Overview of Higgs boson searches at LHC

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CEA-Saclay, IRFU/SPP

On behalf of ATLAS and CMS collaborations

Almost a year ago …

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Back in time (48 years ago…) some dates

- **1964** Brout & Englert, Higgs, Gouralnik, Hagen & Kibble
- **1968** "Higgs" mechanism used in the Standard Model formulation
- 1983 Discovery of W, Z
- **2000** LEP: limits m_H>114.4 GeV
- **2011** LHC: 130<mH<550 GeV, Tevatron: 156<mH<175 GeV, some indications of m_H~125 GeV?
- **2012** LHC: Discovery of a new particle

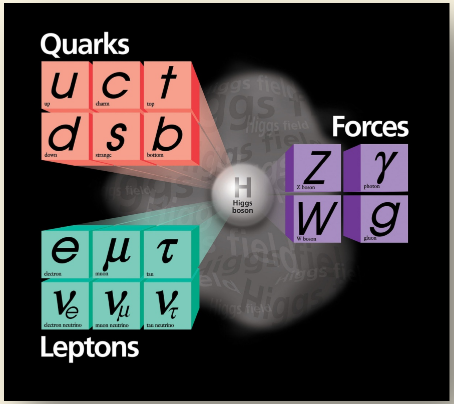
Introduction / Outline

Fundamental questions after this discovery

Is it really the Higgs boson ?

Is it of the Standard Model ?

What are its properties ?



Standard Model:
includes all elementary particles and their interactions
Predicts the unification of EM and weak interactions
Experimentally tested at ‰
Predicts the existence of a new particle: "Higgs" boson

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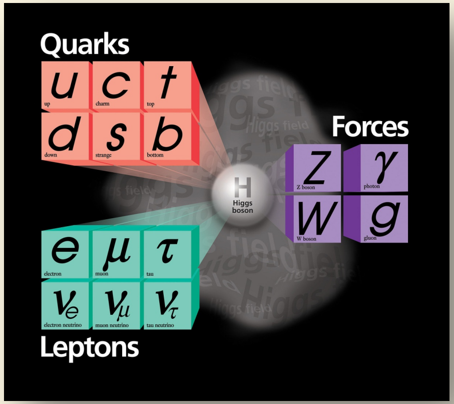

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In this talk an overview of searches at LHC to answer these questions will be presented

- Certainly not an exhaustive list!

List of ATLAS Higgs results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

List of CMS Higgs results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

LHC run I phase

Run I: 2010-2012
In less than 3 years we moved rapidly from "exclusion limits" to the **discovery** of a new boson and the measurements of its properties

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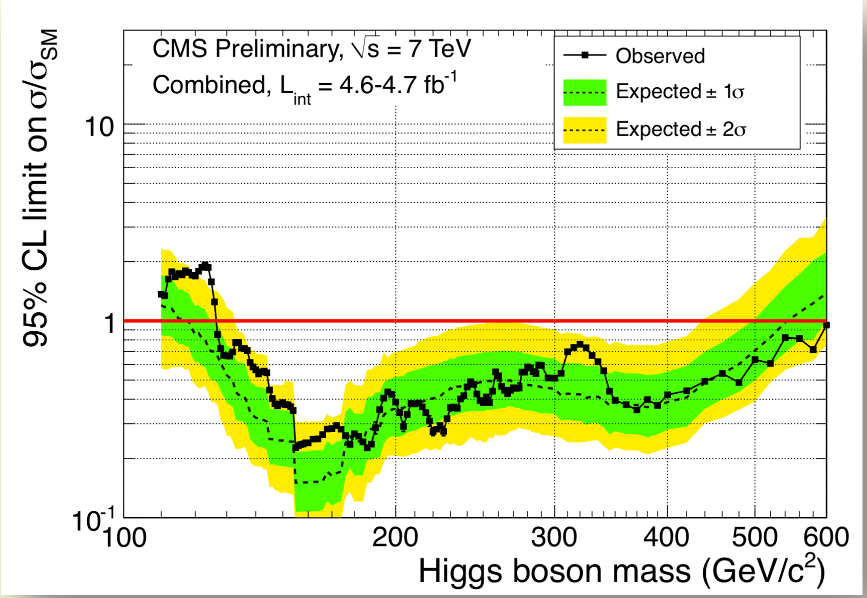

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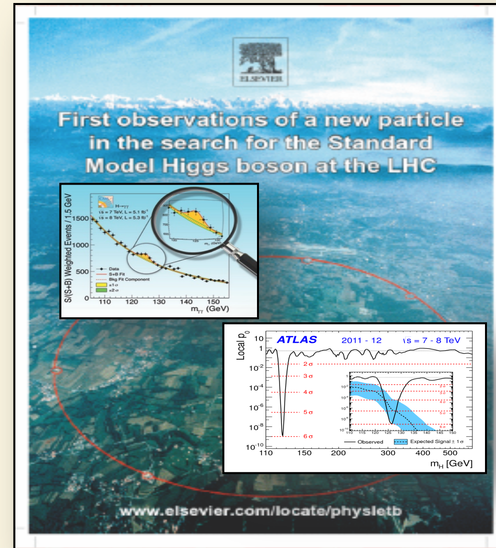
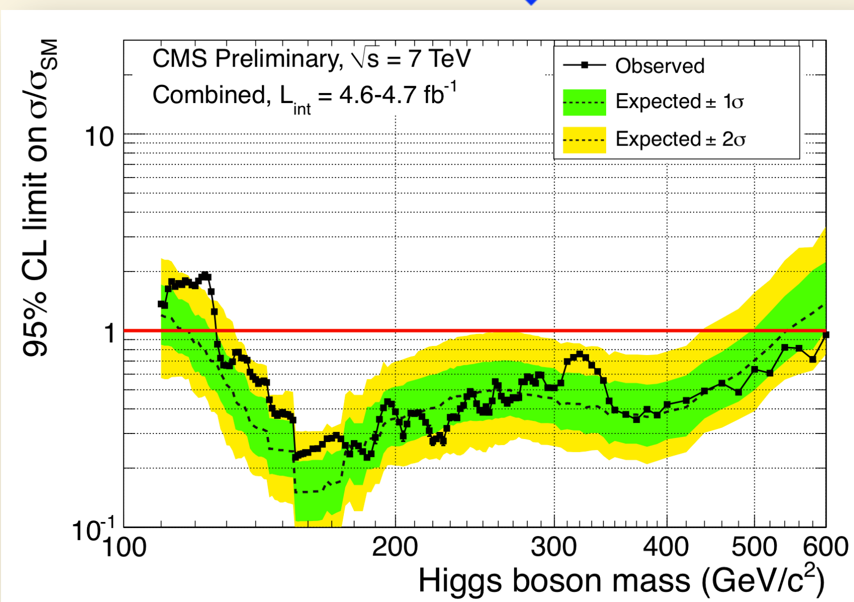
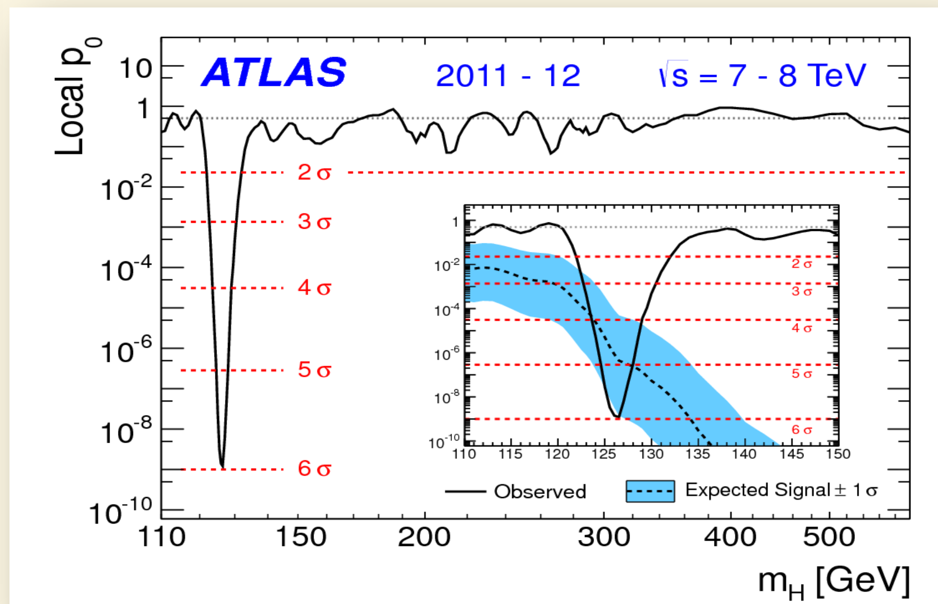
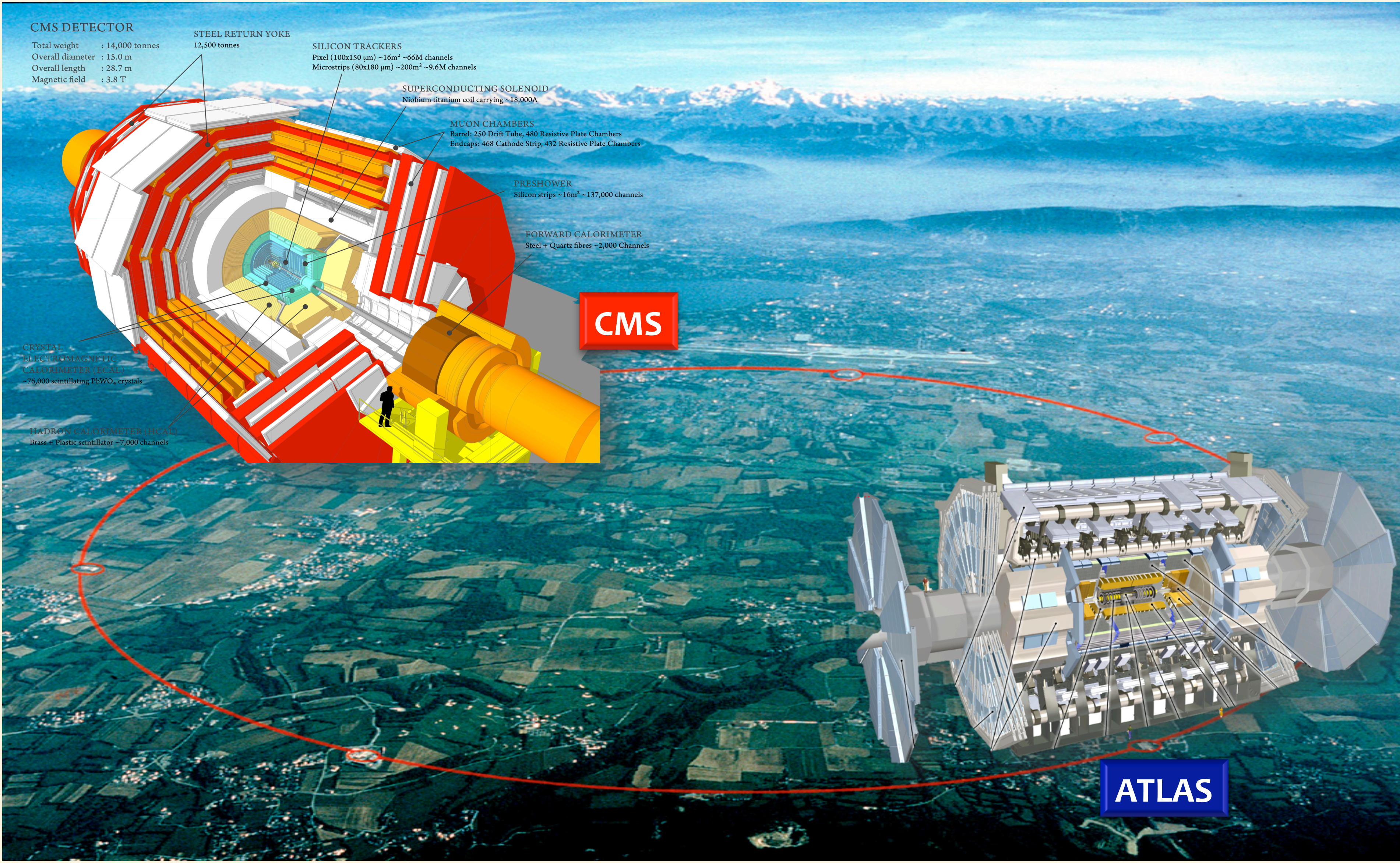






The detectors

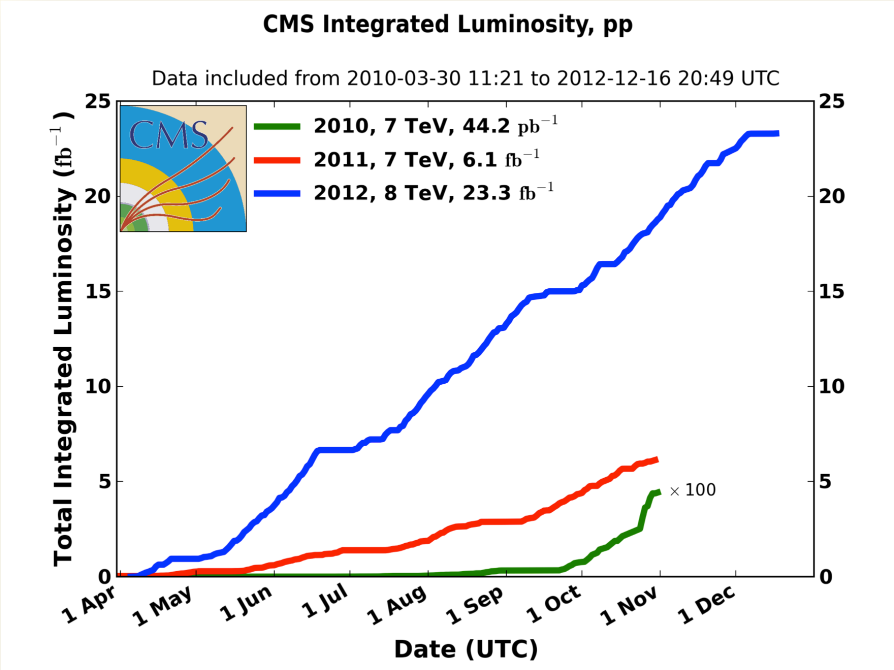
The detectors



Design of the detectors driven by the Higgs boson and other searches

LHC and detectors performance

Key point to the success story:
Outstanding performance of the LHC!



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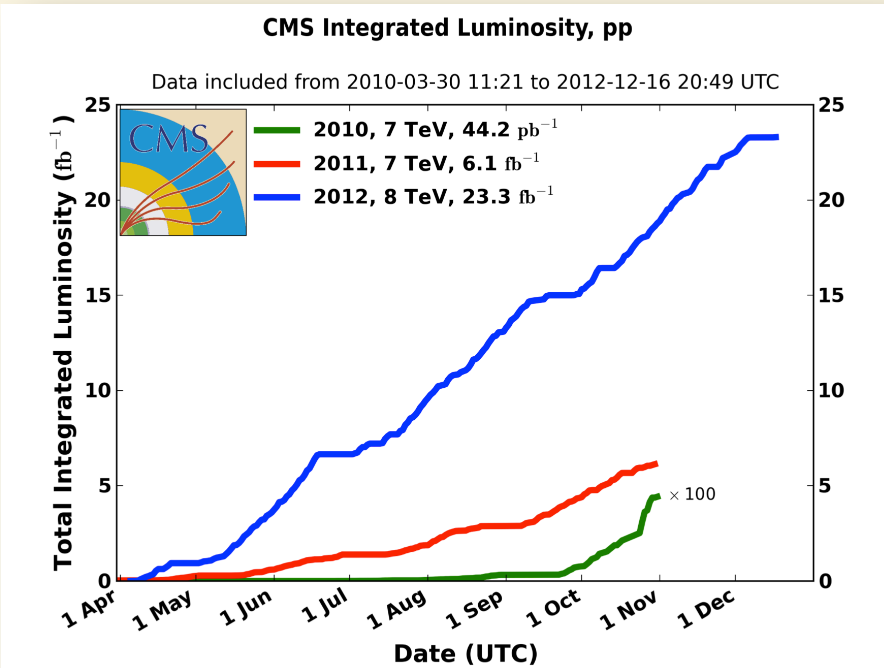


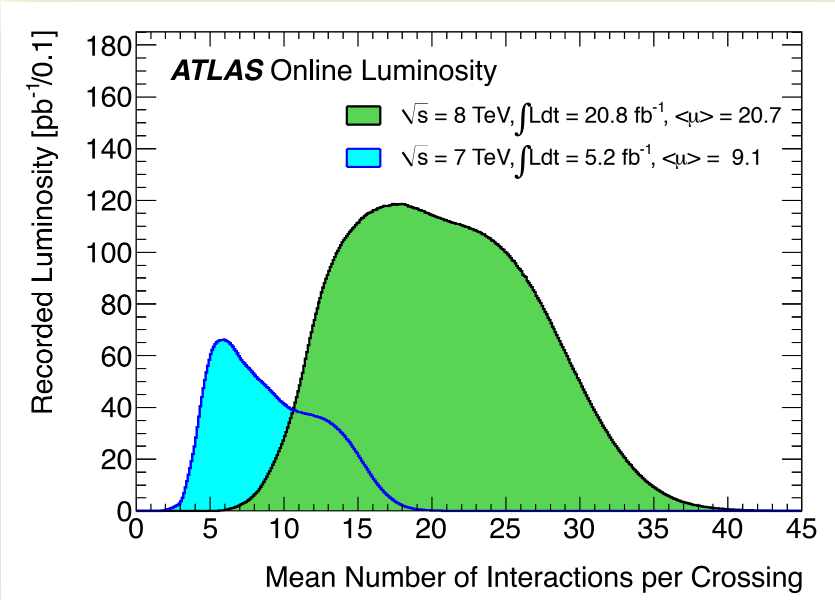
Excellent ATLAS and CMS performance:

experiment	Luminosity fb^{-1}	Data taking eff.	data used in physics
ATLAS	5.6 (@7 TeV) 23.3 (@8 TeV)	94%	90%
CMS	6.1 (@7 TeV) 23.3 (@8 TeV)	94%	91%

High performance of world wide grid computing to cope with processing of the totality of the data and simulated events

Challenge in coping with the high pileup rates
- Trigger, computing, reconstruction of physics objects

Pileup challenge



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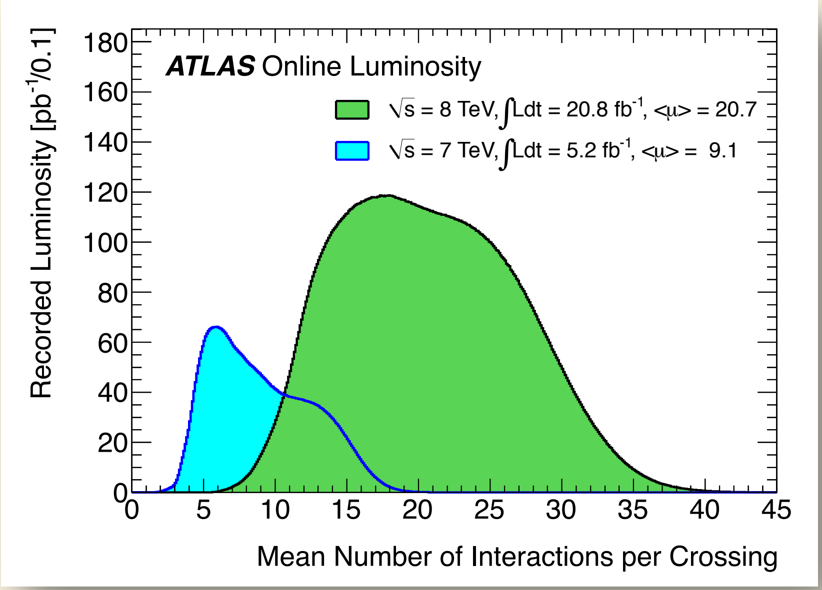
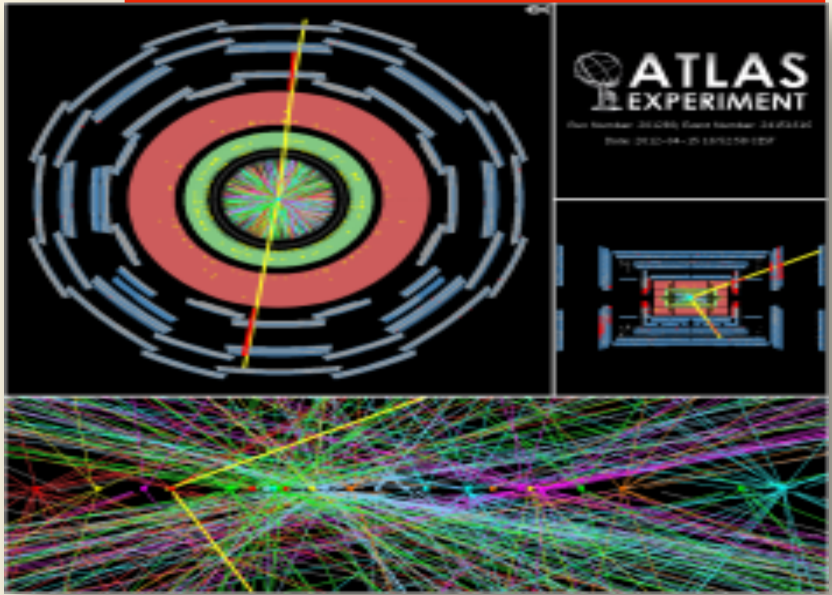


Example: Z→μμ event display with 25 reconstructed vertices



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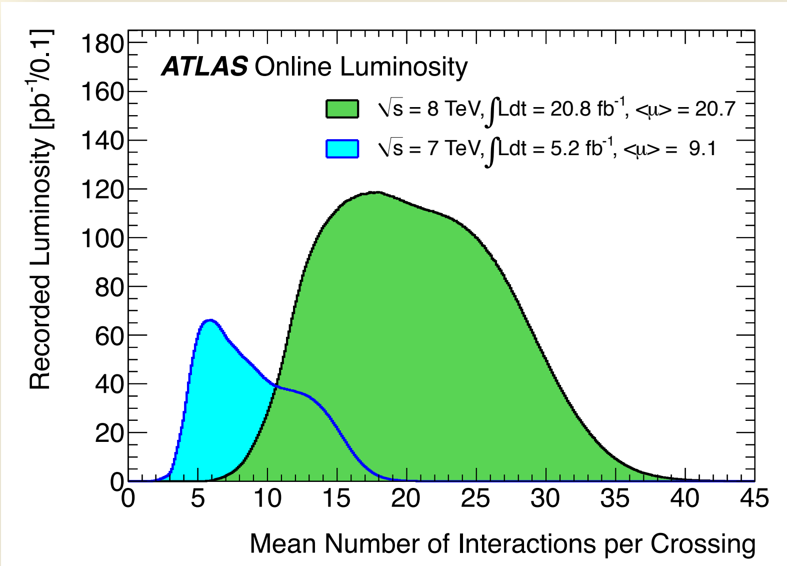
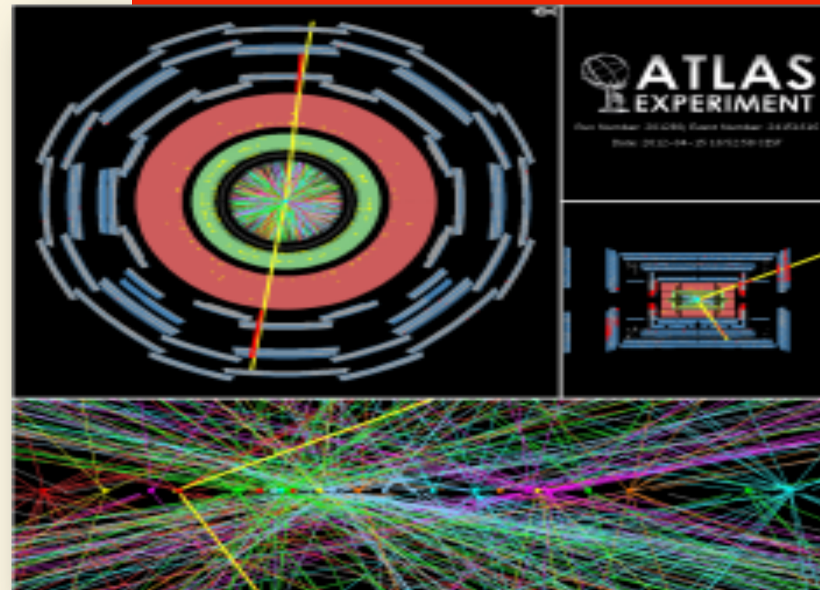
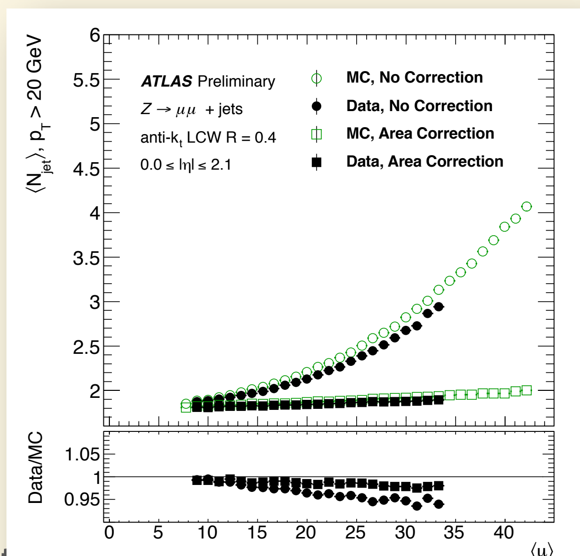




Pileup affects reconstructed objects like lepton isolation, jets, transverse missing energy.

