Status of Higgs measurements at the LHC

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on behalf of the ATLAS and CMS Collaborations

Outline

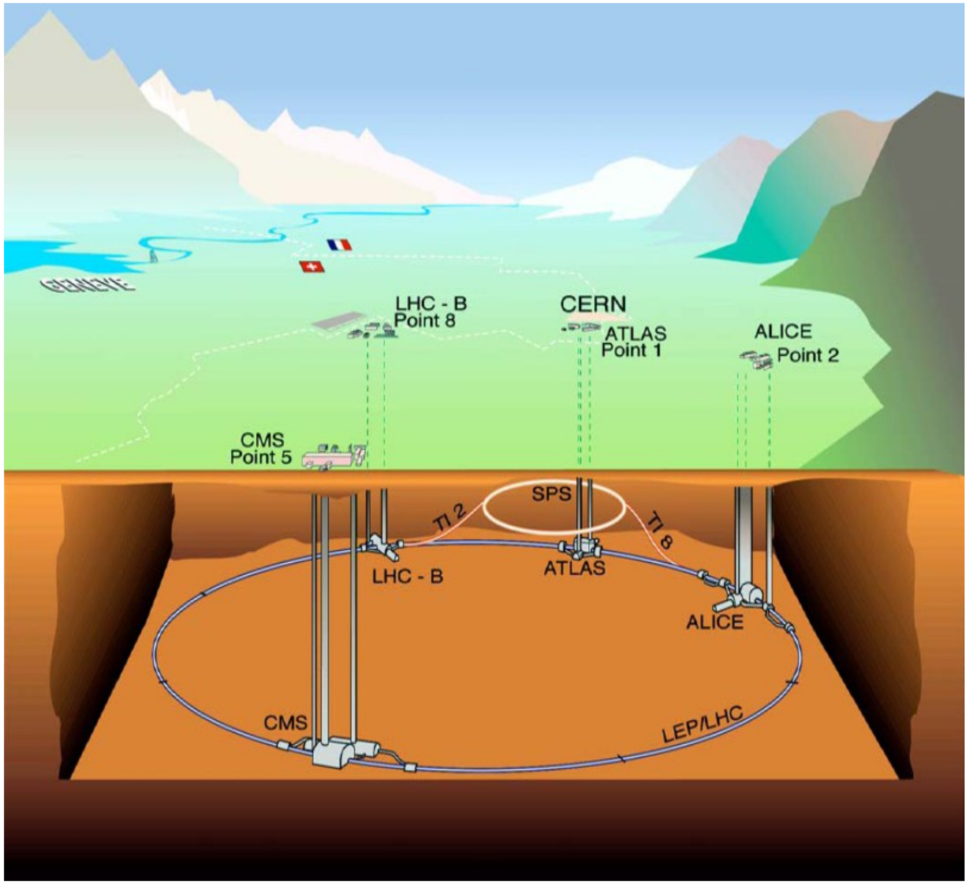
- Introduction
  - LHC; ATLAS and CMS experiments
- Overview of SM Higgs searches
  - production & decay modes
  - new boson X(125) observation in 2012
- Prerequisities
- Measurements of the properties of the new boson X(125)
  - mass
  - couplings
  - spin
- BSM searches for new Higgs fields
- Conclusions

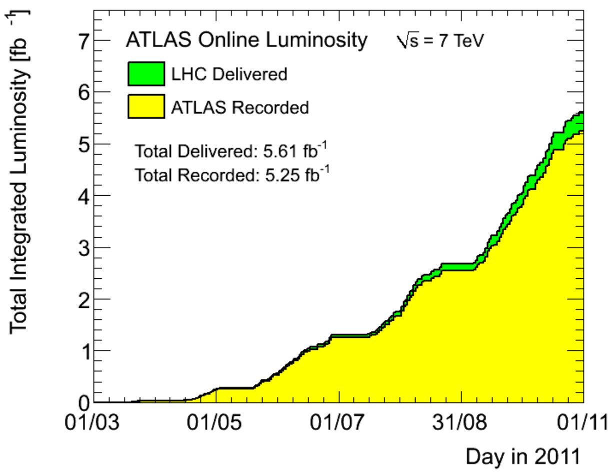
Large Hadron Collider

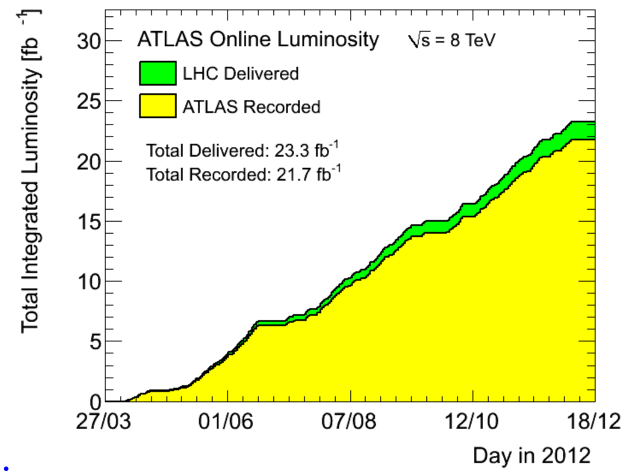
- Two general-purpose experiments (ATLAS, CMS)
- Excellent performance of the accelerator.

  Many thanks to LHC operation team !!

- Parameters achieved in pp collisions:
  - centre-of-mass energy 7 TeV (2011) and 8 TeV (2012)
  - delivered luminosity 5 fb^{-1} (2011) and 21 fb^{-1} (2012)
  - bunch spacing 50 ns

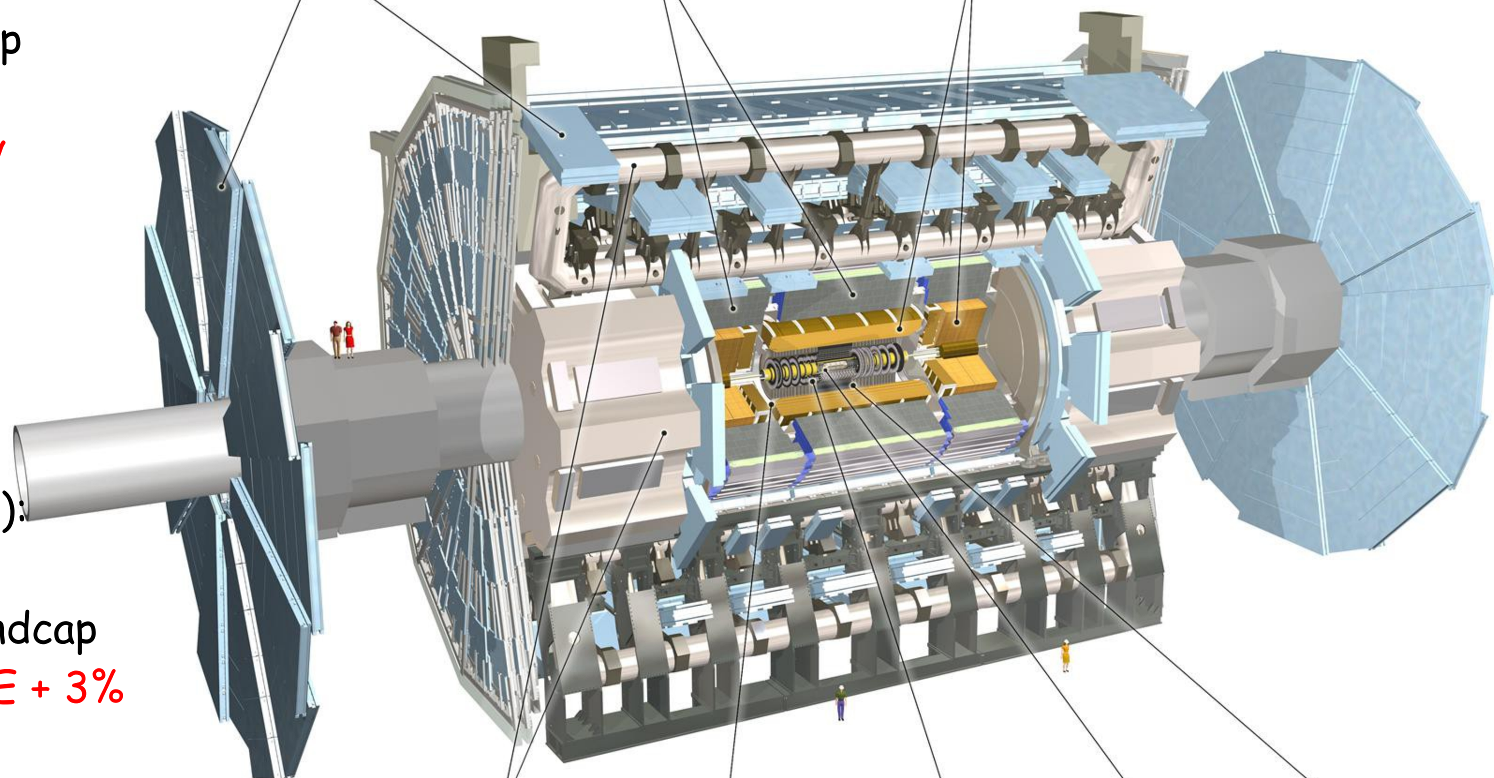






ATLAS experiment

Muon spectrometer:
- air-core toroid magnets: 0.5 T in barrel, 1 T in endcap
- momentum resolution: 2% @ 50 GeV, 10% @ 1 TeV (combined Tracker+Muon spectrometer)



Hadronic calorimeter (HCAL):
- Fe+scint in barrel, Cu+Liquid Argon (LAr) in endcap
- resolution $\sigma(E)/E \approx 50\%/\sqrt{E} + 3\%$ (ECAL+HCAL, barrel part)

Electromagnetic calorimeter (ECAL):
- Pb+LAr technology, accordion geometry
- resolution $\sigma(E)/E \approx 10\%/\sqrt{E} + 0.7\%$

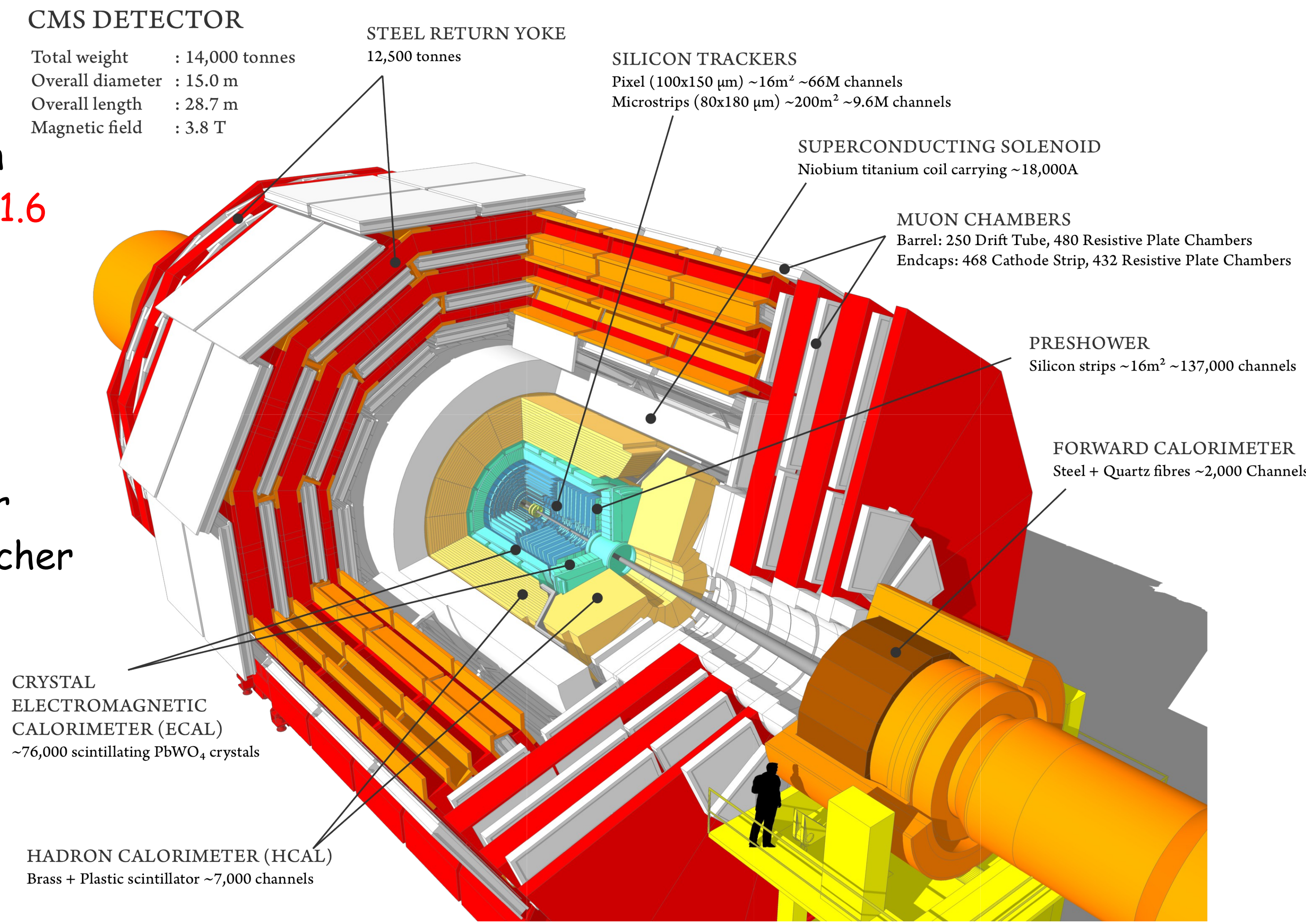
Tracker:
- Si pixels, Si strips, Transition Radiation Tracker (TRT) inside 2 T solenoid
- resolution: $\sigma(p_T^{-1}) \approx 0.36 + 13/(p_T \cdot \sqrt{\sin\theta})$ [TeV^{-1}], (θ being the polar angle wrt beam axis)

