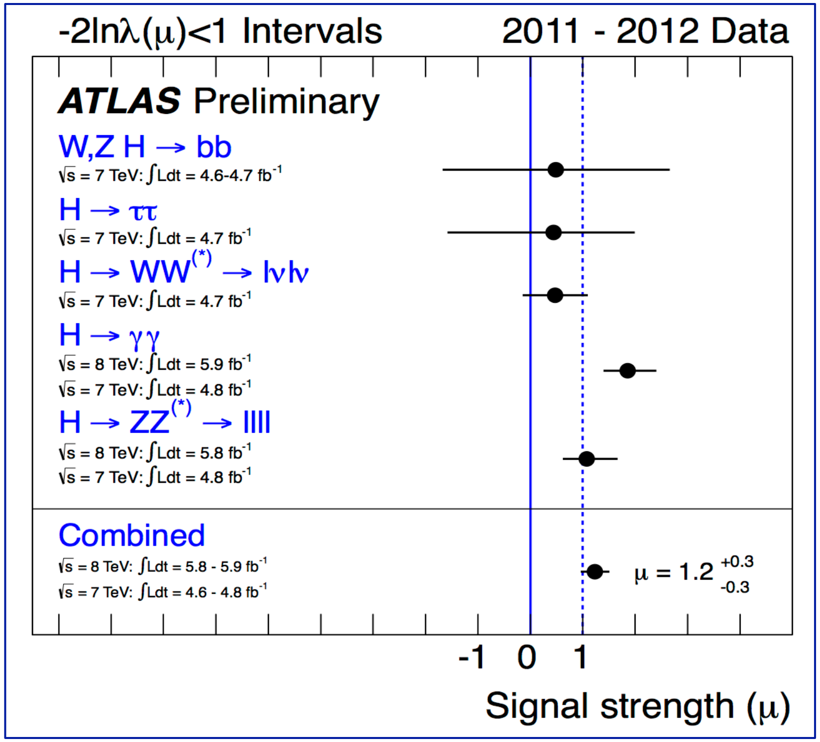
Good agreement with the expectation for a SM Higgs within the present statistical uncertainty

Combination

Are the ZZ (4l) and γγ observations consistent ?

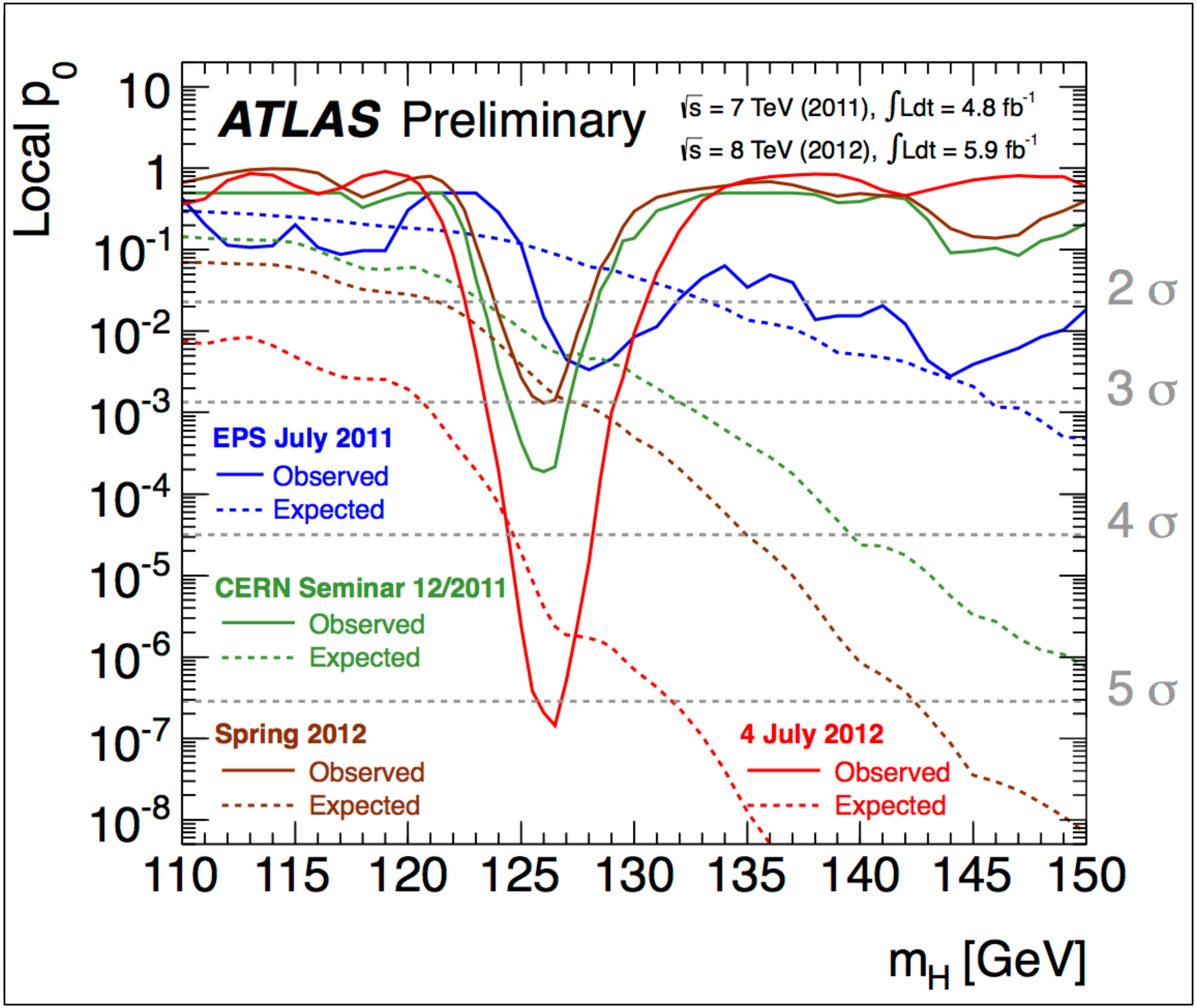
From 2-dim likelihood fit to signal mass and strength →curves show approximate 68% (full) and 95% (dashed) CL contours