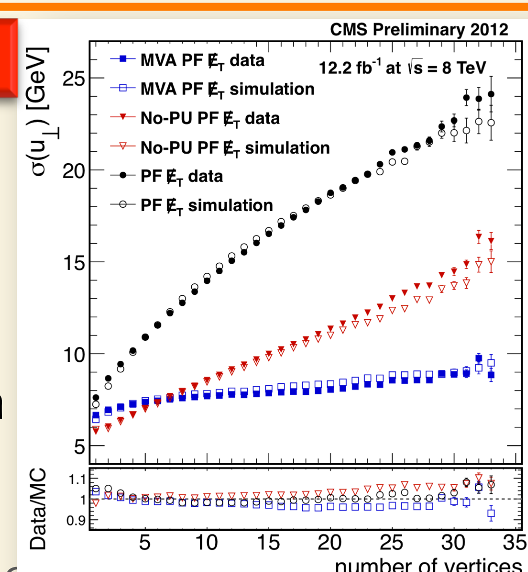
ATLAS

N_{jets}

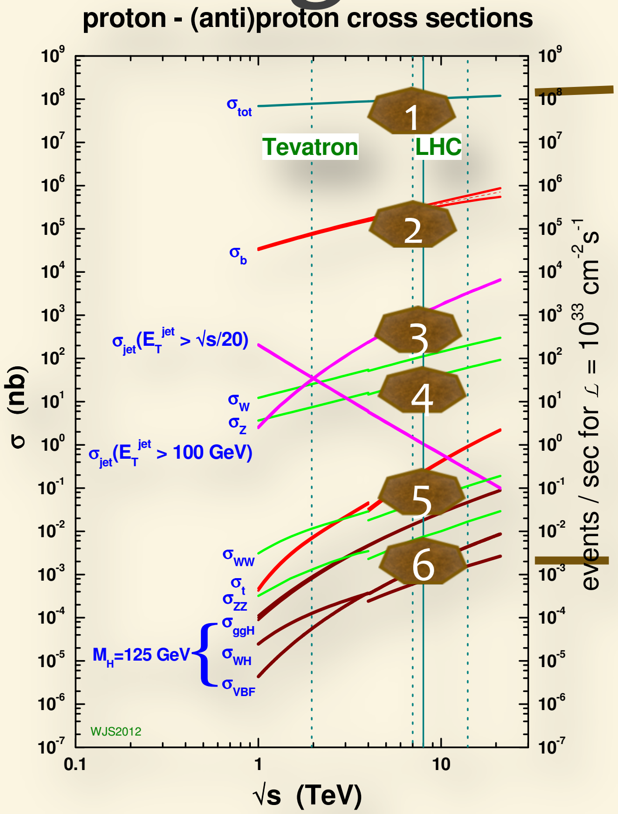


CMS

E_T^{miss} resolution



Testing the Standard Model at LHC

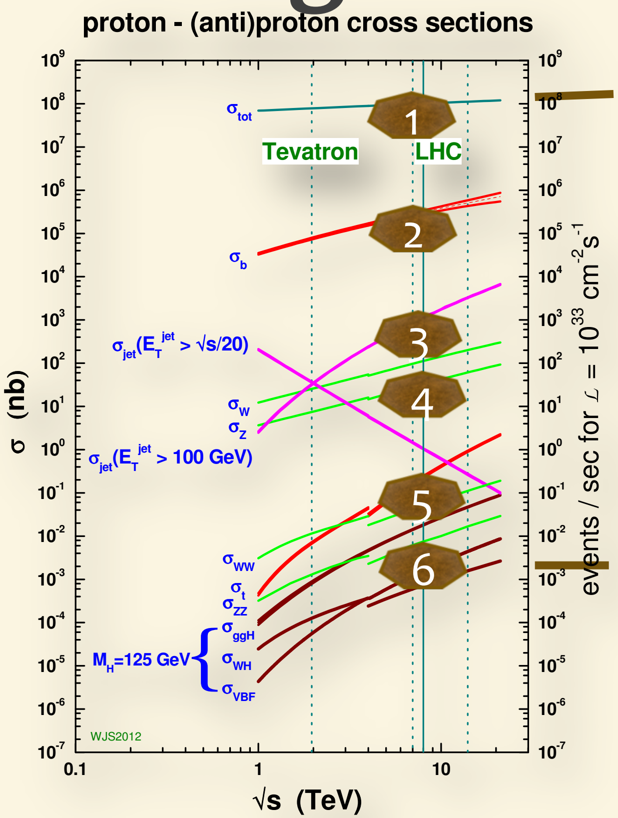


1. Total inelastic
2. B physics
3. Jets
4. W,Z physics
5. top physics
6. Higgs physics

10^{10}

Background rejection very important at LHC

Testing the Standard Model at LHC



1. Total inelastic
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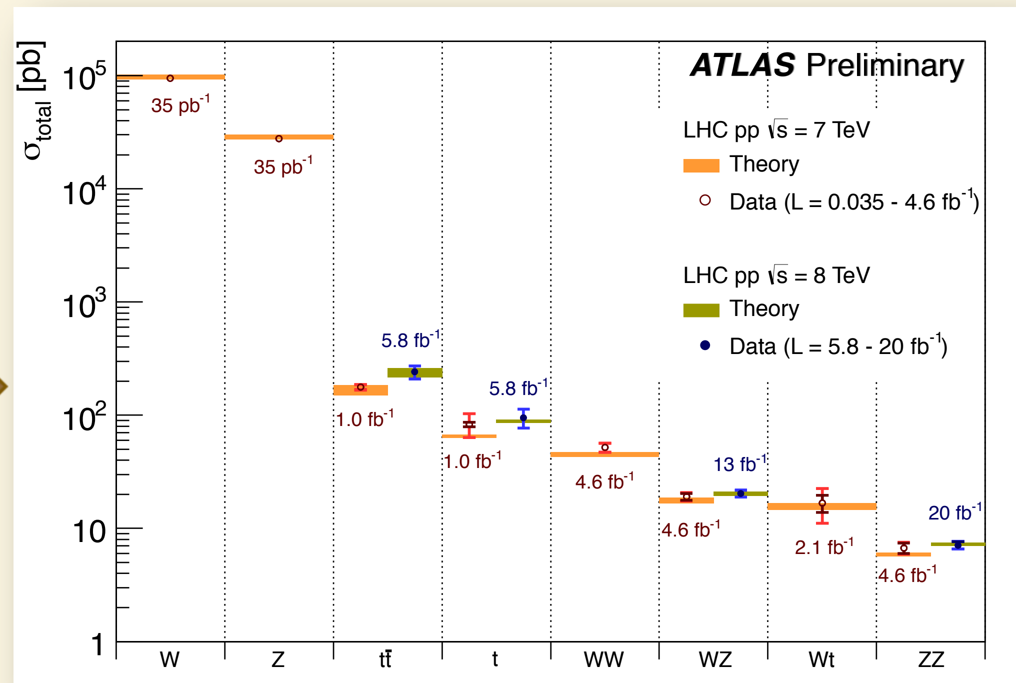
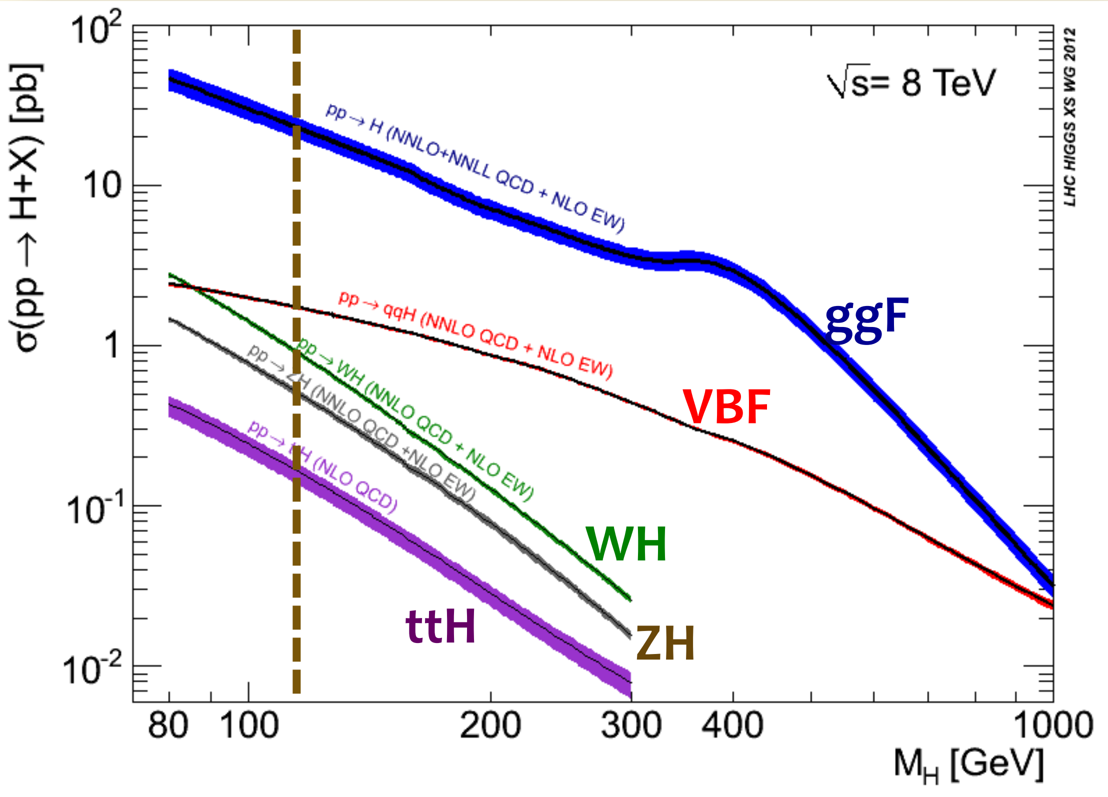
10^{10}

Background rejection very important at LHC

- Standard Model processes as well as detector performance well understood
- they constitute the background to Higgs physics

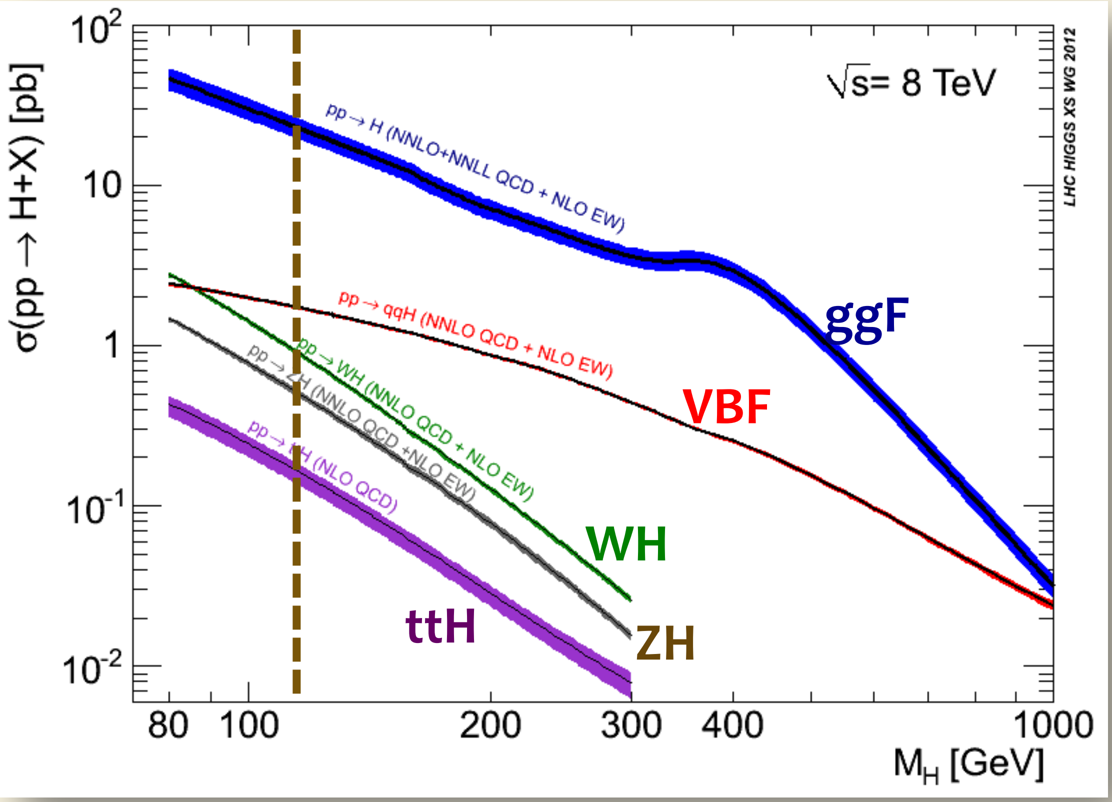


Higgs production at the LHC



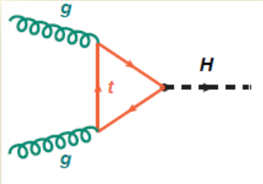
Huge effort from theory to calculate cross -section at N(NLO)

Higgs production at the LHC



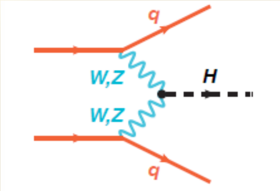
Huge effort from theory to calculate cross -section at N(NLO)

Gluon fusion ggF



Dominant production

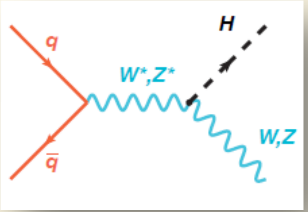
Vector boson fusion VBF

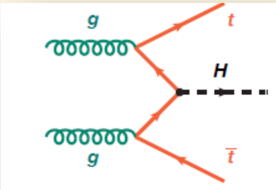


Distinct signatures

Associated with

W, Z top

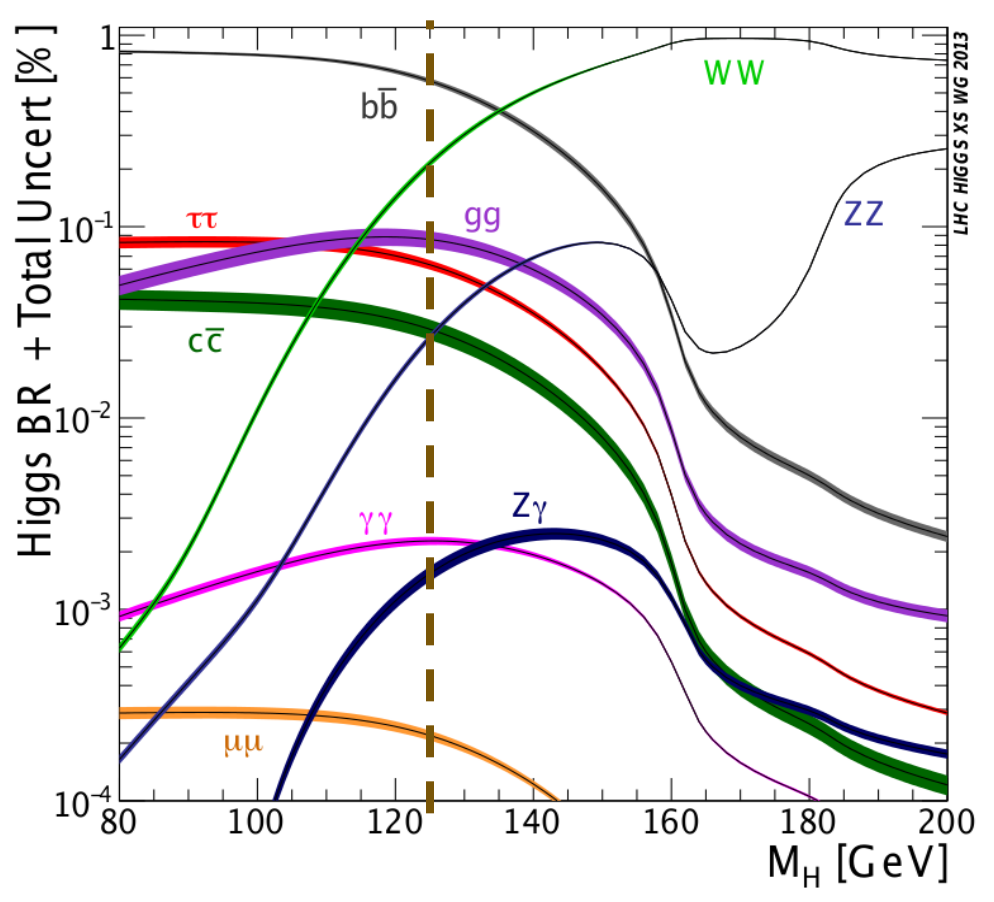




ggF	VBF	VH	ttH
19.5 pb	1.6 pb	1.1 pb	0.1 pb

@m_H=125 GeV

Higgs decay modes



All decay channels are open at ~125 GeV !