Further details in Ref:
G. Aad et al., JINST 3 (2008) S08003

CMS experiment

Tracking system:
- silicon pixels and strips
- expected muon resolution
  $\sigma(p_T)/p_T$ = 1.5-2% for $|\eta|<1.6$
  at p_T=100 GeV

HCAL:
- brass + plastic scintillator
- complemented by tail catcher outside the solenoid in the central part

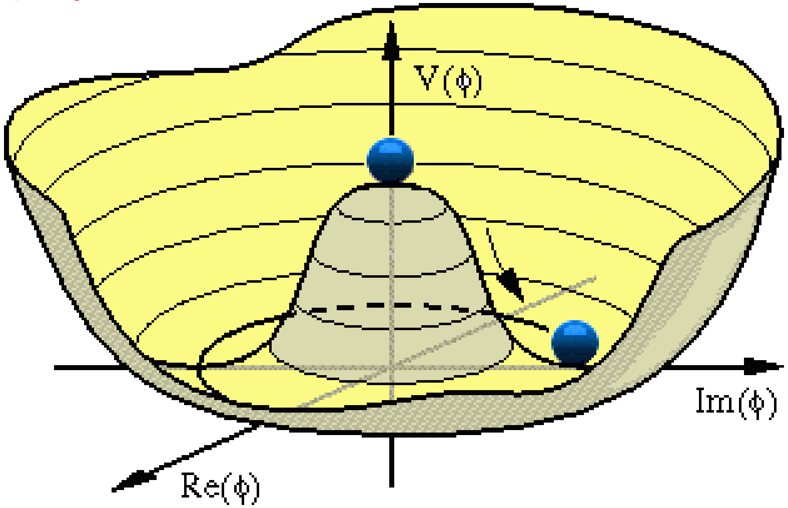


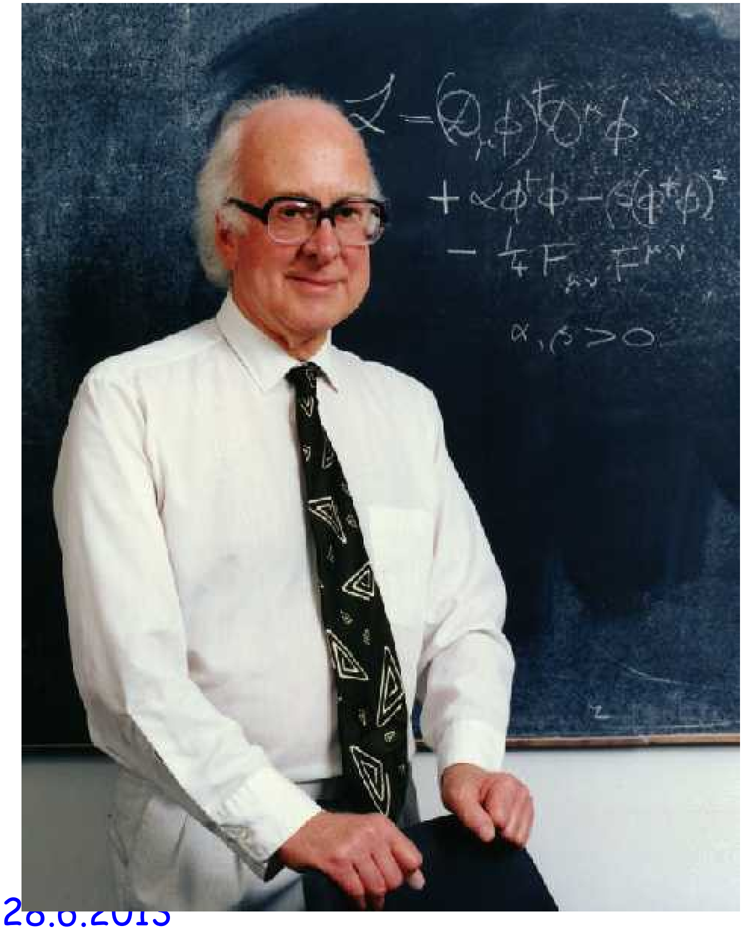
ECAL:
- $PbWO_4$ crystals read by APD and VPT
- testbeam resolution $\sigma(E)/E \approx 2.8\%/\sqrt{E} + 0.3\% + 0.12/E$

Details in Ref:
S. Chatrchyan et al., JINST 3 (2008) S08004

Higgs boson

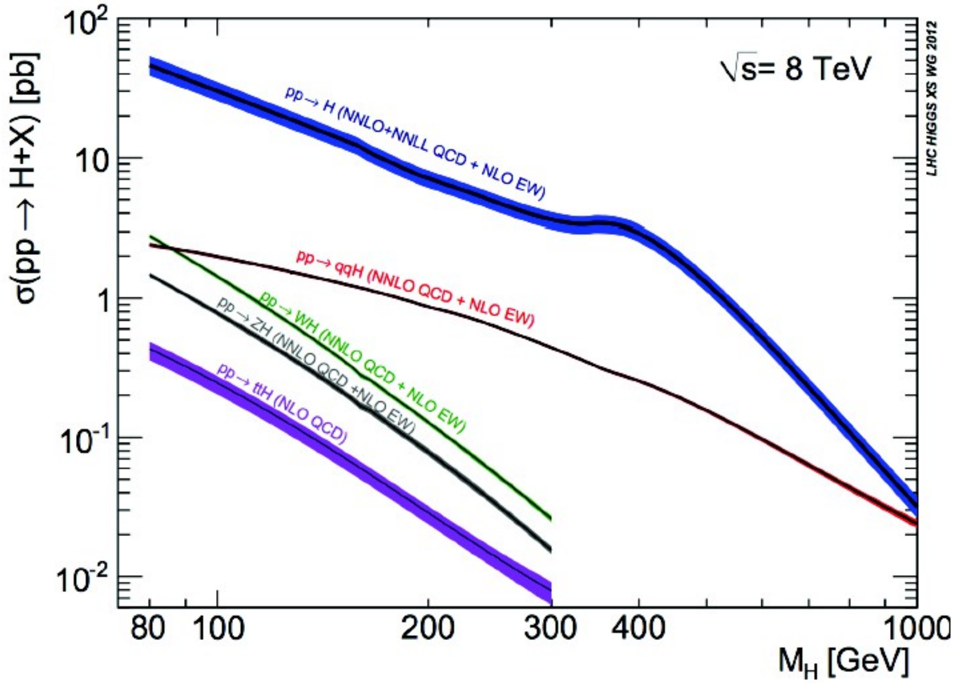
- Concept of the electroweak symmetry breaking in Standard Model via Higgs mechanism:
  - Introduce a doublet of complex scalar fields
  - Interaction terms gauge bosons-Higgs are turned into W, Z mass terms keeping photon massless.
  - Fermion masses are generated through Yukawa coupling terms also in dynamic way.
- Possible extensions beyond SM
  - 2 Higgs doublets model – three neutral and two charged Higgs bosons



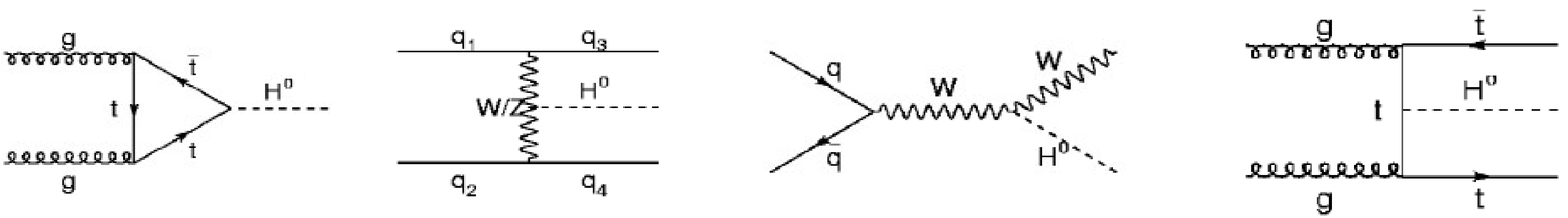


Standard Model Higgs boson production

- The main production modes are
  - gluon-gluon fusion (ggF)
  - vector boson fusion (VBF)
  - associated production (VH, ttH)
- Although the Higgs production is dominated by ggF, other production modes exhibit specific signatures used for triggering and kinematic configurations exploited in analyses.



associated production modes:



pp → H
gluon-gluon fusion

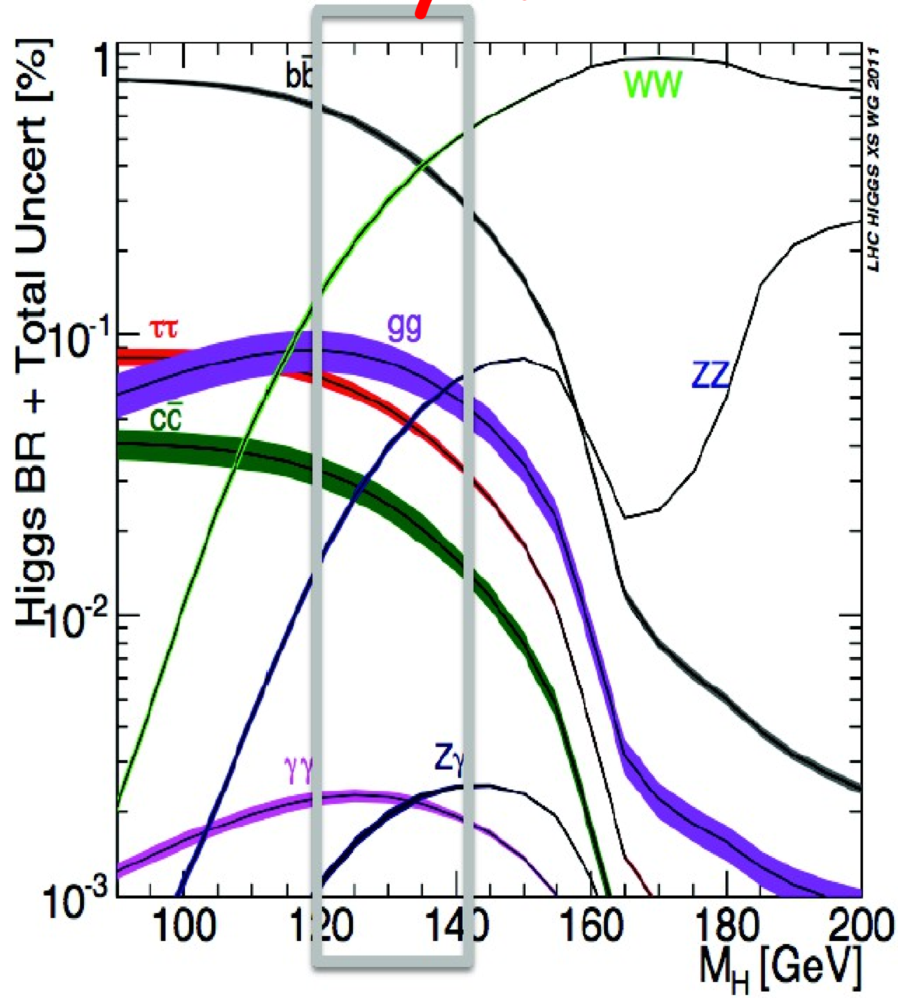
pp → qqH
vector boson fusion

pp → WH
(same diagram with Z)

pp → ttH

Standard Model Higgs boson decay modes

- Branching ratios are highly Higgs mass dependent
- Exploited in analyses:
  - H → γ+γ
  - H → Z+Z → 4l
  - H → W+W → 2l + 2ν
  - H → τ+τ
  - H → b+b in associated production modes (WH, ZH, ttH)
- Other channels are being explored too (e.g. H→WW→lνqq, H→ZZ→llνν, H→ZZ→llqq, H→Zγ, H→μμ, BSM modes, ….)

