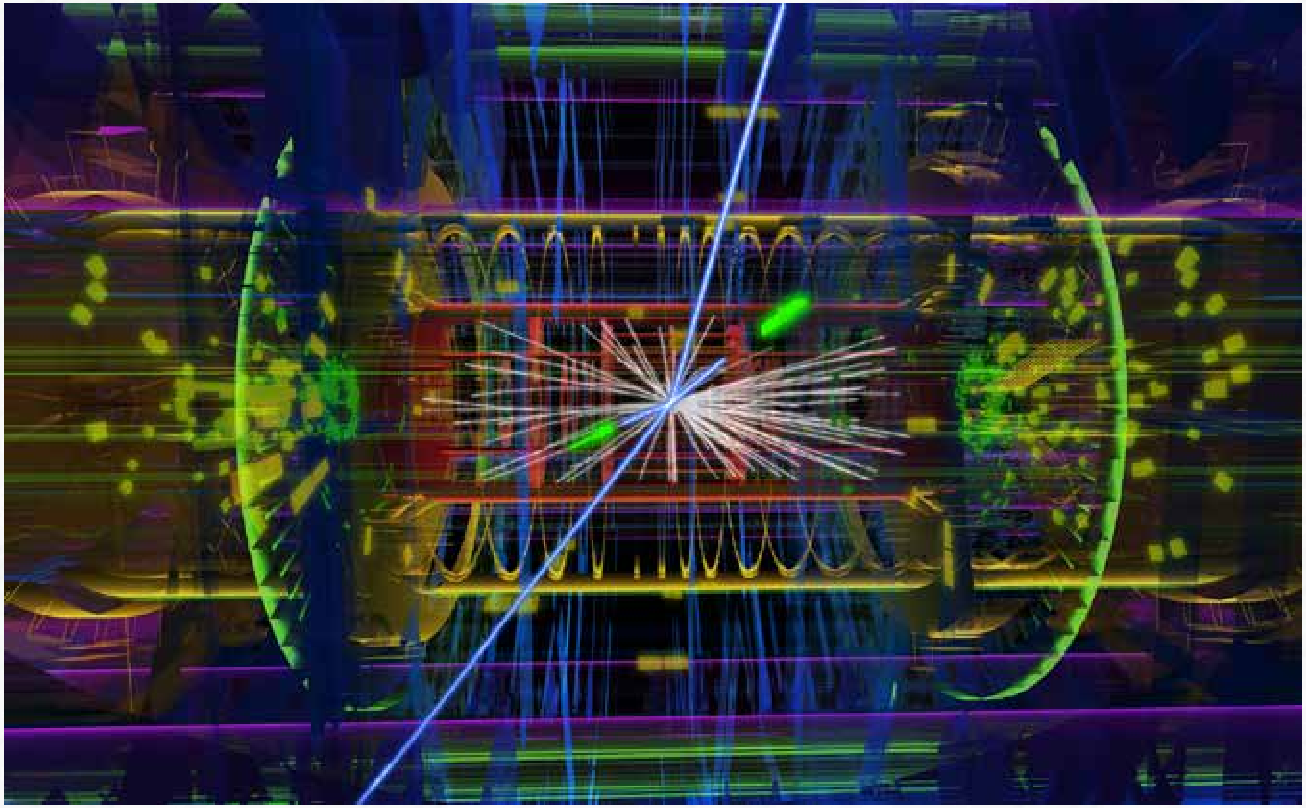
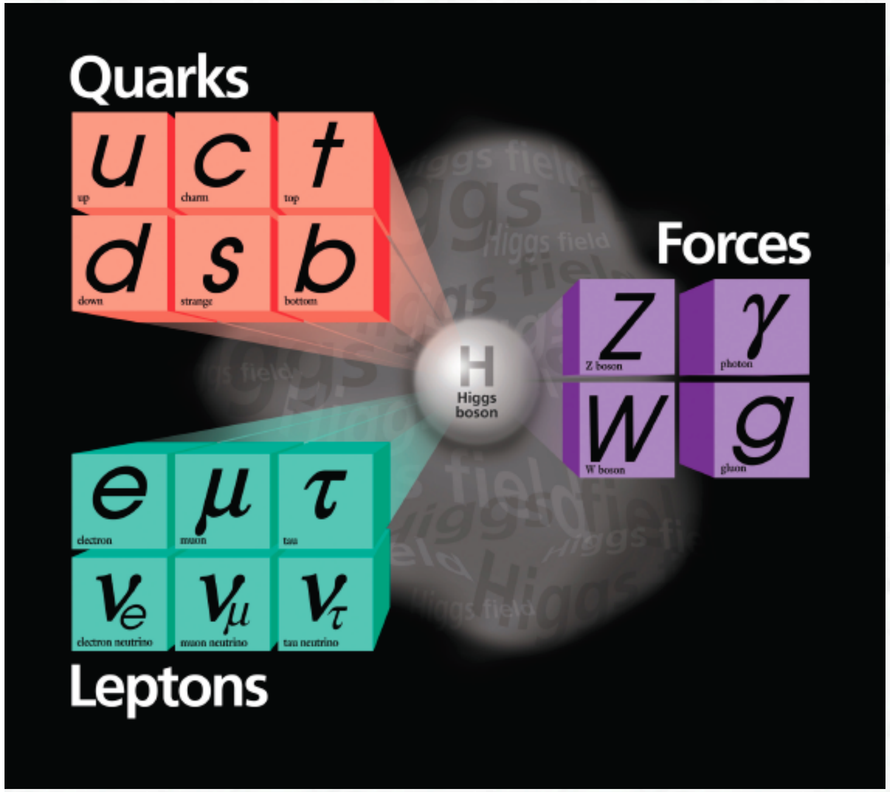
Discovery of a New Boson at the LHC

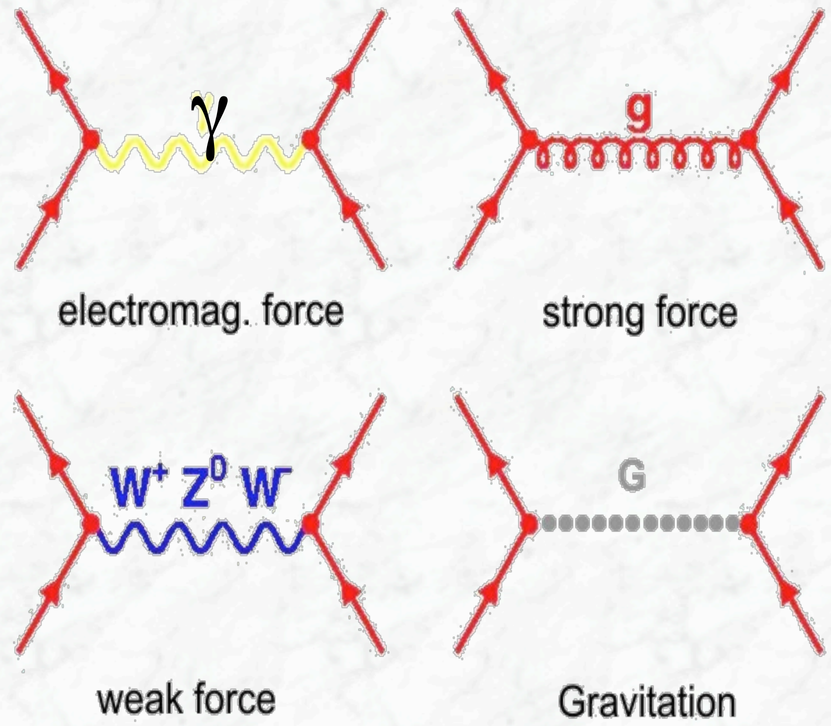
- Or Evidence for the Higgs boson? -



Karl Jakobs
Physikalisches Institut
Universität Freiburg

The Standard Model of Particle Physics





(i) Constituents of matter: quarks and leptons

(ii) Four fundamental forces
(described by quantum field theories, except gravitation)

(iii) The Higgs field (problem of mass)

Why do we need the Higgs boson?

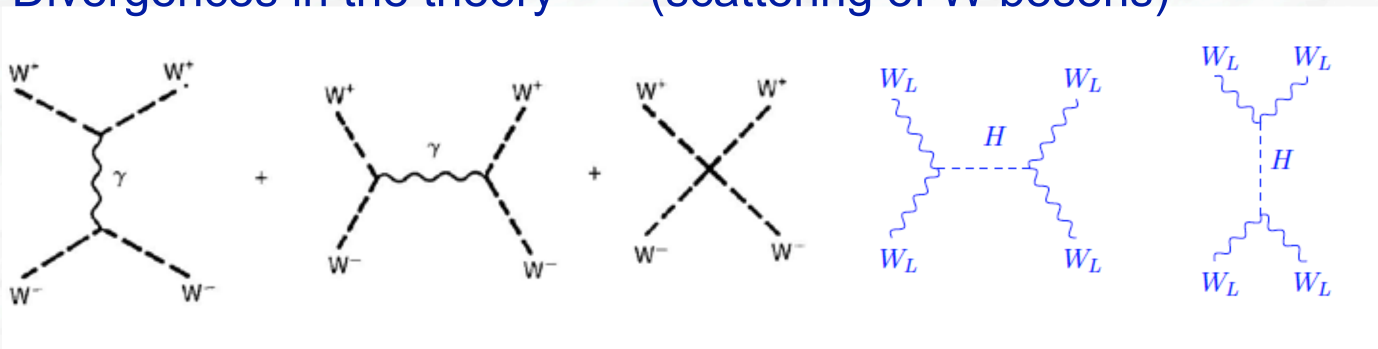
The Higgs boson enters the Standard Model to solve two fundamental problems:

- Masses of the vector bosons W and Z and fermions

Experimental results: $M_W = 80.399 \pm 0.023$ GeV / c^2
$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

Standard Model gauge theories require massless gauge fields

- Divergences in the theory (scattering of W bosons)



$$-iM(W^+W^- \to W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \to \infty$$

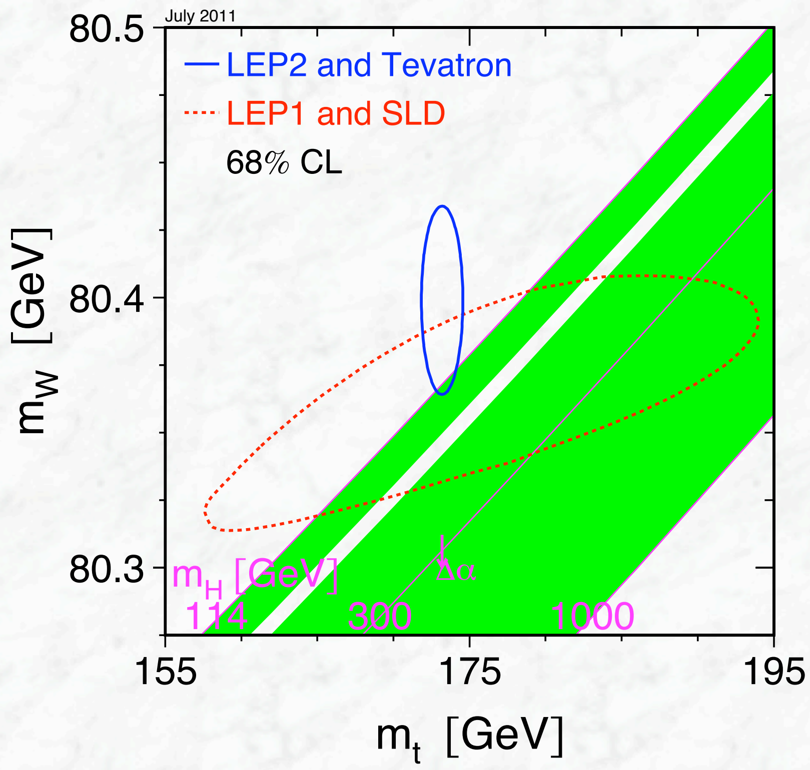
(no Higgs boson)

$$-iM(W^+W^- \to W^+W^-) \sim m_H^2 \quad \text{for} \quad s \to \infty$$

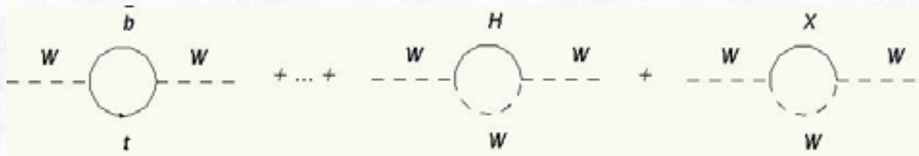
(with Higgs boson)