Channels studied in the context of SM Higgs boson search:

Bosonic decay modes

- H→γγ
- H→ZZ→4l   discovery channels
- H→WW→lνlν
- Zγ

Devoted to high mass studies

- H→ZZ→llqq
- H→ZZ→llνν, WW→lνqq
- H→ZZ→llττ

Fermionic decay modes

- H→ττ, bb, μμ

Rates @ mH=125 GeV				
Bosonic decays	WW 21.5%	ZZ 2.6%	γγ 0.23%	Zγ 0.15%
Fermionic decays	bb 57.7%	ττ 6.3%	μμ 0.02%	

H→γγ

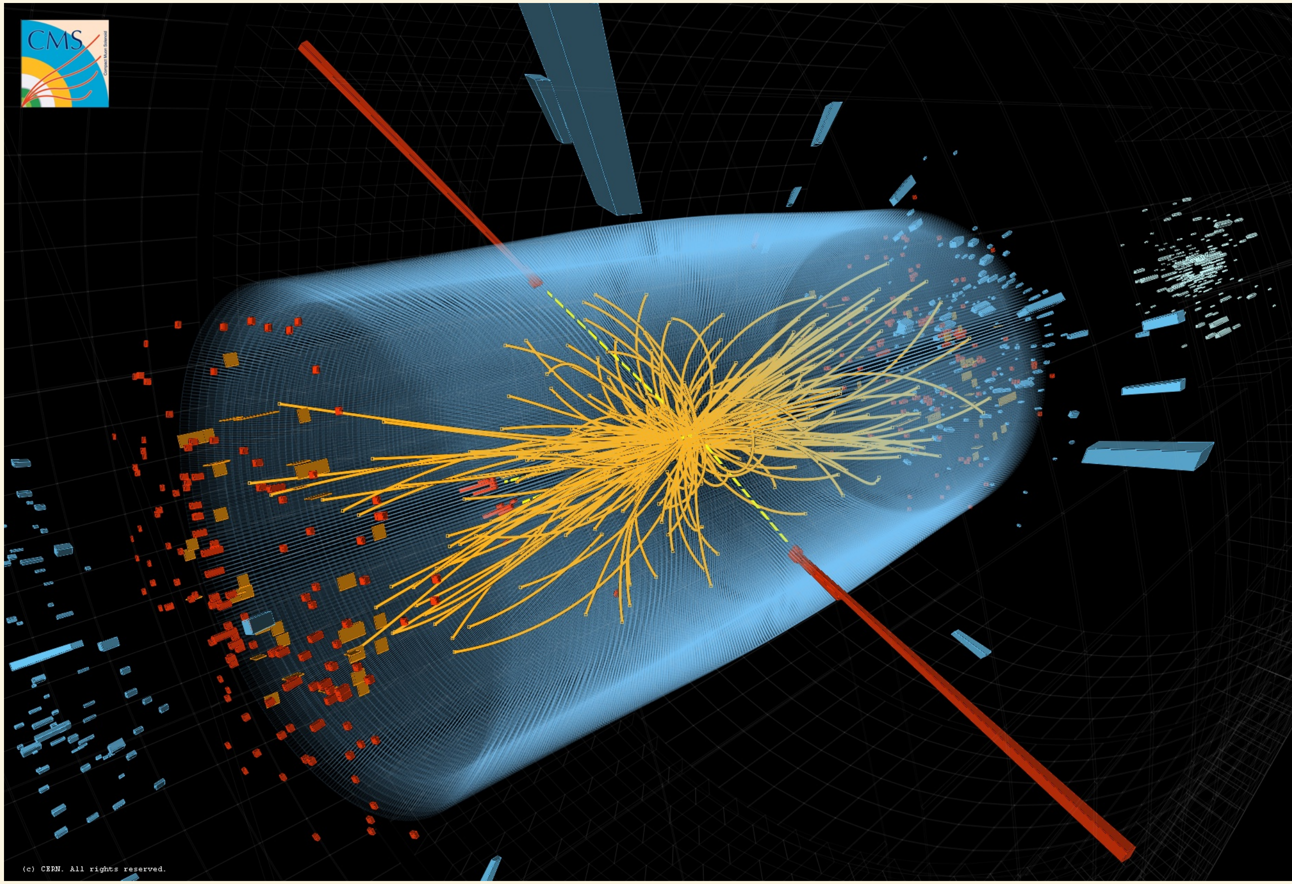
Topology characteristics

Rare decay ~2 ‰

σ x BR ~ 50 fb (m_H=126 GeV)

Two isolated photons

Narrow resonance on top of a continuous background



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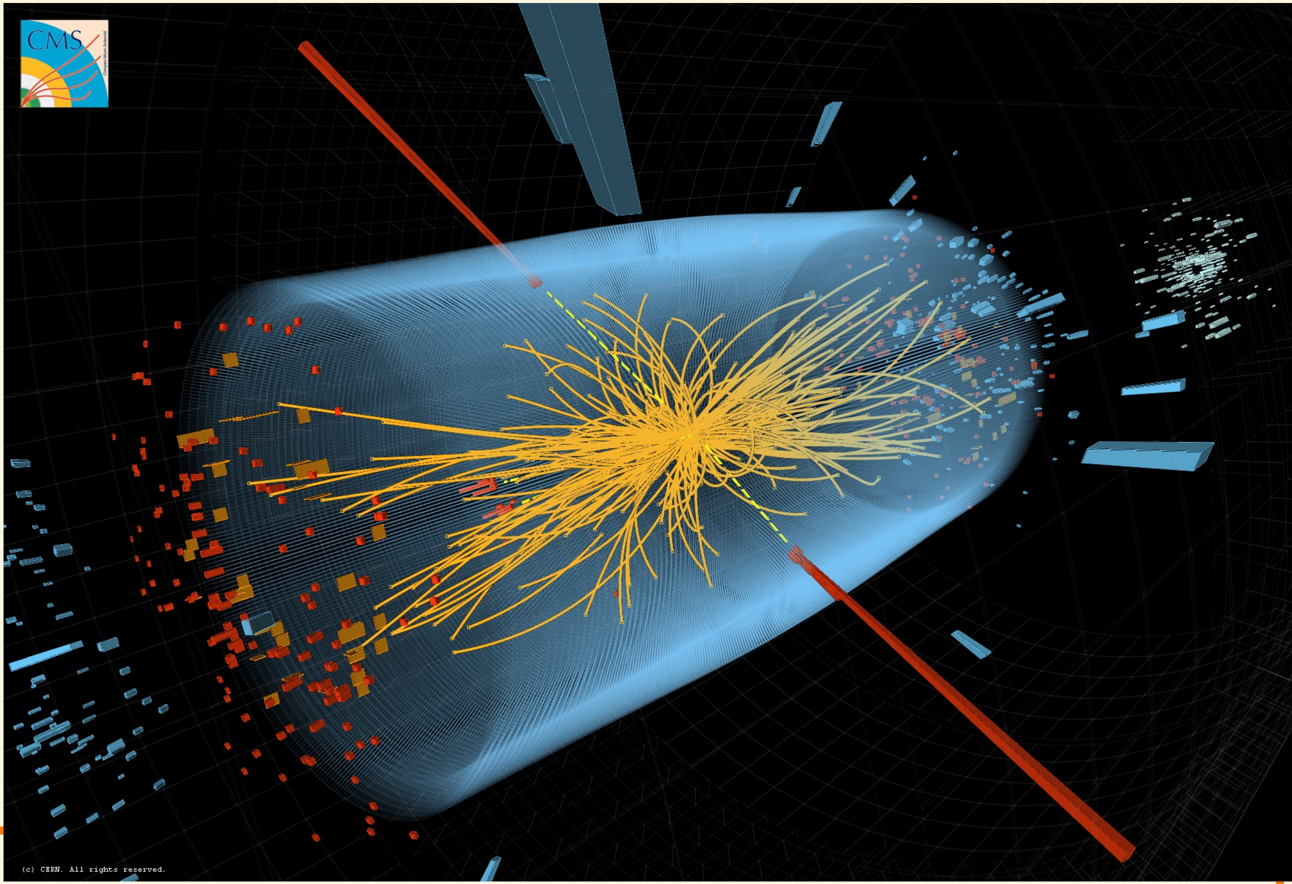

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Quick overview

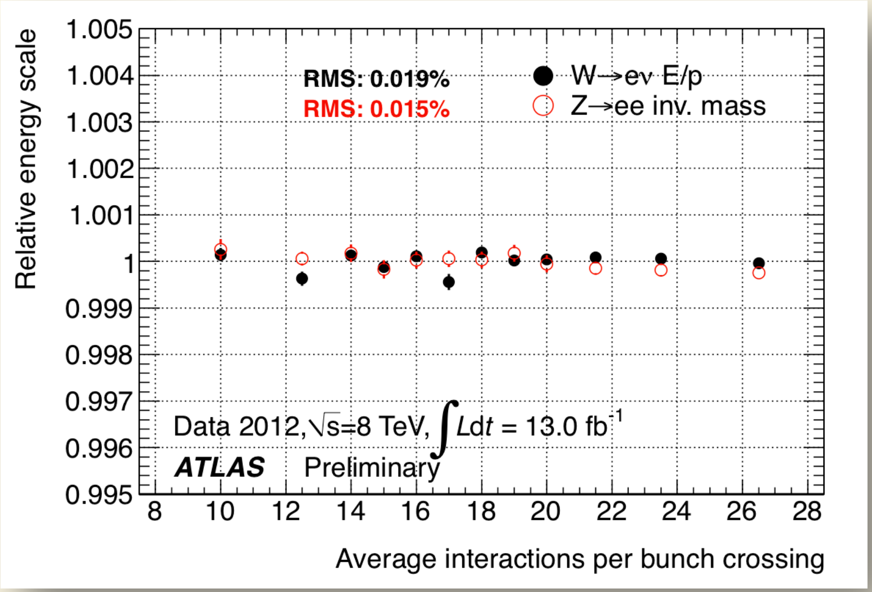
- High 'mass resolution' channel
- High background (γγ continuum, γ-jet, jet-jet)

- Background extrapolated from side bands in data
- Signal/Background ~0.03
- diphoton resolution key ingredient of this analysis

- To increase analysis sensitivity, events are classified w.r.t their production mode (ggF,VBF,VH) and in inclusive categories with different resolution and S/B

Checks on energy scale & mass resolution

ATLAS



Energy scale stable with pileup and time

Checks on energy scale & mass resolution

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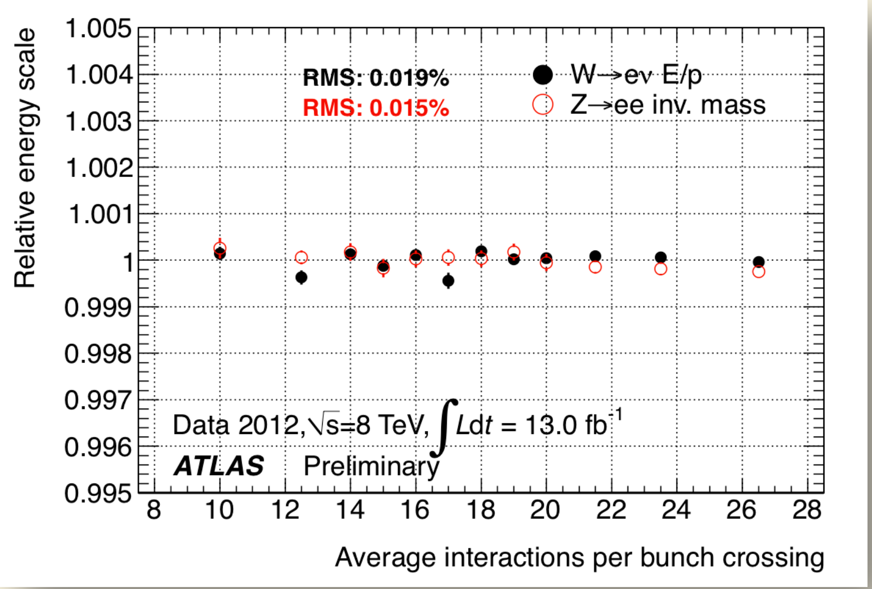
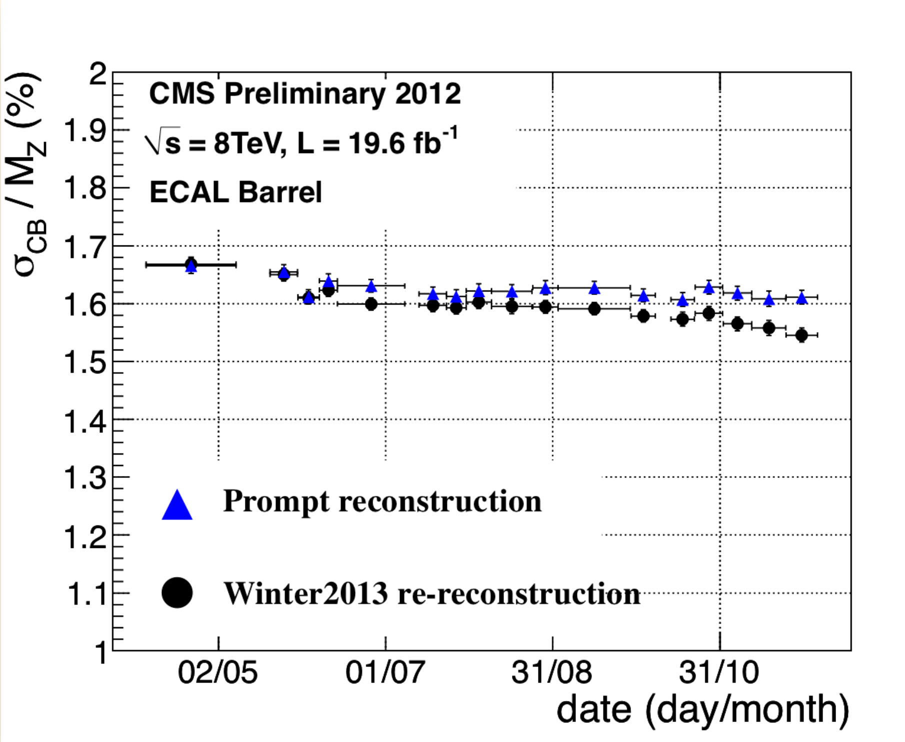


Energy scale stable with pileup and time

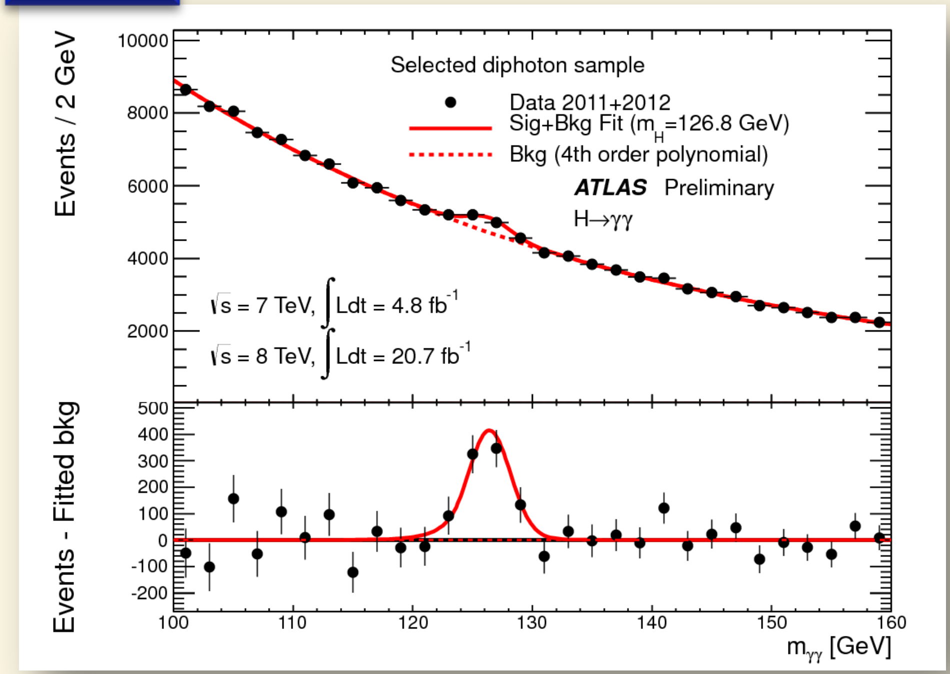
CMS



Mass resolution vs time with $Z \rightarrow e^+e^-$ decays.
Energy resolution stable with time at ‰ level.

H→γγ mass spectrum and signal strength

ATLAS



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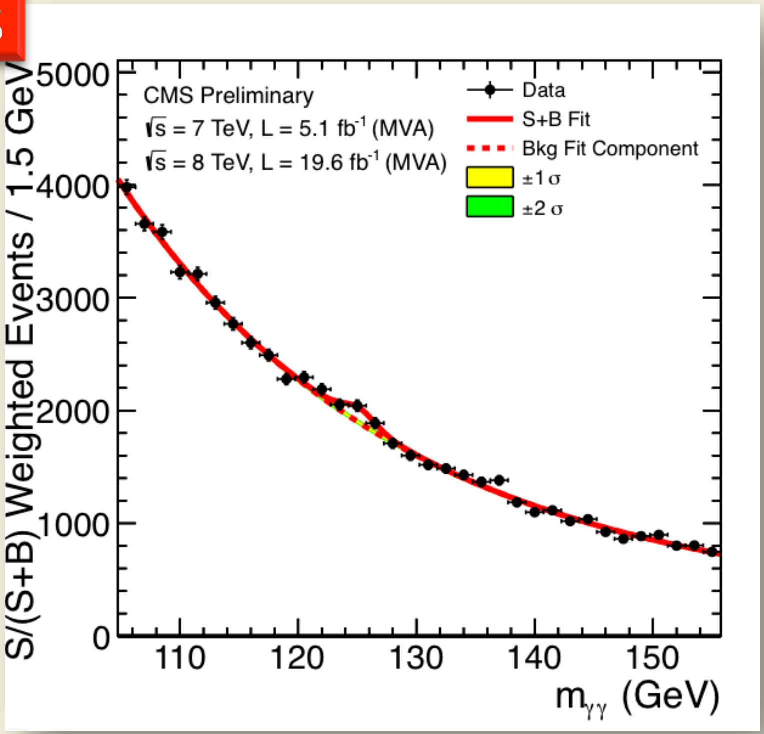

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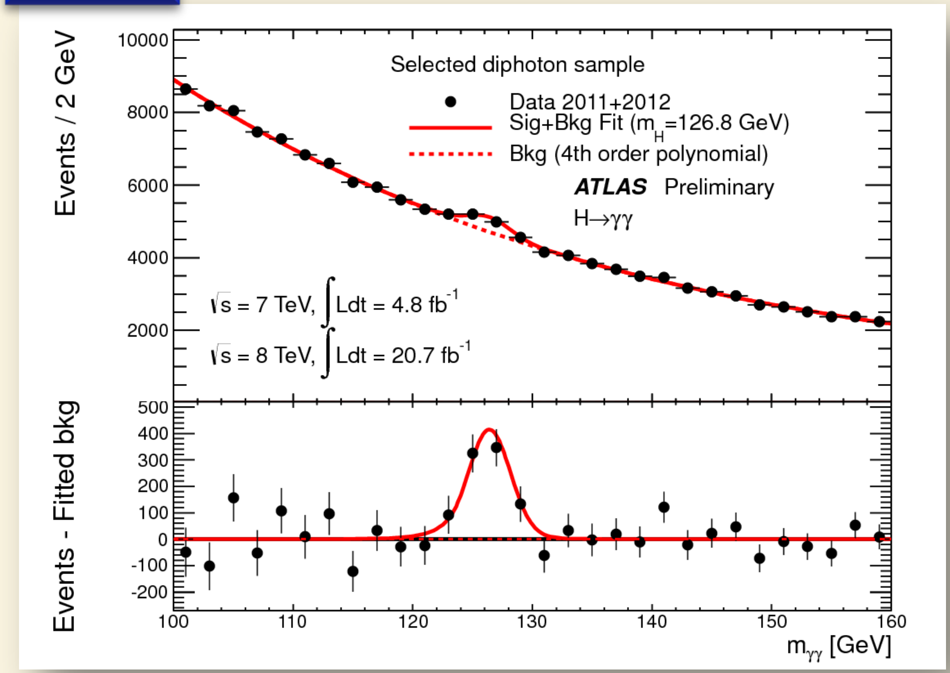

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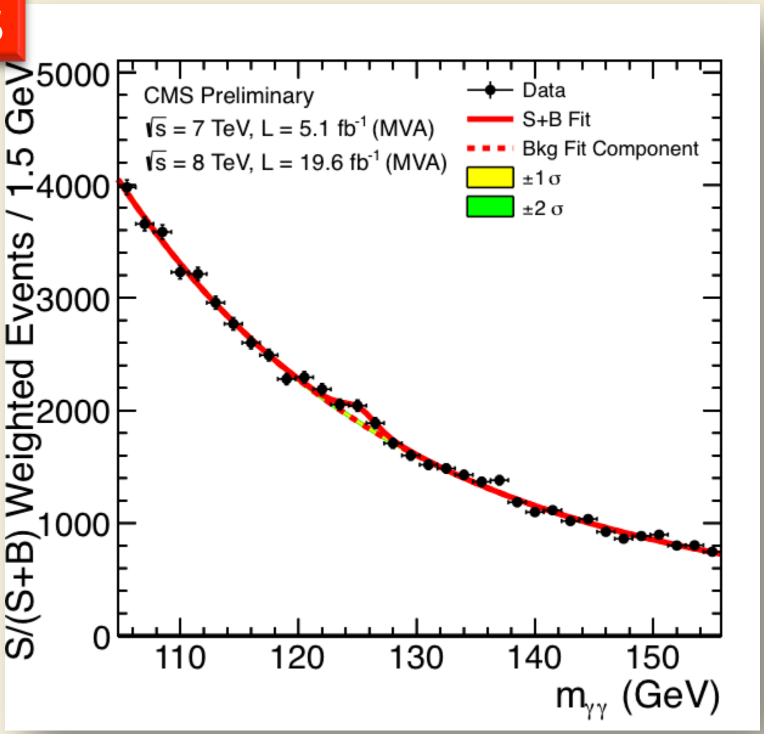
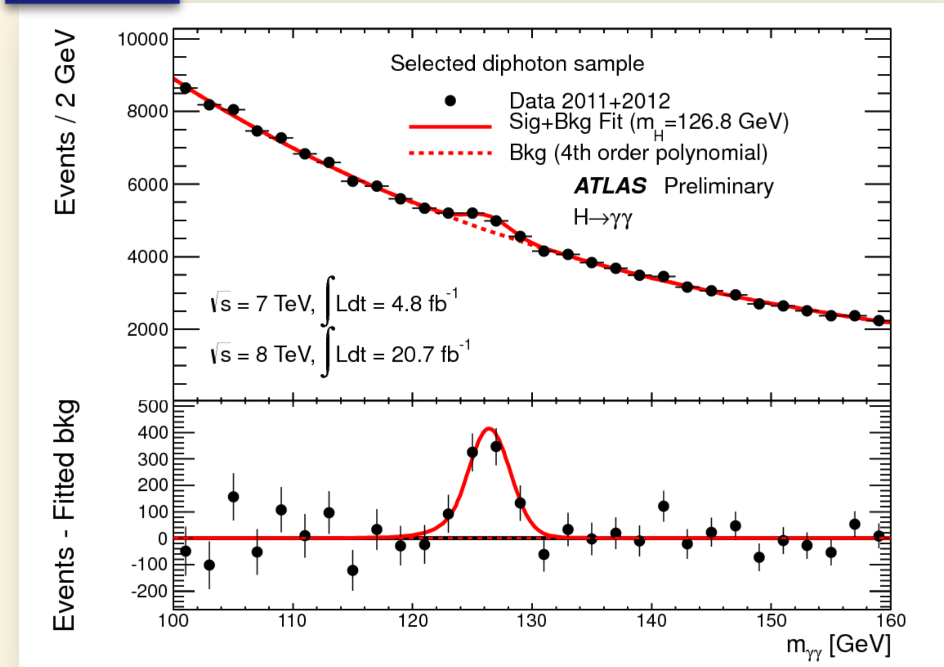


Significance: 7.4σ (4.1σ expected from SM)

Significance: 3.2σ (4.2σ expected from SM)

H→γγ mass spectrum and signal strength

ATLAS



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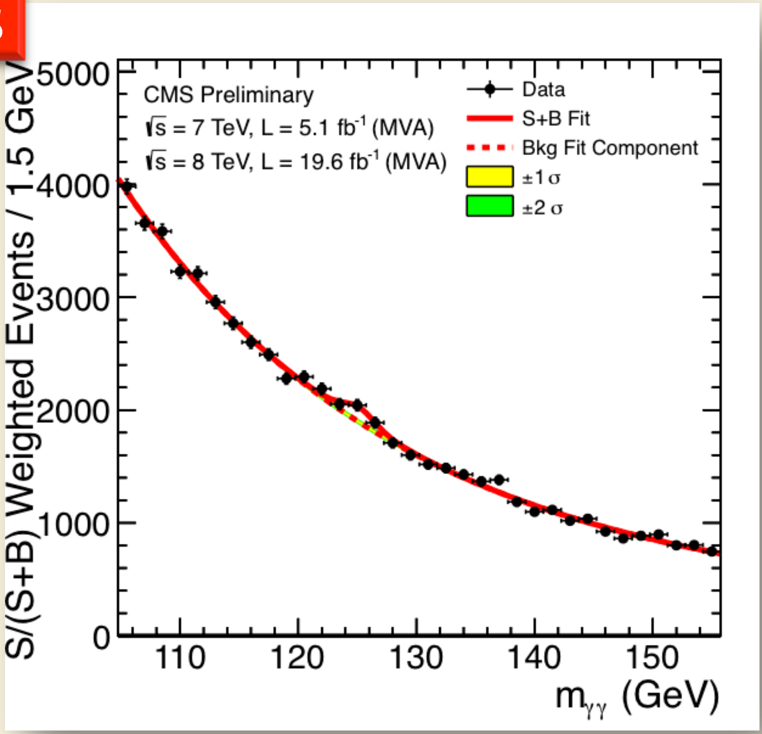