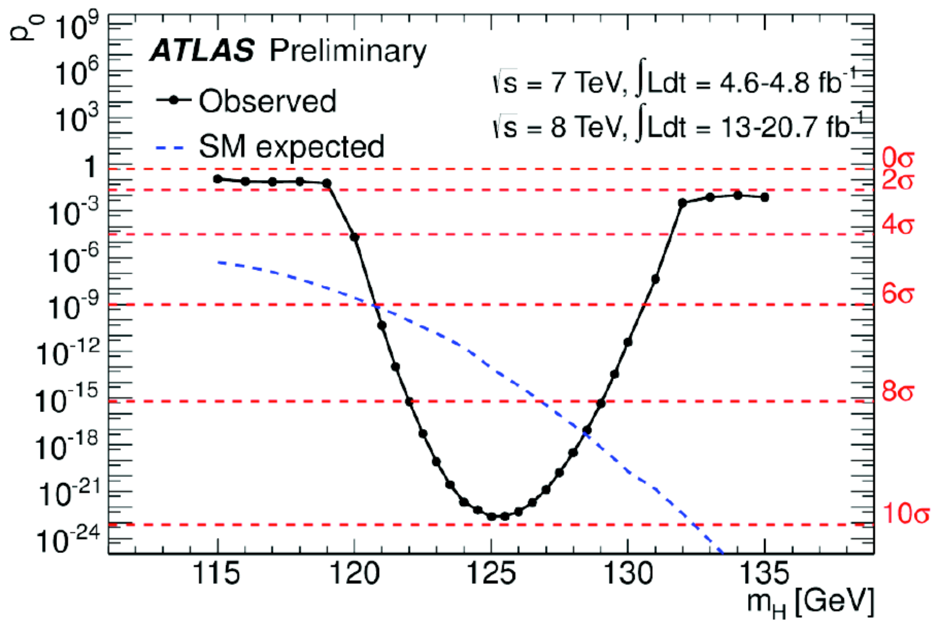


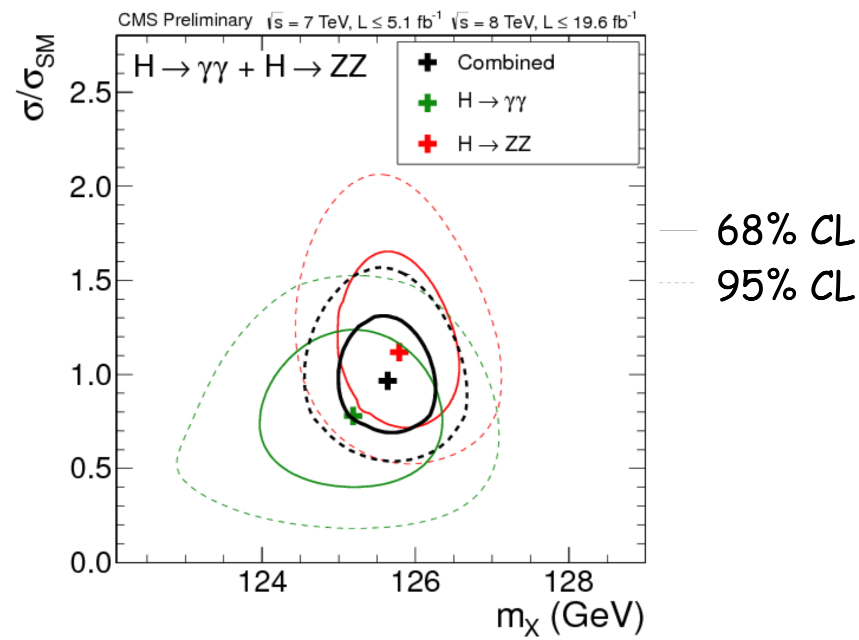
Selected BR @ M_H=125 GeV

Decay	BR [%]
H → bb	57.7
H → WW	21.5
H → ττ	6.3
H → ZZ	2.4
H → γγ	0.23

New boson

- New boson discovery reported in July 2012 by both experiments. Since then, more data have been collected and analyzed:

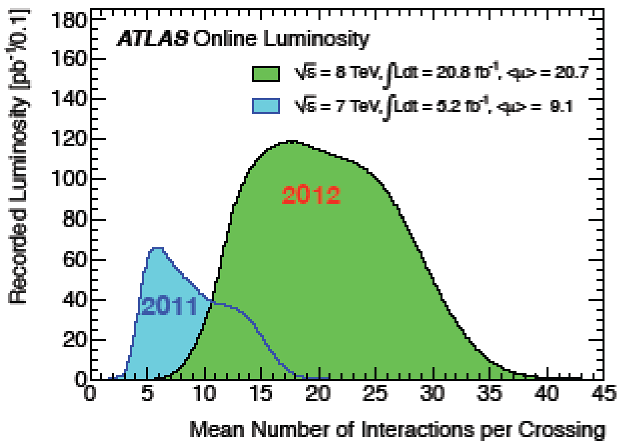


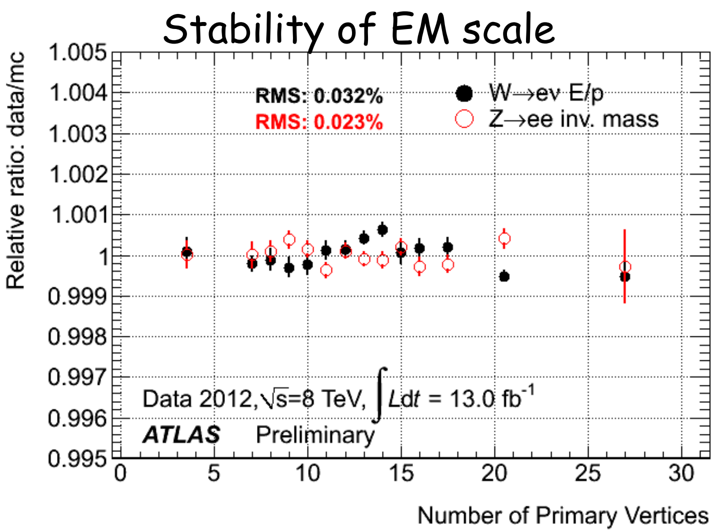


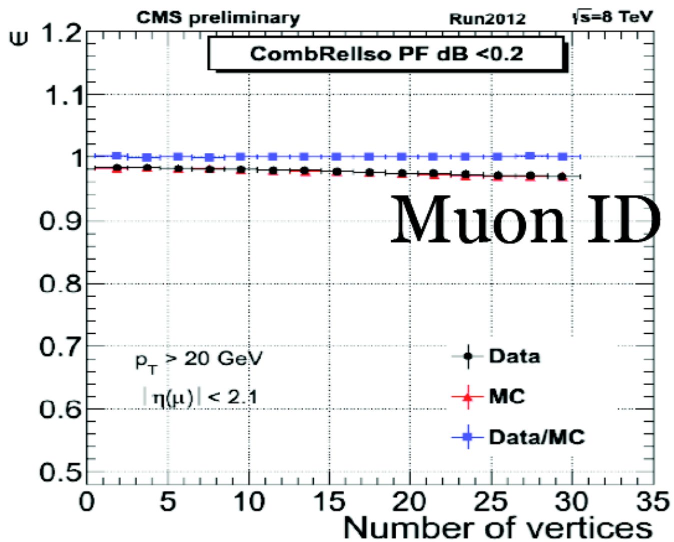
- No doubt about existence of a new particle, however there are still open questions:
  - is it the SM Higgs boson?
  - are there other Higgs(-like) bosons?
- Now entering new era: precision measurements of the particle properties and searches for other Higgs-like resonances

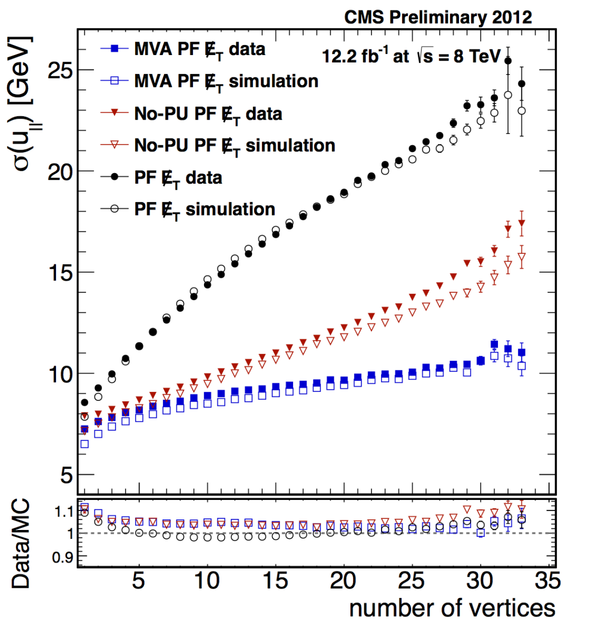
Prerequisitities (1)

- Pile-up:
  - pp interactions both in the same & neighbouring bunch-crossings affect the measurement.
  - Main impact on jet, tau and missing E_T reconstruction.
  - Trigger and analysis tools robust wrt pile-up conditions. Examples of stabilities wrt pile-up:



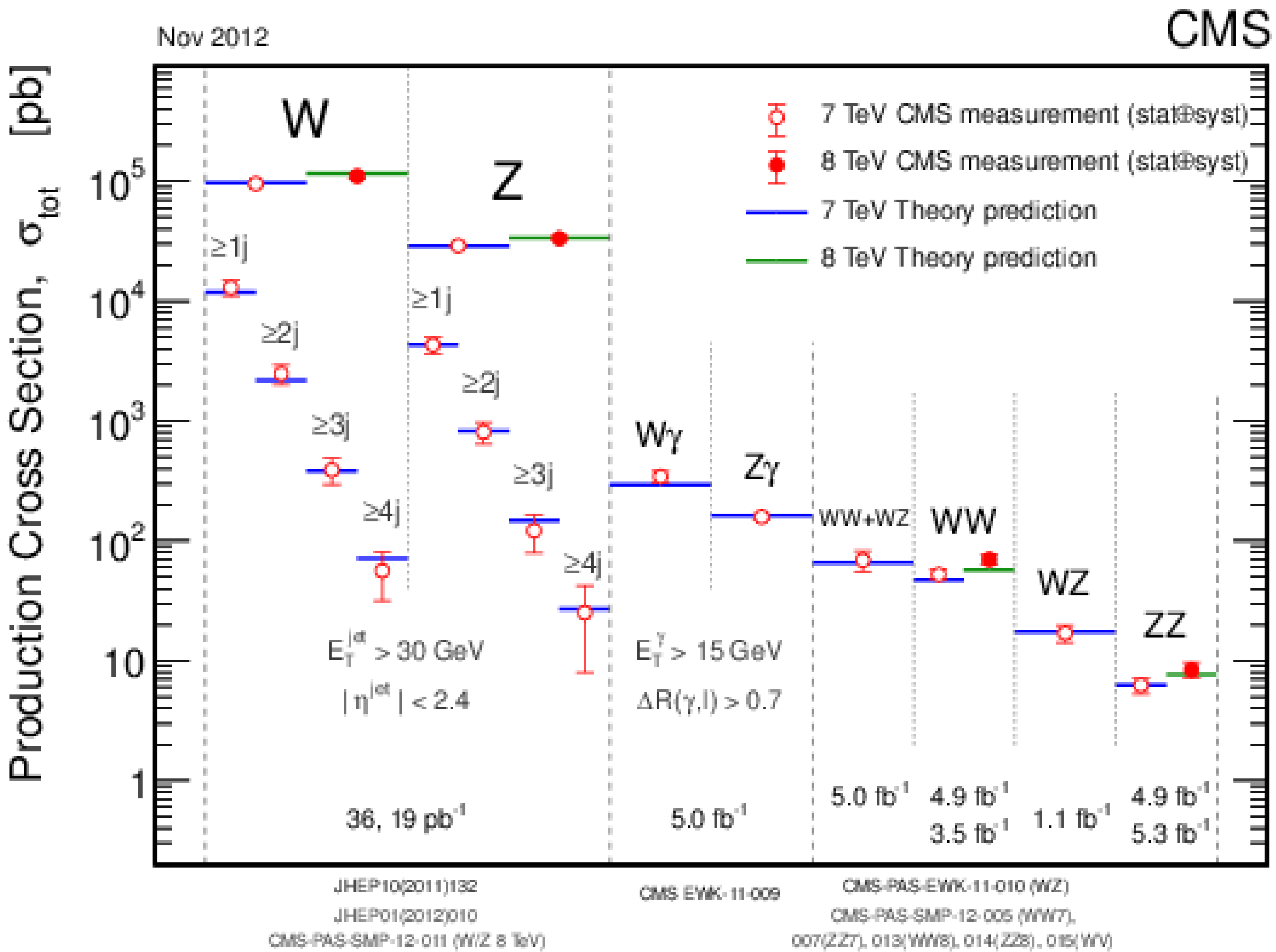






Prerequisities (2)

- The precision SM measurements are very important:
  - demonstrate the understanding of the detector
  - SM processes represent background to new discoveries

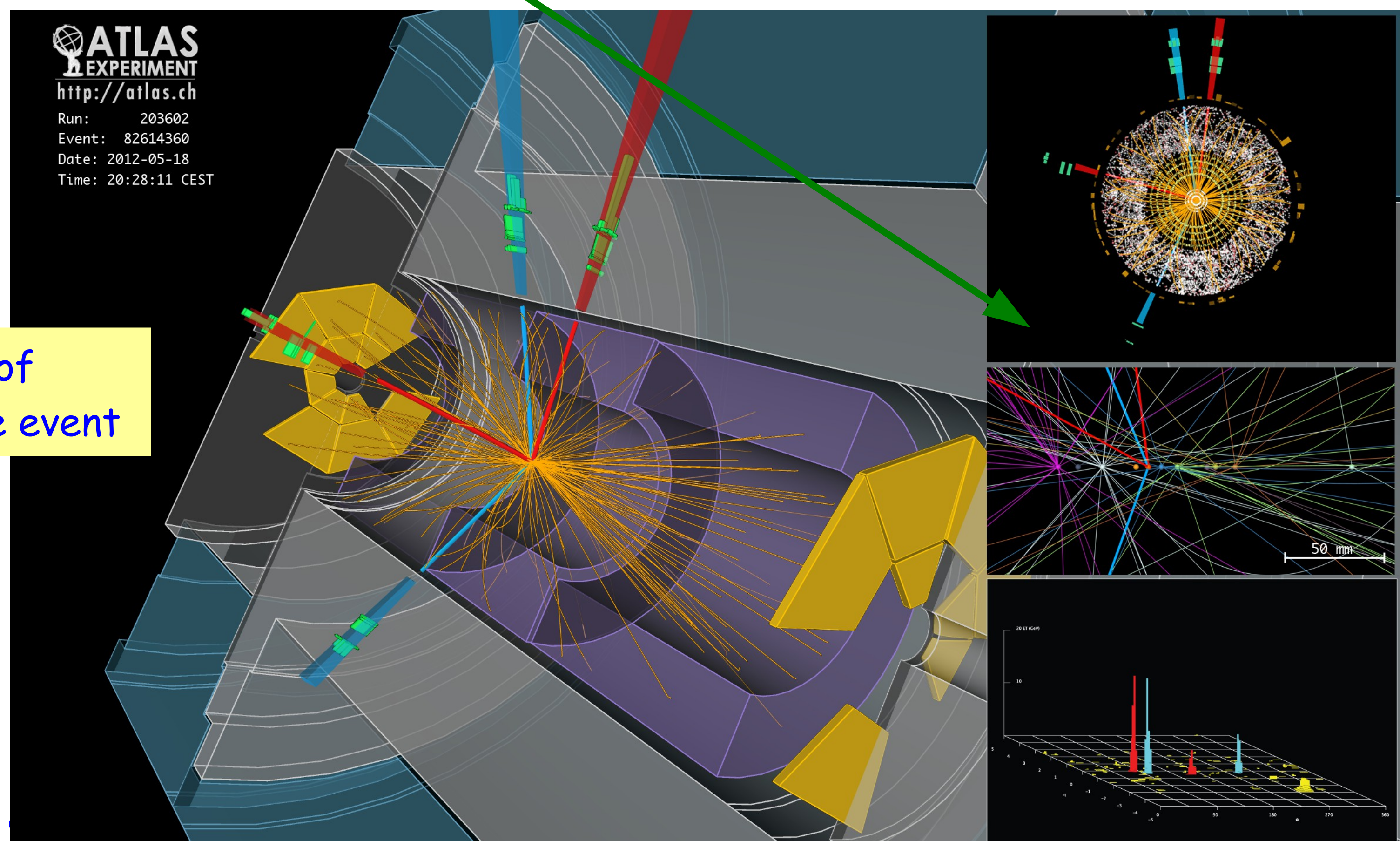


Higgs mass measurement

- Performed in two channels where full kinematical reconstruction is possible
  - $H \rightarrow Z+Z \rightarrow 4l$
  - $H \rightarrow \gamma+\gamma$