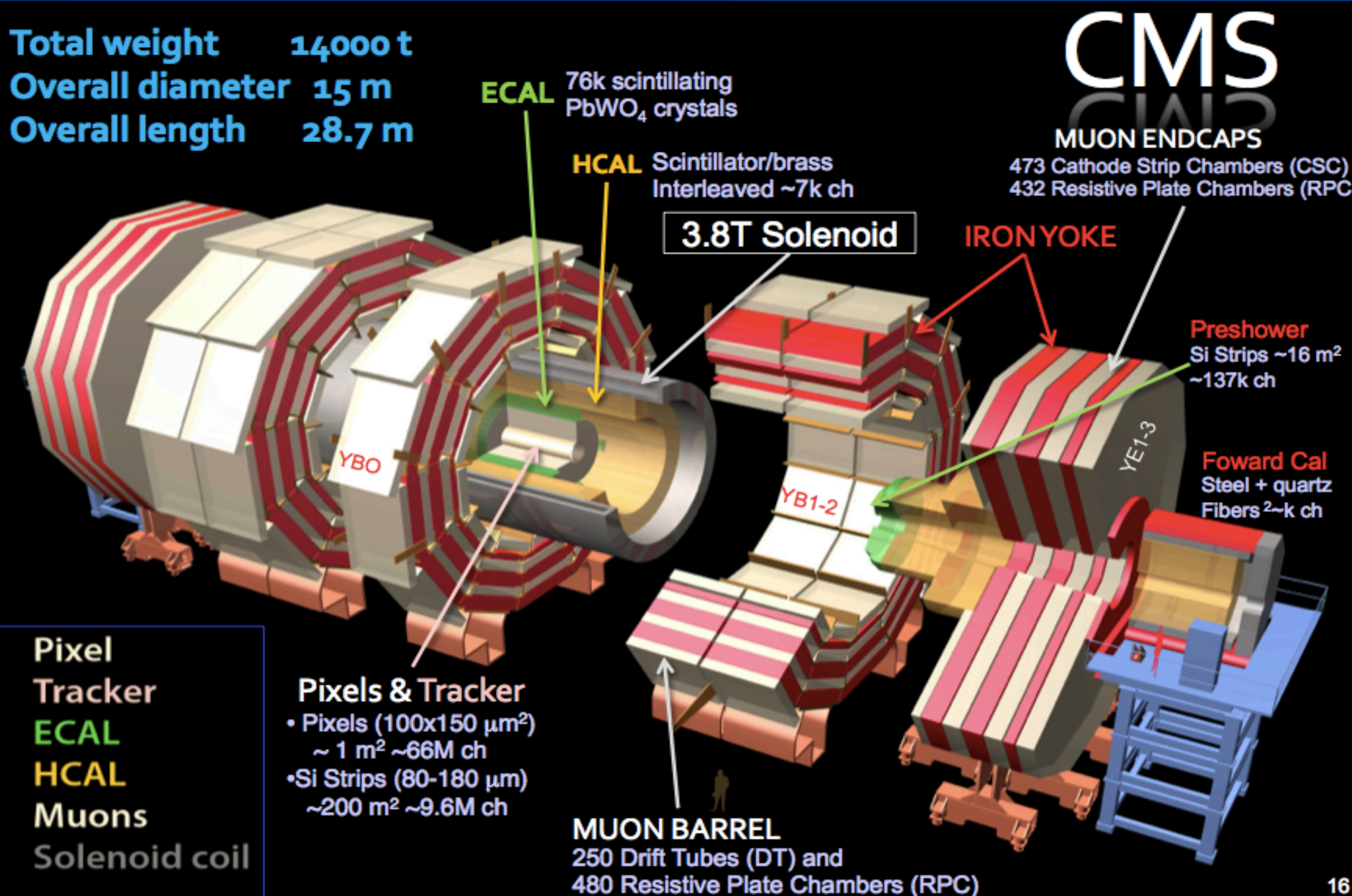


Best-fit signal strengths, normalized to the SM expectations, for all studied channels, at m_H = 126.5 GeV,