Significance: 7.4σ (4.1σ expected from SM)

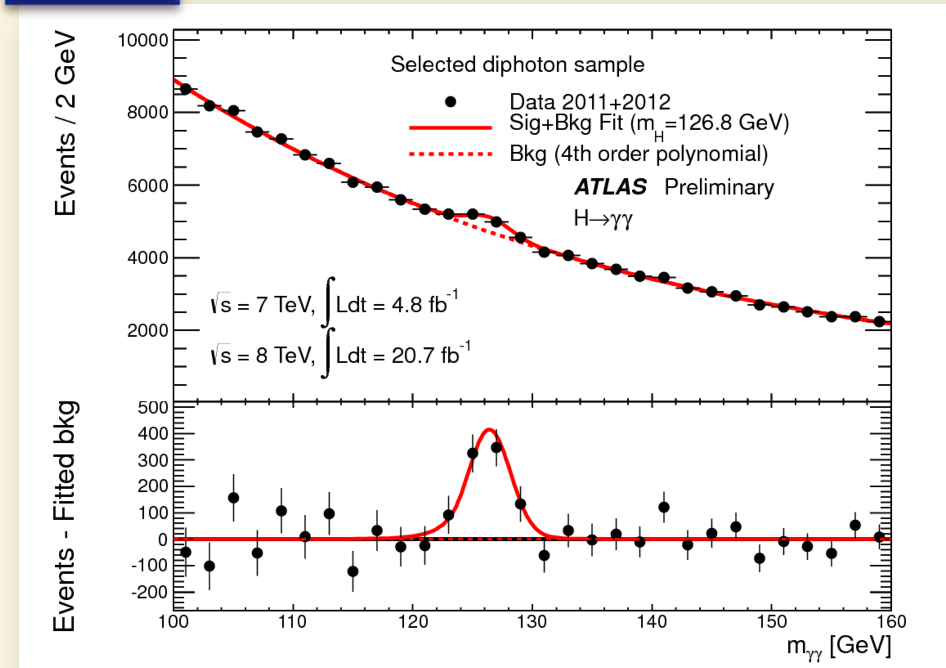
Mass: $m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$ GeV

Significance: 3.2σ (4.2σ expected from SM)

Mass: $m_H = 125.4 \pm 0.5(\text{stat}) \pm 0.6(\text{syst})$ GeV

H→γγ mass spectrum and signal strength

ATLAS



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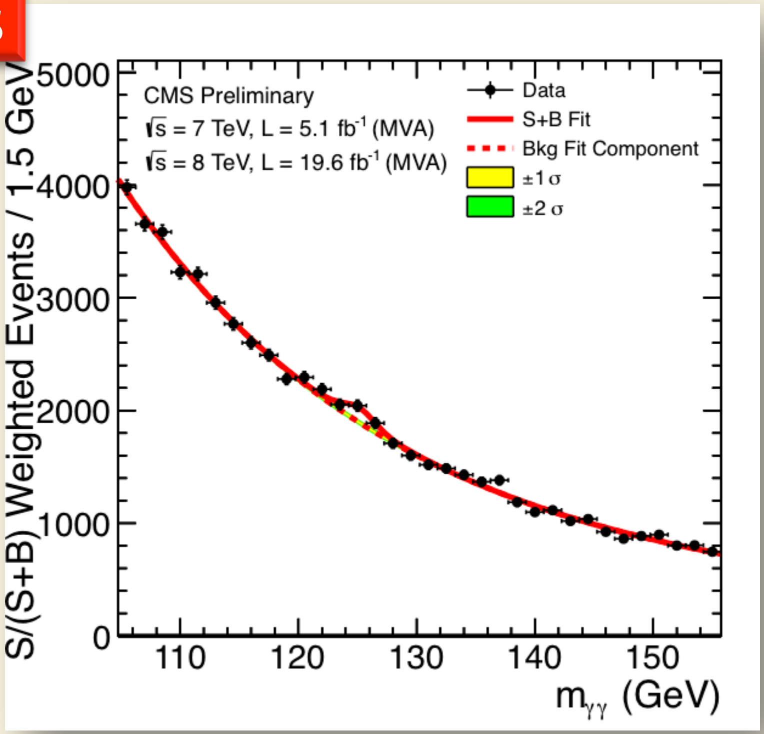


Significance: 7.4σ (4.1σ expected from SM)

Mass: $m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})\ \text{GeV}$

$$\mu = \frac{measured\ rate}{SM\ \ predicted\ rate} = 1.65 \pm 0.24(stat)^{+0.25}_{-0.18}(syst)$$

Significance: 3.2σ (4.2σ expected from SM)

Mass: $m_H = 125.4 \pm 0.5(\text{stat}) \pm 0.6(\text{syst})\ \text{GeV}$

$$\mu = \frac{measured\ rate}{SM\ \ predicted\ rate} = 0.78^{+0.28}_{-0.26}$$

H→ZZ*→4l

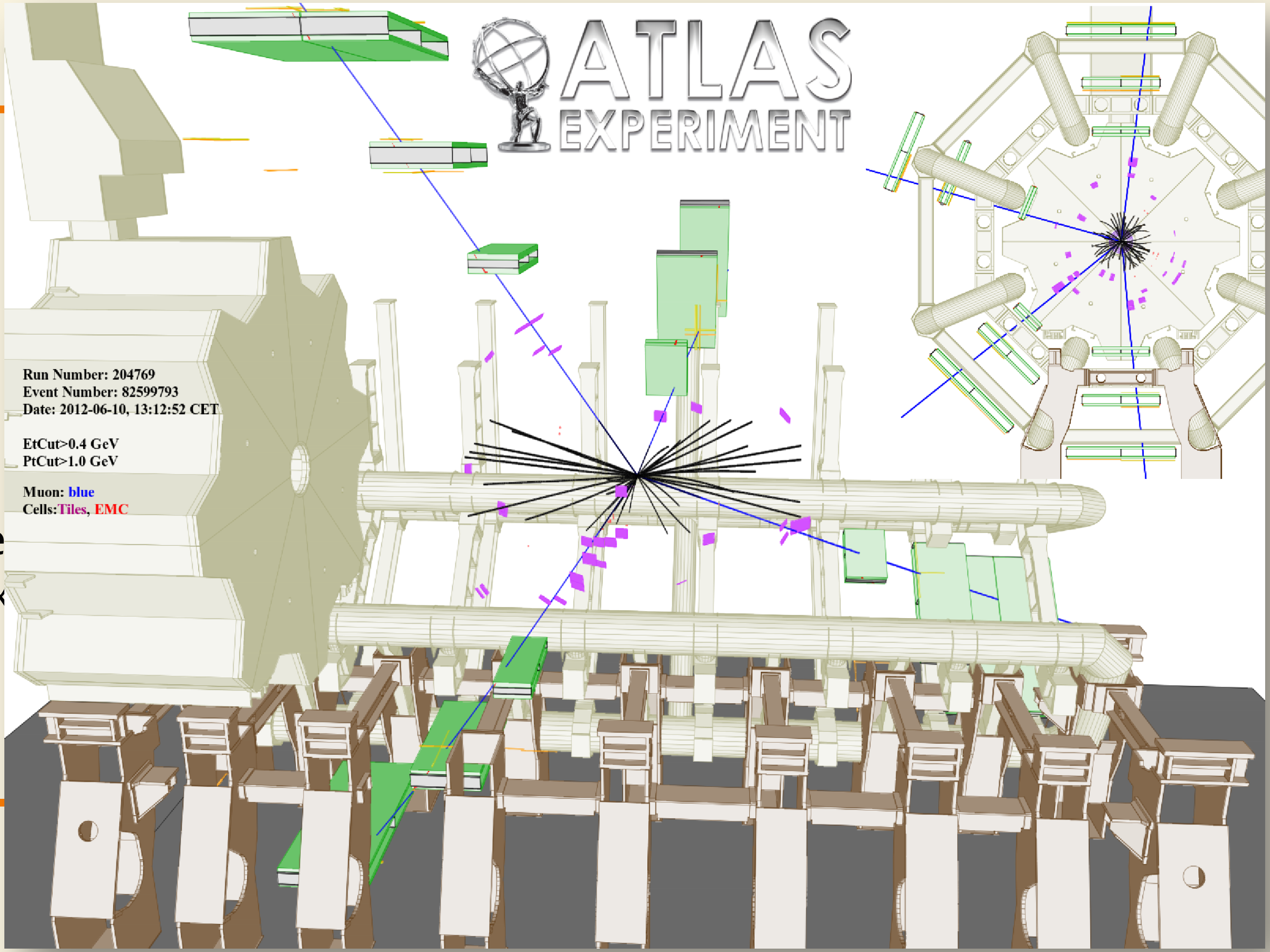
Topology characteristics

Golden channel

Small production rate
σ x BR ~ 2.5 fb (m_H 125 GeV)

Simple topology of 4 isolate
leptons from primary vertex

Narrow resonance on top
of a smooth background



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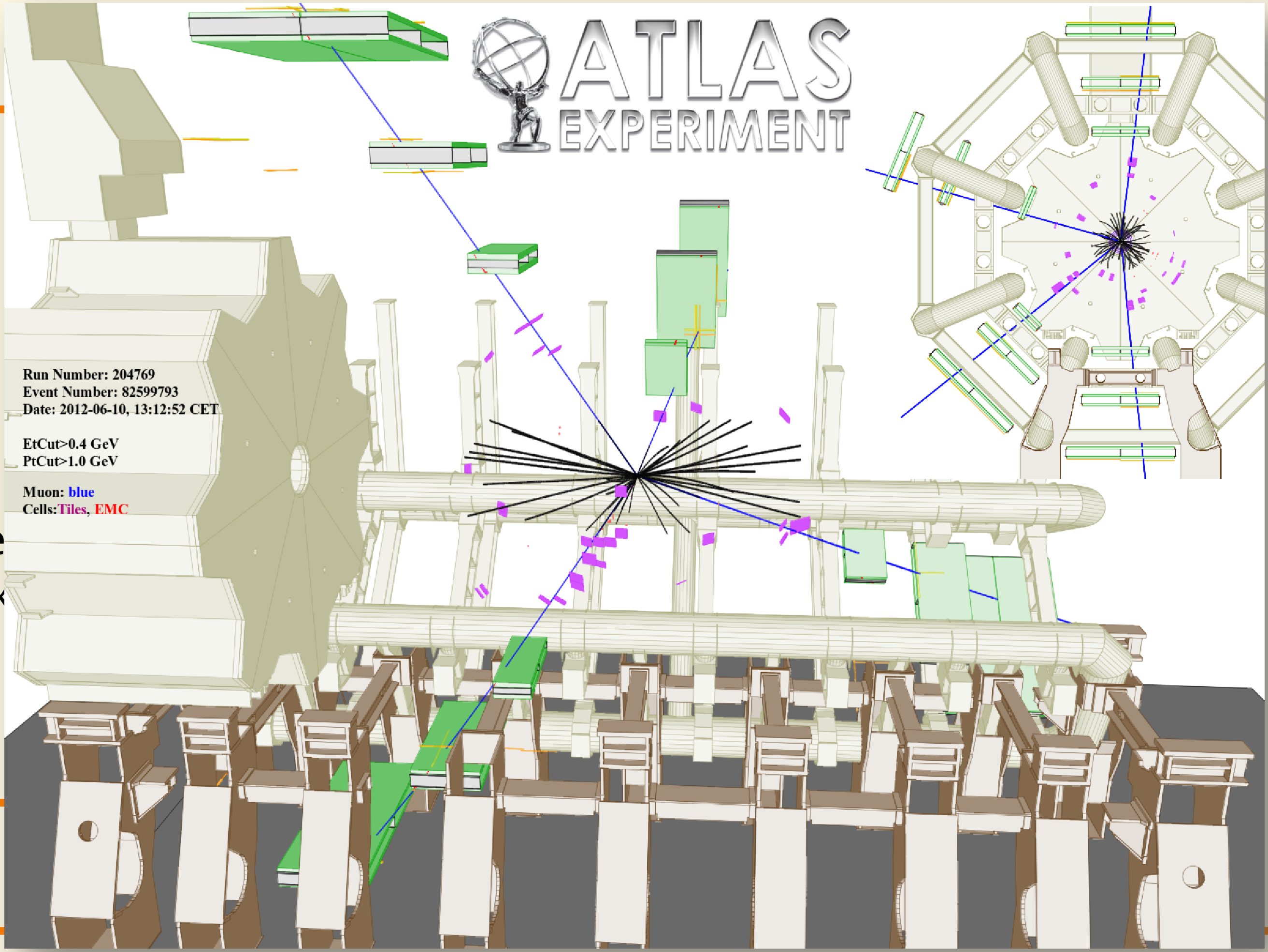
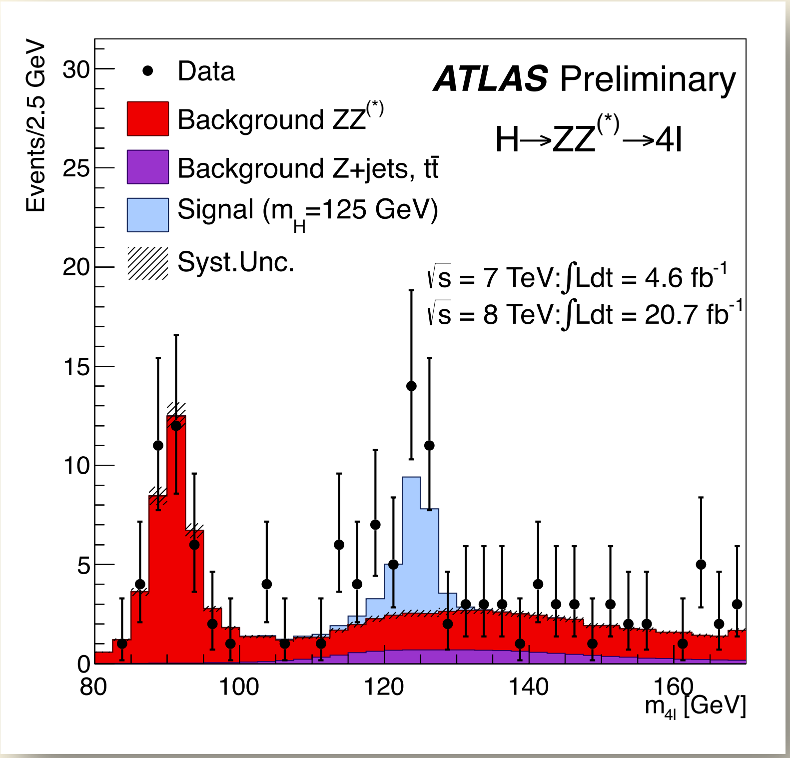


<u>*Quick overview*</u>

- High ‘mass resolution’ channel
- Backgrounds:
  - Irreducible from ZZ* and reducible from Z+jets, Z+ bb, tt
- S/B ~ 2 (CMS) , 1.6 (ATLAS) @mH=125 GeV

H→ZZ*→4l mass and strength

ATLAS



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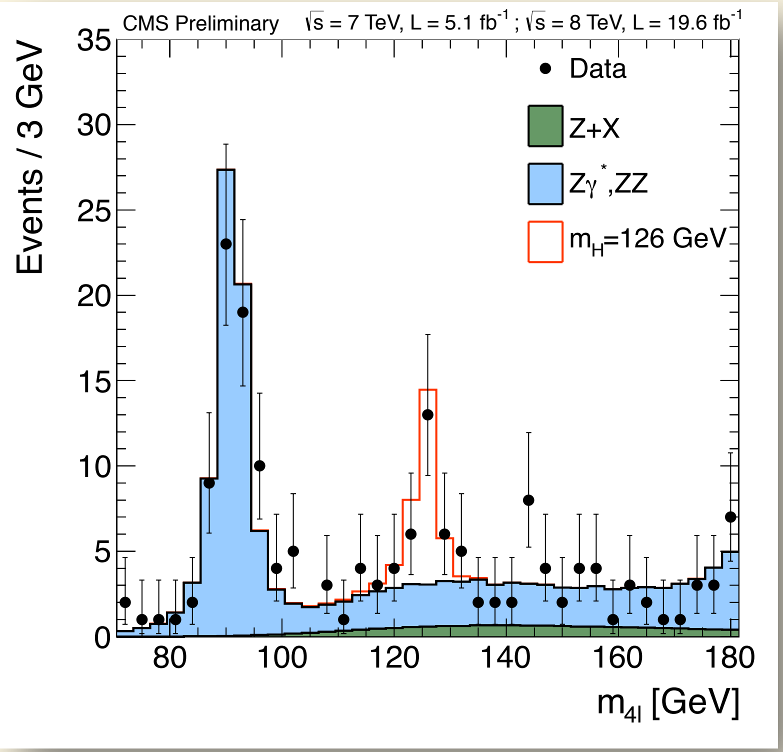
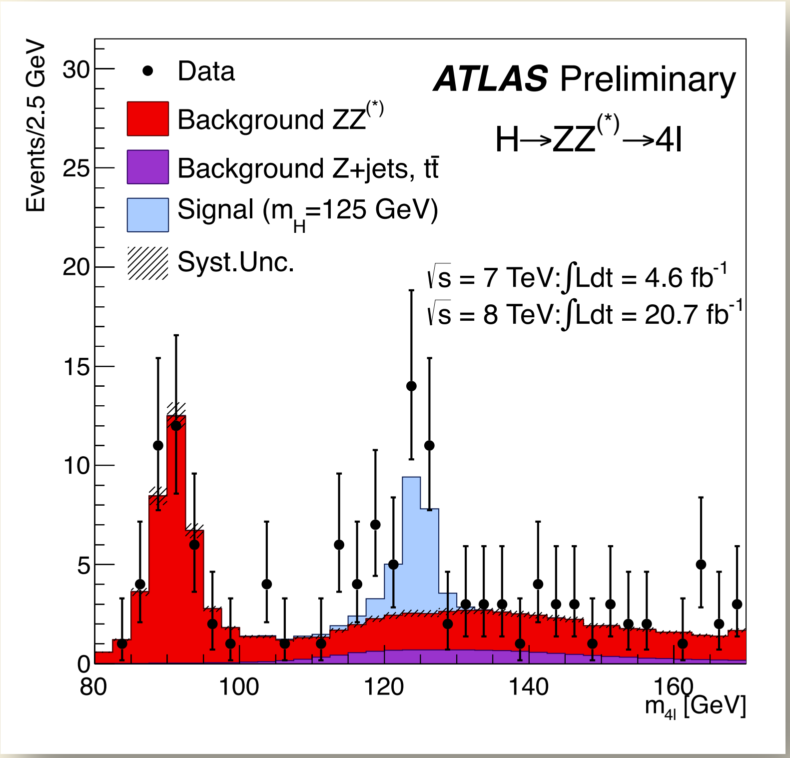


H→ZZ*→4l mass and strength

ATLAS



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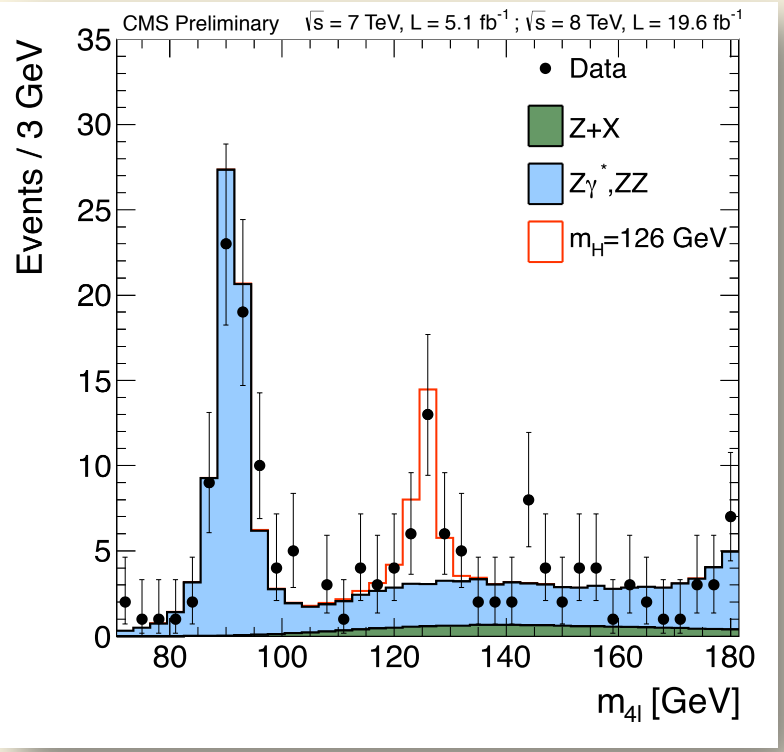

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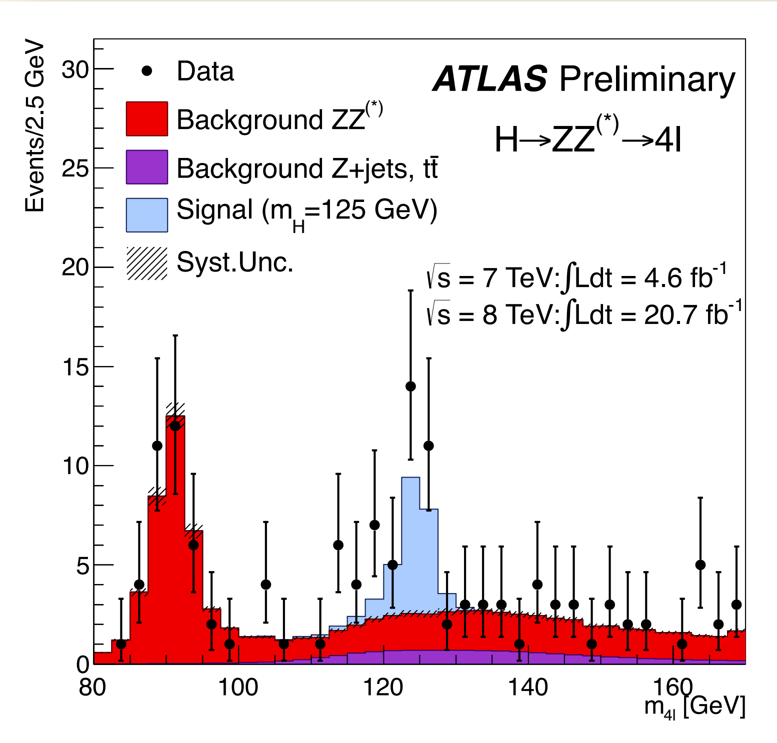
Significance: 6.7σ (7.2σ expected from SM)