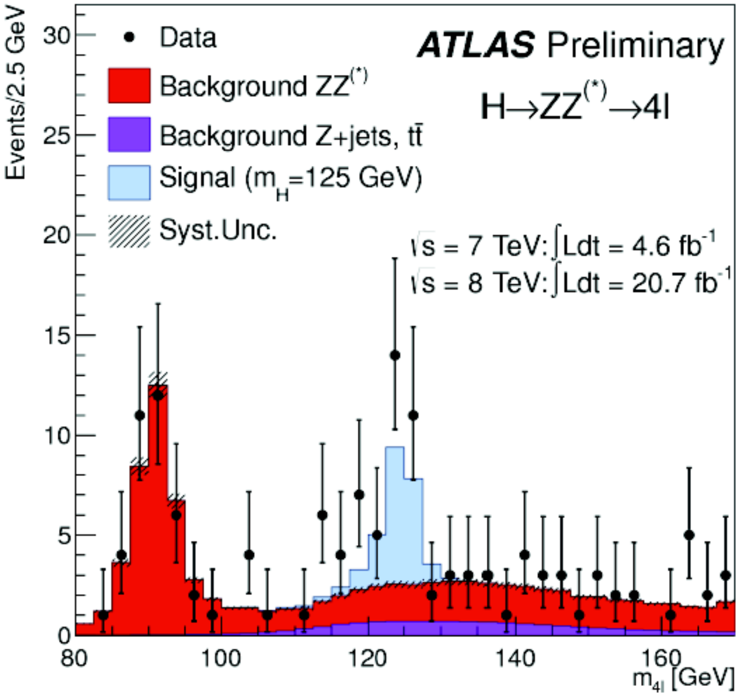
$H \rightarrow Z+Z \rightarrow 4l$ (1)

- Search for four isolated leptons (e, μ) coming from reconstructed primary vertex
- One pair of opposite-charge same-flavour leptons corresponds to m_Z
- Calibration performed with "standard candles"
  - $J/\psi \rightarrow e^+e^-/\mu^+\mu^-$
  - $\Upsilon \rightarrow e^+e^-/\mu^+\mu^-$
  - $Z \rightarrow e^+e^-/\mu^+\mu^-$

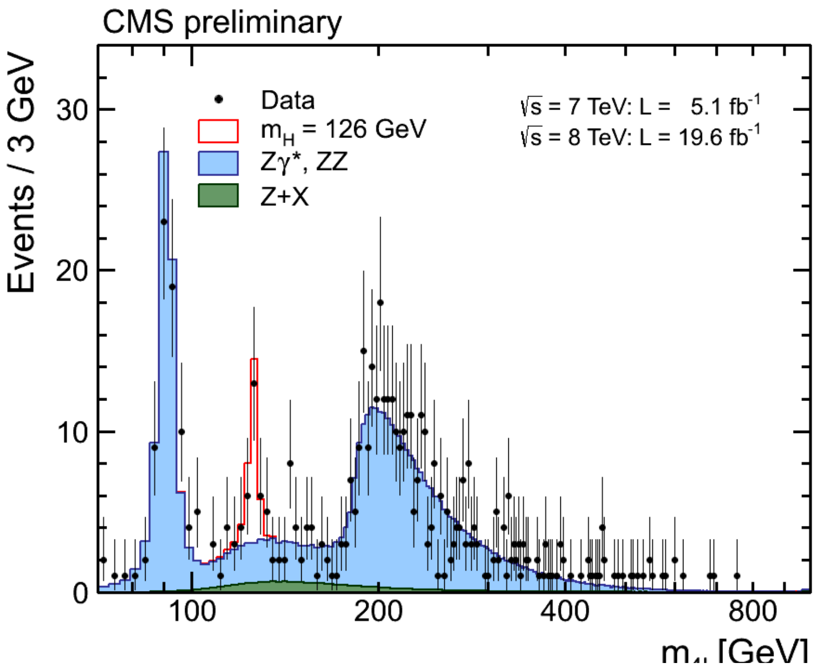


Example of
$H \rightarrow Z+Z \rightarrow 4e$ event

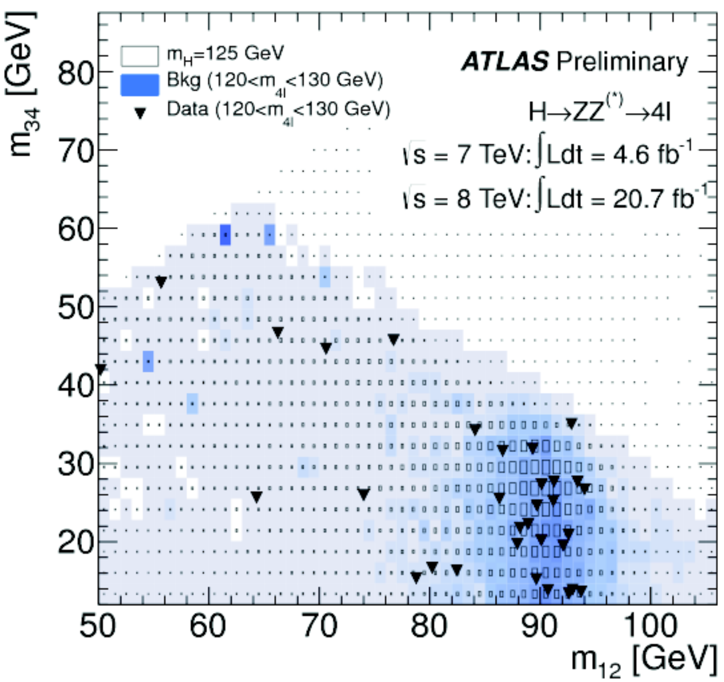
H → Z+Z → 4l (2)



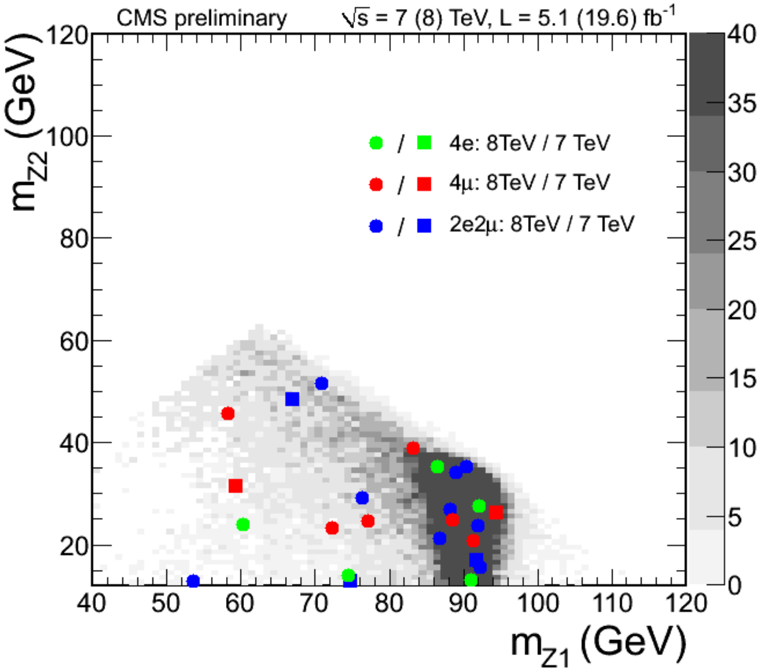
ATLAS Preliminary
H→ZZ(*)→4l
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
Events/2.5 GeV
m4l [GeV]



CMS preliminary
Data
mH = 126 GeV
Zγ*, ZZ
Z+X
√s = 7 TeV: L = 5.1 fb-1
√s = 8 TeV: L = 19.6 fb-1
Events / 3 GeV

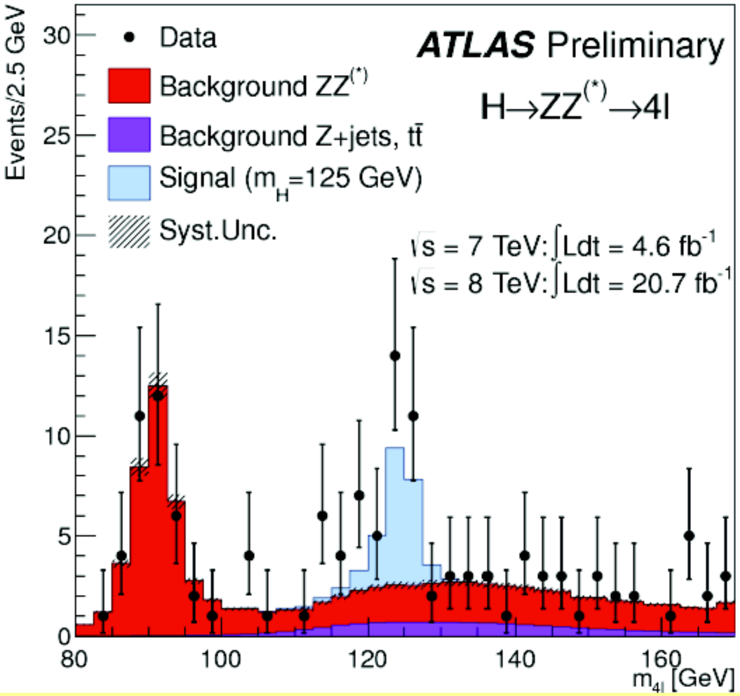


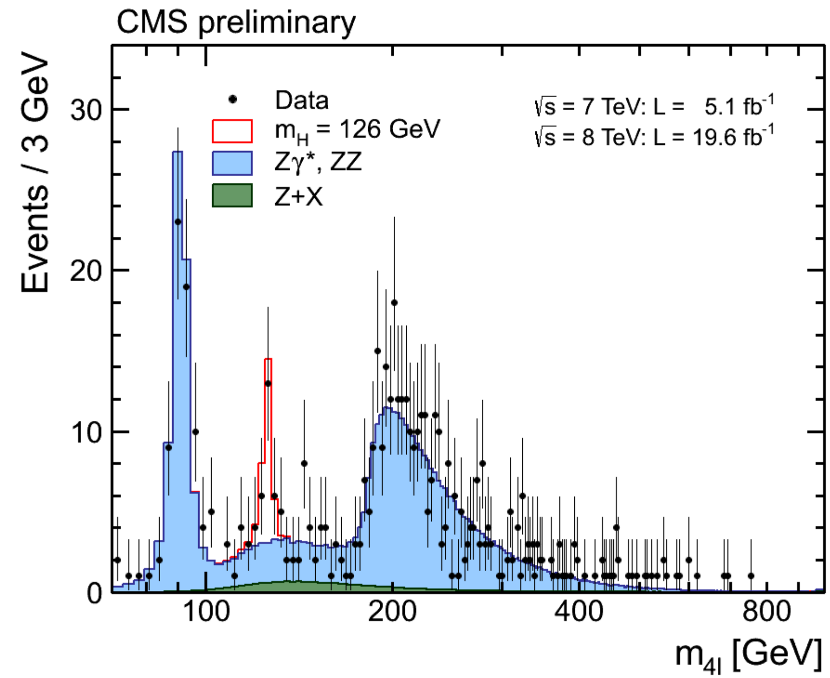
ATLAS Preliminary
H→ZZ(*)→4l
mH=125 GeV
Bkg (120<m4l<130 GeV)
Data (120<m4l<130 GeV)
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
m34 [GeV]
m12 [GeV]



CMS preliminary
√s = 7 (8) TeV, L = 5.1 (19.6) fb-1
4e: 8TeV / 7 TeV
4μ: 8TeV / 7 TeV
2e2μ: 8TeV / 7 TeV
mZ2 (GeV)
mZ1 (GeV)

$H \rightarrow Z+Z \rightarrow 4l$ (2)