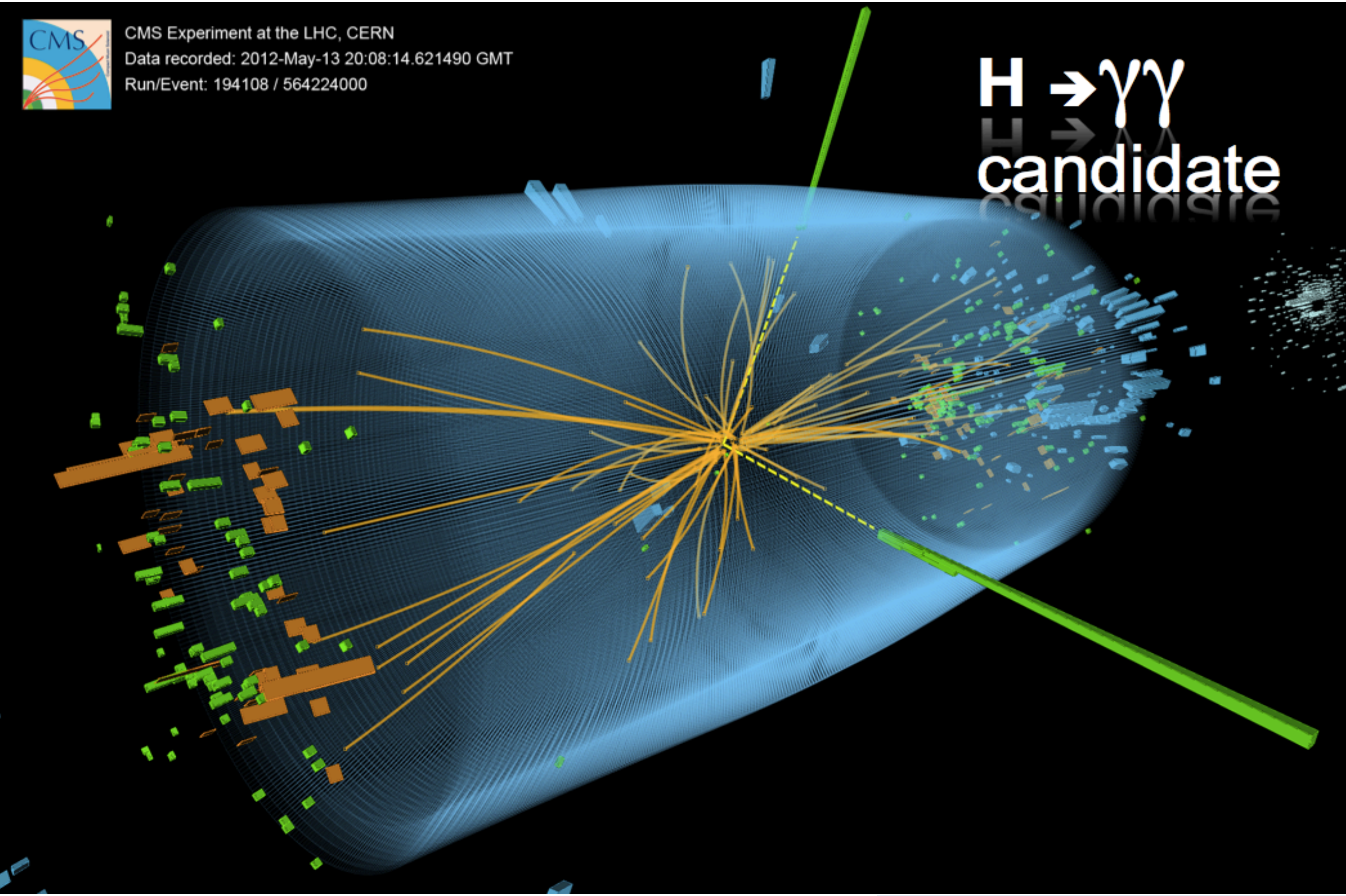
Evolution of an Excess



CMS Detector

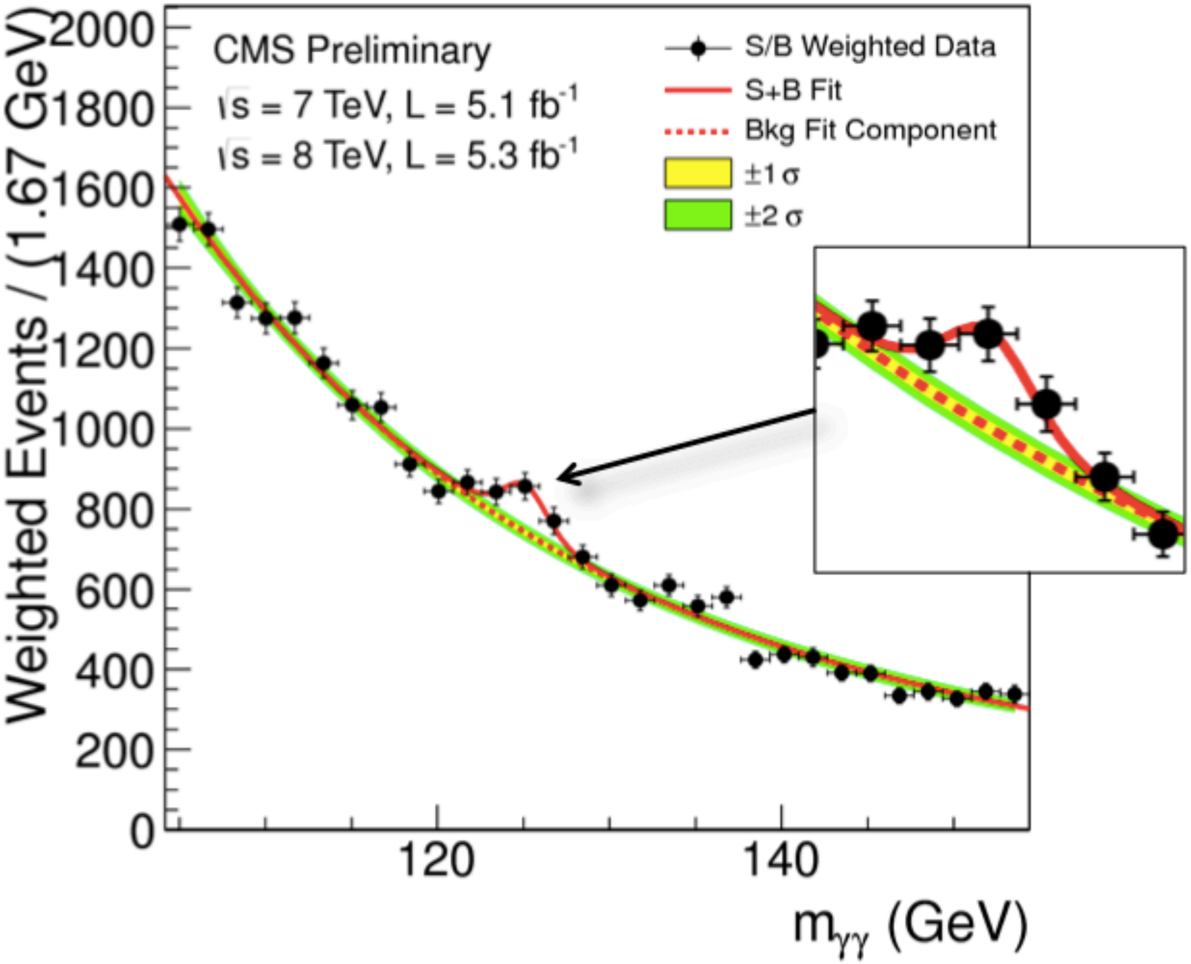


CMS Results



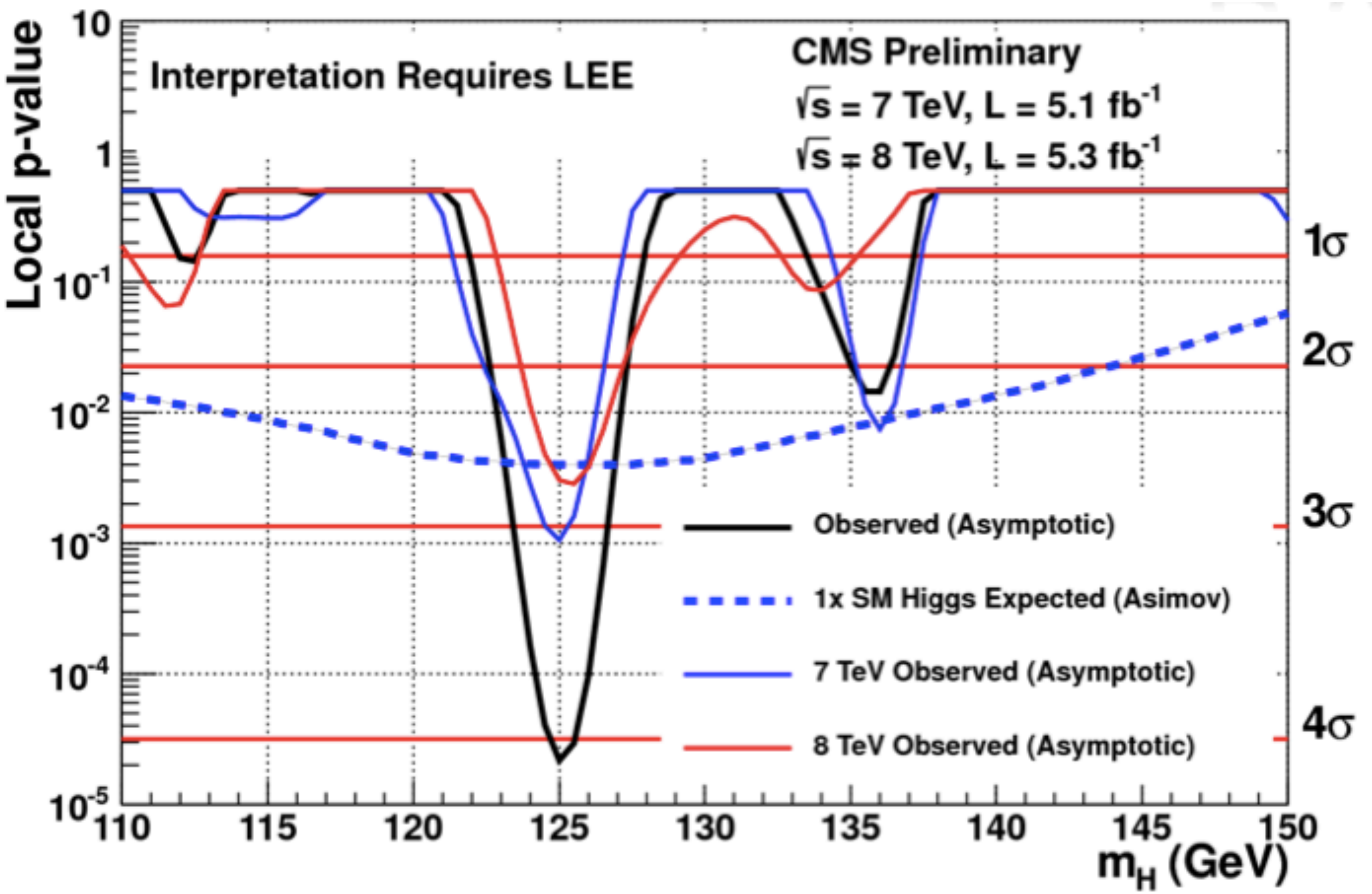
CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
candidate