Constraints on the Higgs boson mass (before LHC)

- $m_H > 114.4$ GeV/c^2 from direct searches at LEP
- $m_H < 156$ GeV/c^2 .or. $m_H > 177$ GeV/c^2 from direct searches at the Tevatron



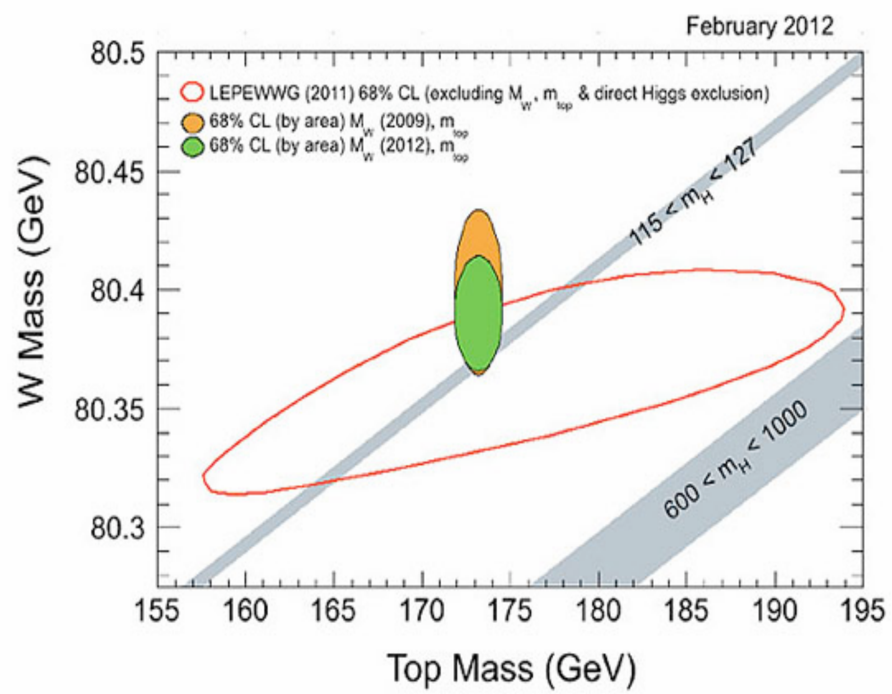
July 2011



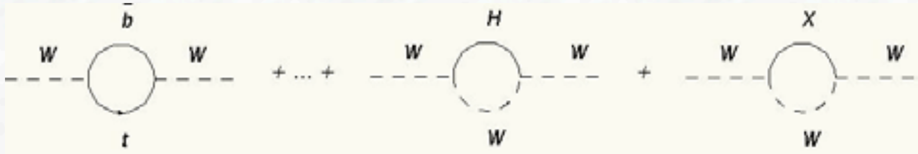
$m_H = 92^{+34}_{-26}$ GeV/c^2
$m_H < 161$ GeV/c^2 (95 % C.L.)

- Indirect constraints from precision measurements (quantum corrections)

Constraints on the Higgs boson mass (Feb. 2012)



February 2012



m_H = $92\ ^{+34}_{-26}$ GeV/c^2

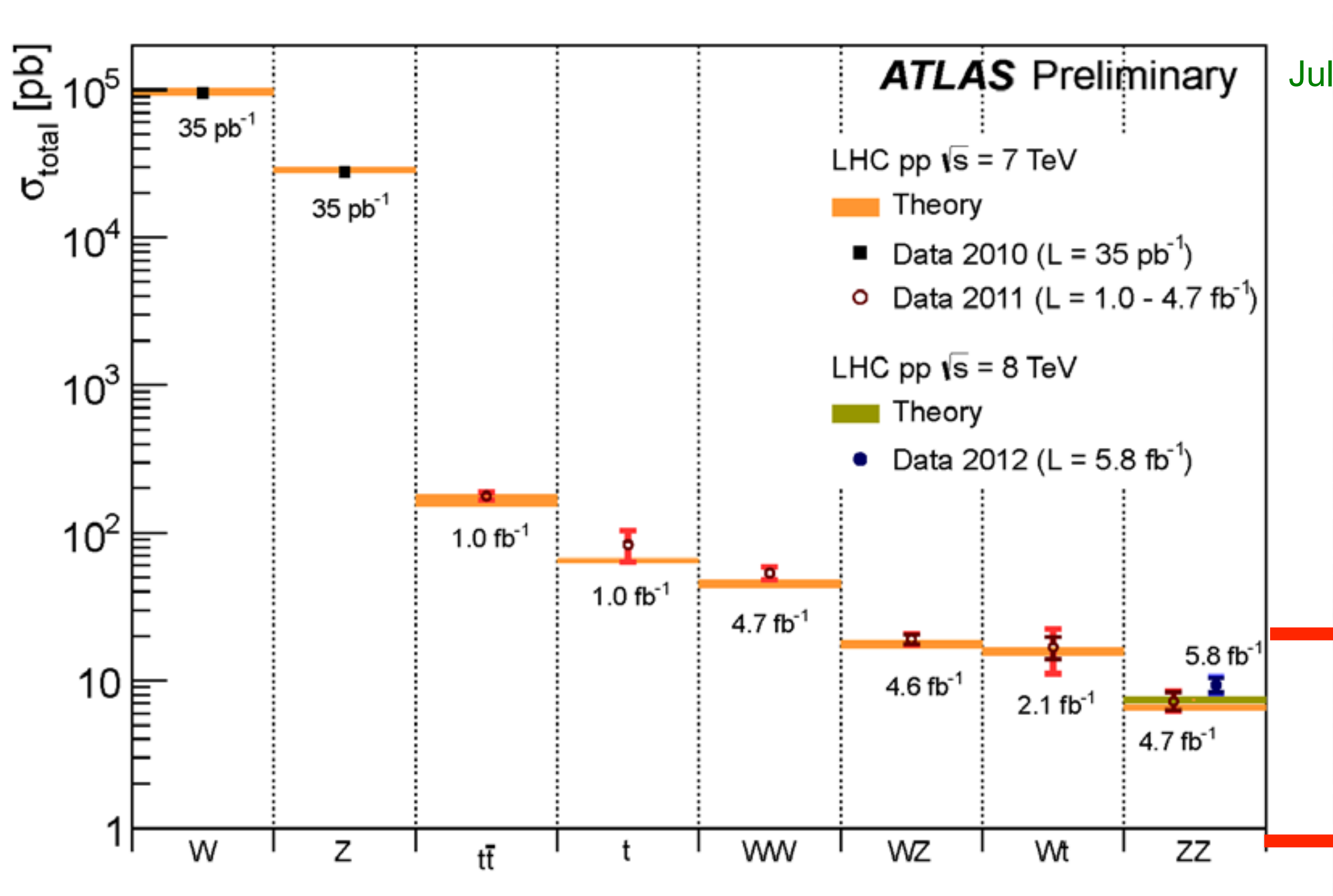
115 GeV/c^2 < m_H < 161 GeV/c^2 (95 % C.L.)

Two impressive results (2011/12):

- LHC has ruled out a huge mass range, after only ~2 years of data taking
  (only a narrow mass range left open at low mass)

- Impressive precision in m_W (and m_t) achieved at the Tevatron
  (might provide the basis for the ultimate test of the Standard Model)

The Standard Model at the LHC



July 2012

H (20pb)

$H \rightarrow ZZ$ (0.5 pb)

4th July 2012

Higgs boson-like particle discovery claimed at LHC

COMMENTS (1665)

By Paul Rincon
Science editor, BBC News website, Geneva

The moment when Cern director Rolf Heuer confirmed the Higgs results

Cern scientists reporting from the Large Hadron Collider (LHC) have claimed the discovery of a new particle consistent with the Higgs boson.

4. Juli 2012

Frankfurter Allgemeine
Wissen

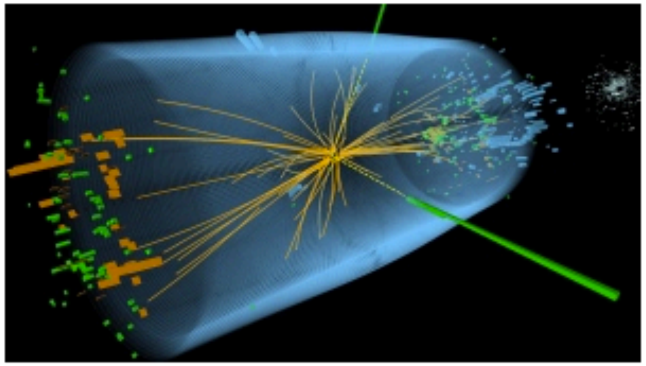
Erfolg bei Suche nach Higgs-Teilchen

„Eine wissenschaftliche Sensation“

04.07.2012 · Wissenschaftler im Teilchenforschungszentrum Cern in Genf glauben, das jahrzehntelang gesuchte Higgs-Teilchen gefunden zu haben. Monatelang war im weltgrößten Teilchenbeschleuniger danach gefahndet worden – jetzt liegen die bahnbrechenden Ergebnisse vor.