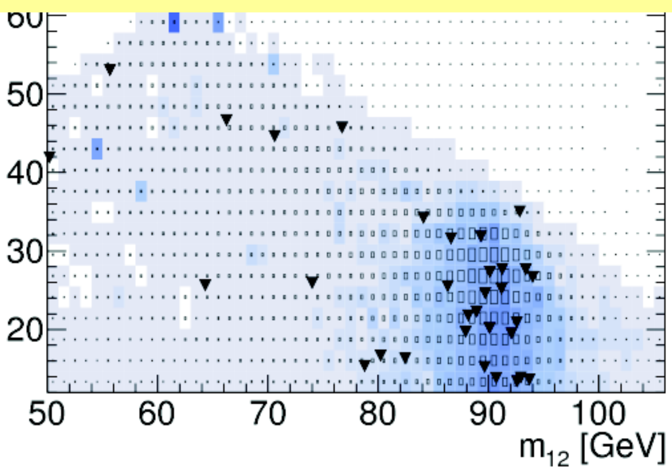


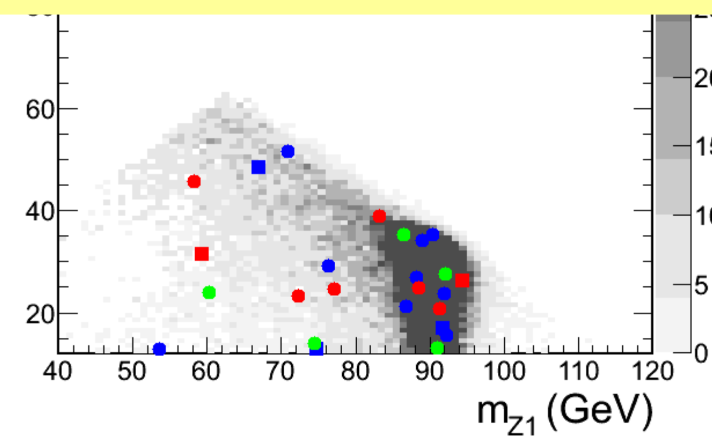
ATLAS:

- $m_H = 124.3^{+0.6}_{-0.5}$(stat) $^{+0.5}_{-0.3}$(syst) GeV
- signal strength $\mu = 1.7^{+0.5}_{-0.4}$

CMS:

- $m_H = 125.8 \pm 0.5$(stat)± 0.2(syst) GeV
- signal strength $\mu = 0.91^{+0.30}_{-0.24}$

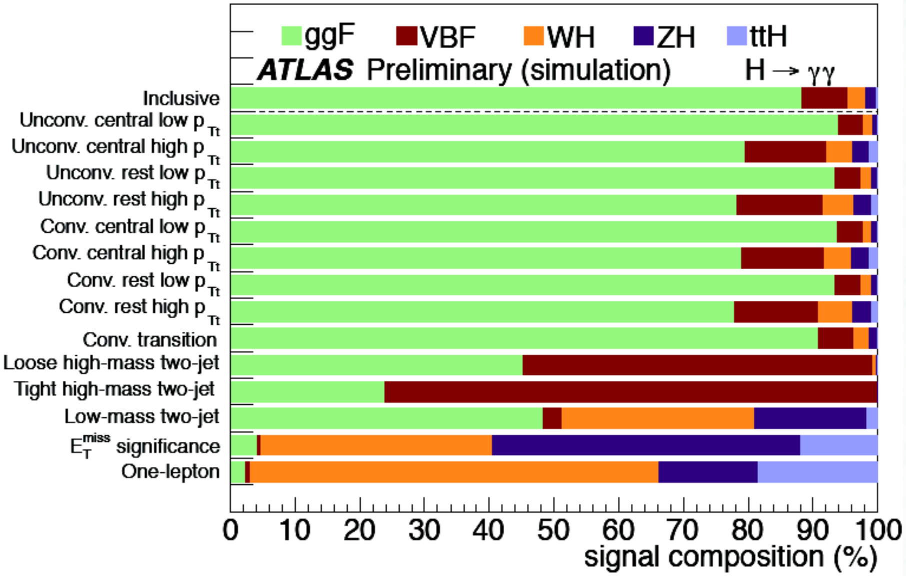




$H \to \gamma+\gamma$ (1)

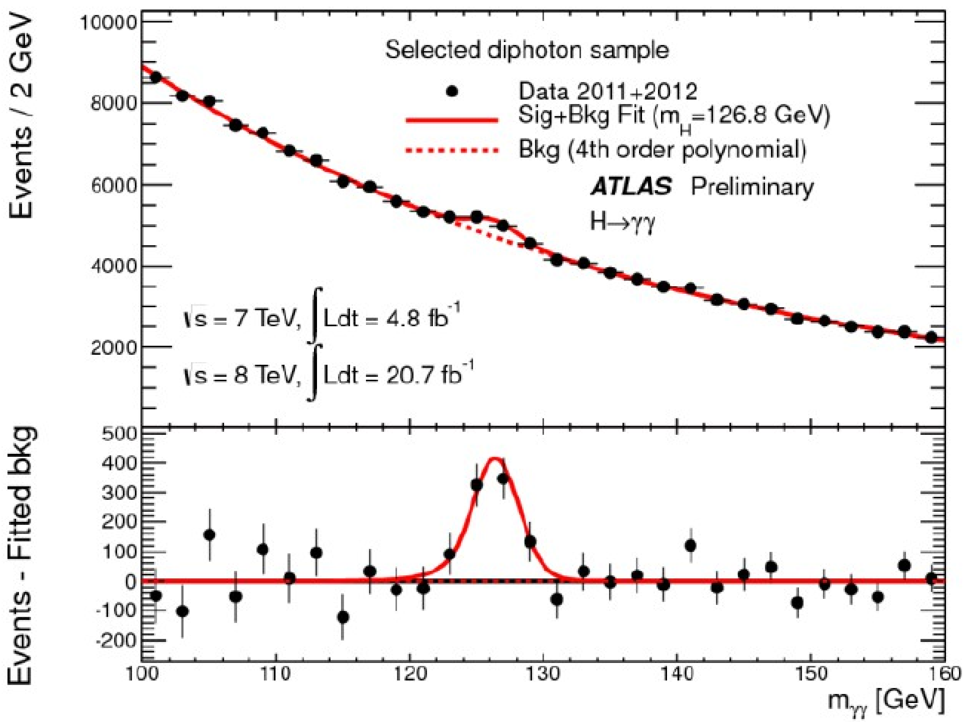
- Search for isolated high-p_T photons
- Reduce impact of pile-up and improve mass resolution by requiring photons pointing to reconstructed primary vertex
- Several categories based on event properties
  - different S/B ratio and mass resolution
  - different share of the production modes
- Critical items:
  - EM scale calibration, performed with $J/\psi \to e^+e^-$ and $Z \to e^+e^-$, extrapolation for photons via MC vs. testbeam data comparison
  - amount of material upstream of the EM calorimeter

ATLAS categories

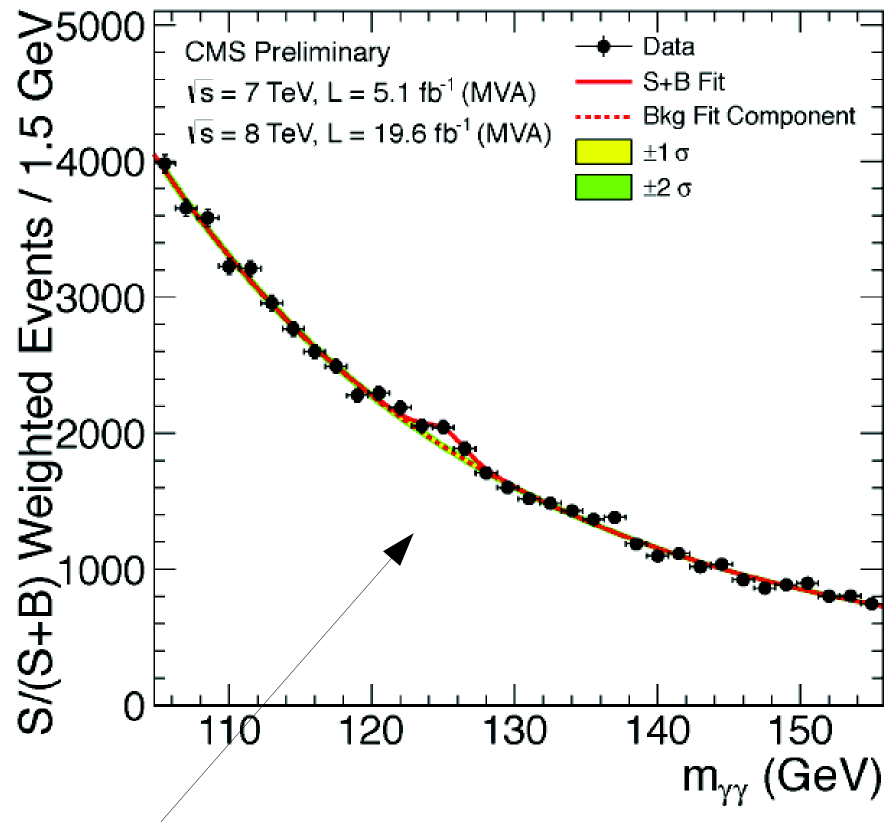


$H \rightarrow \gamma+\gamma$ (2)

- ATLAS
  - m_H = 126.8±0.2(stat)±0.7(syst) GeV
  - signal strength μ = 1.65±0.24±0.22



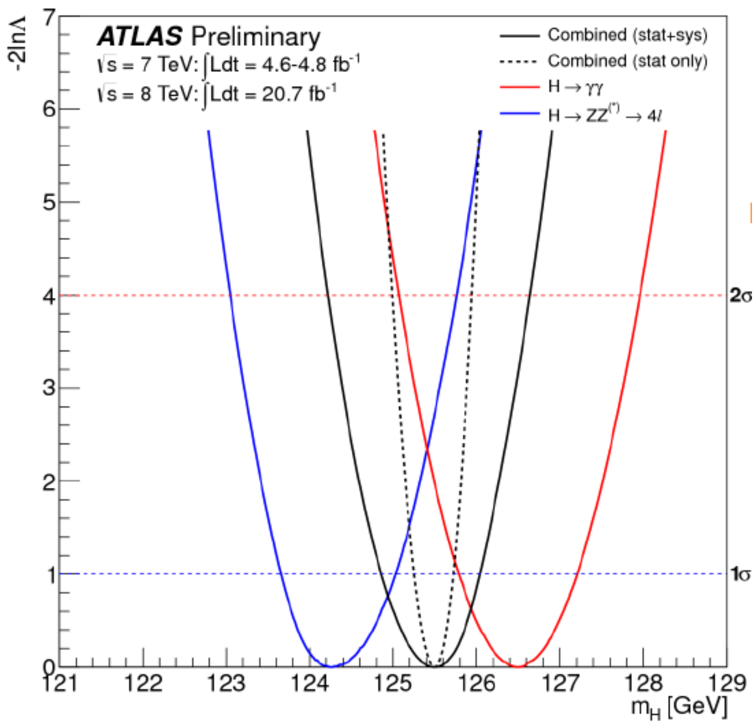
- CMS
  - m_H = 125.4±0.5(stat)±0.6(syst) GeV
  - signal strength μ = 0.78±0.27



  - MVA (primary) and cut-based (cross-check) analysis

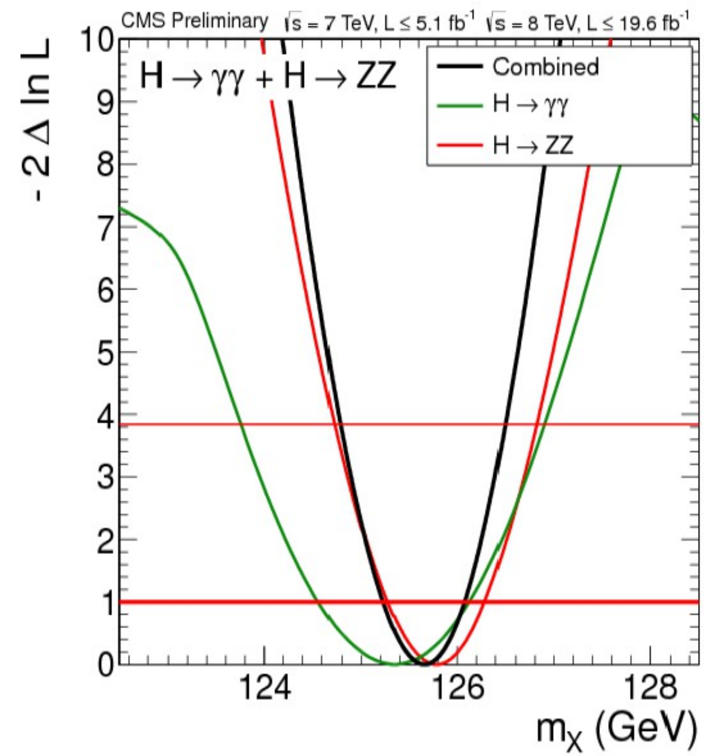
Higgs mass combination

- ATLAS combination



  - combined mass
    m_H = 125.5±0.2(stat)±0.6(syst) GeV
  - mass difference (H → γ+γ vs. H→ Z+Z) compatibility 1.5% (2.4σ), increases to 8% with more conservative systematics treatment