S/B Weighted Mass Distribution



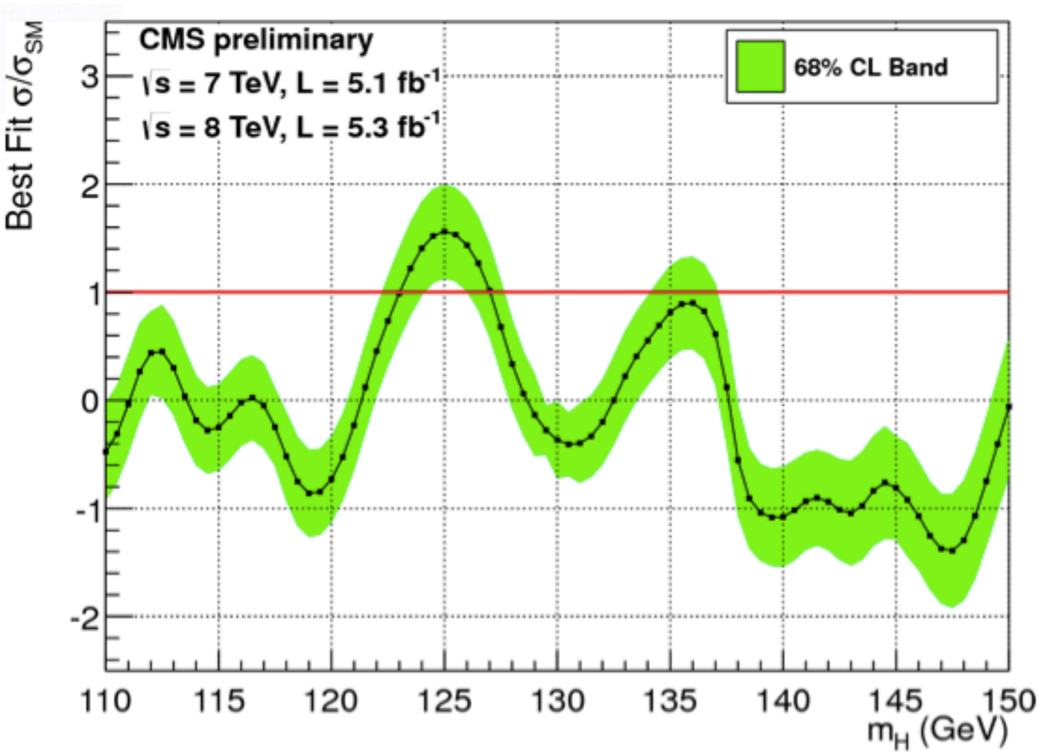
- Sum of mass distributions for each event class, weighted by S/B
- B is integral of background model over a constant signal fraction inteval