Von MANFRED LINDINGER

Selten waren die Erwartungen am europäischen Forschungszentrums Cern bei Genf, dem Mekka der Teilchenphysik, so groß wie an diesem Mittwoch morgen. Alle drängten in den großen Hörsaal und wollten dem Seminar beiwohnen, zu dem der Generaldirektor des Cern, Rolf-Dieter Heuer, eingeladen hatte. Im Hörsaal saßen viele Veteranen des Cern,



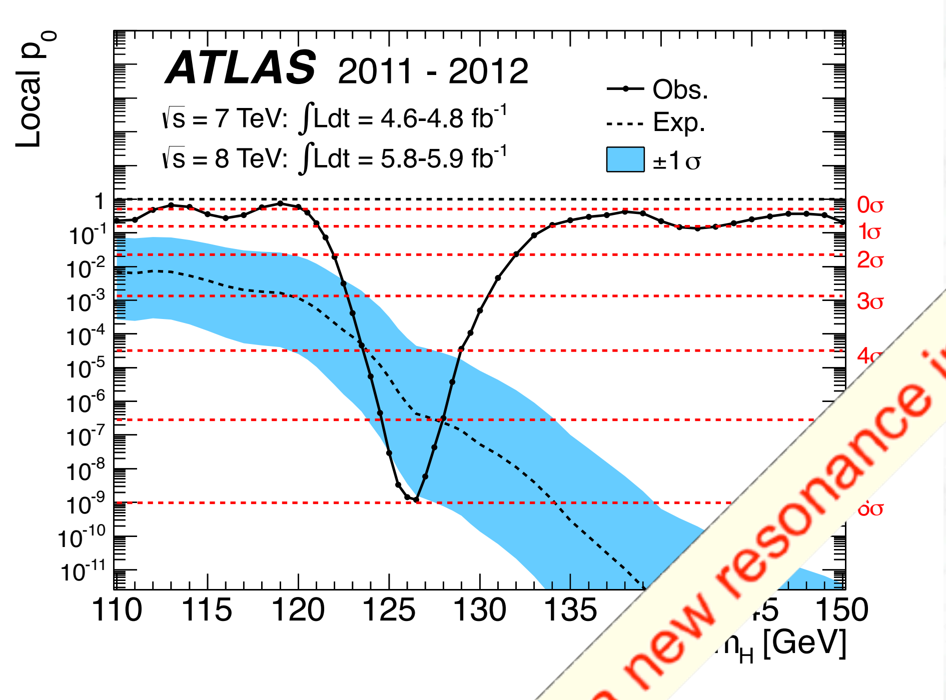
© DAPD

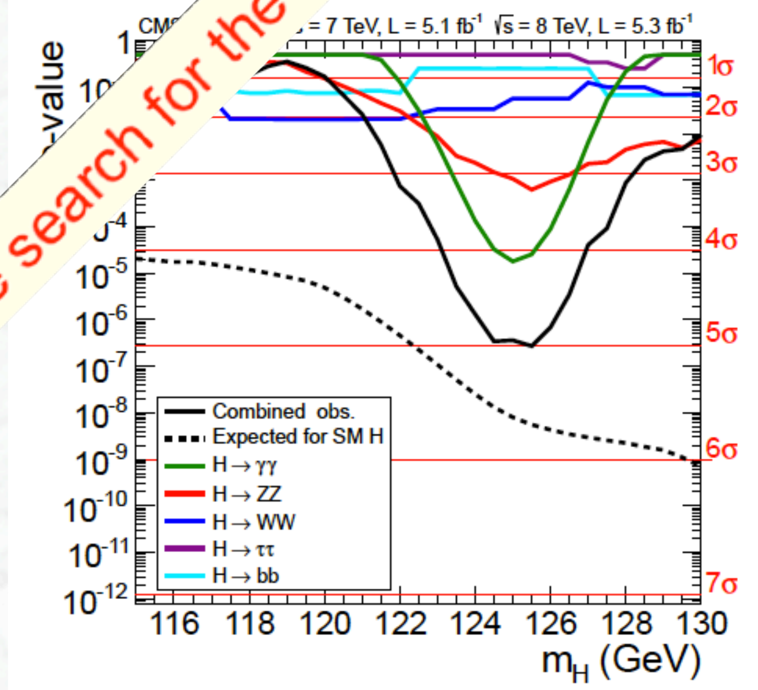
Die Grafik einer Proton-Proton-Kollision im Experiment stellt die zu erwarteten Charakteristiken zweier hochenergetischer Photonen beim Zerfall des

…. physicists knew already on the evening before that it would be

worth while to spend the night in front of the CERN auditorium

Test of background-only hypothesis for the combin… of the γγ, ZZ, WW, ττ and bb channels -ATLAS and CMS-





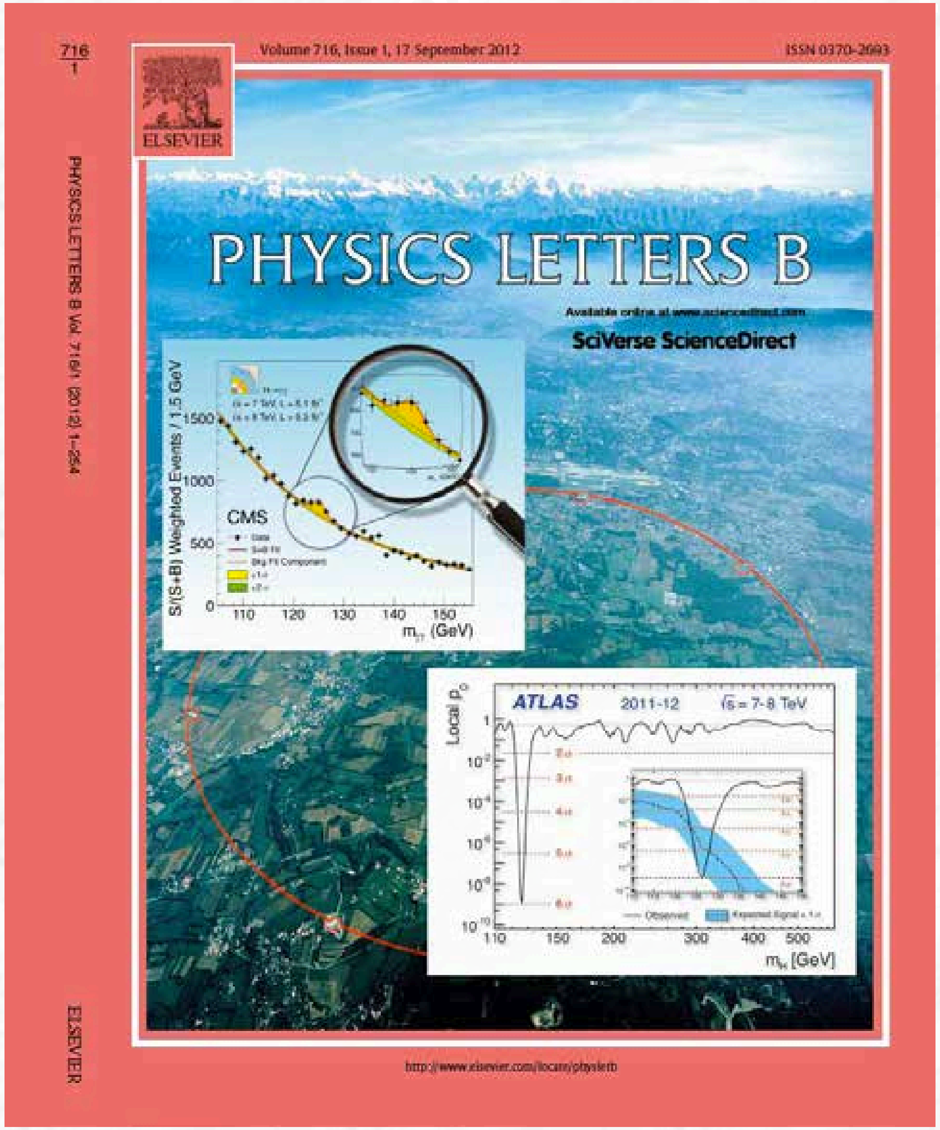
Observation of a new resonance in the search for the Higgs boson

Small probabilitie… ackground-only hypothesis observed for:

ATLAS: 12… eV: 5.9σ (expected for m_H = 126.0 GeV: 5.0 σ)

CMS: …25.3 GeV: : 5.0σ (expected for m_H = 125.3 GeV: 5.8 σ)

Observation of a New Particle



Submission to PLB on 31. July 2012

Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

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

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

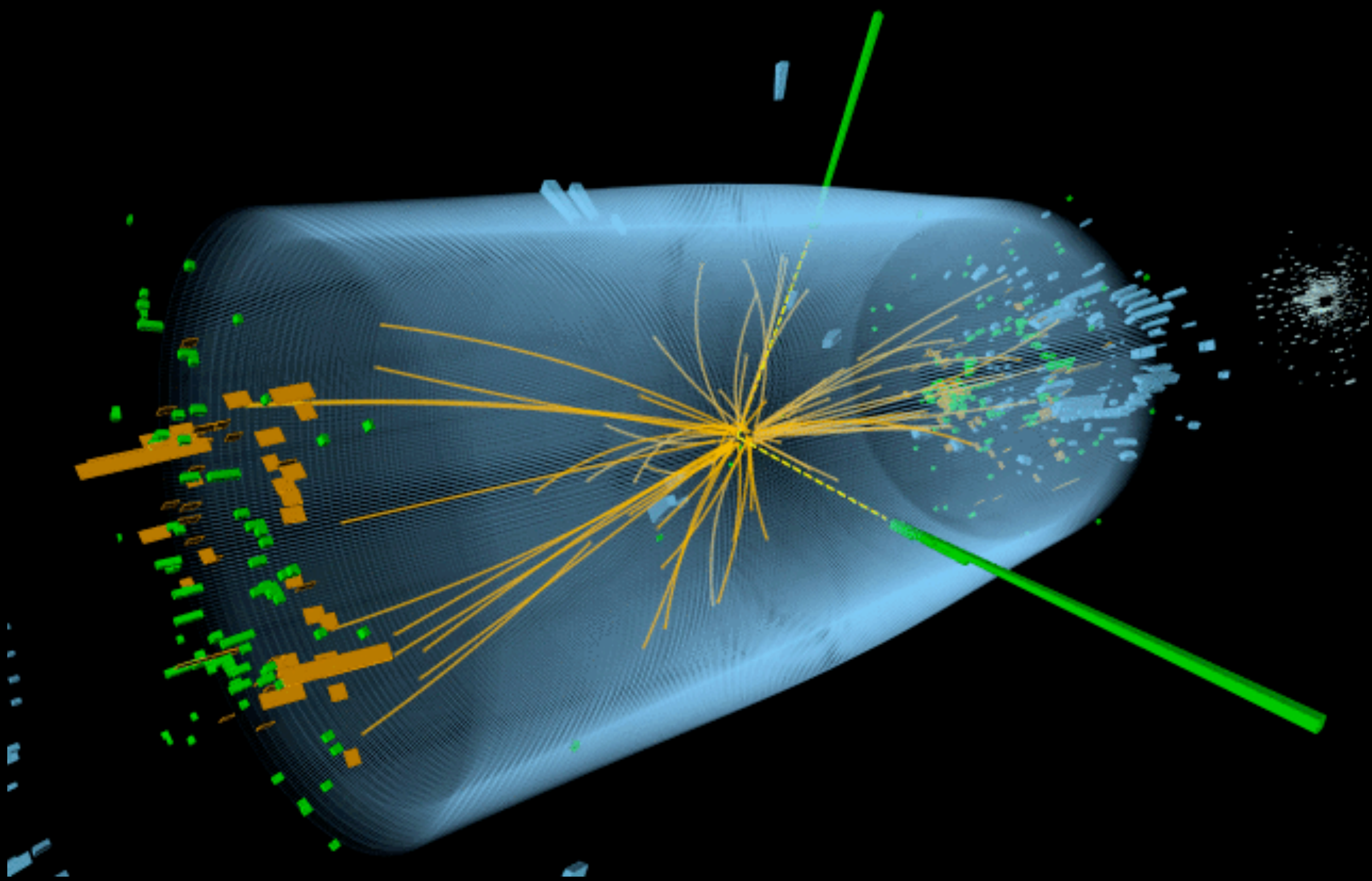
CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

Decay observed into particles with same spin and electric charge sum = 0

→ a new neutral boson has been discovered

Current status on the New Boson



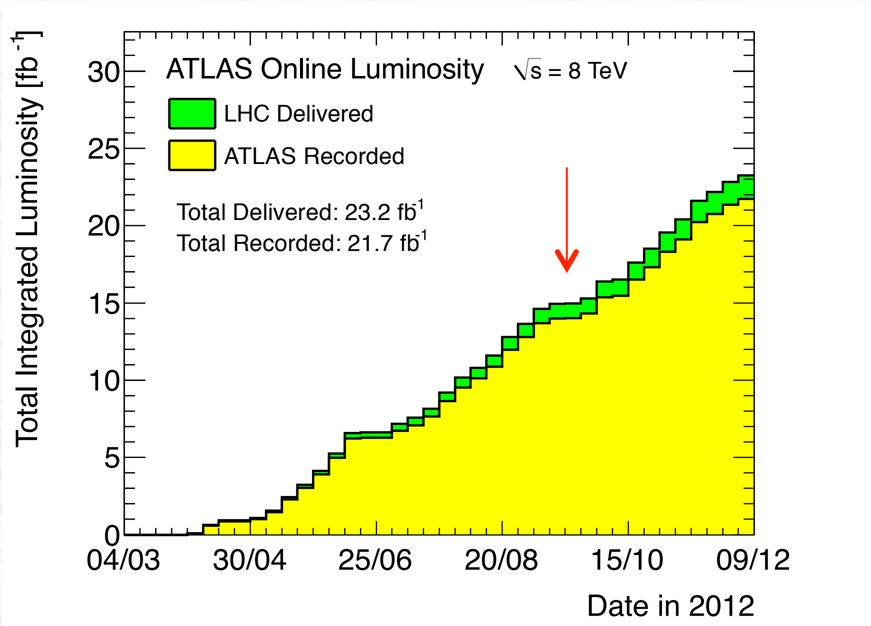
results include new data since ICHEP, 12-13 fb^{-1} at $\sqrt{s}$ = 8 TeV

What do the new data say?