- CMS combination



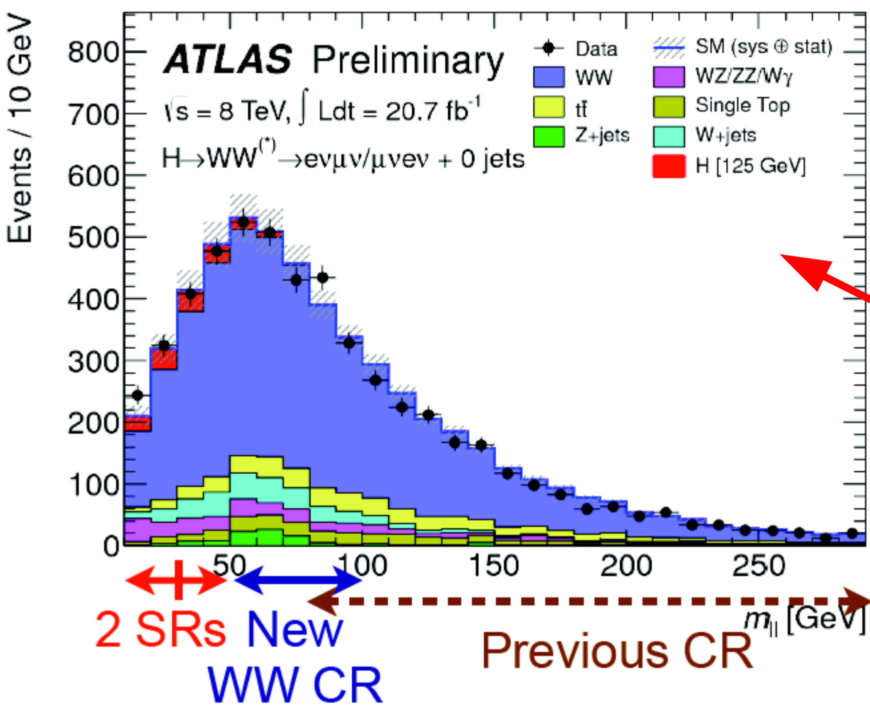
  - combined mass
    m_H = 125.7±0.3(stat)±0.3(syst) GeV, quite good match between both decay modes

H → W+W → 2l+2ν (1)

- Channel with very high σ•BR, nevertheless full reconstruction not possible, use transverse mass m_T or lepton invariant mass m_{ll} instead
- require two high-p_T leptons, missing E_T, topological cuts
- different categories (jet multiplicity 0,1,2; lepton flavours)

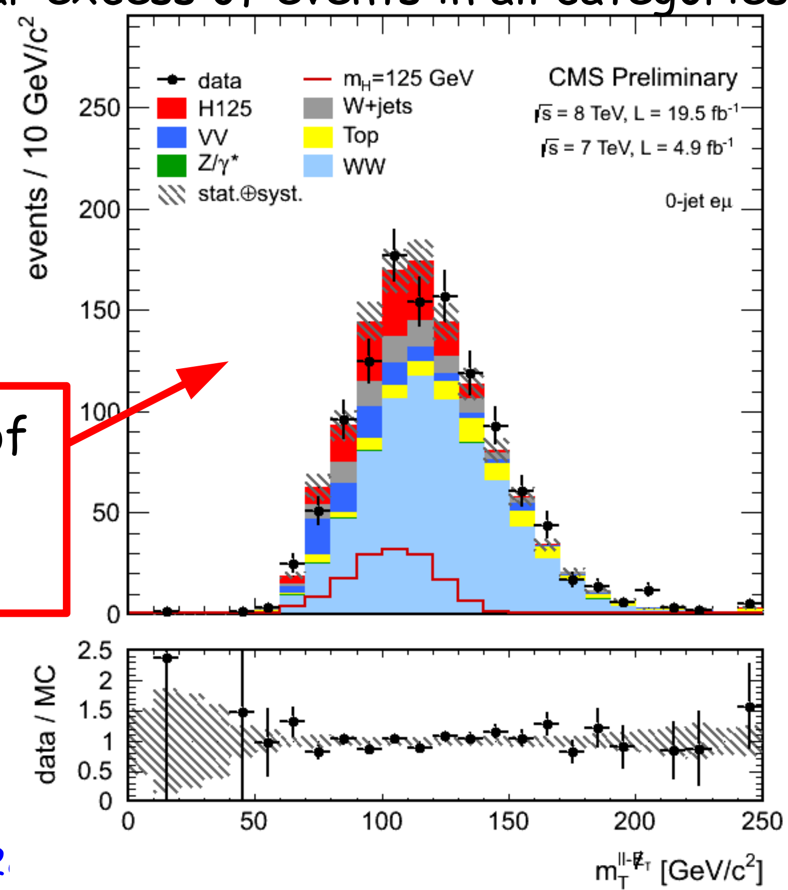
ATLAS

- optimized control region for WW background, reduced syst to 2%



CMS

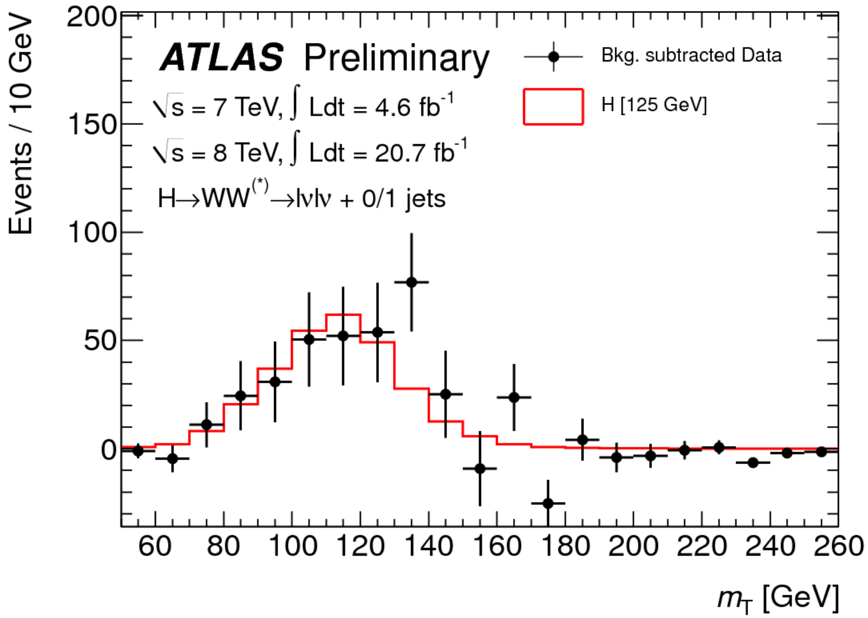
- clear excess of events in all categories



examples of eμ+0 jet category

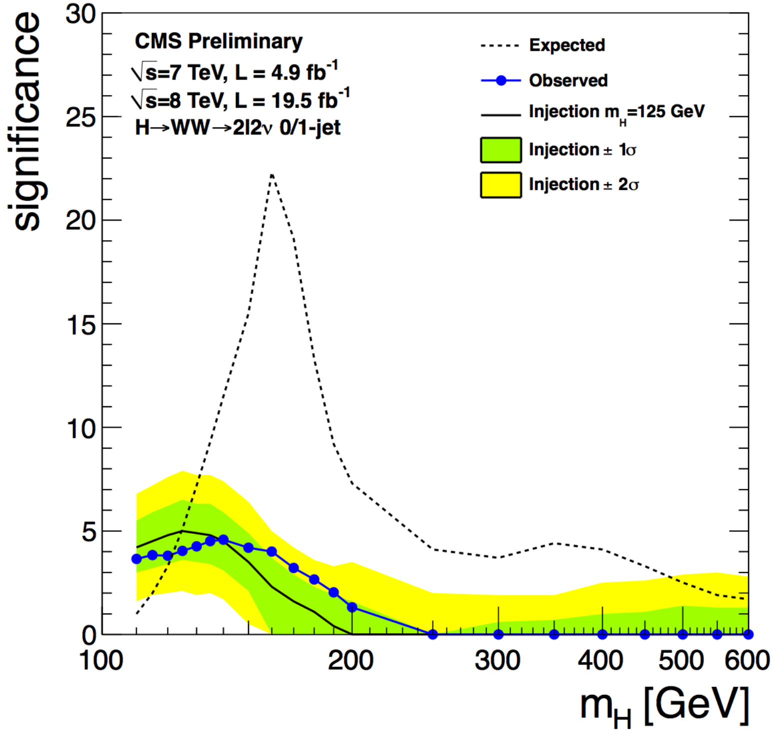
$H \rightarrow W{+}W \rightarrow 2l{+}2\nu$ (2)

- ATLAS
  - final discrimination from transverse mass m_T shape



  - signal strength $\mu = 1.01 \pm 0.31$
  - observed significance 3.8σ, expected 3.7σ

- CMS
  - excess at low mass compatible with the expected Higgs signal

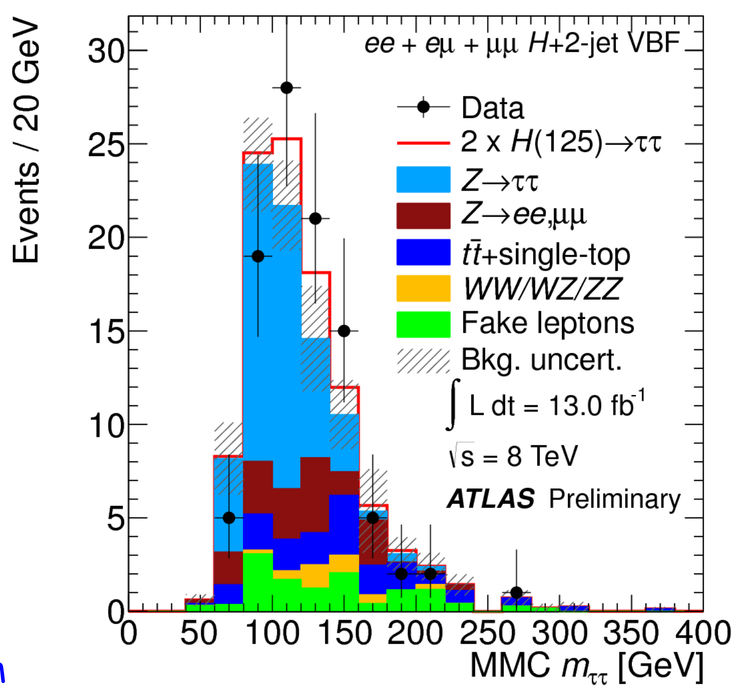


  - signal strength $\mu = 0.76 \pm 0.21$
  - observed significance 3.9σ, expected 5.3σ

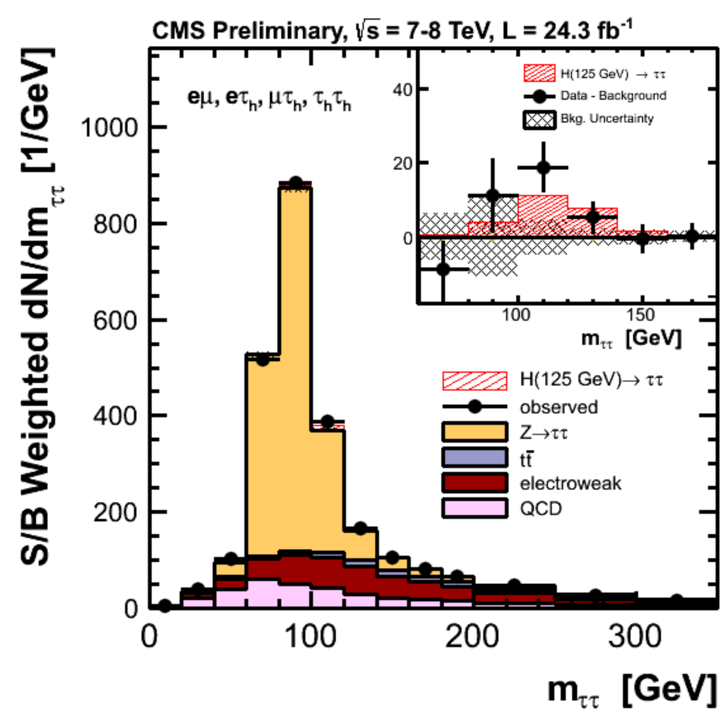
H → τ+τ (1)

- Search for isolated leptons, τ_{had}, and missing E_T. Final states include $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ combinations with different #jet categories
- Main irreducible background from Z → τ+τ
- Final discriminant $m_{\tau\tau}$ obtained with missing mass constraint

- ATLAS: not full statistics yet
  - highest sensitivities for VBF and boosted ggF