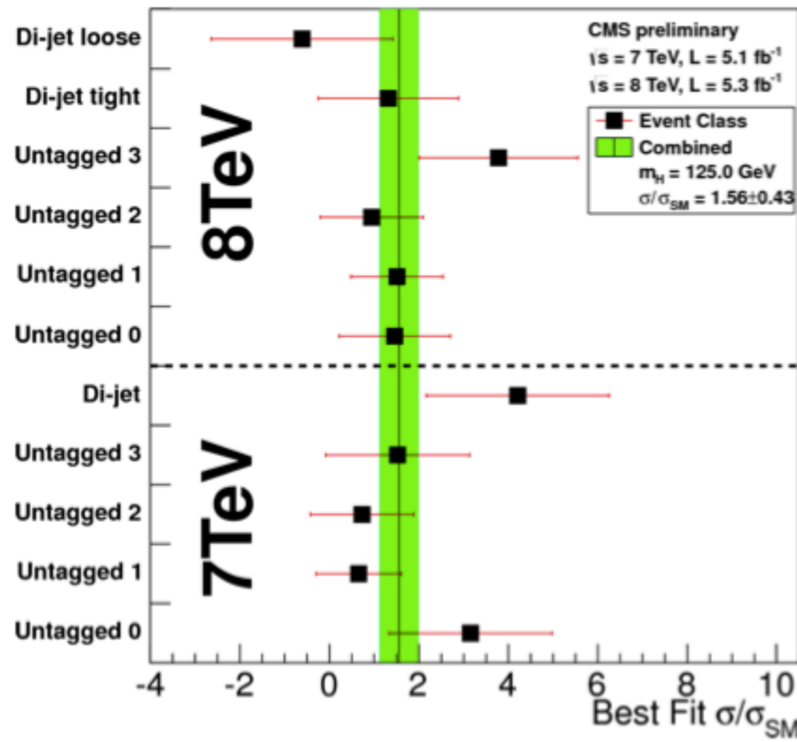
P-value



- Minimum local p-value at 125 GeV with a local significance of 4.1 σ

Fitted Signal Strength

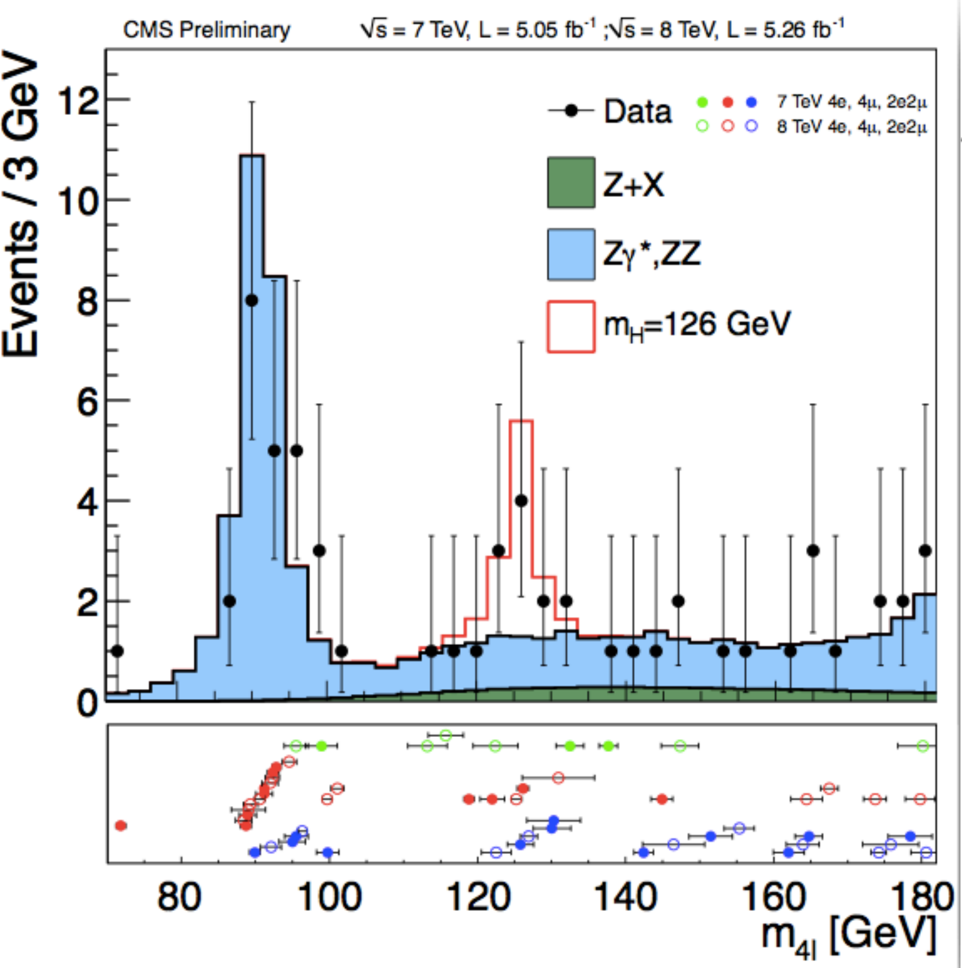


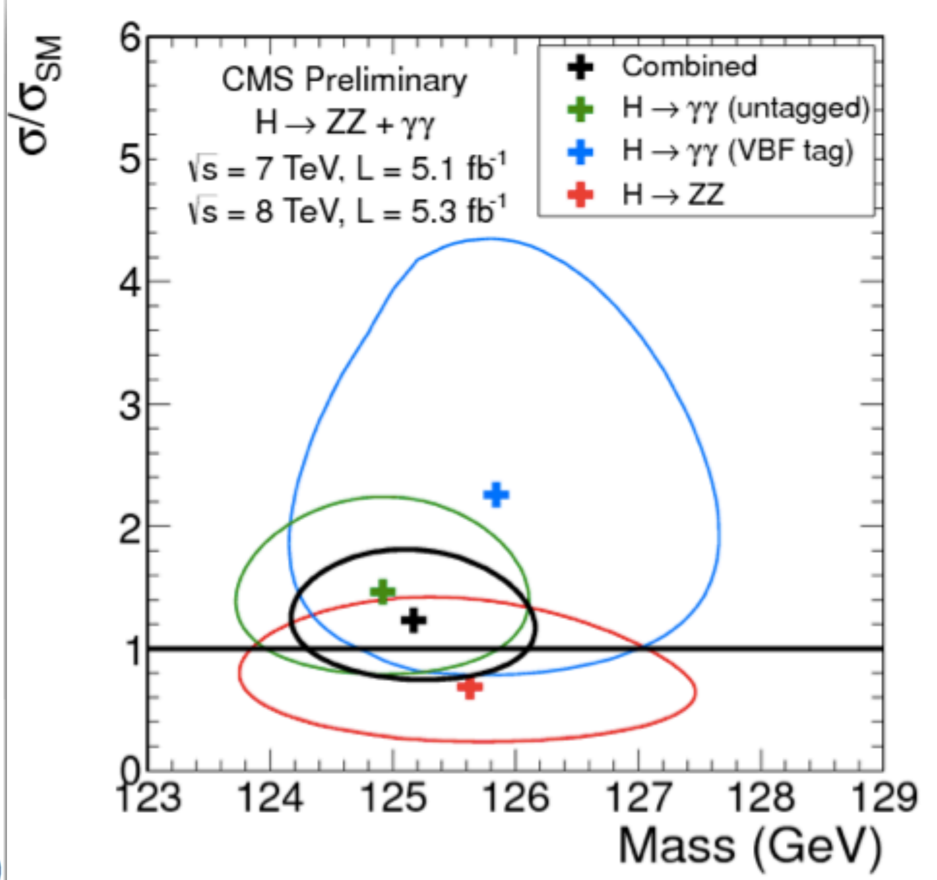


Combined best fit signal strength
σ/σ_{SM} = 1.56±0.43 x SM, consistent with SM.