-2012 data since 4th July-

- Results based on 13 fb^{-1} at $\sqrt{s}$ = 8 TeV have been presented recently at the *Hadron Collider Physics Symposium* in Kyoto / Japan

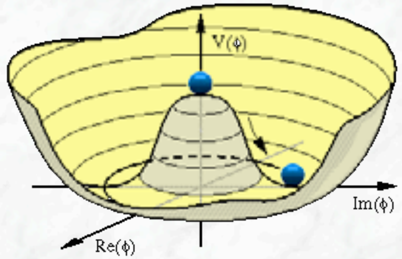
- In particular new input on $H \rightarrow \tau\tau$ and $H \rightarrow bb$ decays

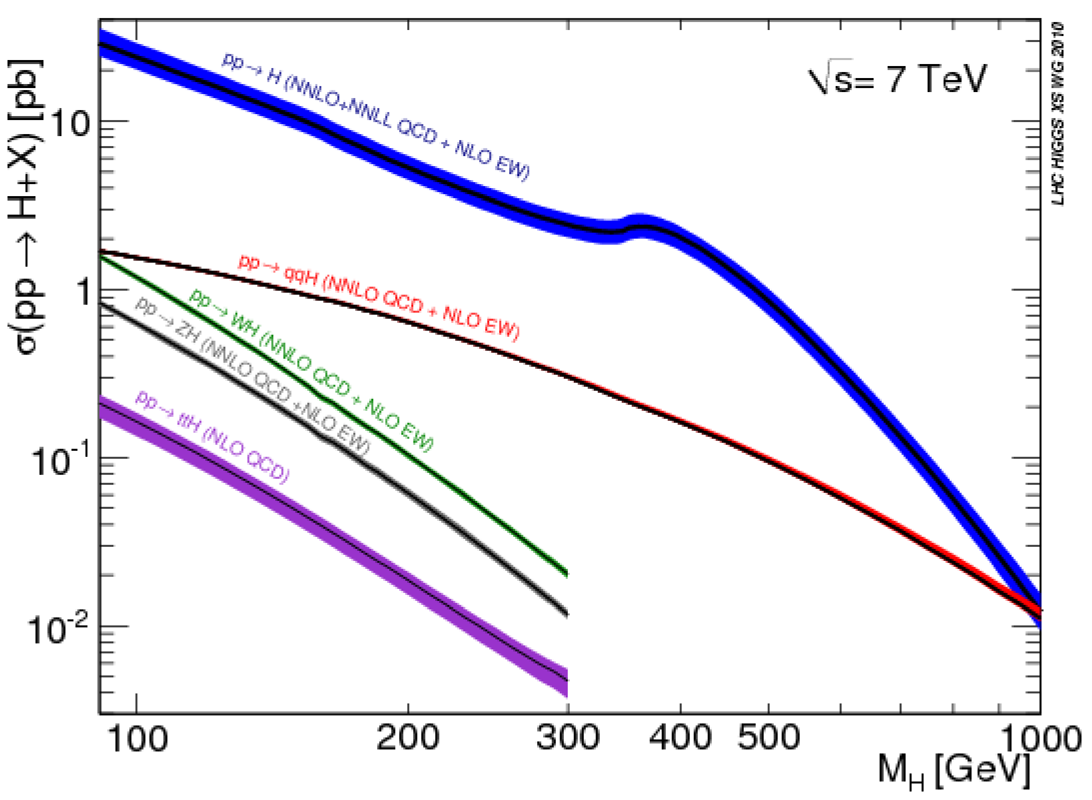


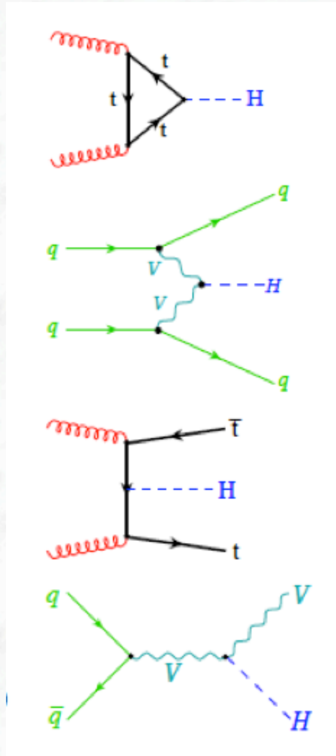
Hadron Collider Physics Symposium 2012

Kyoto, Japan, 14 November 2012

Higgs Boson production at the LHC







Gluon Fusion

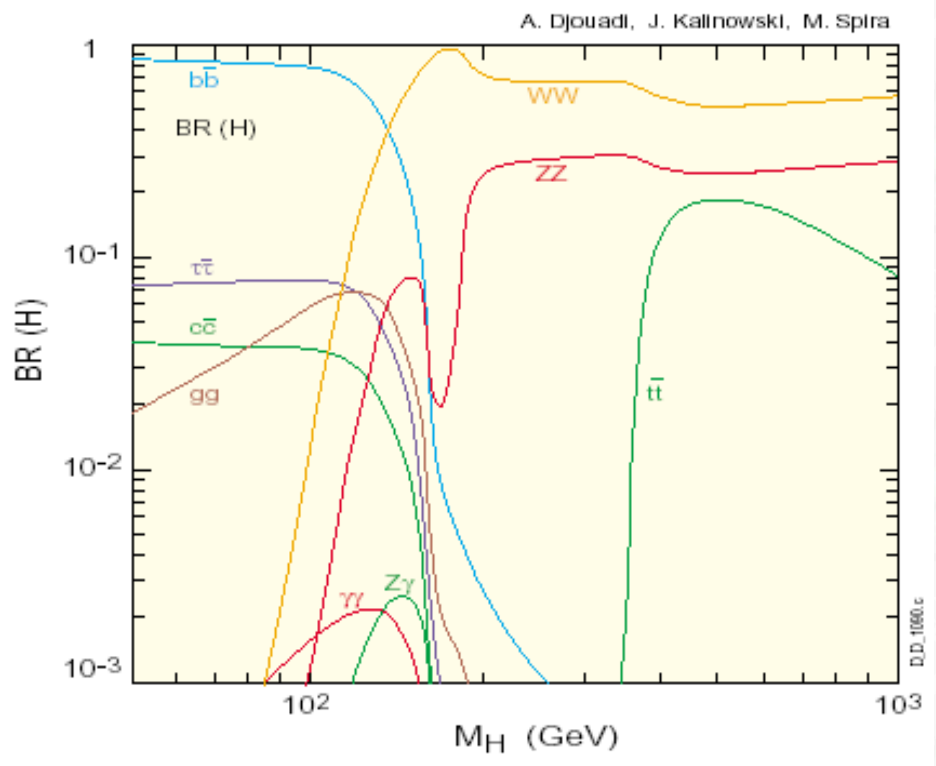
Vector boson fusion

tt associated production

WH/ZH associated production

- See lecture by Lance Dixon for the discussion of the state of the (N)NLO calculations;
- Impressive progress over the past decades

Useful Higgs Boson Decays at a Hadron Collider



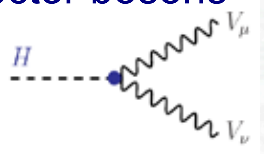
at high mass:
Lepton final states
(via H → WW, ZZ)

at low mass:
Lepton and Photon final states
(via H → WW*, ZZ* and H → γγ)

Tau final states

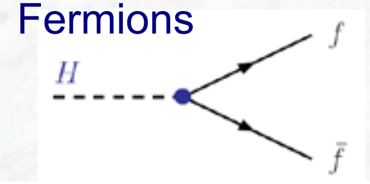
The dominant **bb decay mode** at low mass is only useable, if the Higgs boson is produced in association with a W or Z boson, e.g. pp → WH → ℓν bb

Vector bosons



$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2$

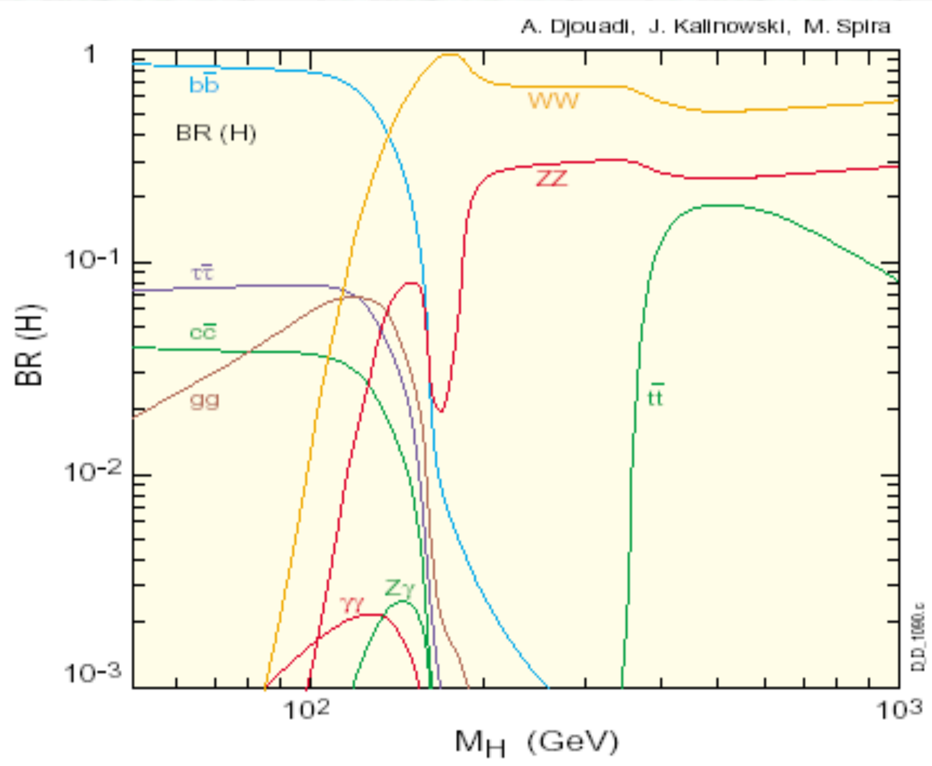
Fermions



$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f$

Important channels: H → WW → ℓν ℓν
H → γγ
H → ZZ → ℓ⁺ℓ⁻ ℓ⁺ℓ⁻

Useful Higgs Boson Decays at a Hadron Collider



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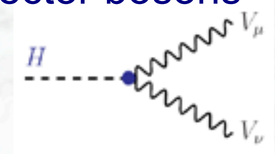
Vector bosons