H→ZZ*→4l mass and strength

ATLAS



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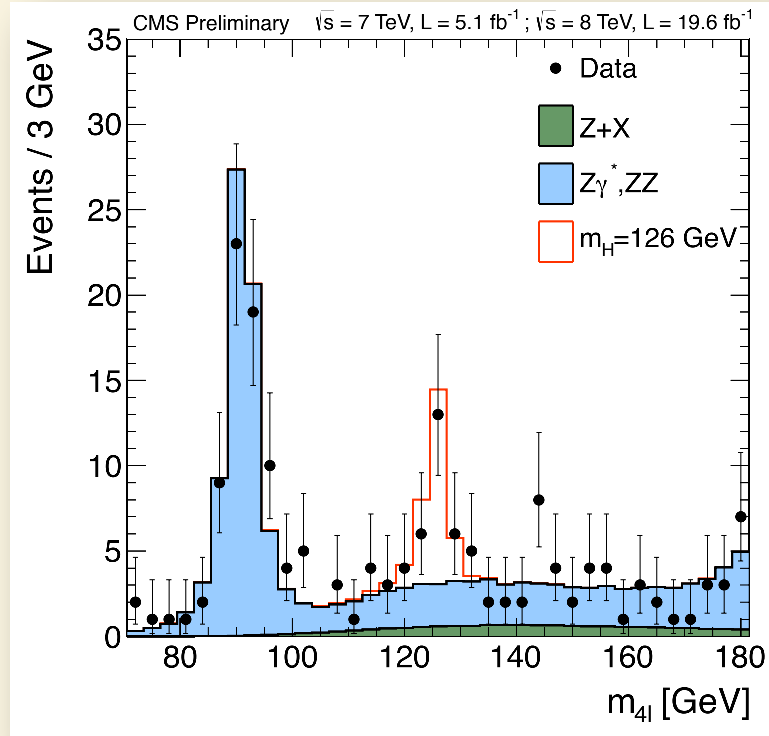

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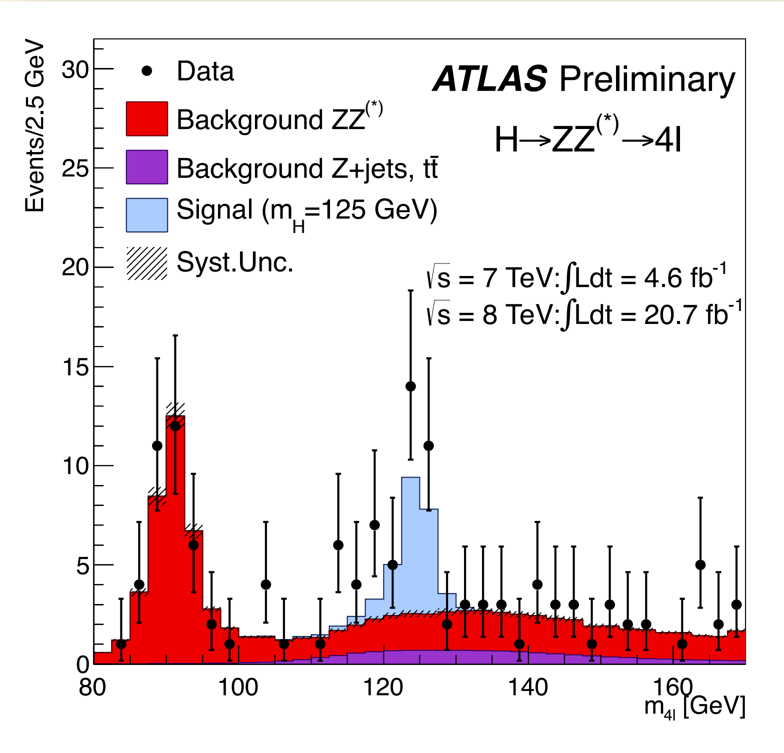
Significance: 6.7σ (7.2σ expected from SM)

Mass: $m_H = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{syst})\ \text{GeV}$

H→ZZ*→4l mass and strength

ATLAS



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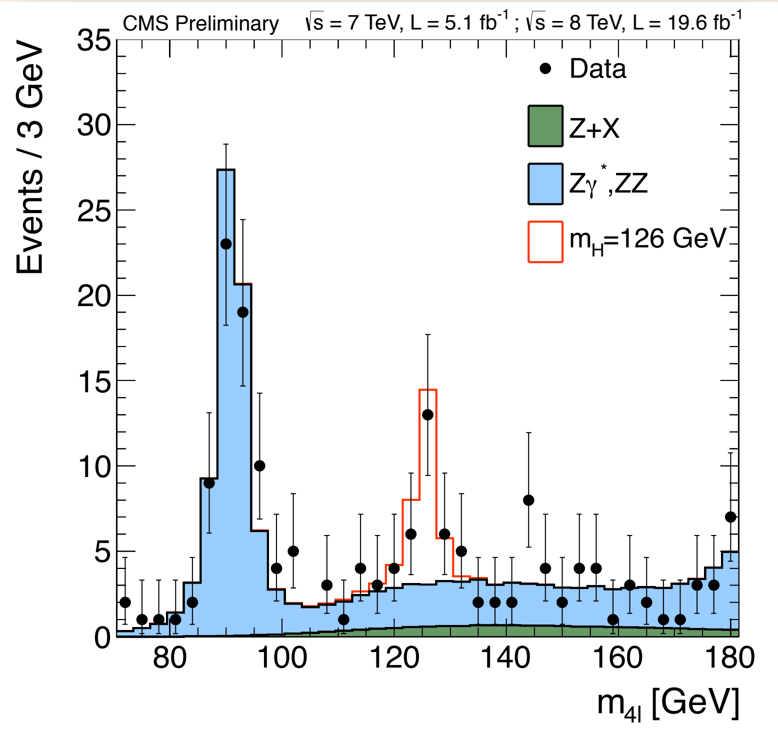

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$$\mu = \frac{measured\ rate}{SM\ \ predicted\ rate} = 1.7^{+0.5}_{-0.4}$$

CMS

Significance: 6.7σ (7.2σ expected from SM)

Mass: $m_H = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{syst})\ \text{GeV}$

$$\mu = \frac{measured\ rate}{SM\ \ predicted\ rate} = 0.91^{+0.30}_{-0.24}$$

H→WW$^{(*)}$→lνlν

Large production rate

σ x BR ~ 200 fb (m_H 125 GeV)

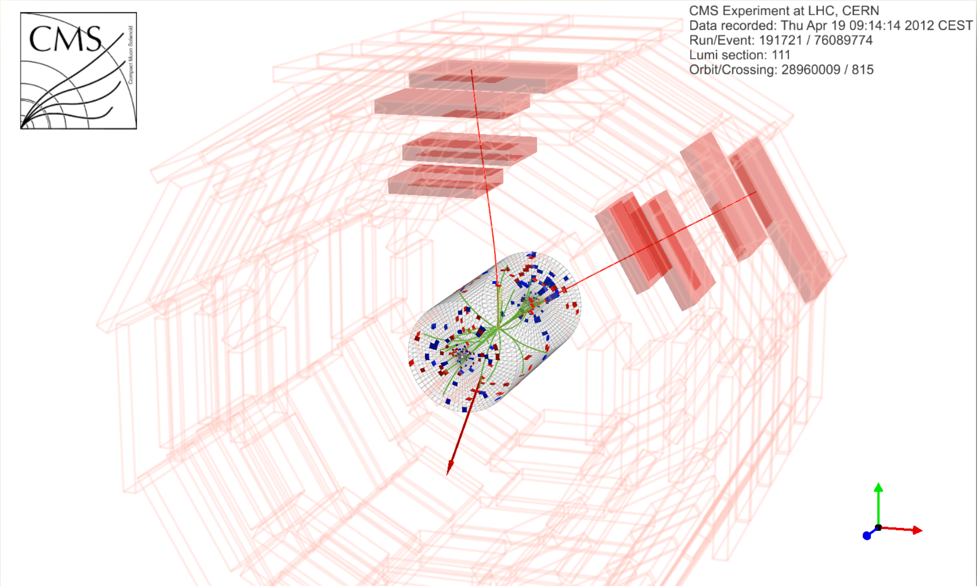
Clear dilepton signature

No full mass reconstruction possible

Discriminants

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (|\overrightarrow{P_T^{ll}} + \overrightarrow{E_T^{miss}}|)^2}$$

Δφ(l1,l2) small due to spin-0 Higgs



H→WW(*)→lνlν

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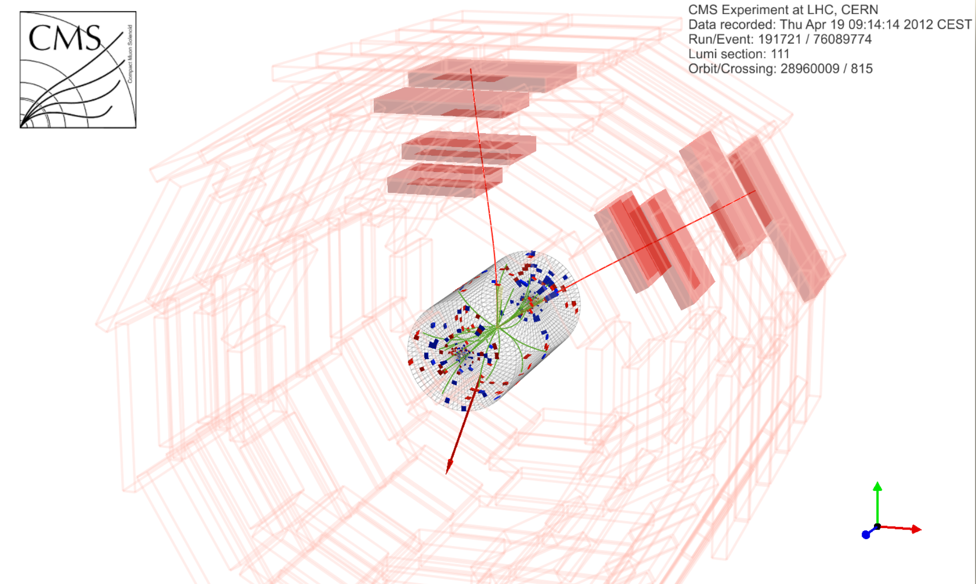
No full mass reconstruction possible

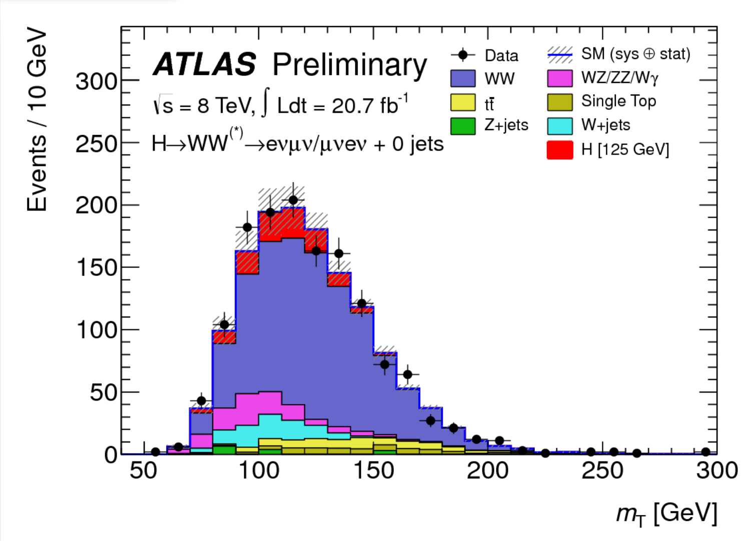
Discriminants

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (|\overrightarrow{P_T^{ll}} + \overrightarrow{E_T^{miss}}|)^2}$$

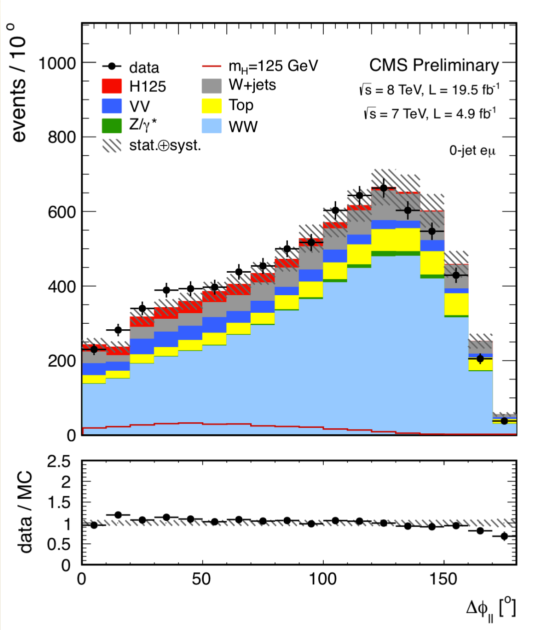
Δφ(l1,l2) small due to spin-0 Higgs



ATLAS

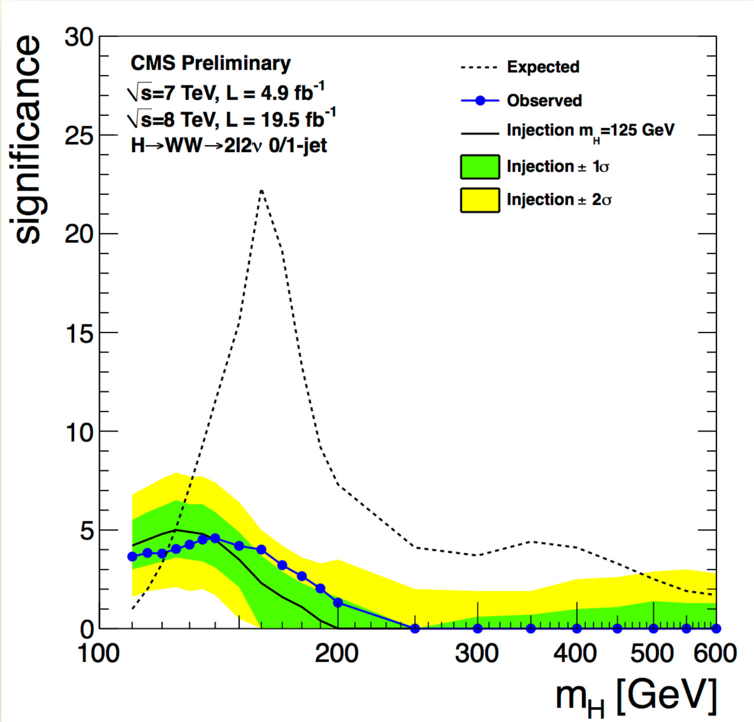


CMS



H→WW$^{(*)}$→lνlν

CMS

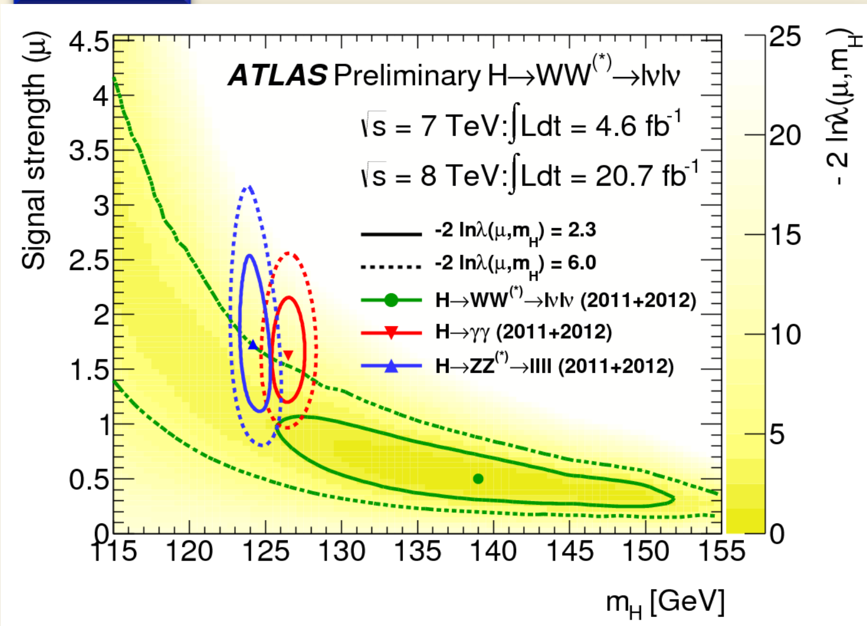


Significance: 4.0σ (expected 5.1σ from SM)

$$\mu = \frac{measured\ \ rate}{SM\ \ predicted\ \ rate} = 0.76 \pm 0.21$$ (m_H=125 GeV)

H→WW^(*)→lνlν

ATLAS



Significance: 3.8σ (expected 3.7σ from SM)

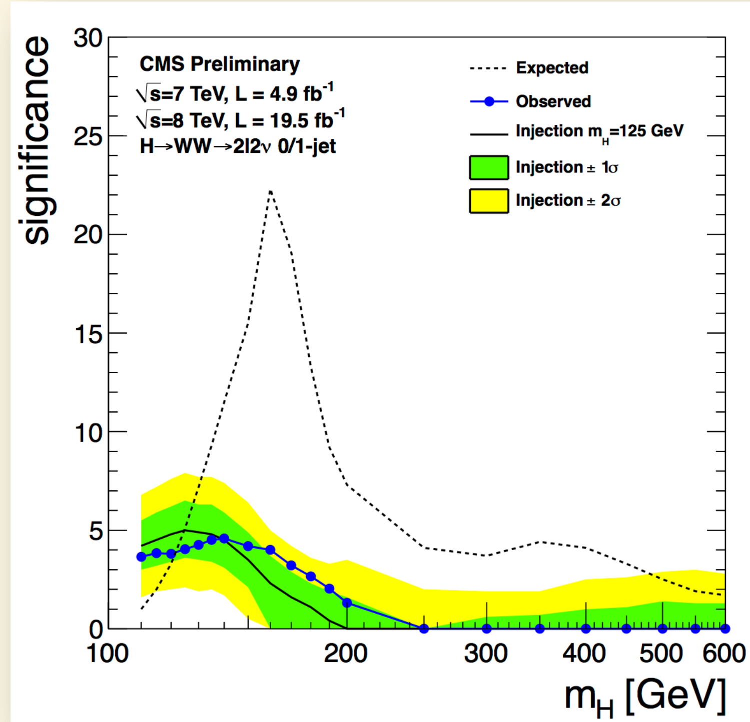
$$\mu = \frac{measured\ \ rate}{SM\ \ predicted\ \ rate} = 1.01 \pm 0.31$$ (m_H=125 GeV)

VBF production search :

Significance: 2.5σ (expected 1.6σ from SM)

$$\mu = \frac{measured\ \ rate}{SM\ \ predicted\ \ rate} = 1.66 \pm 0.79$$ (m_H=125 GeV)

CMS

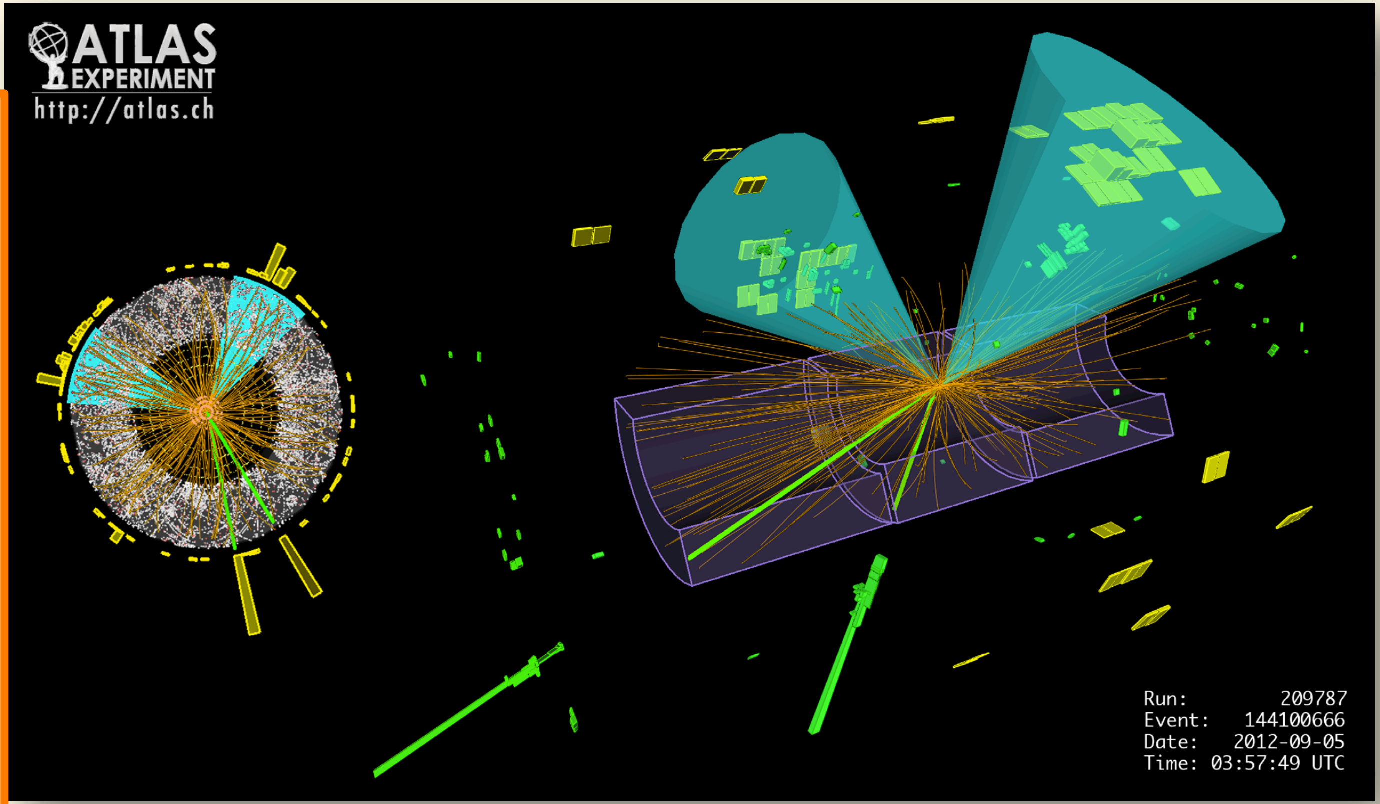


Significance: 4.0σ (expected 5.1σ from SM)

$$\mu = \frac{measured\ \ rate}{SM\ \ predicted\ \ rate} = 0.76 \pm 0.21$$ (m_H=125 GeV)