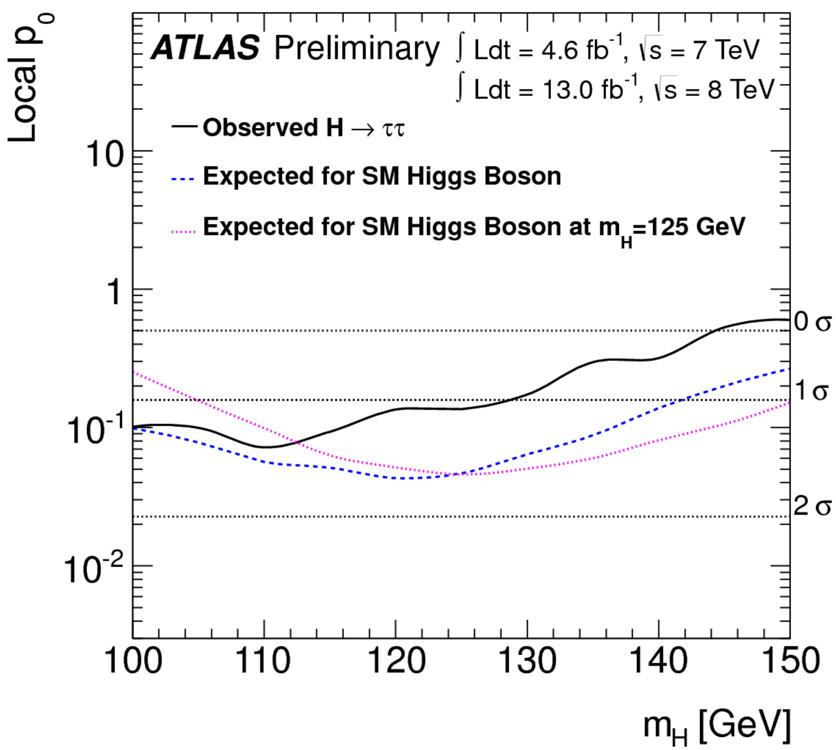


- CMS: already with full statistics 2011+2012

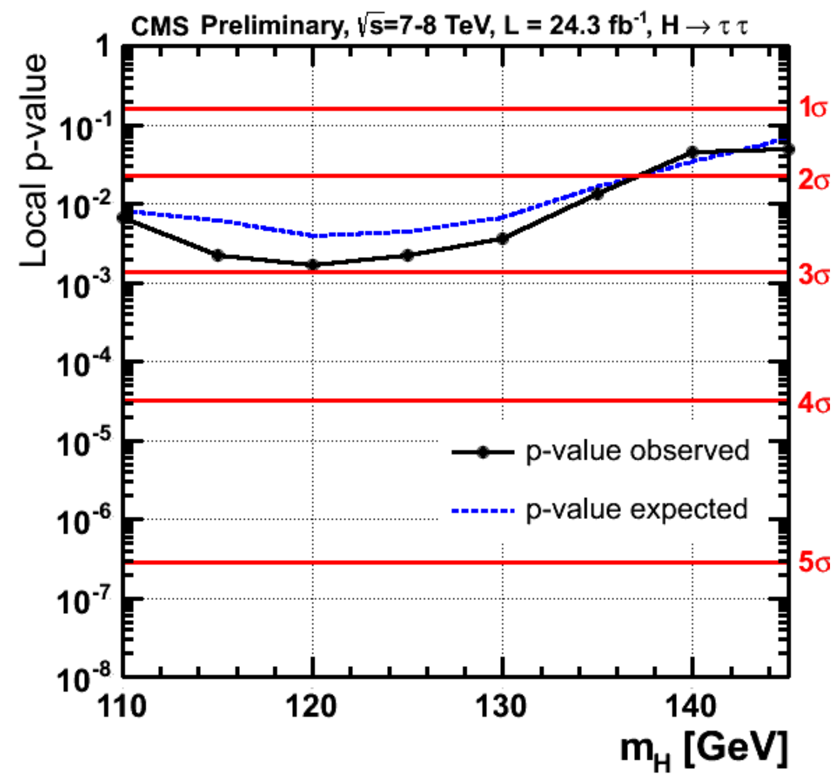


$H \to \tau+\tau$ (2)

- ATLAS
  - observed deviation from background-only hypothesis for m_H=125 GeV corresponds to local significance of 1.1σ, expected 1.7σ

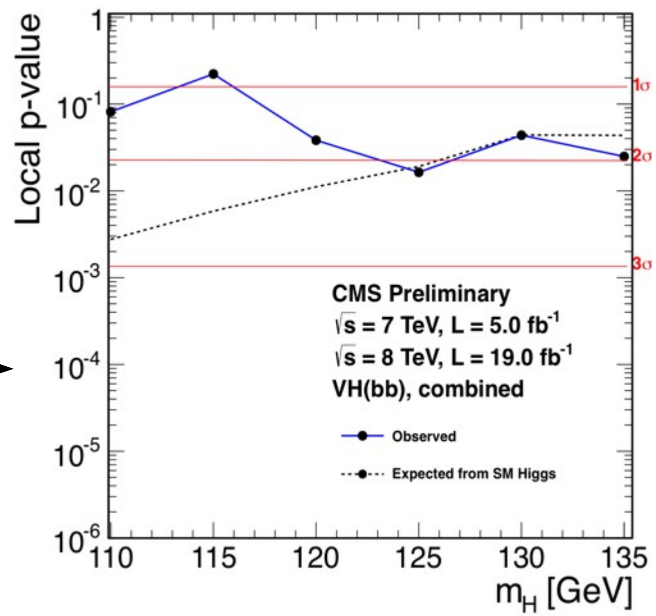


- CMS
  - broad event excess at low mass compatible with expected Higgs signal
  - signal strength μ = 1.1±0.4 (m_H=125 GeV)
  - observed significance 2.8σ, expected 2.6σ (m_H=125 GeV)



$H \rightarrow b+bbar$

- Important channel: decay to fermions (Yukawa coupling), highest BR for m_H < 135 GeV
- Large background and complex final states make the signal extraction very difficult
- The best sensitivity so far in associated production (WH, ZH), see CMS result →

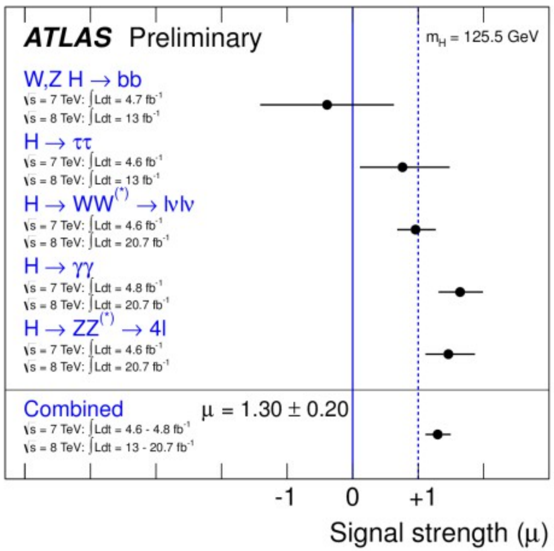


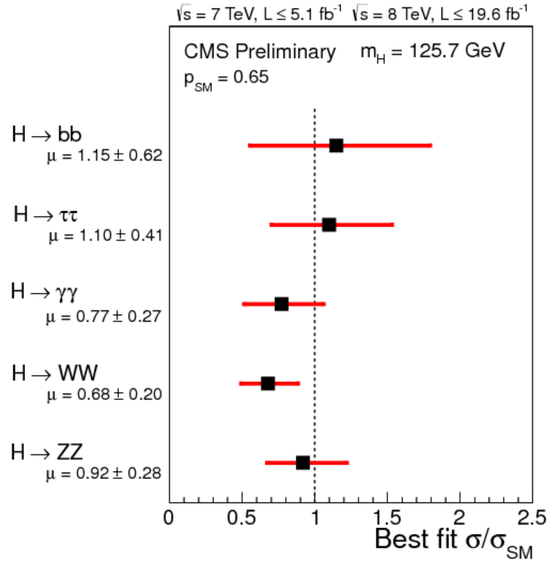
- Summary (analyses in blue not yet with full statistics)

	ATLAS		CMS	
Production mode	significance, signal strength	95% CL limit on σ/σ_{SM} obs. (exp)	significance, signal strength	95% CL limit on σ/σ_{SM} obs. (exp)
WH, ZH	-	1.8 (1.9)	2.1σ (2.1σ) μ = 1.0±0.5	-
VBF	-	-	μ = 0.7±1.4	3.6 (3.0)
ttH	-	13.1 (10.5)		5.8 (5.2)

Summary on Higgs searches

- Signal strength relative to that expected from SM:





Decay Mode	ATLAS (M_H = 125.5 GeV)	CMS (M_H = 125.7 GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	**1.30 ± 0.20**	**0.80 ± 0.14**

- Signal sensitivity:

	Significance observed (expected)	
Decay Mode	ATLAS (m_H=125.5 GeV)	CMS (m_H=125.7 GeV)
H → γ+γ	7.4σ (4.1σ)	3.2σ (3.9σ)
H → ZZ → 4l	6.6σ (4.4σ)	6.7σ (7.1σ)
H → WW	3.8σ (3.7σ)	3.9σ (5.3σ)
H → τ+τ	1.1σ (1.7σ)	2.8σ (2.6σ)
H → b+bbar	-	2.0σ (2.2σ)

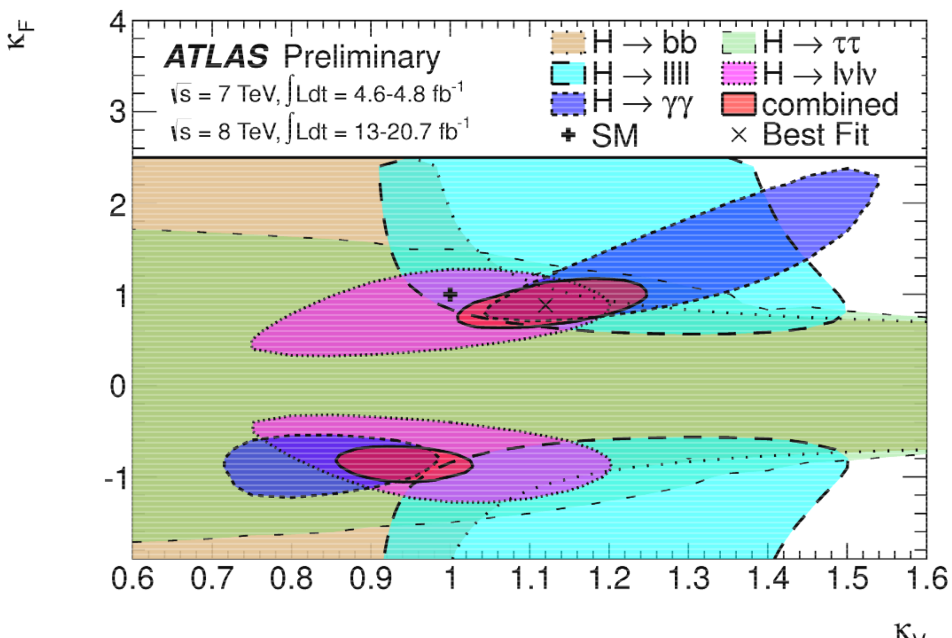
Couplings (1)

- Event yield in the given channel assumed $[\sigma \bullet BR](ii \rightarrow H \rightarrow ff) = \sigma_{ii}\Gamma_{ff}/\Gamma_{tot}$. Define scale factors κ: $\sigma_{ii} = \kappa_i^2\sigma_{ii}^{SM}$, $\Gamma_{ff} = \kappa_i^2\Gamma_{ff}^{SM}$
- Tests performed:
  - evidence for VBF process
    - 3.1σ in ATLAS
  - custodial symmetry ($\lambda_{WZ} = \kappa_W/\kappa_Z$)
    - $\lambda_{WZ} = 0.80 \pm 0.15$ (ATLAS), λ_{WZ} in [0.73,1.00] at 68% CL (CMS)
  - probing for BSM contributions (new undetected particles in final state and/or in loops)
    - BR < 0.6 at 95% CL (ATLAS), BR < 0.52 at 95% CL (CMS)

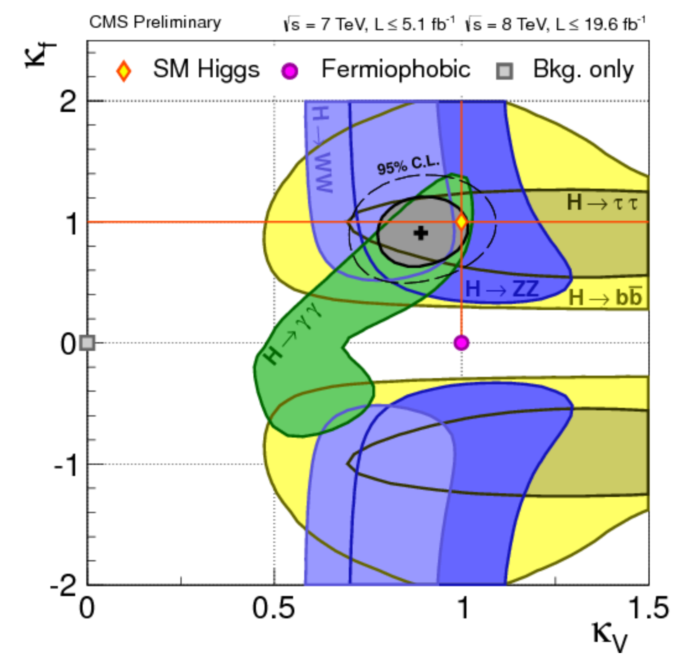
Couplings (2)

- fermion vs vector boson couplings (assuming $\kappa_V=\kappa_Z=\kappa_W$, $\kappa_F=\kappa_b=\kappa_\tau$.....)