Best fit signal strength consistent between different classes

H->ZZ

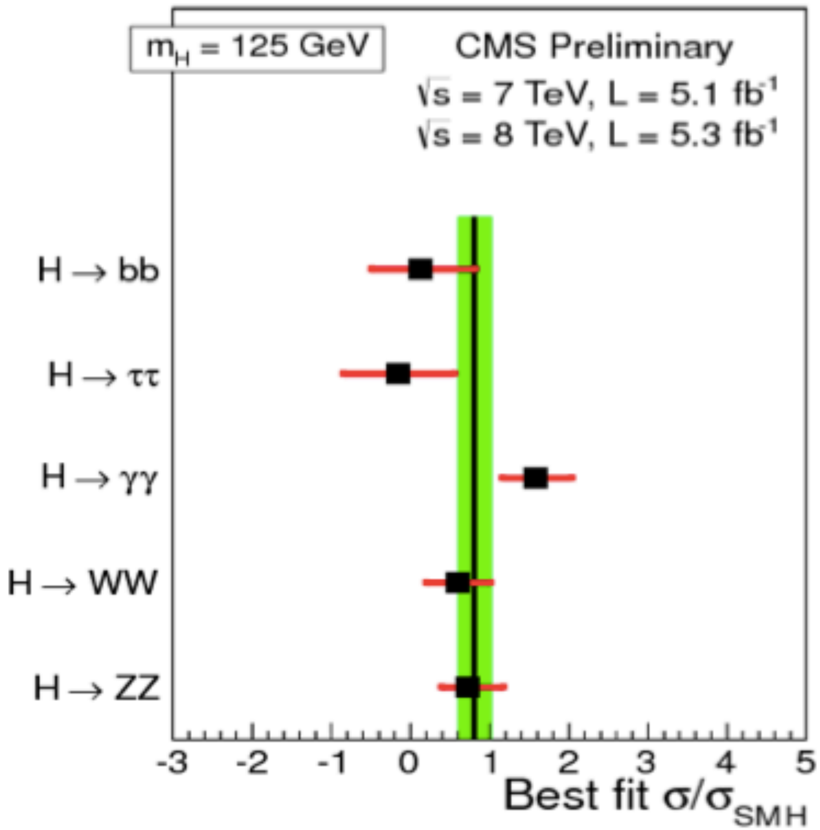


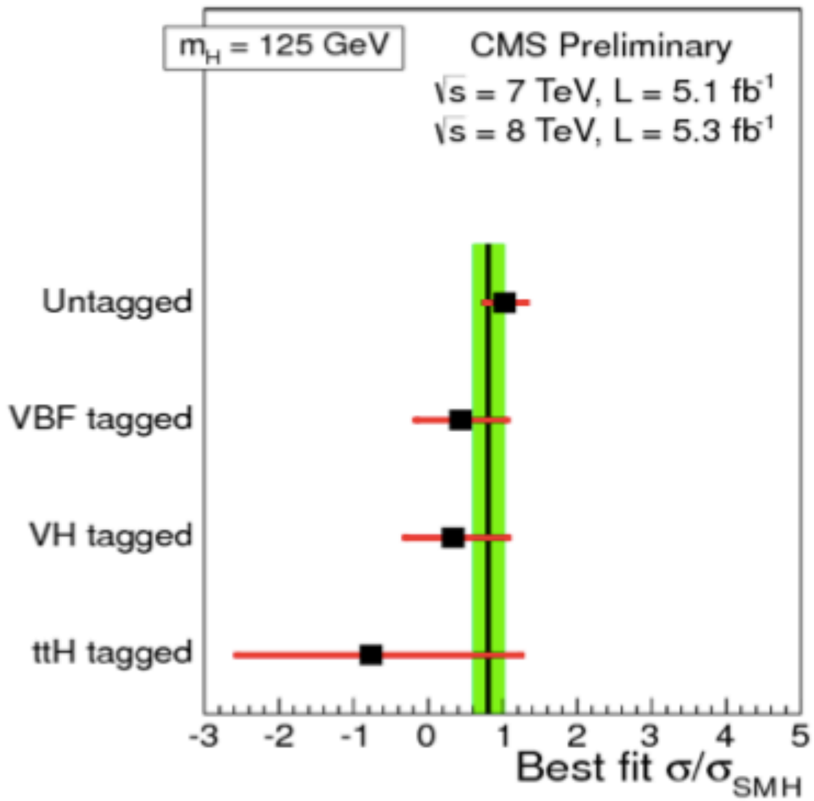


Enrich signal using Matrix Element Likelihood Analysis

Likelihood scan for mass and signal strength In three high mass resolution channels

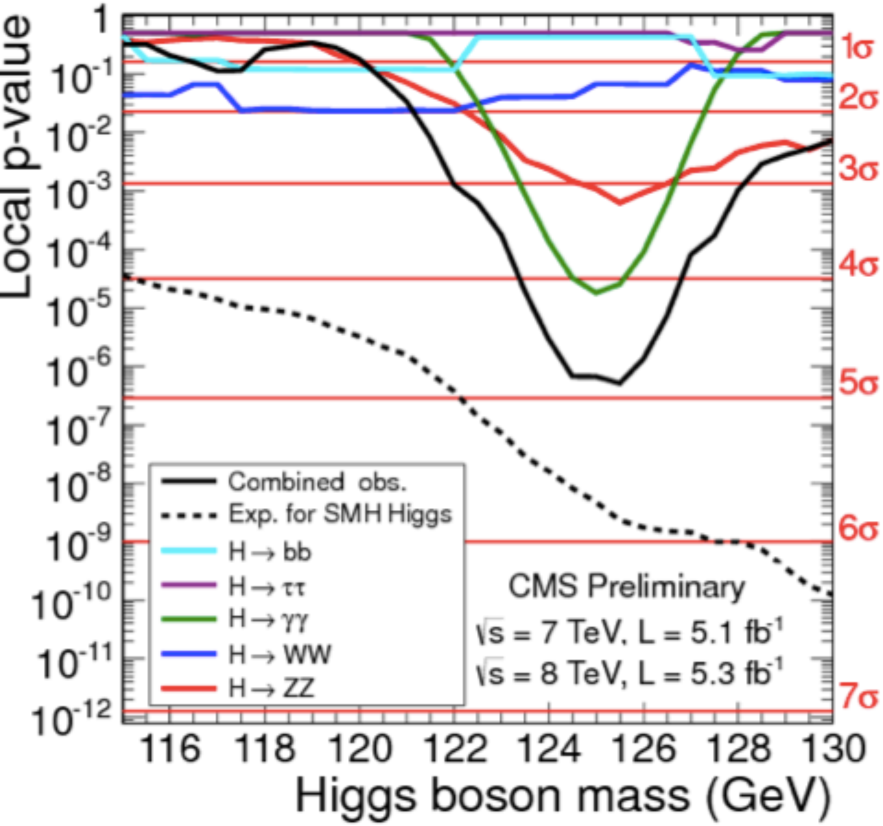
Compatibility with SM Higgs boson





- Event yields in different decay modes are self-consistent
- Event yields in different production topologies are self-consistent