$H \to bb$

- Important rate $BR(H \to bb) \sim 58\%$ (m_H=125 GeV)
- Can provide direct constraint to Higgs couplings to fermions/ quarks
- Challenging due to high jet-background



Quick Overview

Use of associated V(W,Z) H production

- Topologies $W(l\nu)H \to bb$, $Z(\nu\nu)H \to bb$, $Z(ll)H \to bb$, $l=e,\mu$

Final states with b-jets, leptons, missing E_T

Analysis: Require two b-jets and classify events according to their missing E_T, $P_T(V)$

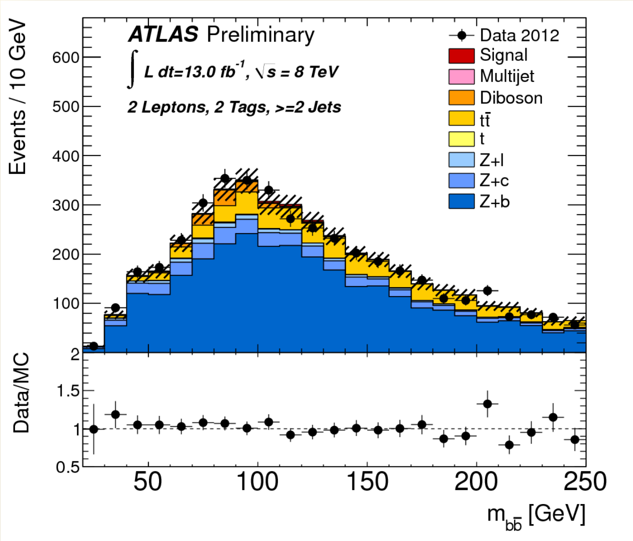
Discriminant: m_{bb} , (multivariate analysis combined in a BDT for CMS)

H→bb

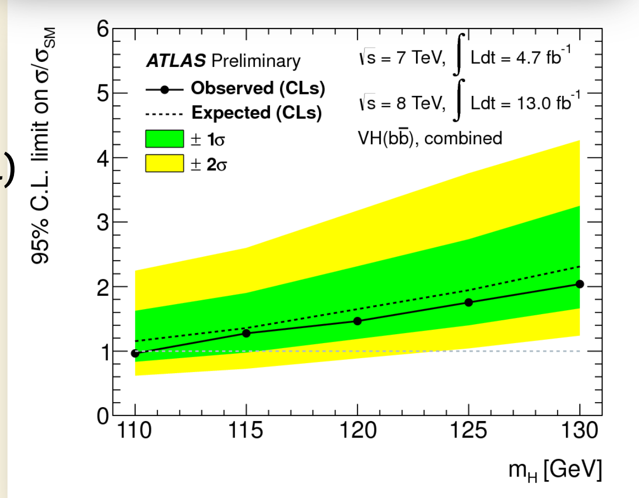
ATLAS

Subsample of dataset analyzed

ZH→llbb



Combination of
ZH→ννbb
ZH→llbb (l=e,μ)
WH→lνbb (l=e,μ)



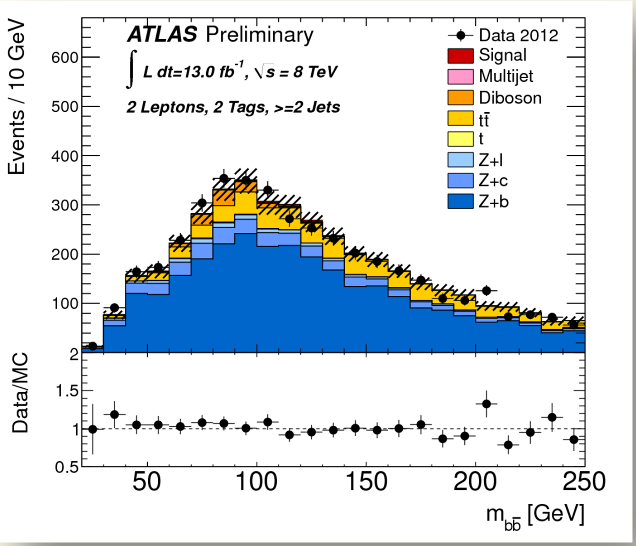
95% C.L limit on cross-section x BR:
Observed (expected)1.8xSM (1.9xSM)

H→bb

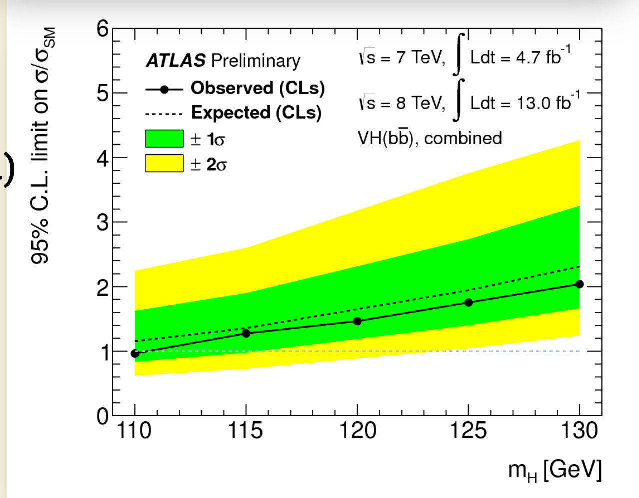
ATLAS

Subsample of dataset analyzed

ZH→llbb



Combination of
ZH→ννbb
ZH→llbb (l=e,μ)
WH→lνbb (l=e,μ)



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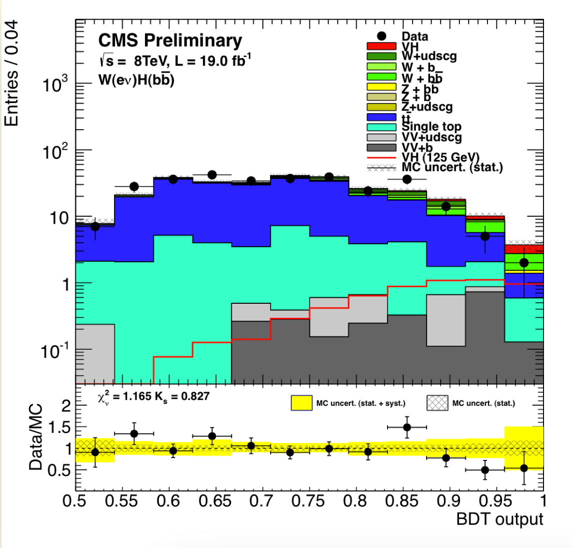
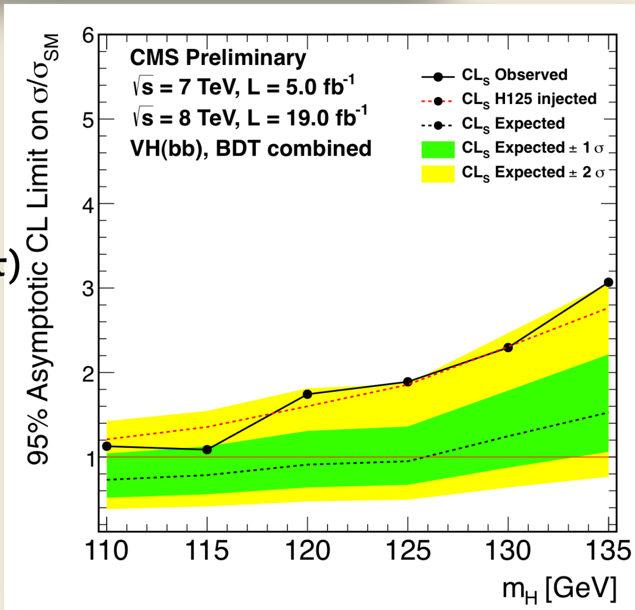


WH→eνbb

Combination of
ZH→ννbb
ZH→llbb (l=e,μ)
WH→lνbb (l=e,μ,τ)



95% C.L limit on cross-section x BR:
Observed (expected) 2.5xSM (1.2xSM)
Significance: 2.2σ (expected 2.1σ)

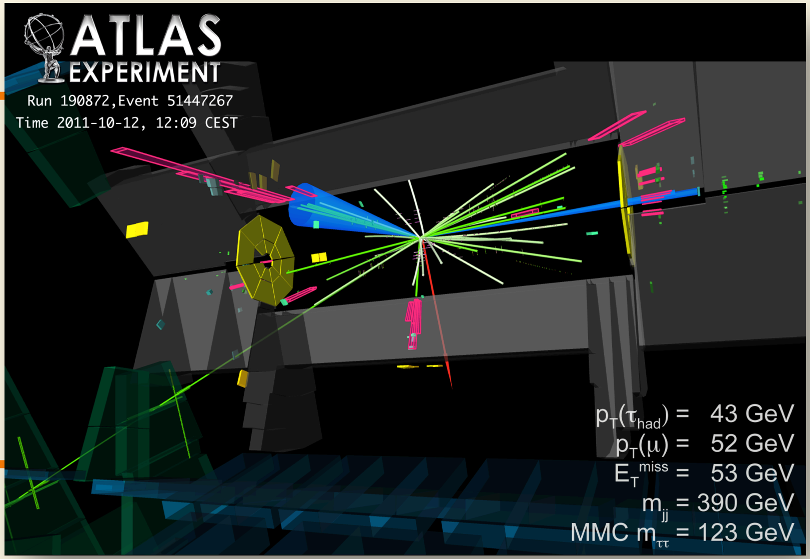
H→ττ

Important to study the H decays to fermions/leptons

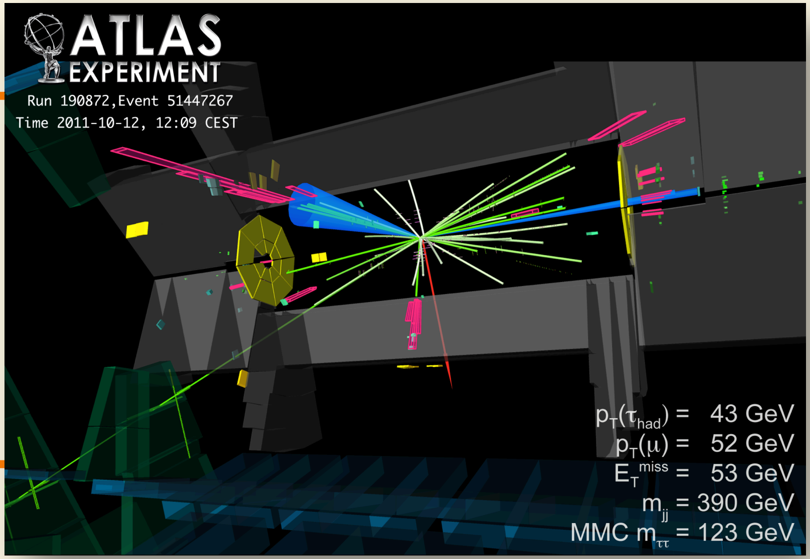
- 2nd in BR to fermions but high sensitivity due to experimental signature

Analysis strategy: Split events according to tau decay modes and Higgs production modes

Discriminant $m_{\tau\tau}$



H→ττ



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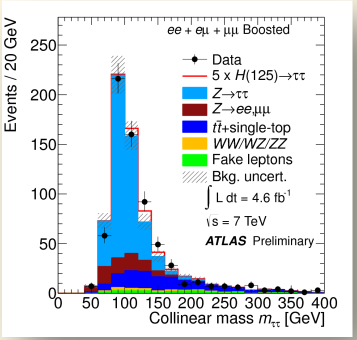
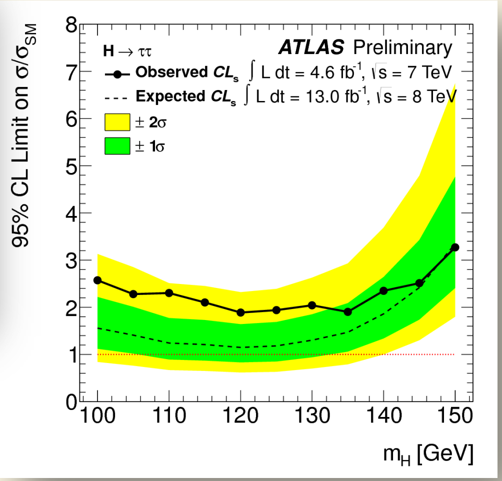
ATLAS

Subsample of dataset analyzed





95% C.L limit on cross-section x BR:
Observed (expected) 1.9xSM (1.2xSM)
Significance: 1.1σ (expected 1.7σ)

H→ττ

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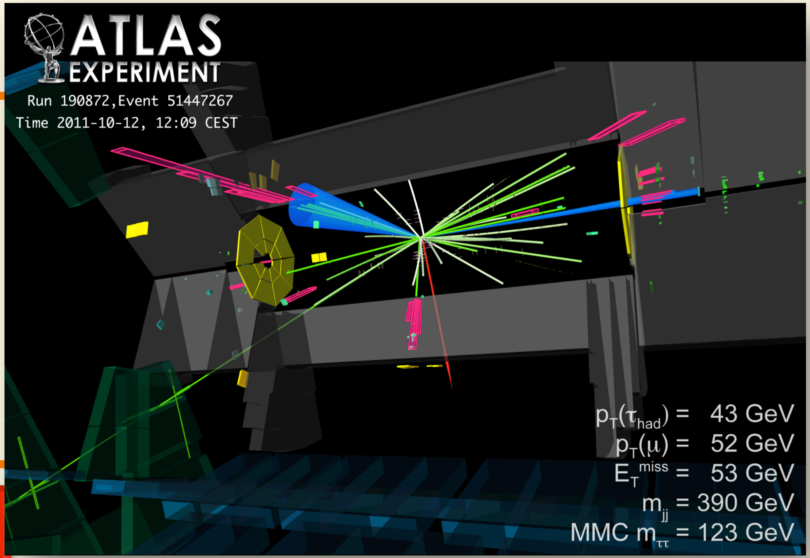
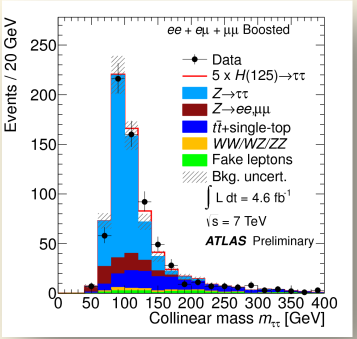
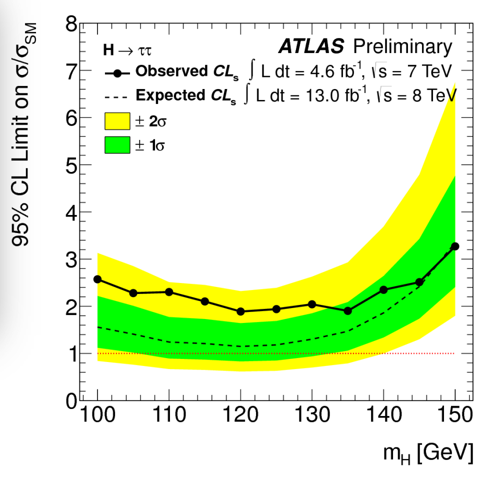


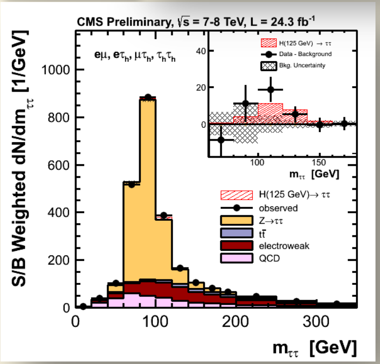
ATLAS

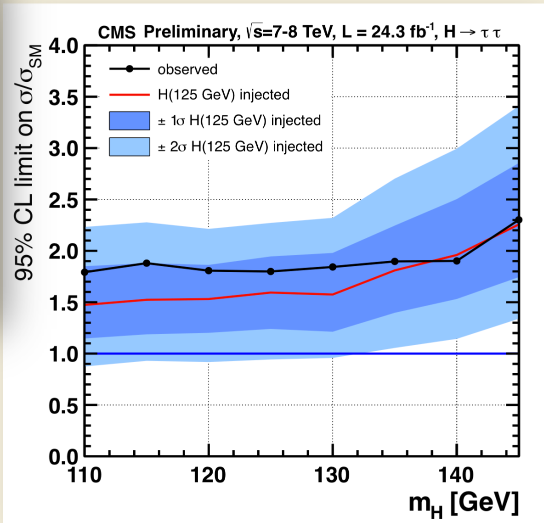
Subsample of dataset analyzed





CMS





95% C.L limit on cross-section x BR:
Observed (expected) 1.9xSM (1.2xSM)
Significance: 1.1σ (expected 1.7σ)

95% C.L limit on cross-section x BR:
Observed (expected) 1.8xSM (0.8xSM)
Significance: 2.8σ (expected 2.6σ)

What is next?

Is it a Higgs?
hints for physics BSM?

How do we know what we have found?

Combination

- Mass measurement
- Signal Strength

Properties of the new particle

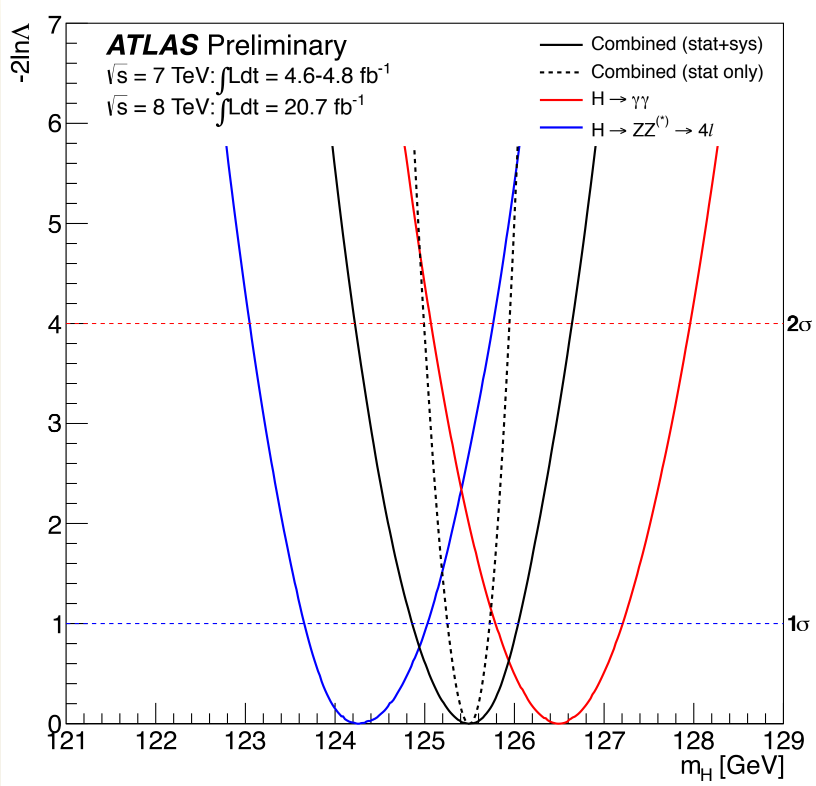
- Spin/parity studies
- Study of its couplings
  - to fermions and gauge bosons

Mass measurements

Combining measurement from H→γγ and H→4l decays

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

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



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

Mass measurements

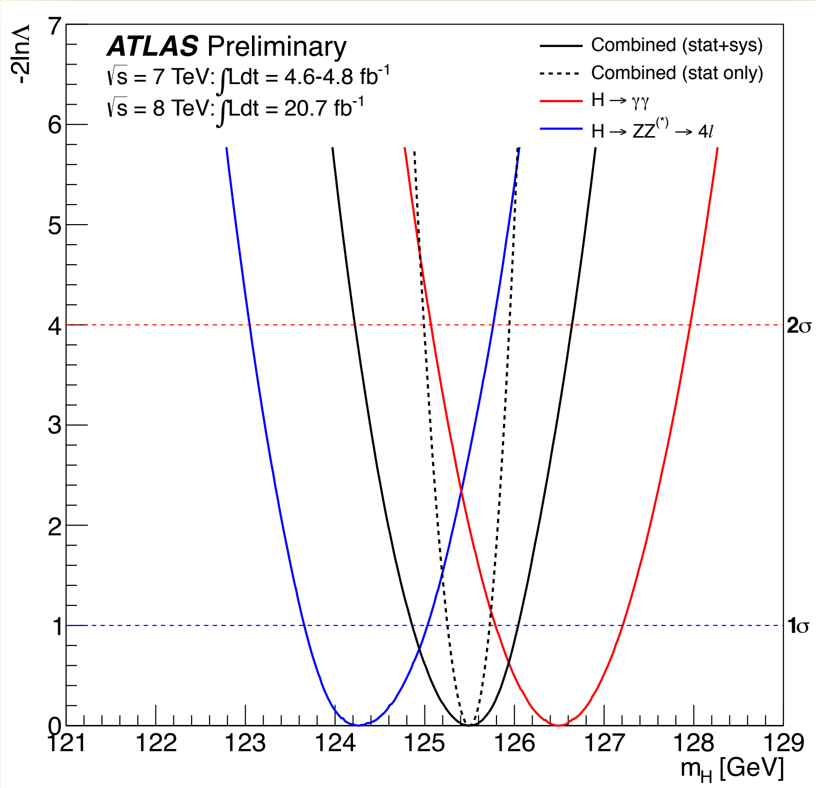
Combining measurement from H→γγ and H→4l decays

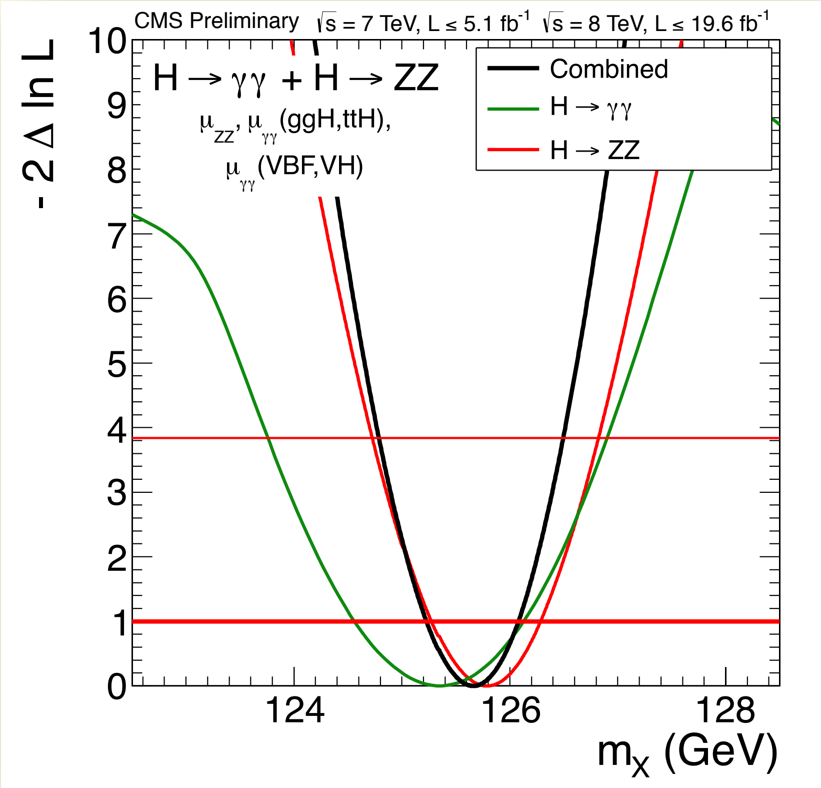
H→γγ $m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$ GeV