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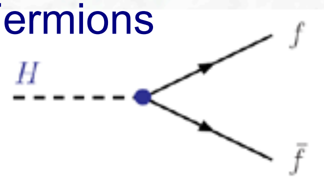
Fermions



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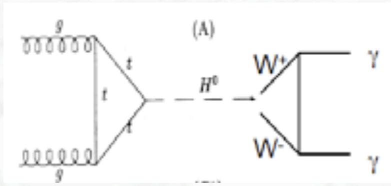
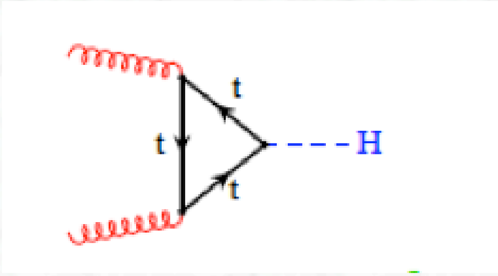


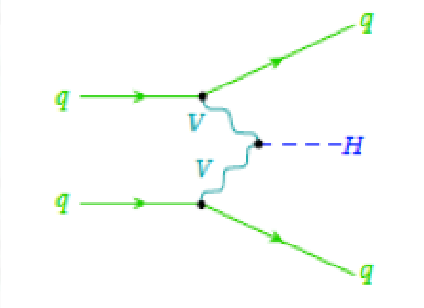
Higgs boson decays in massless particles via higher order processes (small rate)

The important Higgs boson search channels at the LHC

(i) The bosonic decay channels

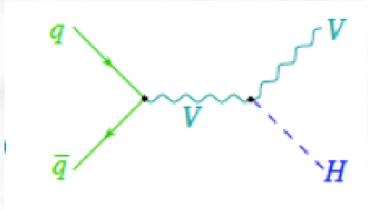


Important channels: $H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$
$H \rightarrow \gamma\gamma$
$H \rightarrow ZZ \rightarrow \ell^+\ell^-\ \ell^+\ell^-$



- dominated by gluon fusion
- valuable contributions from vector boson fusion

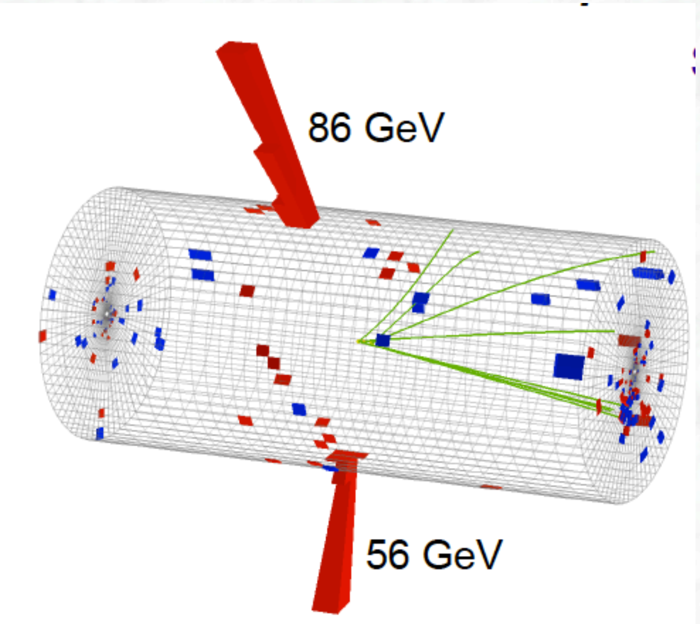
(ii) The fermionic decay channels



Important channels: $qq\ H \rightarrow qq\ \tau\ \tau$
VH, $V \rightarrow ll$ ($l=e,\mu,\nu$) $H \rightarrow bb$

- associated production essential (suppression against overwhelming backgrounds from multijet production)
- exploit VBF topology (tag jets, no colour flow in central region) high-p_T topologies

Search for the H → γγ decay

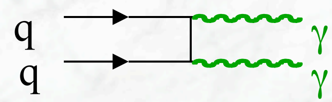


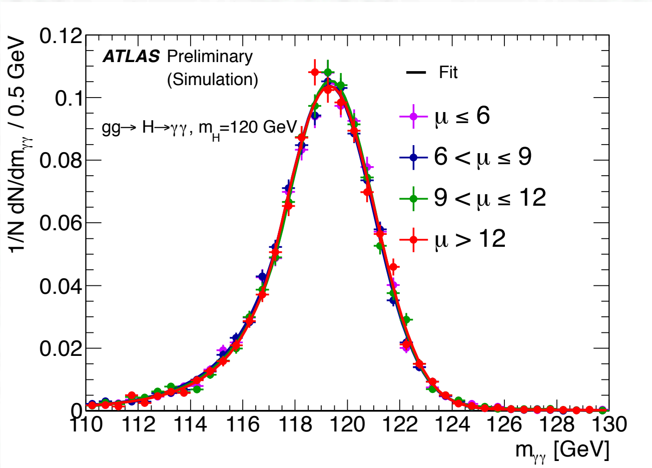
- 2 photons (isolated) with large transverse momenta

- Mass of the Higgs boson can be reconstructed $m_{\gamma\gamma}$

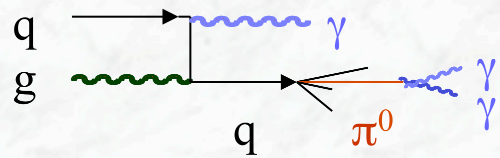
  Both experiments have a good mass resolution
  ATLAS: ~1.7 GeV/c^2 for m_H ~120 GeV/c^2

- Challenges:
  - signal-to-background ratio
    (small, but smooth irreducible γγ background)





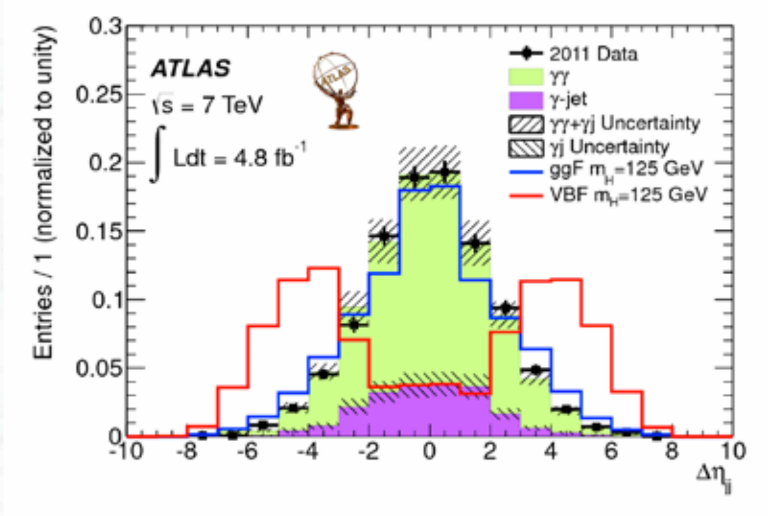
  - reducible backgrounds from γj and jj
    (several orders of magnitude larger than irreducible one)



$\gamma\gamma$ event classification

- Increased sensitivity due to separation of events according to resolution and S/B

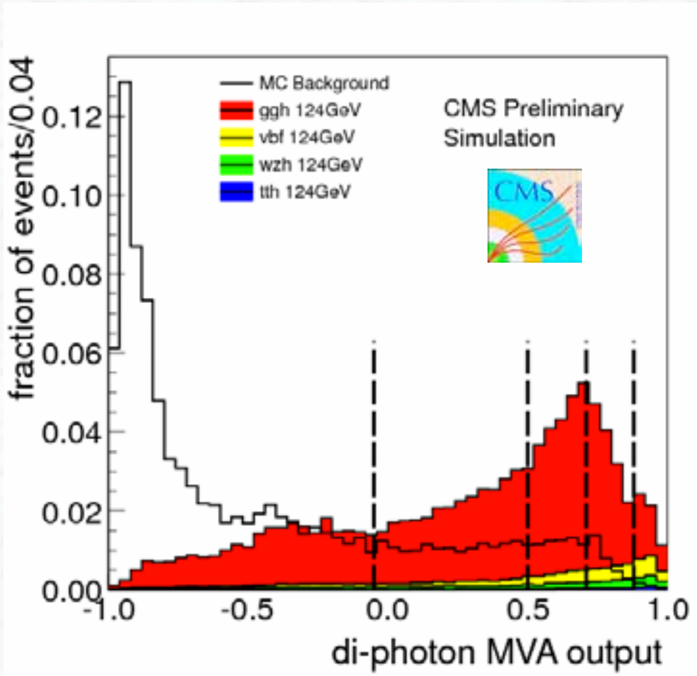
  - Separate out events with VBF-like signature (Require two jets with large angular separation)



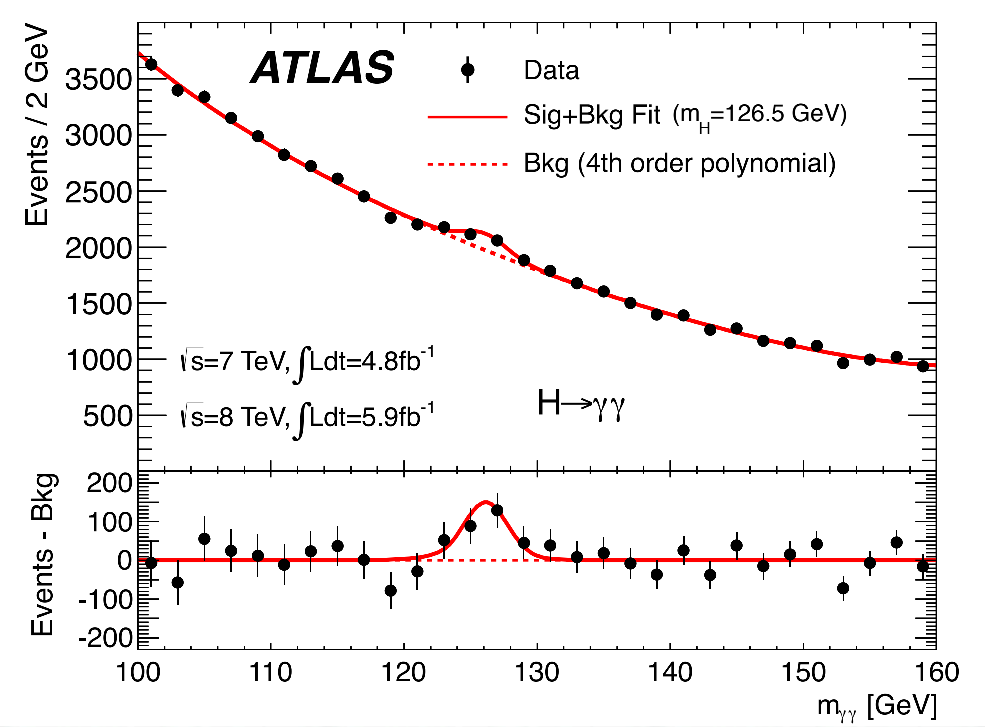
  - Classify remaining events:

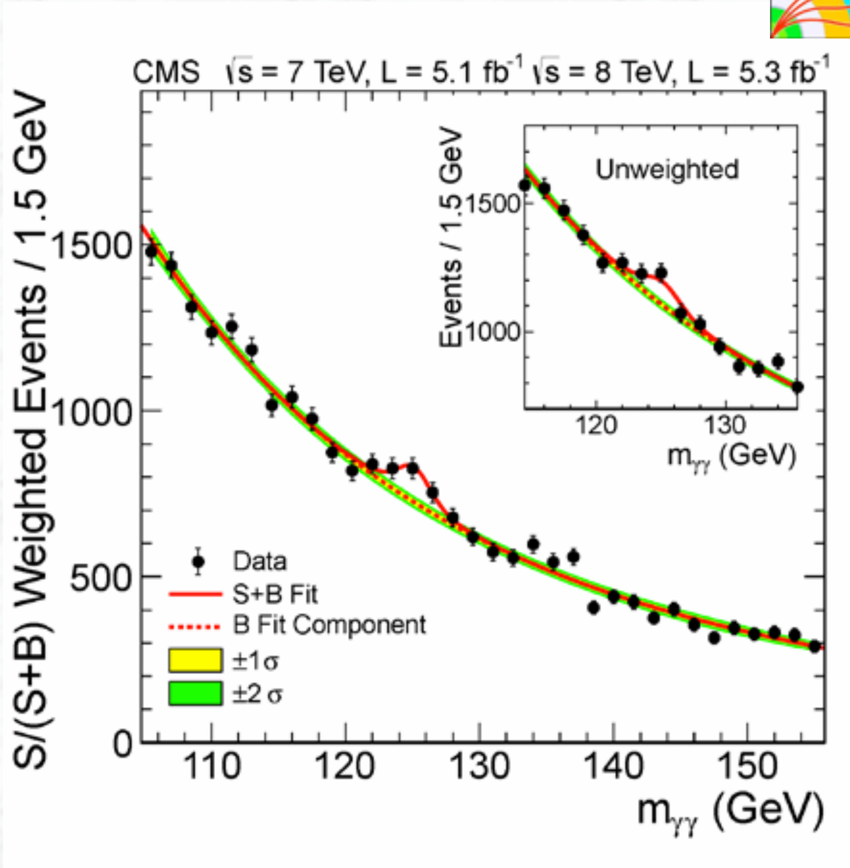
ATLAS: photon direction, photon conversion status, di-photon p_{Tt}

CMS: Boosted decision tree based on photon momentum and direction, di-photon opening angle, mass resolution



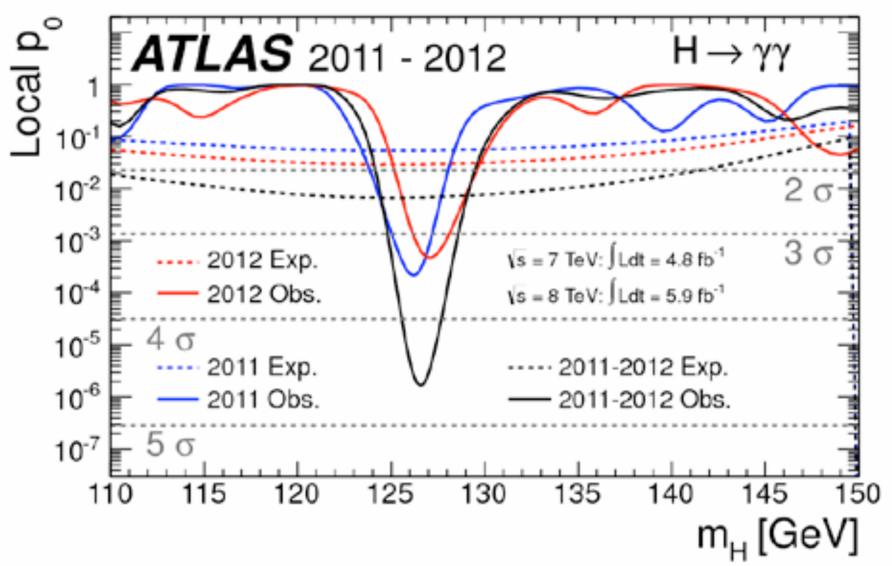
Results of the search for H → γγ

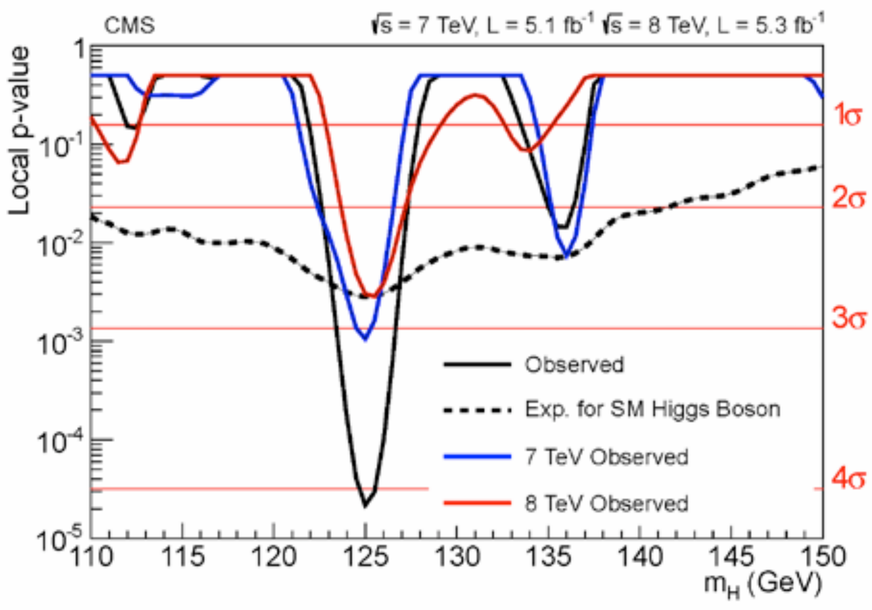




- Background model: exponential / polynomial function, determined directly from data (different models have been used → systematics)

Search for H → γγ: compatibility with background hypothesis



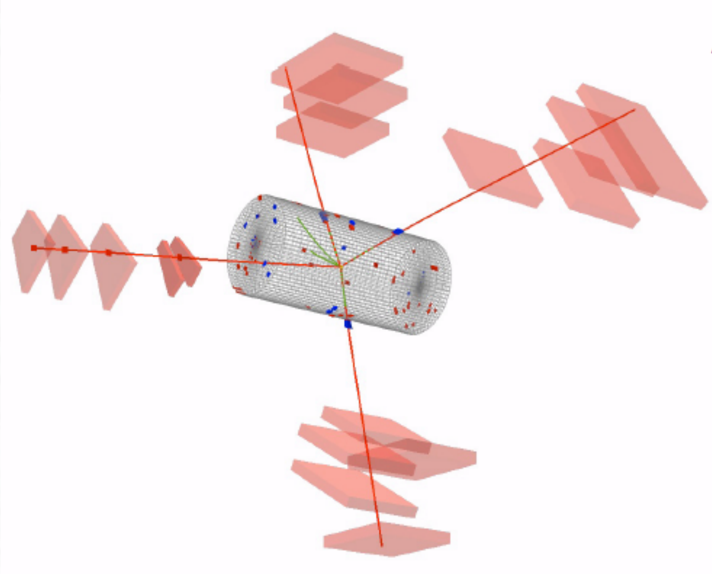


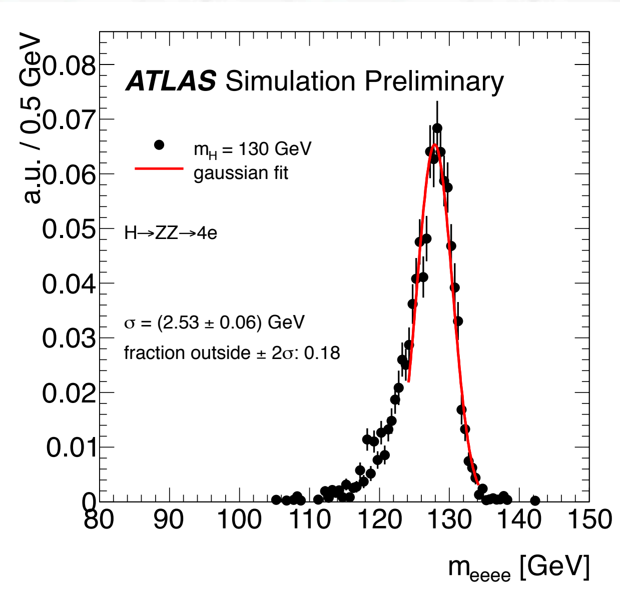
- Maximum deviation from background-only expectation observed for:

	ATLAS		CMS	
	m_H~126.5 GeV/c^2		m_H ~125 GeV/c^2	
- local p_0-value:	$2 \cdot 10^{-6}$	4.5σ	$2.5 \cdot 10^{-5}$	4.1σ
- expected significance:		2.4σ		2.8σ

* p_0: consistency of the data with the background-only hypothesis

Search for the H → ZZ$^{(*)}$ → ℓ$^+$ℓ$^-$ ℓ$^+$ℓ$^-$ decay



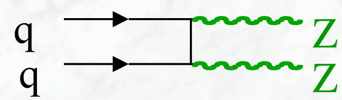


- The "golden mode"
  4 leptons (isolated) with large transverse momenta

- Mass of the Higgs boson can be reconstructed $m_{4\ell}$

  Both experiments have a good mass resolution
  ATLAS: ~2.5 GeV/c^2 (4e) for m_H ~130 GeV/c^2
  ~2.0 GeV/c^2 (4μ) for m_H ~130 GeV/c^2