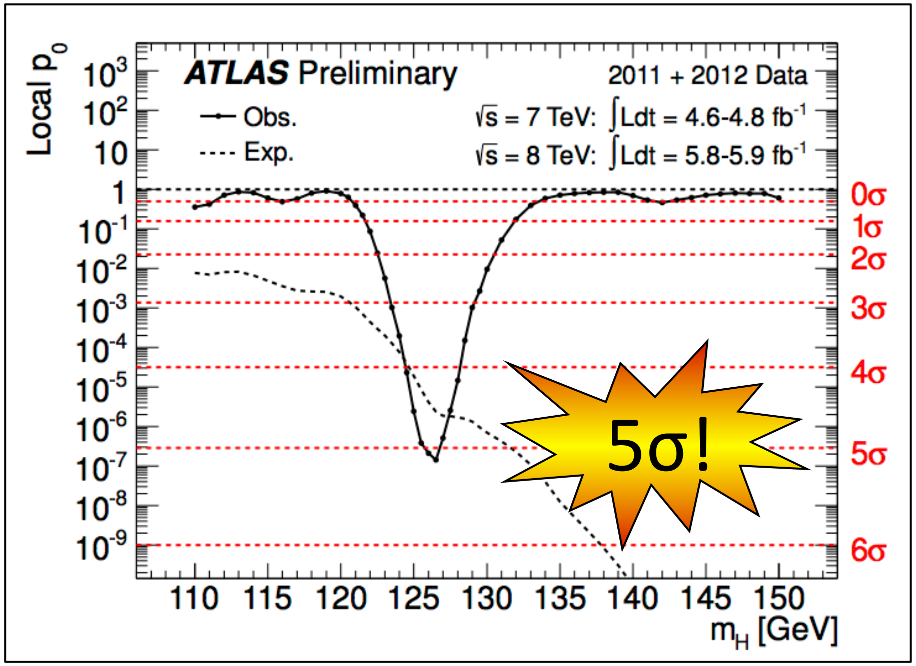
Characterization of excess near 125 GeV

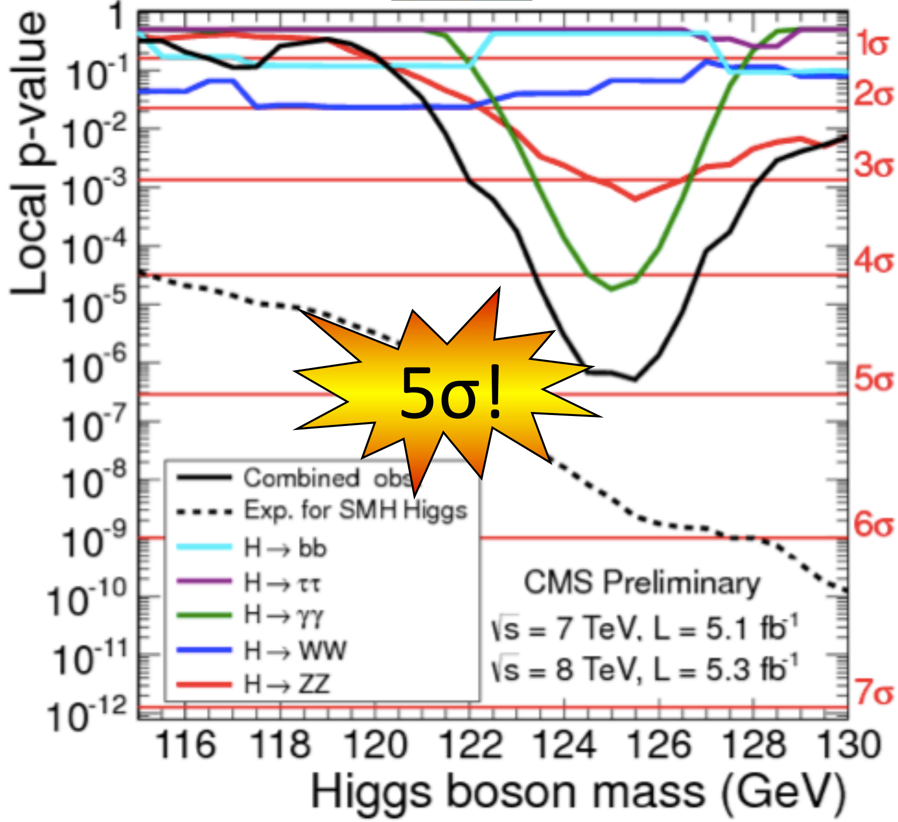


- **all channels together: comb. significance: 4.9 σ**
- **expected significance for SM Higgs: 5.9 σ**

$m_X = 125.3 \pm 0.6$ GeV

Summary / Conclusion





Both experiments see an excess near 125 GeV! at ~5σ
…consistent with the Standard Model Higgs hypothesis

The Next Steps

ATLAS and CMS will submit a paper based on the data presented at the end of July to the same journal

H→ $WW^{(*)}$ → lνlν channel: plan is to include results in the July paper
H→ ττ , W/ZH → W/Z bb: first results with 2012 data expected later in the Summer

MORE DATA will be essential to:

- ❑ Establish the observation in more channels, look at more exclusive topologies
- ❑ start to understand the nature and properties of the new particle

This is just the BEGINNING !

We are entering the era of "Higgs" measurements
First question: is the observed excess due to the production of a SM Higgs boson ?

we have only recorded ~ 1/3 of the data expected in 2012
the LHC and experiments have already accomplished a lot and much faster than expected