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

H→γγ $m_H = 125.4 \pm 0.5(\text{stat}) \pm 0.6(\text{syst})$ GeV

H→4l $m_H = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{syst})$ GeV





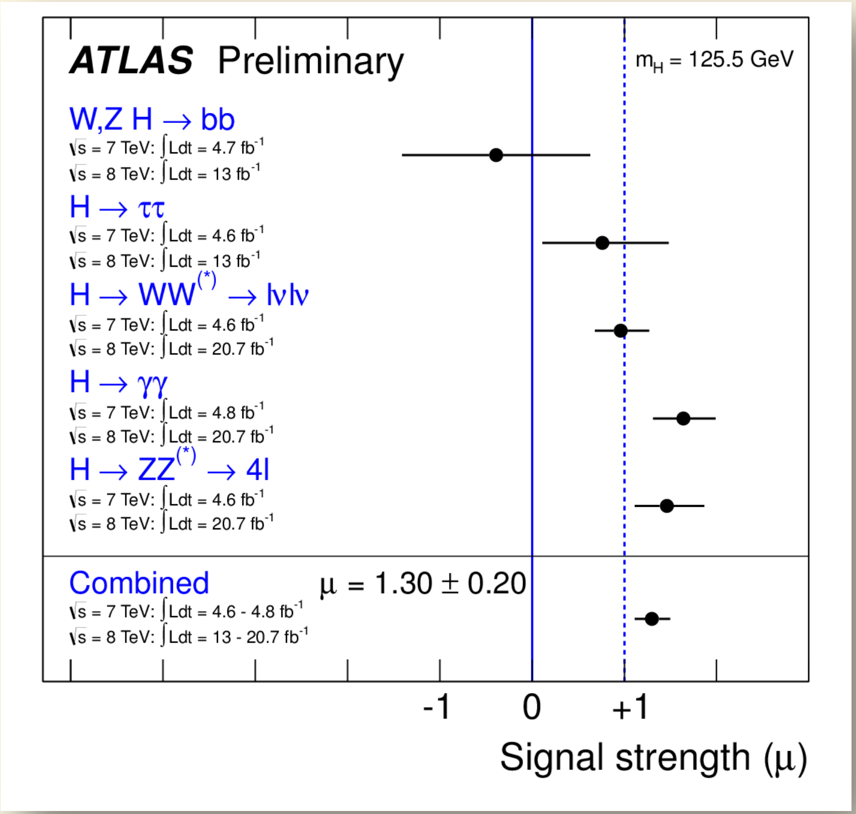
$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ GeV

$m_H = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst})$ GeV

Signal strength

Compatibility of the observed rate with the SM Higgs boson hypothesis

$$\mu = \frac{\sigma^{obs}}{\sigma^{SM}}, \ (\mu \approx 1 \ \text{means compatible with SM})$$



$$\mu = 1.30 \pm 0.13(stat) \pm 0.14(syst)$$

Signal strength

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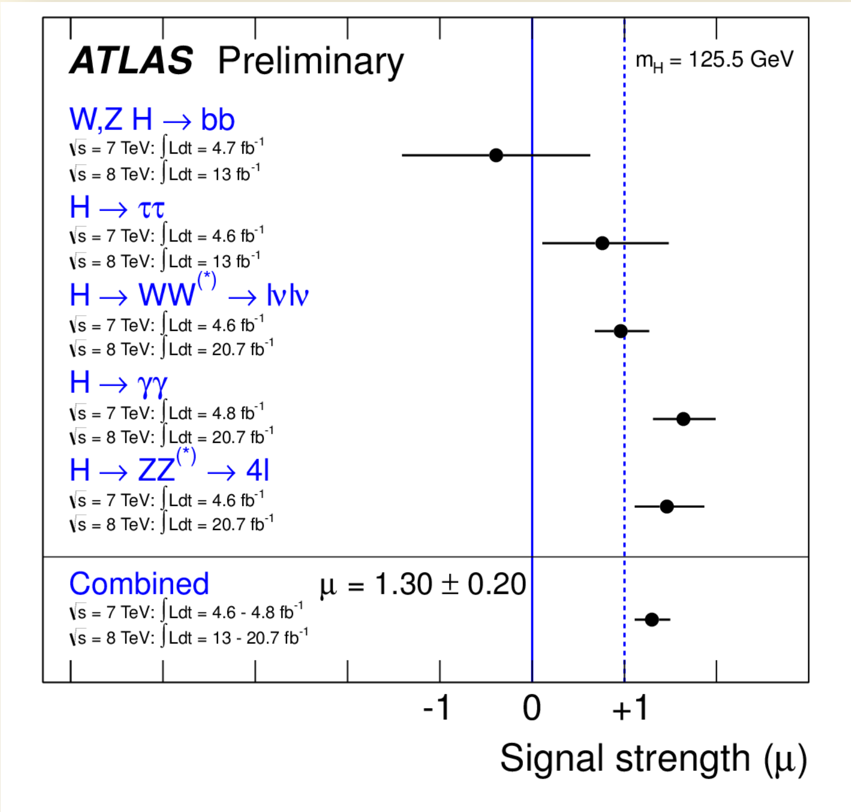
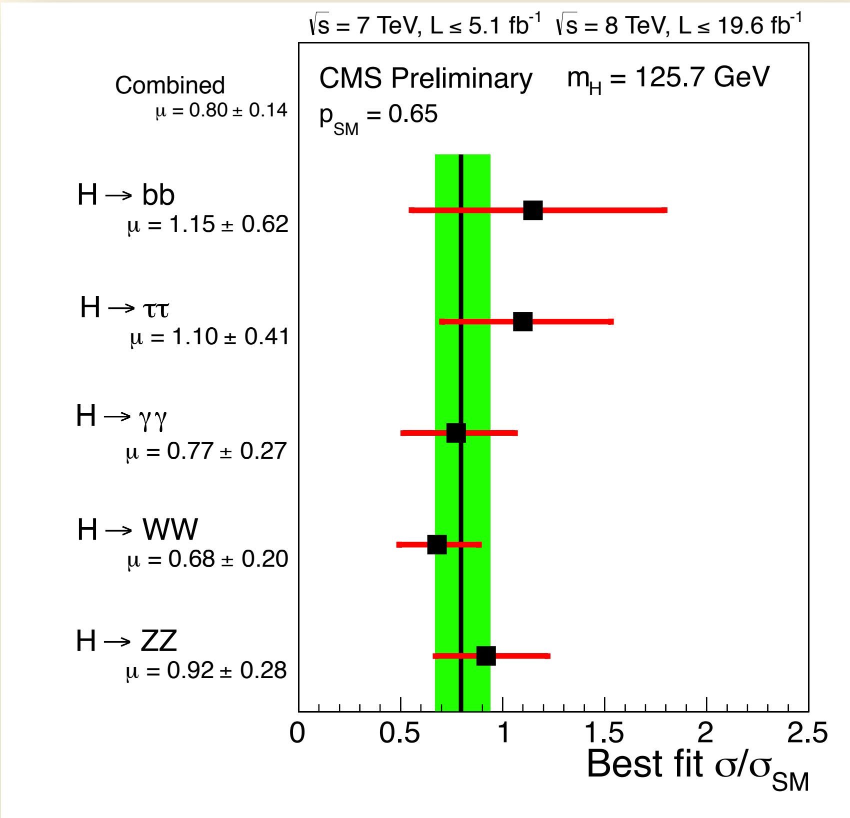




$$\mu = 1.30 \pm 0.13(stat) \pm 0.14(syst)$$

$$\mu = 0.80 \pm 0.14$$

Spin/CP studies / Introduction

- SM Higgs boson has $J^P = 0^+$
- The $H \rightarrow \gamma\gamma$ decay mode excludes spin-1 possibility (Landau Yang theorem)
- Observed decay channels into $\gamma\gamma$, ZZ^*, WW^* imply integer spin

Spin/CP studies / Introduction

- SM Higgs boson has $J^P = 0^+$
- The H→γγ decay mode excludes spin-1 possibility (Landau Yang theorem)
- Observed decay channels into γγ, ZZ*,WW* imply integer spin

- Studies of $J^P = 0^-, 1^{\pm}, 2^+$ possible states have been performed by ATLAS, CMS
  - H→ZZ* for 0^-
    - and a 0^+ beyond the SM coming from higher order operator (CMS)
  - H→WW, ZZ for $J=1^{\pm}$
  - H→γγ,ZZ*,WW* for 2^+
    - and a 2^- hybrid model (ATLAS)

• For $J^P=2^+$ a "graviton" like with minimal coupling model is used with an unknown fraction of the two production mechanisms qq and gg

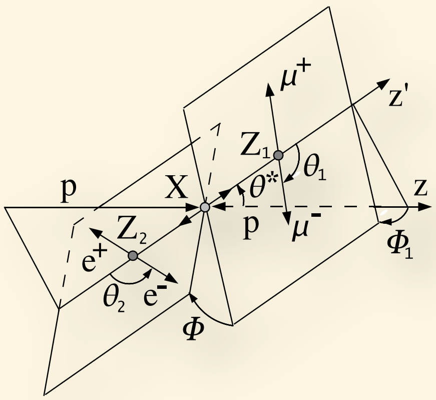
- Use of different discriminants (variables) per channel
  - Example: H→γγ (photon production angle in the γγ center-of mass frame)

Spin and parity studies

$H \rightarrow ZZ^* \rightarrow 4l$

- *Discriminants:* (multivariate analysis)
  - invariant masses m_{12}, m_{34} (Z, Z*)
  - 5 angles $\theta^*, \varphi_1, \varphi, \theta_1, \theta_2$
- kinematics exploited through discriminants

built from LO Matrix Element method from Vector Algebra (CMS) or analytical parameterizations/BDT (ATLAS)



Spin and parity studies

H→ZZ*→4l

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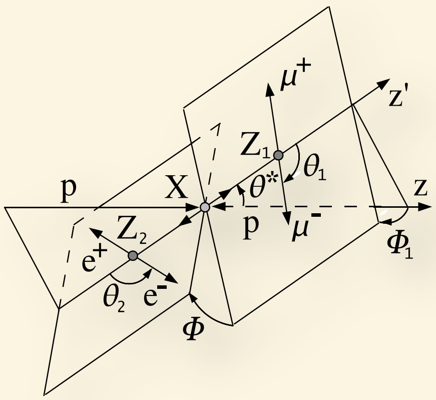
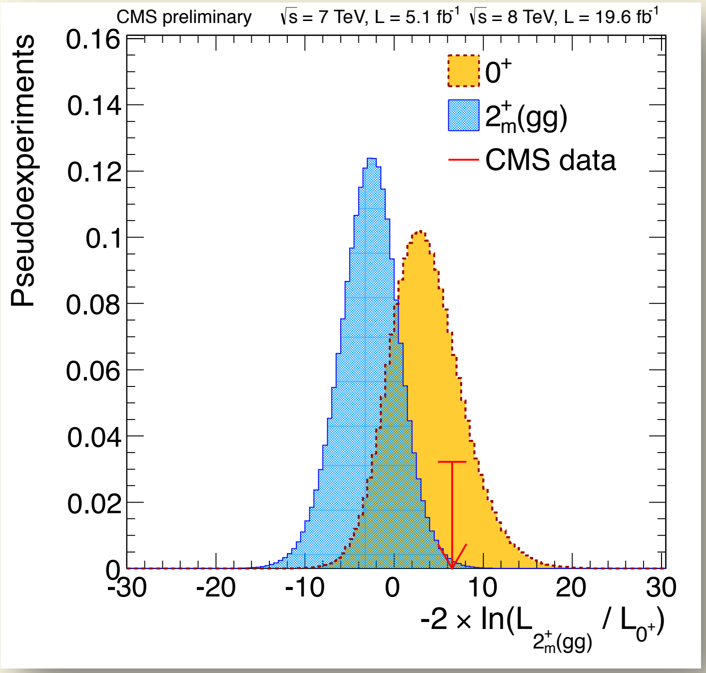
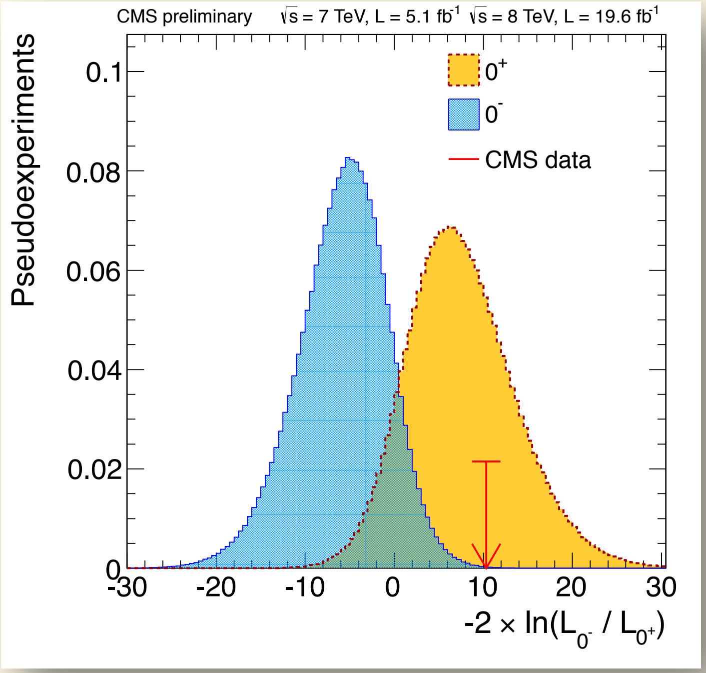


CMS





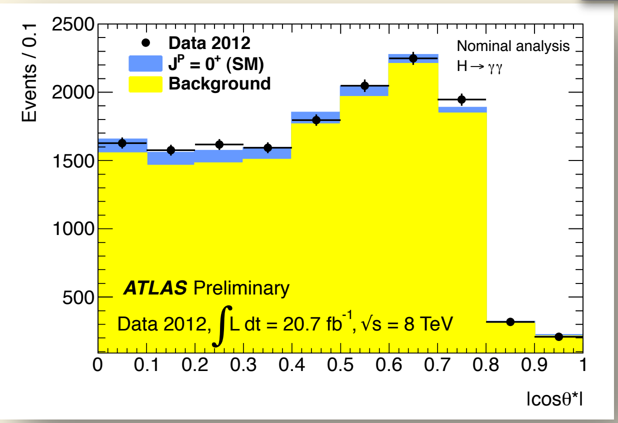
Data always compatible to 0^+ state and disfavor other spin CP states

Spin and parity studies

H→γγ : Compare SM spin 0^+ to a spin 2^+ "graviton like" with minimal couplings

ATLAS

Discriminant:
polar angle θ* of the γ's in the resonance rest frame (isotropic for spin-0)

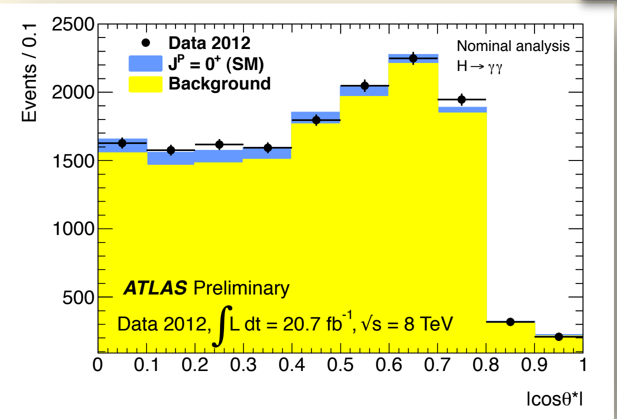


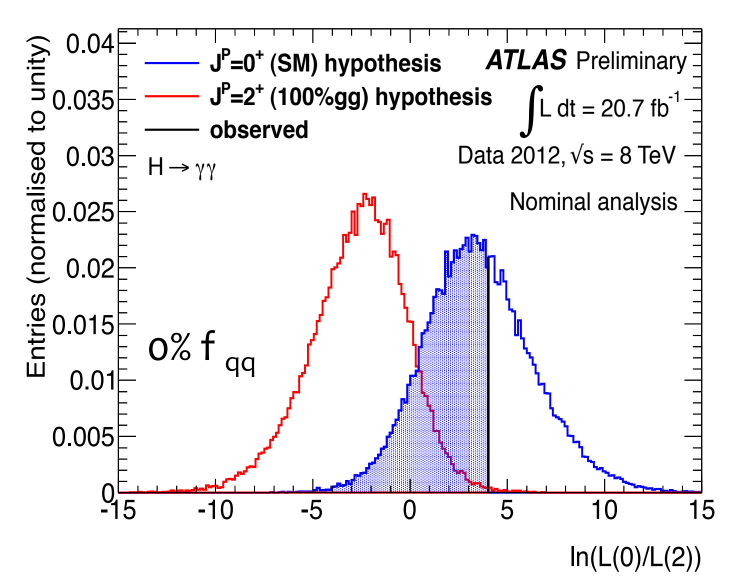
Spin and parity studies

H→γγ : Compare SM spin 0⁺ to a spin 2⁺ "graviton like" with minimal couplings

ATLAS

Discriminant:
polar angle θ* of the γ's in the resonance rest frame (isotropic for spin-0)





Sensitivity depends on $f_{qq} = \sigma_{qq}/(\sigma_{qq}+\sigma_{gg})$

Spin and parity studies

H→γγ : Compare SM spin 0⁺ to a spin 2⁺ "graviton like" with minimal couplings

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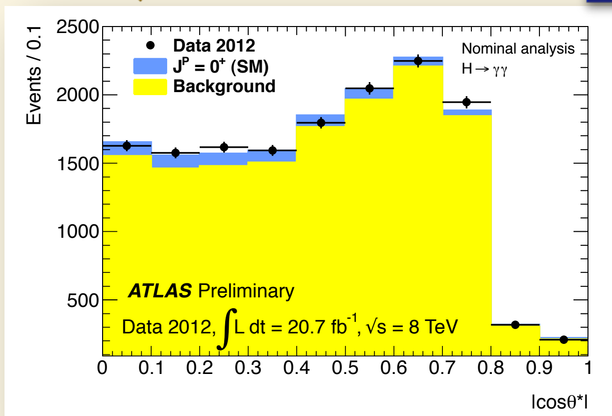
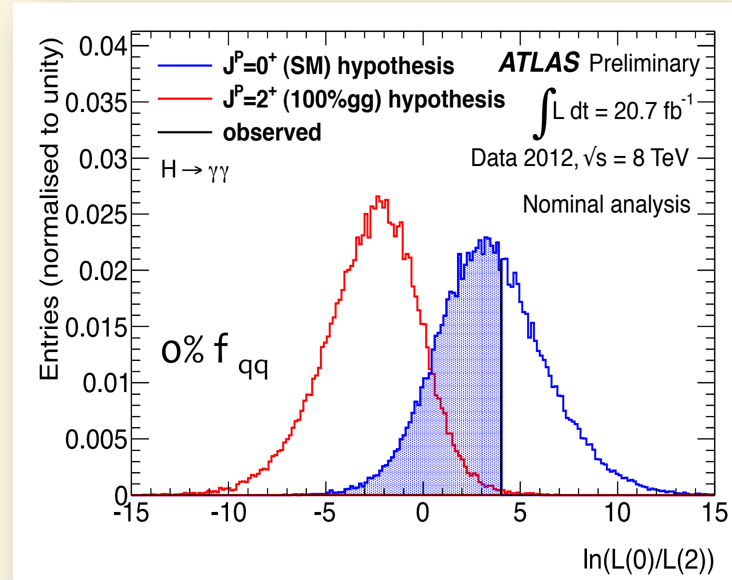
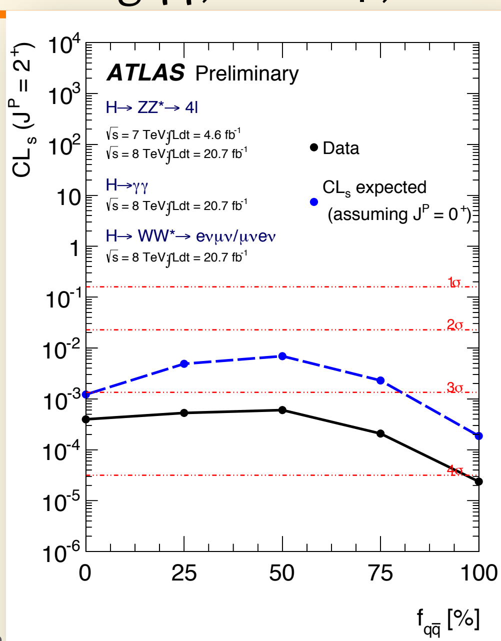




Sensitivity depends on $f_{qq} = \sigma_{qq}/(\sigma_{qq}+\sigma_{gg})$

Combining γγ, ZZ*→4l, WW*→eνμν

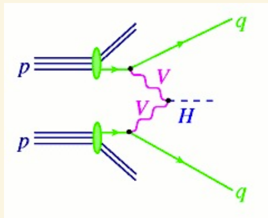


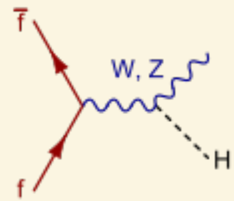
Observation compatible to spin-0⁺
Exclusion of spin 2⁺ at >99 %C.L

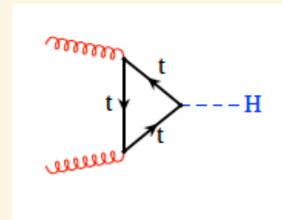
Strength of different production mechanisms

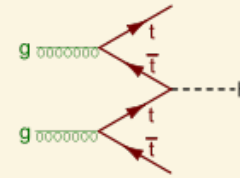
The main Higgs production mechanisms depend on V-H or top-H couplings