ATLAS



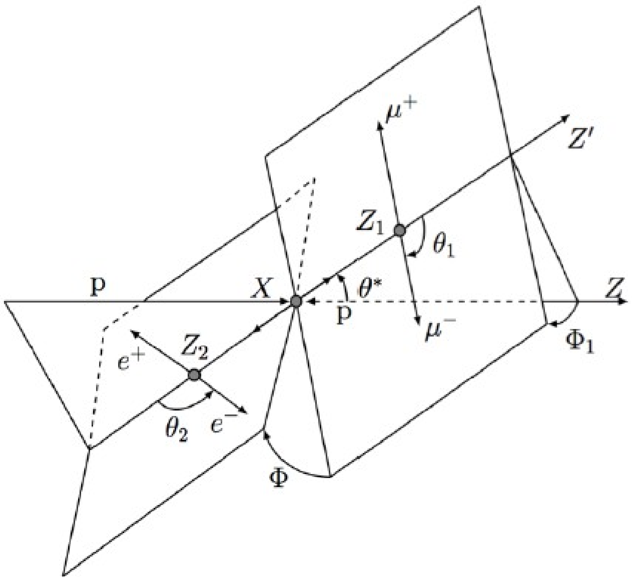
CMS



– $\kappa_F/\kappa_V = 0.85^{+0.23}_{-0.13}$, important as indirect evidence of the Higgs-to-fermion coupling

Spin and parity measurement (1)

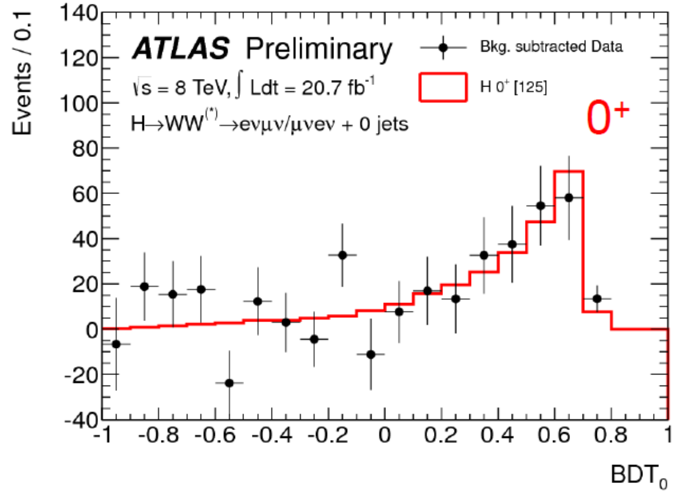
- The decay H → γ+γ excludes spin 1 (Landau-Yang theorem). For spin 2 hypothesis, minimal graviton-inspired model was considered.
- Various J^P hypotheses tested in the following channels:
  - H → γ+γ: use of production angle Θ* in the Collins-Soper frame
  - H → Z+Z → 4l: use of m_{12}, m_{34} and five production & decay angles

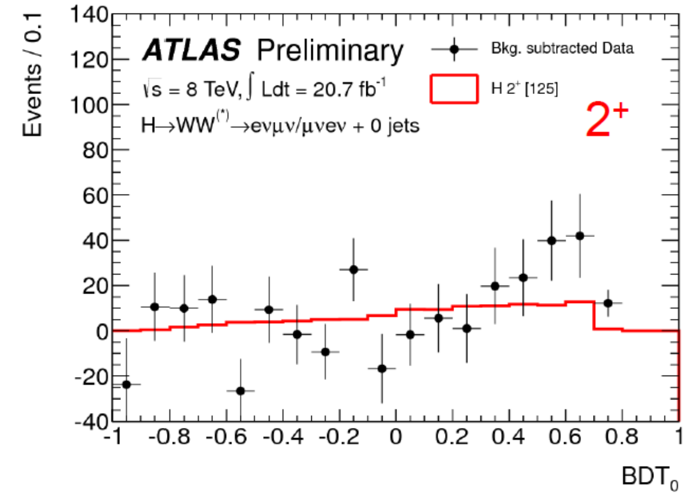


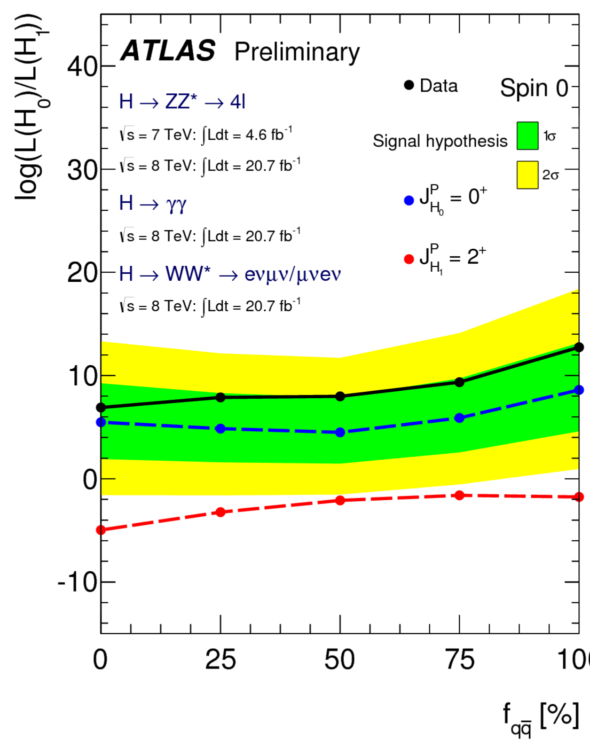
  - H → W+W → 2l+2ν: direct reconstruction not possible, use several kinematic distribution (e.g. m_{ll}, p_T^{ll}, $\Delta\varphi_{ll}$, m_T)

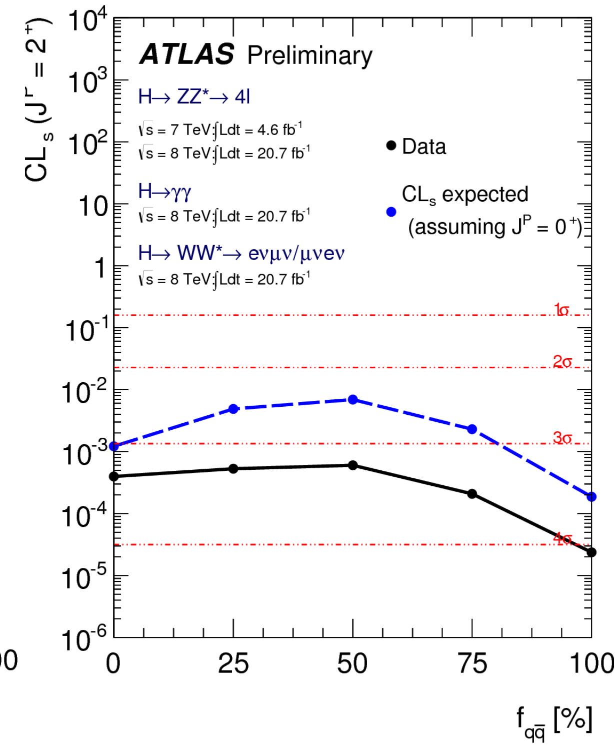
Spin and parity measurement (2)

- ATLAS
  - H→WW→eνμν: $J^P=0^+$ favoured
  - H→ZZ→4l: excludes $J^P=0^-$, 1^+, 1^- at >95%, >95% and 94% CL respectively
  - combining all three channels: $J^P=2^+_m$ is excluded at 99.9% CL over the full range of f_{qq} (fraction of spin-2 production mechanism via q+qbar)



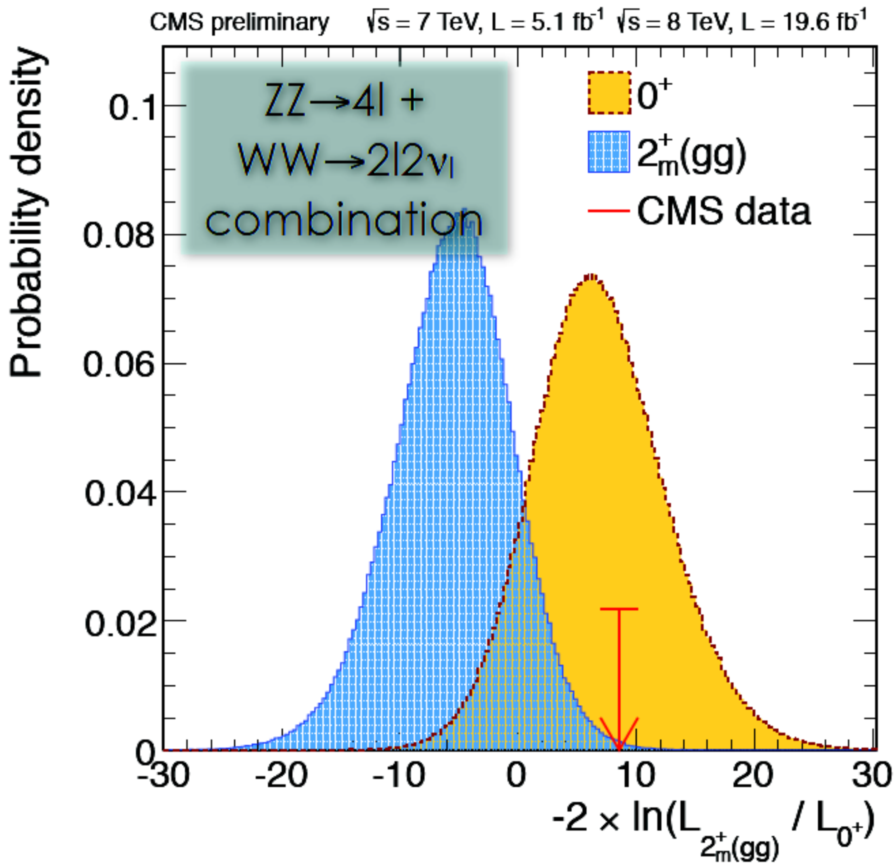






Spin and parity measurement (3)

- CMS:
  - tests in H→ZZ→4l channel disfavour $J^P=0^-$ wrt $J^P=0^+$ with 99.84% CL
  - combination of H→WW→2l2ν and H→ZZ→4l channels disfavours $J^P=2^+_m$ with 99.4% CL



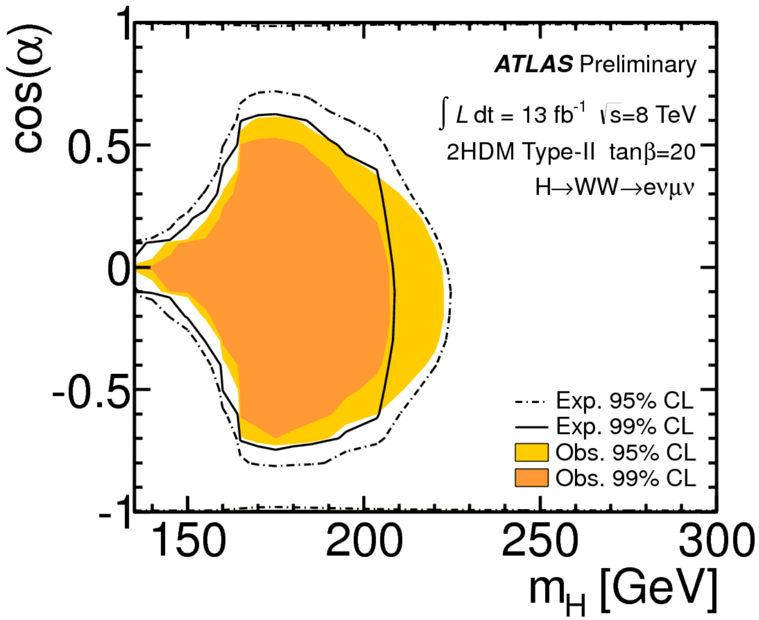
2^+_m(gg) corresponds to f_{qq}=0% (gluon-gluon fusion only)

Beyond SM searches

- Searches for other Higgs boson(s) in BSM scenarii include 2HDM, MSSM, additional singlet… Examples of searches:

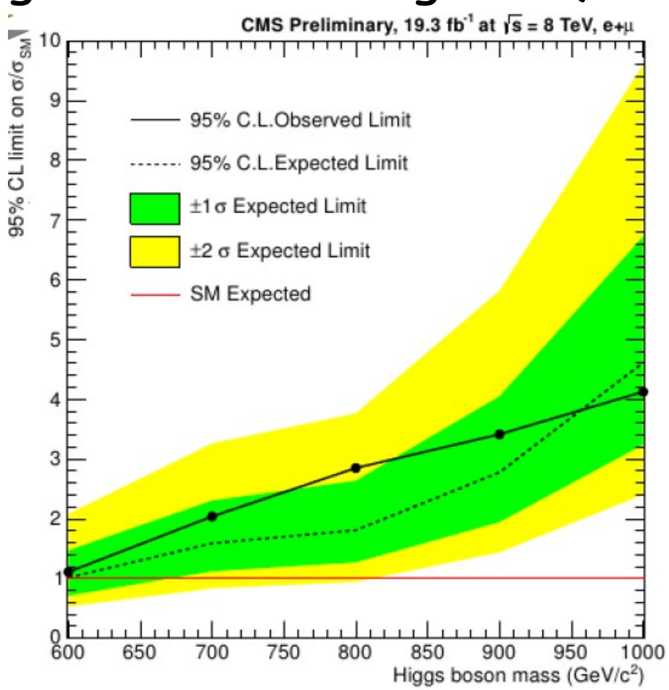
ATLAS

- heavier H→WW → eνμν, h assumed at 125 GeV (2HDM)



CMS

- heavy (m_H > 600 GeV) H→WW→lνjj (require lepton, missing E_T, "fat" jet), singlet model mixing to X(125)



- Ultimately the VV scattering will tell us if the object at 125 GeV is capable alone to restore the unitarity.

Conclusions

- Existence of the new particle with mass of 125 GeV well established.
- Observed decay modes and other properties suggest a Higgs boson, however still a lot of work ahead:
  - Need to improve the signal strength measurements (current results by ATLAS and CMS a bit different, however still compatible within errors)
  - Spin and parity strongly favour $J^P=0^+$
  - Couplings to individual particles still with large uncertainties, but evidence for non-zero fermion coupling
  - No clear discrepancy wrt SM predictions observed so far
  - Aim to measure the Higgs self-coupling at next LHC runs
- Analyses of 2012 data still ongoing, also looking forward for new data in 2015.

Backup slides

References

- For more detailed information, please visit the ATLAS and CMS public physics results, especially:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- Most of the presented results come from the following sources:

ATLAS

- ATLAS-CONF-2013-012
- ATLAS-CONF-2013-013
- ATLAS-CONF-2013-014
- ATLAS-CONF-2013-027
- ATLAS-CONF-2013-030
- ATLAS-CONF-2013-034
- ATLAS-CONF-2013-040

CMS

- CMS-PAS-HIG-13-005
- CMS-PAS-HIG-13-004
- CMS-PAS-HIG-13-003
- CMS-PAS-HIG-13-002
- CMS-PAS-HIG-13-001
- CMS-PAS-HIG-13-012
- CMS-PAS-HIG-13-011