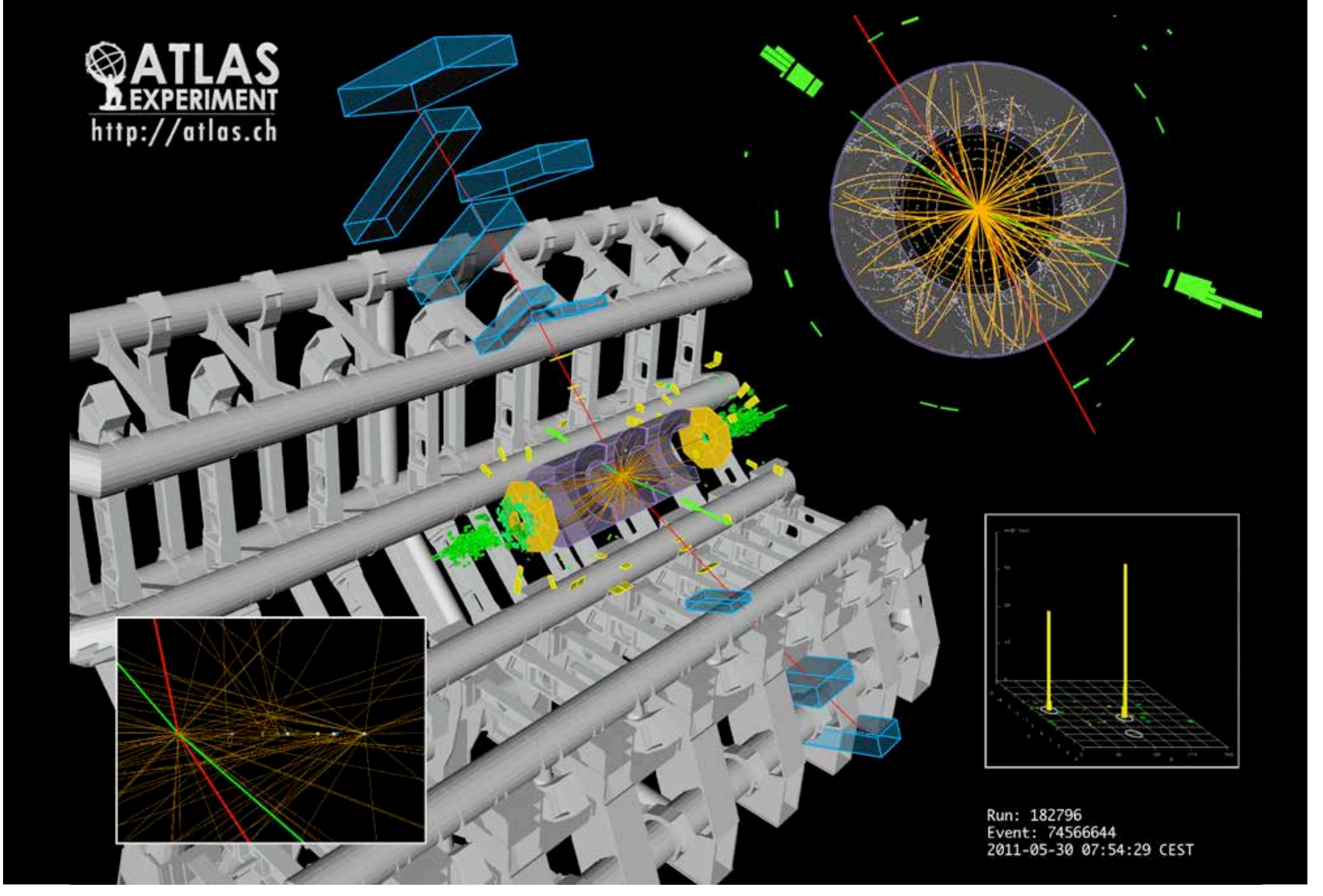
- Low signal rate, but also low background:
  - Mainly from ZZ continuum



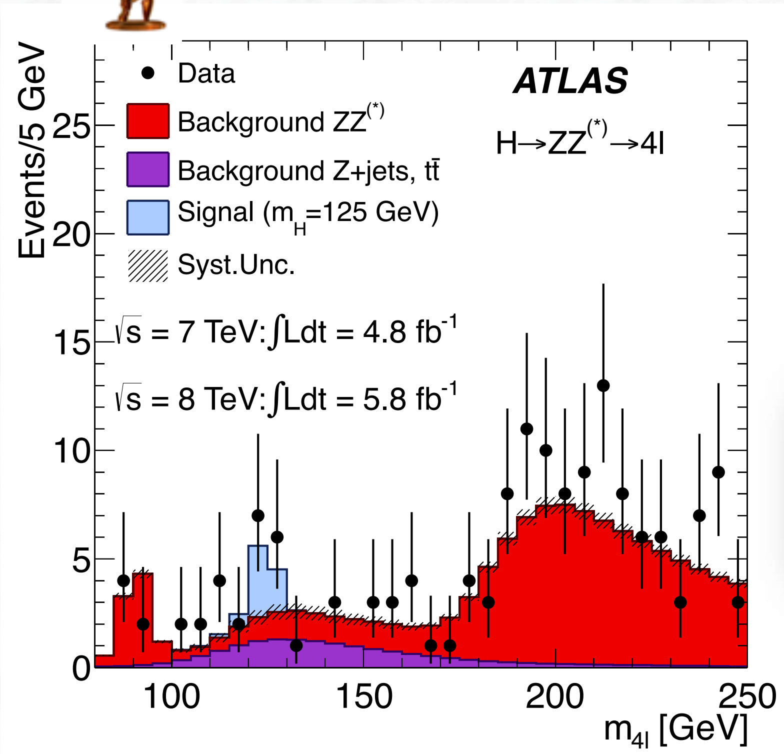
- In addition from tt and Zbb events:
  tt → Wb Wb → ℓν cℓν ℓν cℓν
  Z bb → ℓℓ cℓν cℓν
  however: leptons are non-isolated and do not originate from the primary vertex

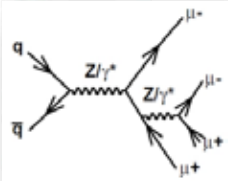
  rejection possible in excellent LHC tracking detectors

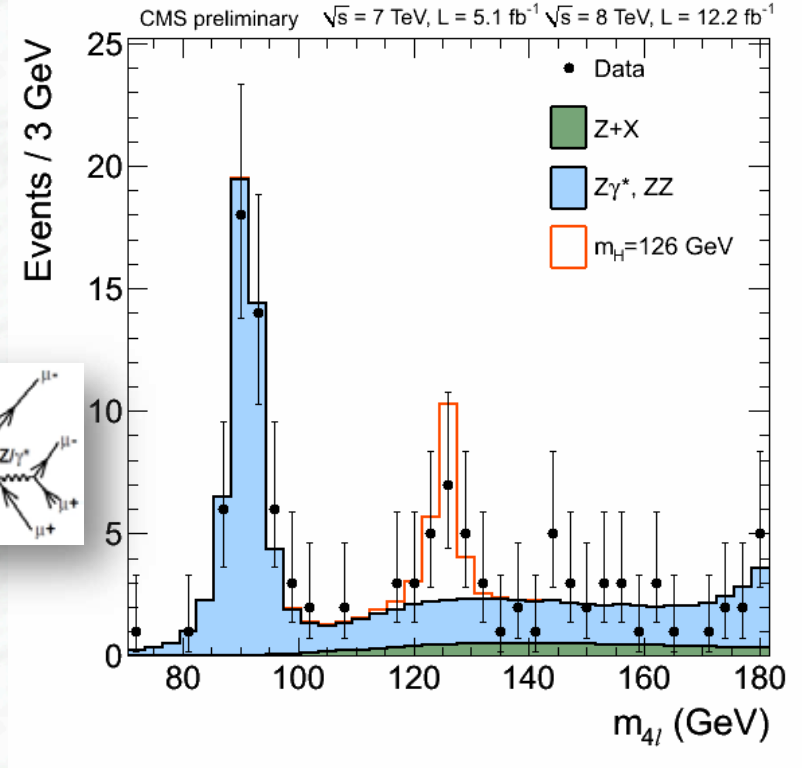
Candidate event for a H → ZZ → $e^+e^- \mu^+ \mu^-$ decay



4ℓ invariant mass spectra



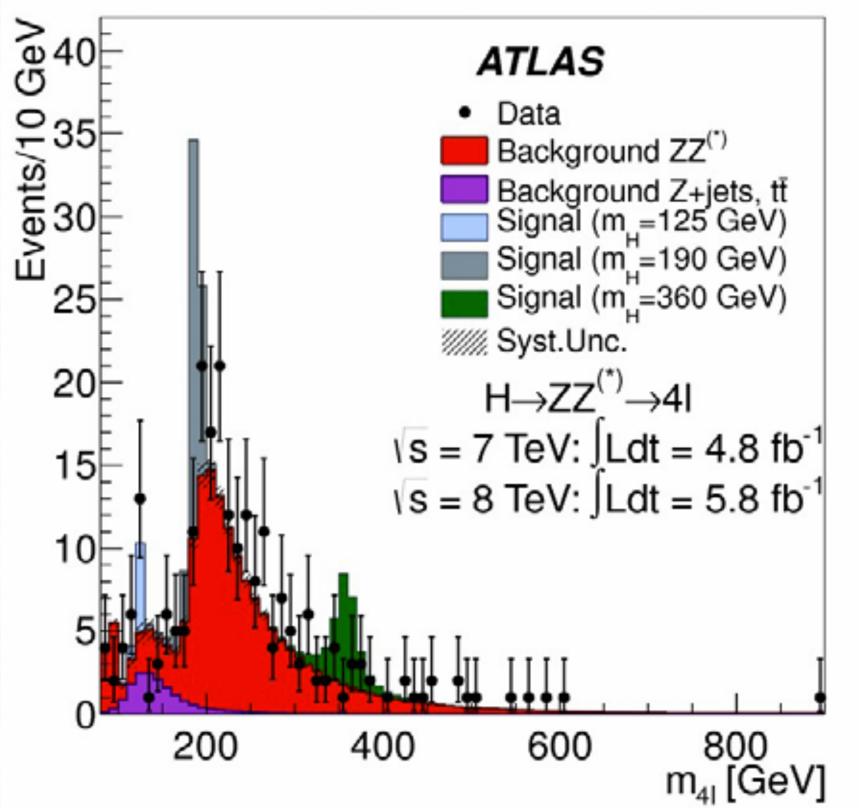


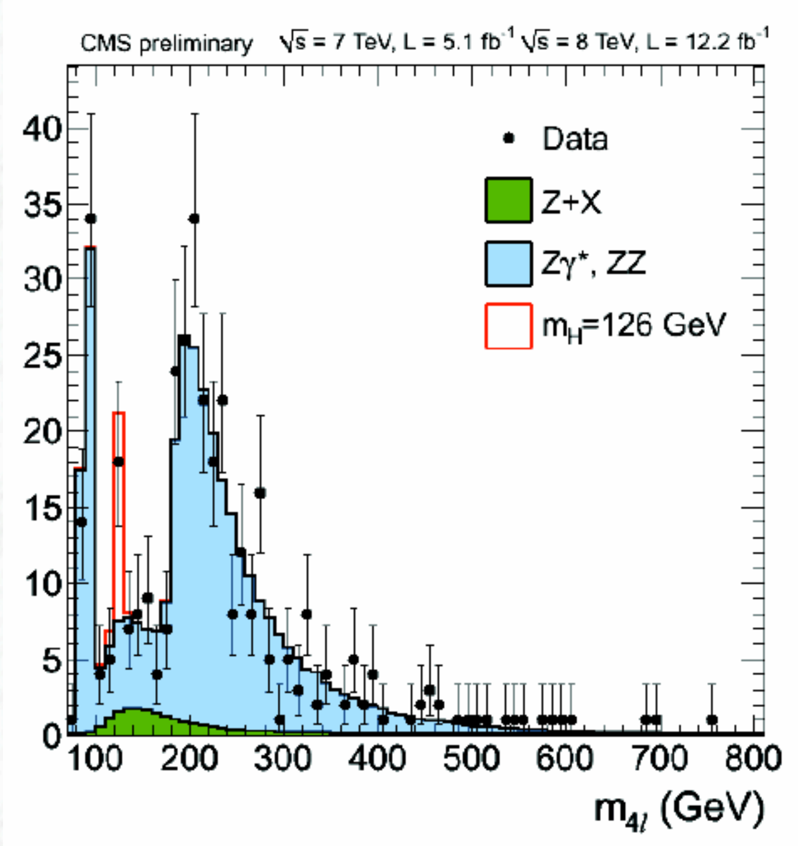


- Reducible backgrounds from Z+jets, Zbb, tt giving 2 genuine + 2 fake leptons measured using background-enriched, signal-depleted control regions in data

- Irreducible background from non-resonant continuum ZZ production seems slightly underestimated in NLO Monte Carlo simulation; normalized in high-mass region;