V-H couplings









top-H couplings

Strength of different production mechanisms

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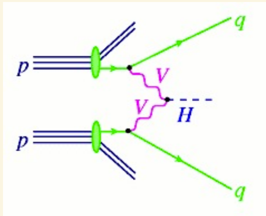
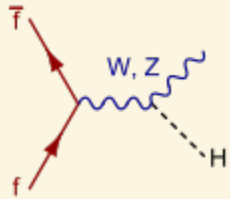
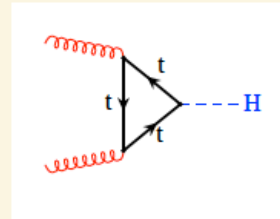
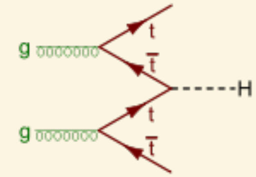
V-H couplings









top-H couplings

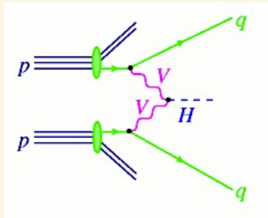
Define signal strengths relative to production mechanisms:

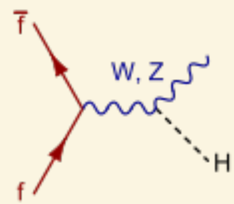
- $\mu_{ggF+ttH}$: for production modes mediated by couplings to fermions
- μ_{VBF+VH} : for production modes mediated by couplings to bosons

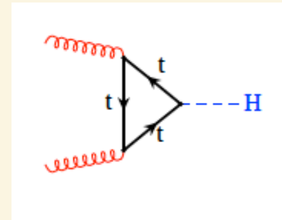
Strength of different production mechanisms

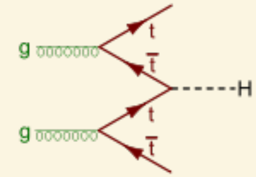
The main Higgs production mechanisms depend on V-H or top-H couplings

V-H couplings









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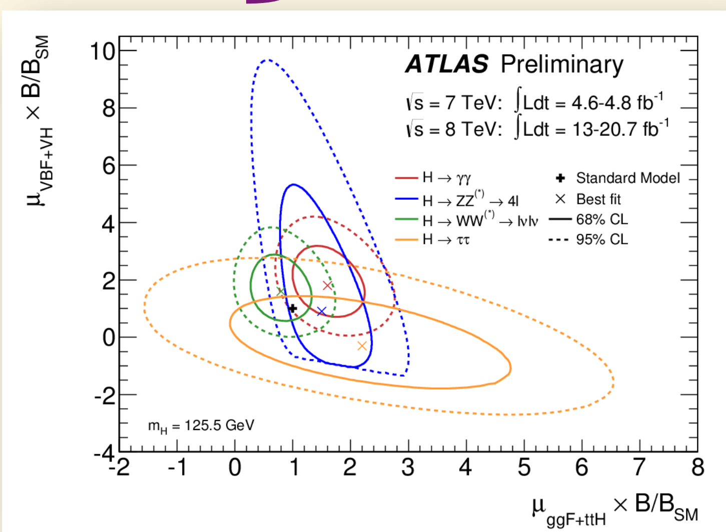
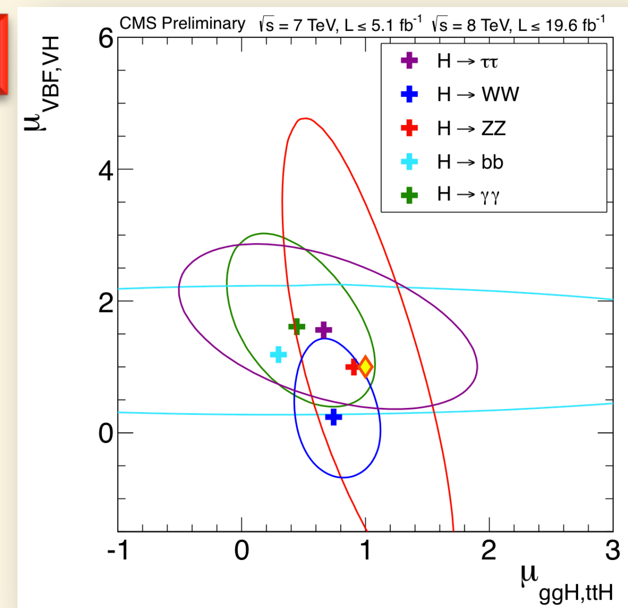
ATLAS



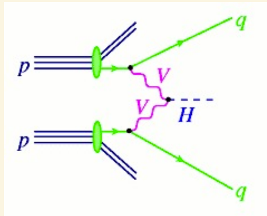
CMS

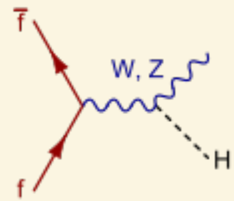


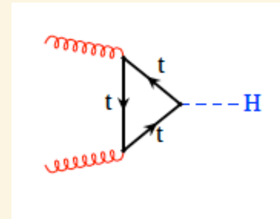
Strength of different production mechanisms

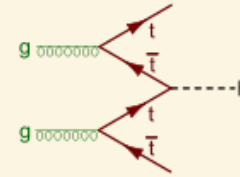
The main Higgs production mechanisms depend on V-H or top-H couplings

V-H couplings







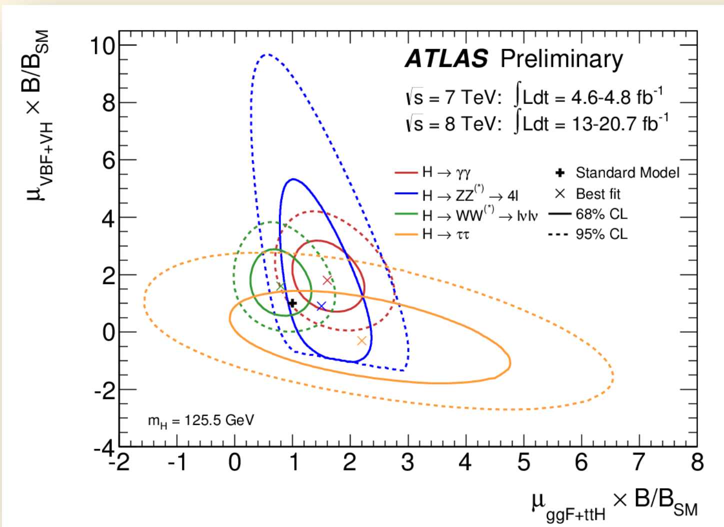


top-H couplings

Define signal strengths relative to production mechanisms:

- $\mu_{ggF+ttH}$: for production modes mediated by couplings to fermions
- μ_{VBF+VH} : for production modes mediated by couplings to bosons

ATLAS



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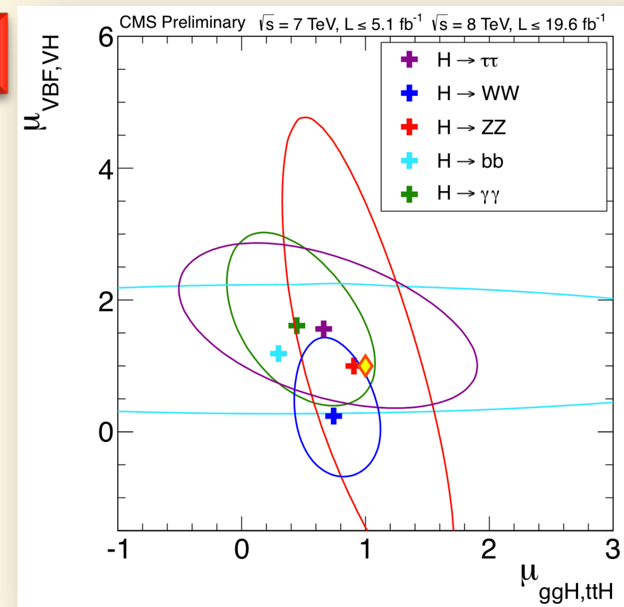


~3σ evidence for non vanishing VBF production

Results of both experiments compatible with SM prediction

Coupling studies

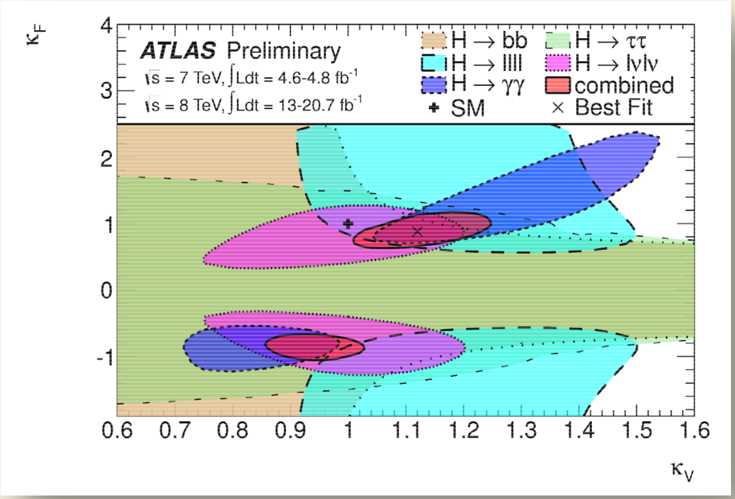
Basic assumptions:

- Only one “narrow“ resonance
- Tree level scaling of couplings

Example:

Test of scaling factors of couplings to fermions (κ_F) and W/Z bosons (κ_V) keeping the loop structure as in SM and check the correlations

ATLAS



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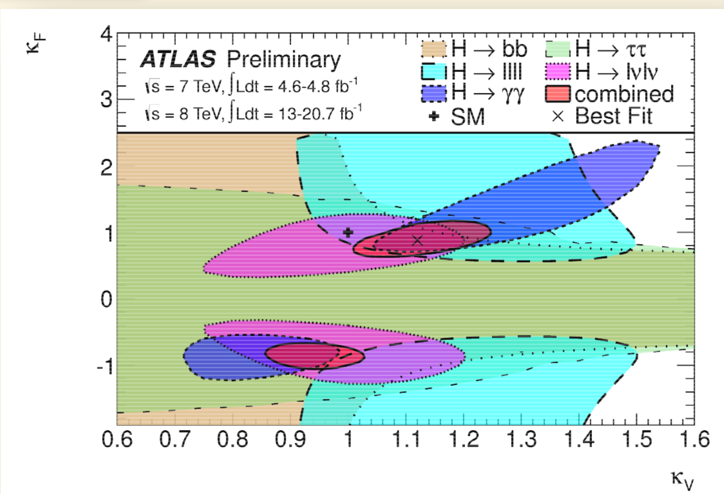
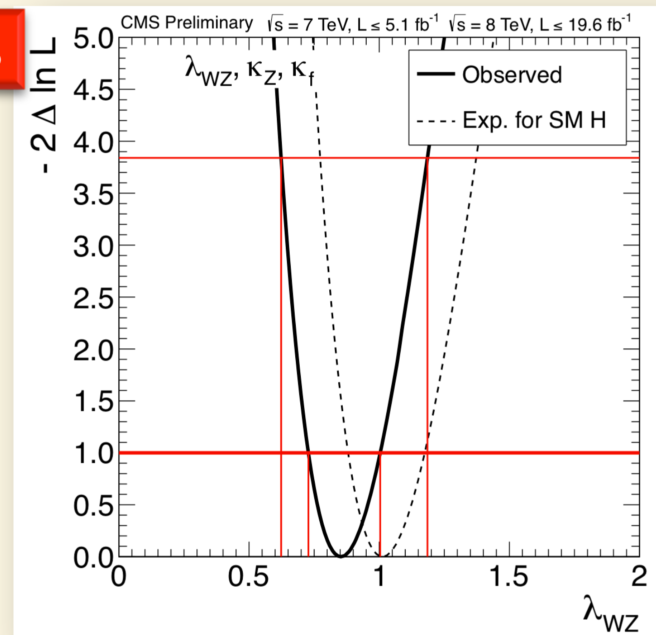


<u>*Custodial symmetry:*</u>
- $SU(2)_{L+R}$ symmetry in the Higgs sector: Tree level mass m_Z/m_W and H-V coupling ratios g_Z/g_W protected from large rad. corrections
- Test it by introducing κ_W, κ_Z scaling factors that modify the SM Higgs boson couplings to W,Z
- Ratio of $\lambda_{WZ} = \kappa_W / \kappa_Z$ =1 in SM

CMS

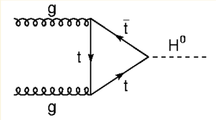


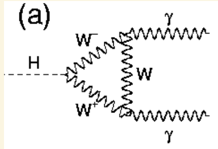
95% CL interval for λ_{WZ} = [0.62 1.19] consistent with SM

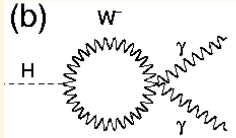
Test of new physics in loops

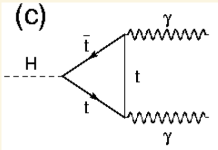
New particles in the loops:

$gg \rightarrow H$, $H \rightarrow \gamma\gamma$ processes induced by loop diagrams









Sensitive to new particles beyond the SM in the loop

Assuming SM Higgs boson but allowing for new particles in the loop

- κ_g (κ_γ) effective couplings to gluons (photons)

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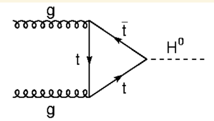

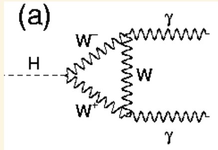

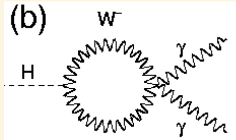

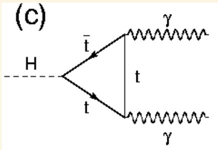

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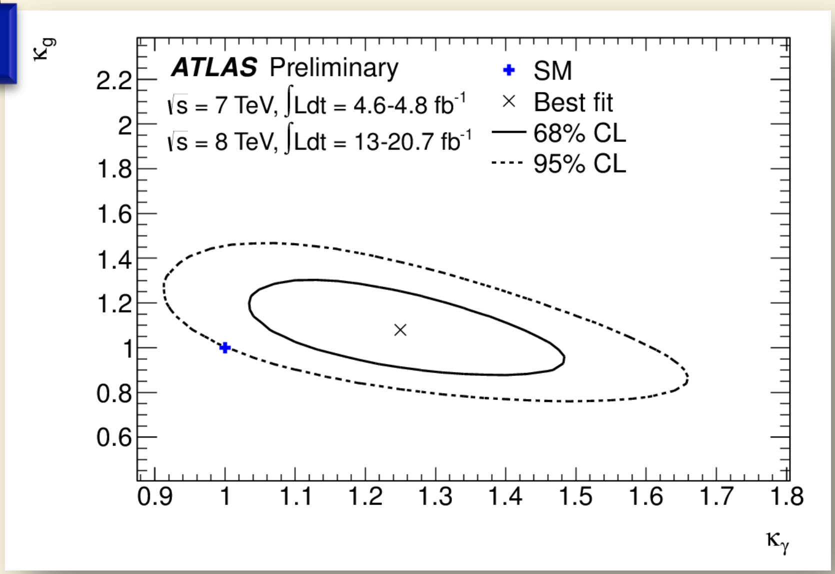

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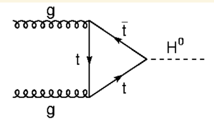

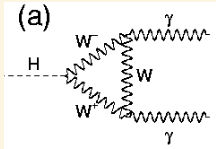

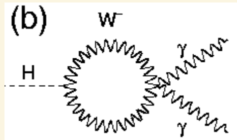

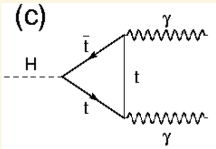

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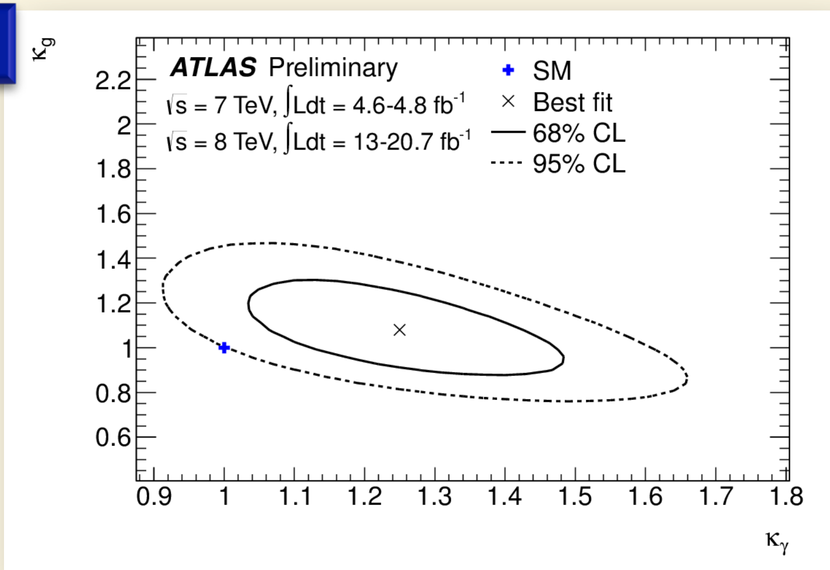

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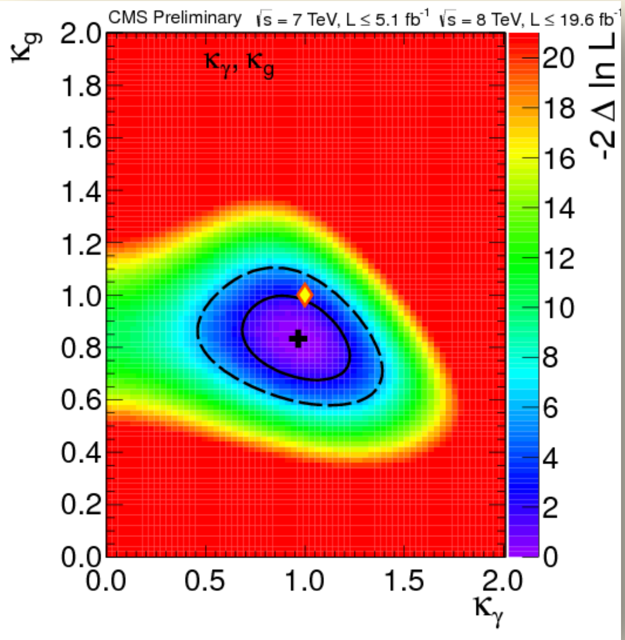

Results compatible with the SM strength

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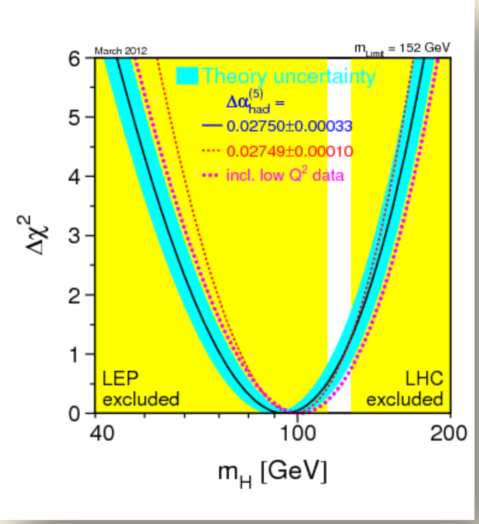

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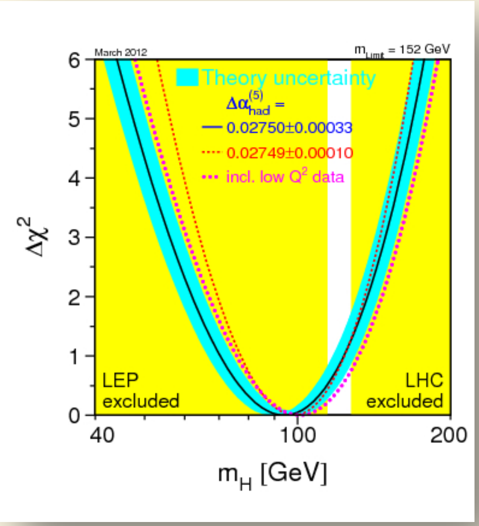

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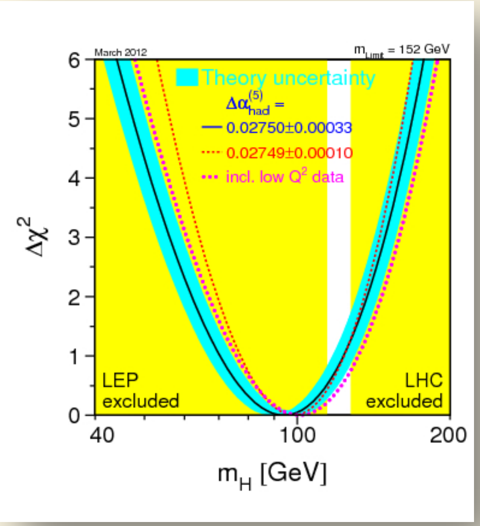

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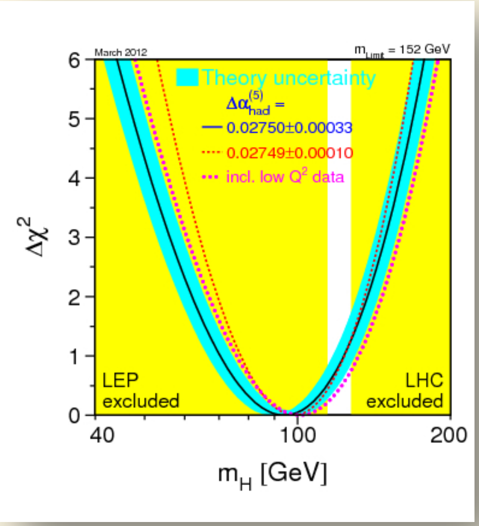

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" Results indicate that the particle discovered at CERN is a Higgs boson"

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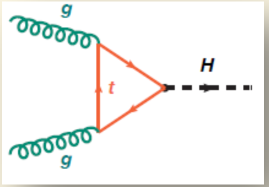

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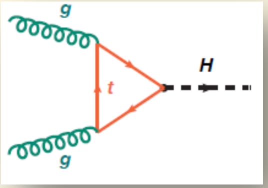

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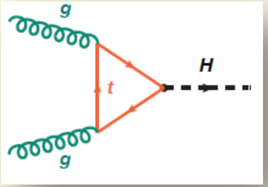

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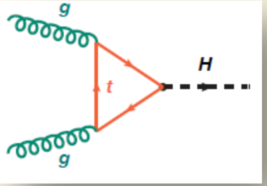

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Certainly not the end of this exciting adventure

✓ Run II period starting at 2015 with more statistics and at higher energy will allow us to do more precise studies