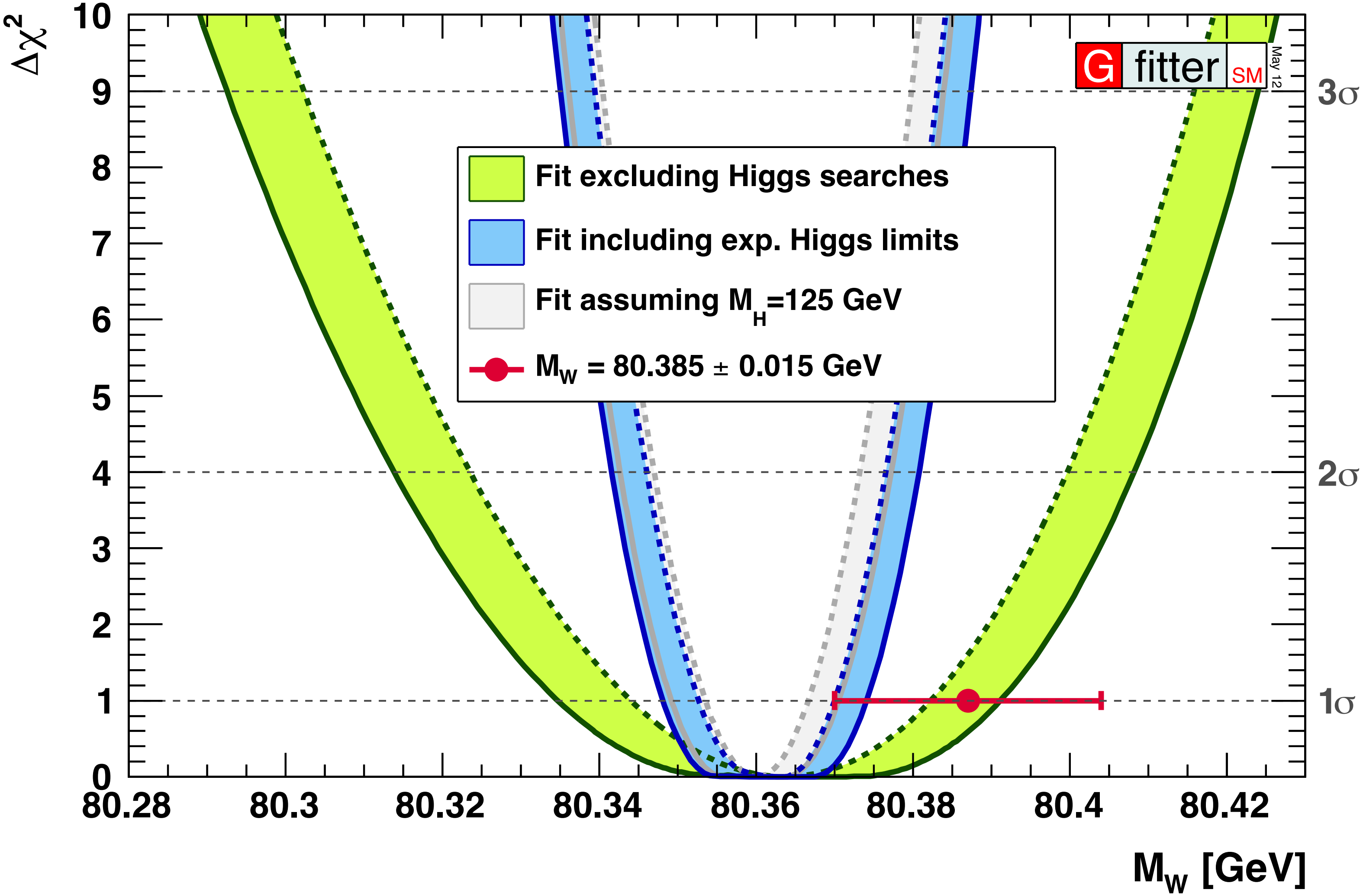
From Canada

Canadian Efforts

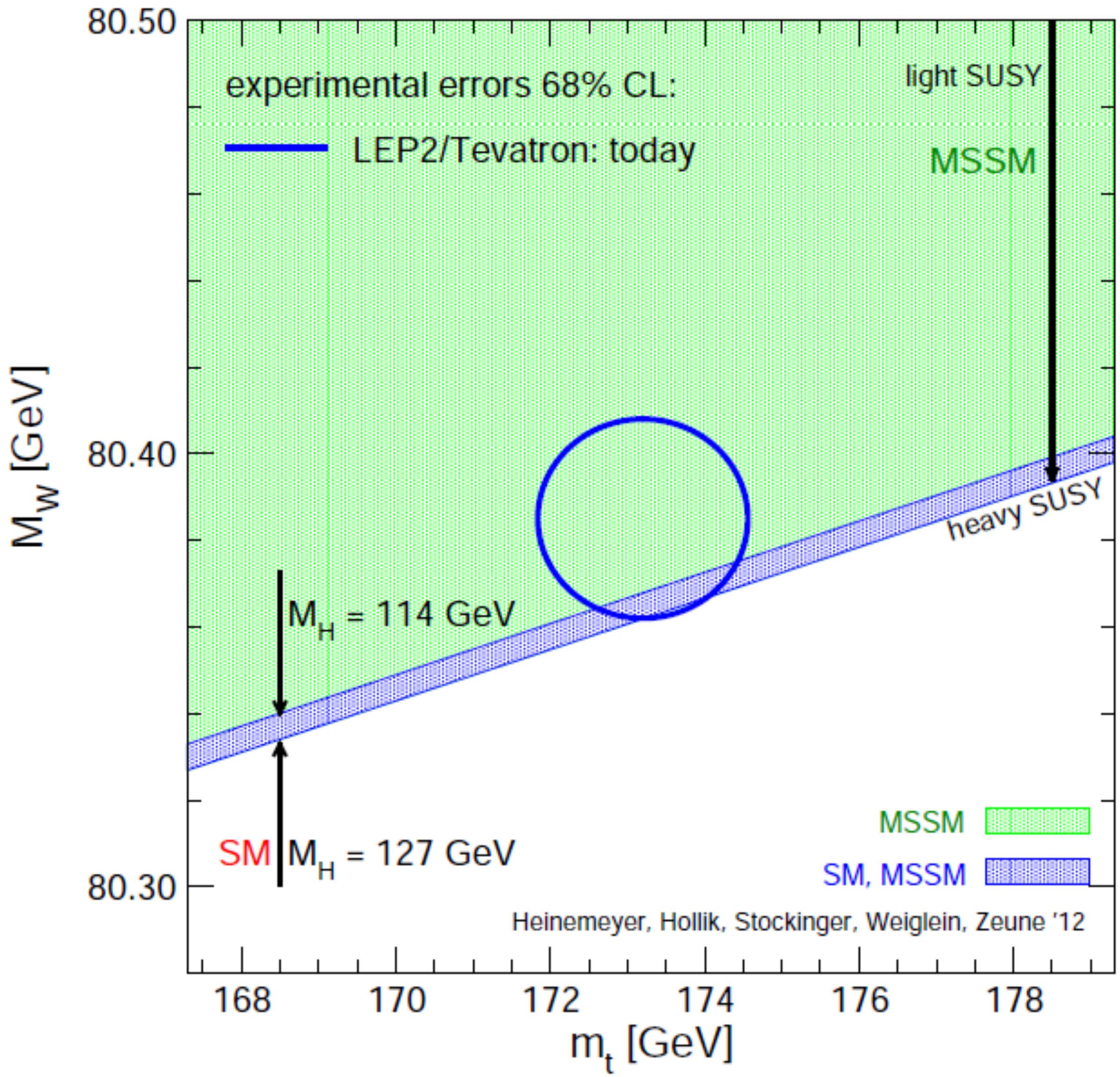
- ~ 30 Canadians work directly on Higgs Boson searches with ATLAS
- We also built and maintain key detector systems essential for analysis, optimize trigger strategies, and host computer analysis centres for ATLAS
- And made key contributions to the LHC itself
- ATLAS/LHC is a large international collaboration (3000 people) but ~150 person Canadian effort is critical to program

Alberta
Carleton
McGill
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

Direct and Indirect M_W

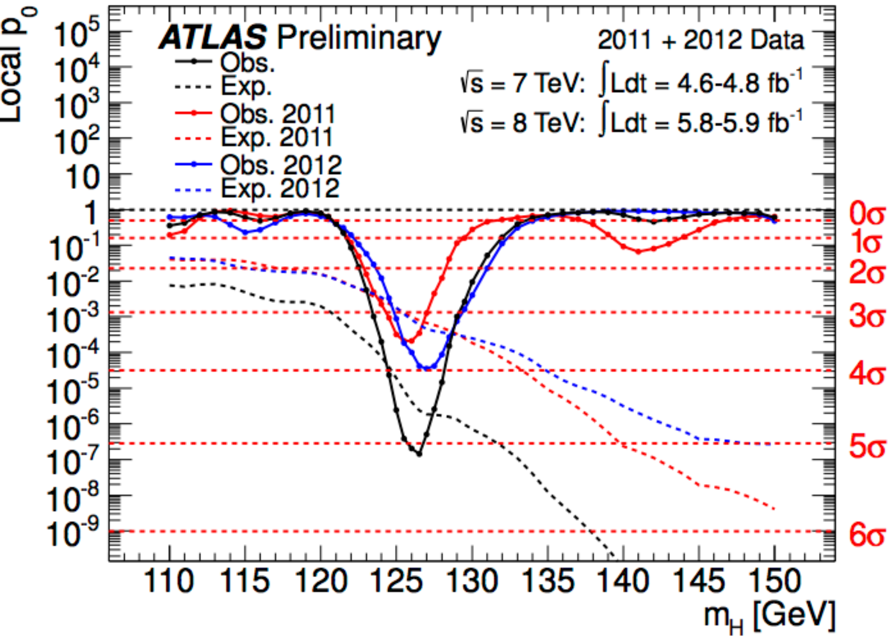


SUSY



experimental errors 68% CL:
LEP2/Tevatron: today
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM M_H = 127 GeV
MSSM
SM, MSSM
Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '12
80.50
80.40
80.30
M_W [GeV]
168
170
172
174
176
178
m_t [GeV]

Comparison



Similar expected significances in both years (more luminosity and larger cross-section in 2012, but only two channels included)

	Max deviation at m_H	Observed (exp.) significance
2011 data	126 GeV	3.5 (3.1) σ
2012 data	127 GeV	4.0 (3.3) σ