Normalization at high mass





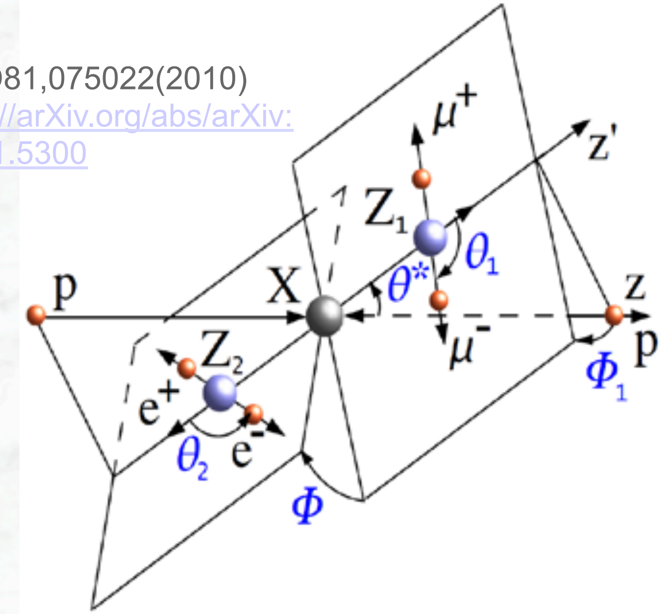
Yields for $m_{4l} > 160$ GeV/c^2	Observed	Expected
ATLAS (L = 4.8 + 5.8) fb^{-1}	191	146.7
CMS (L = 5.1 + 12.2) fb^{-1}	269	250

R (Data/MC) ~1.3

R (Data/MC) ~1.1

CMS: use additional information on decay kinematics, MELA discriminant

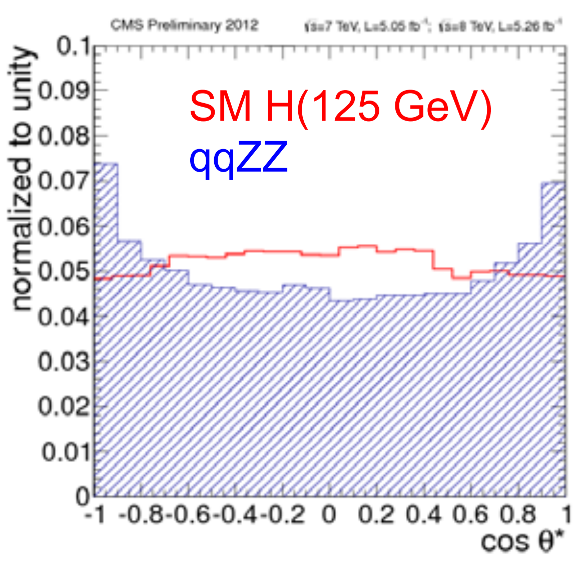
PRD81,075022(2010)
http://arXiv.org/abs/arXiv:1001.5300

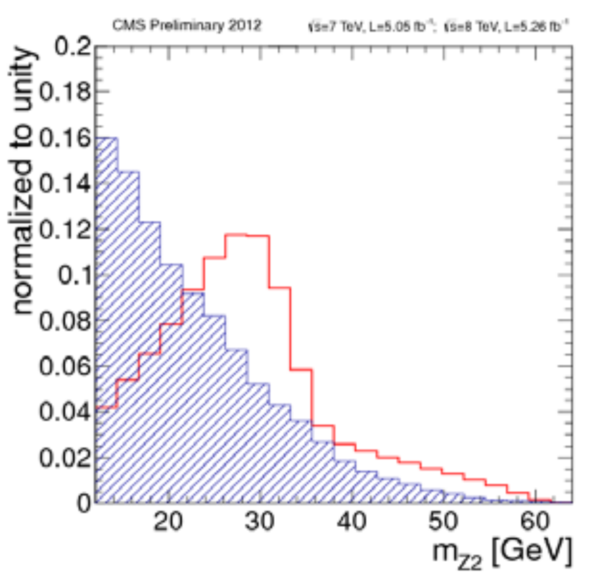


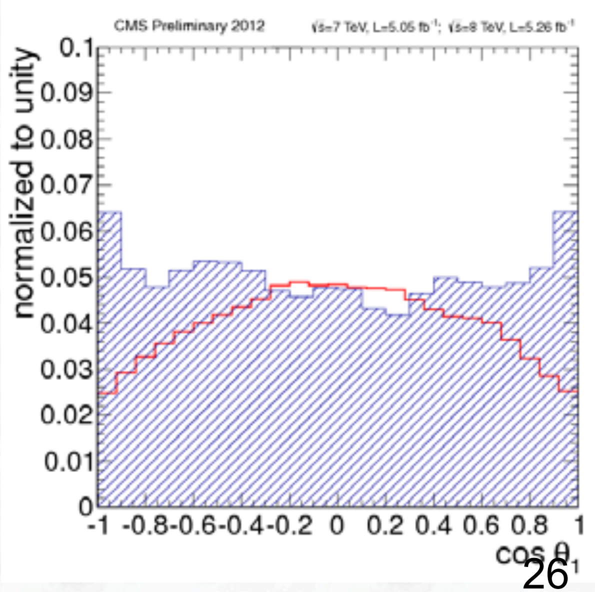
Matrix Element Likelihood Analysis:

uses kinematic inputs for signal to background discrimination $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

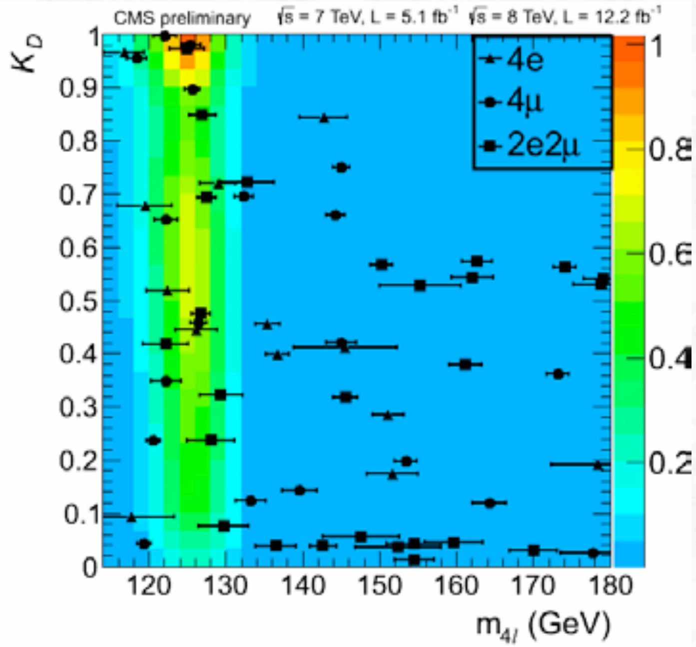




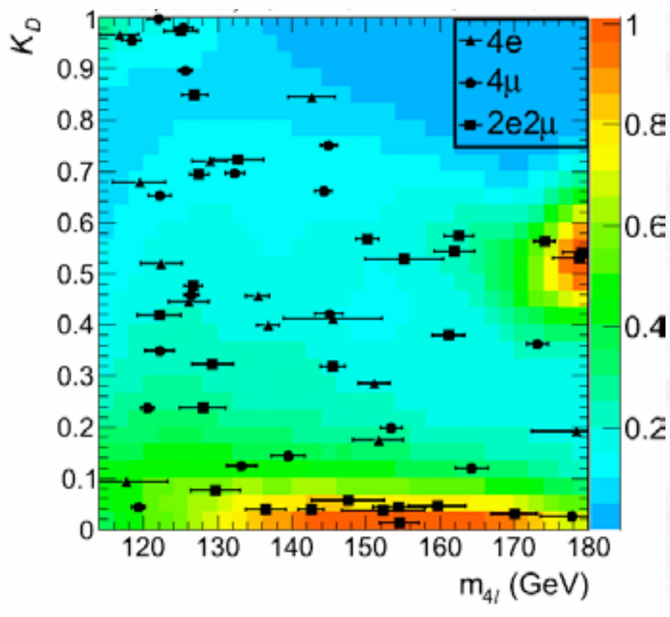


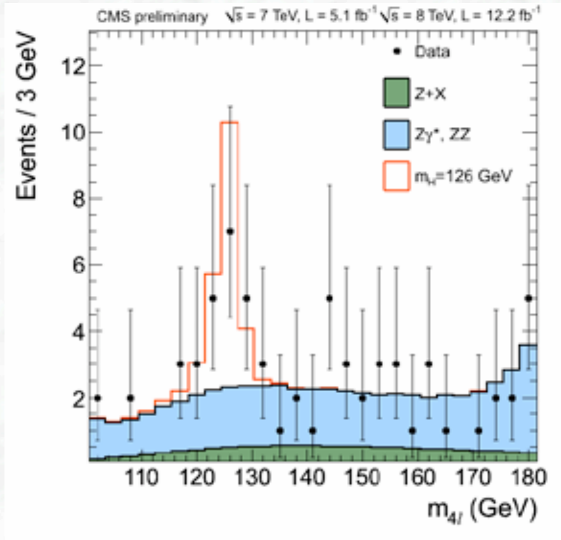
2D analysis using {m_{4l},MELA}

signal

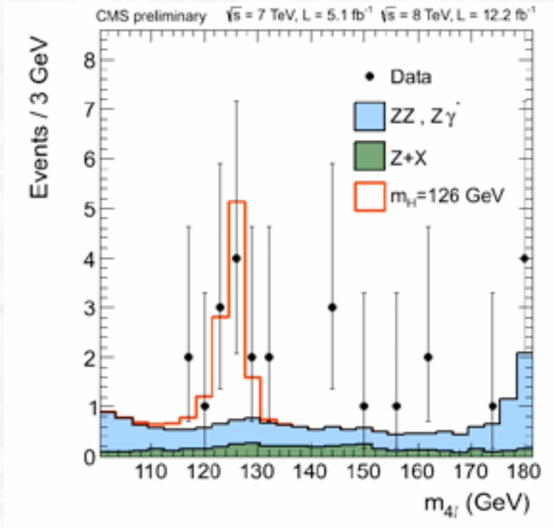


background





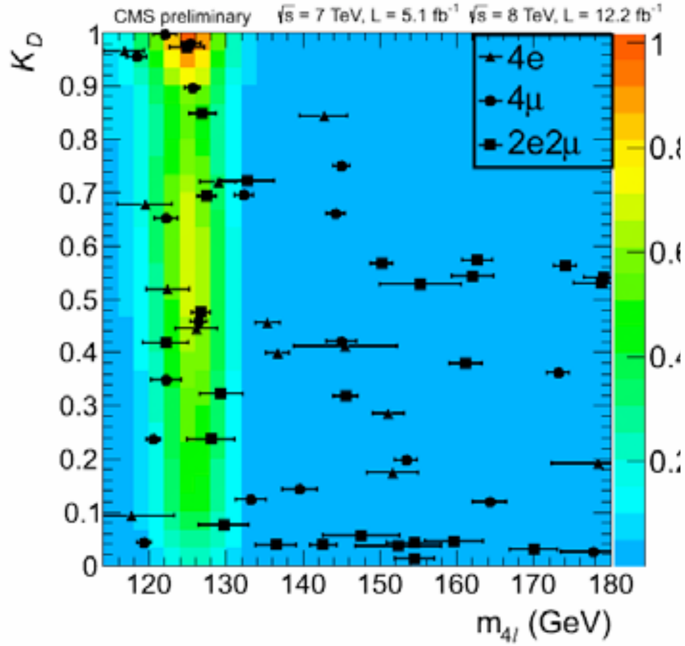
MELA > 0.5

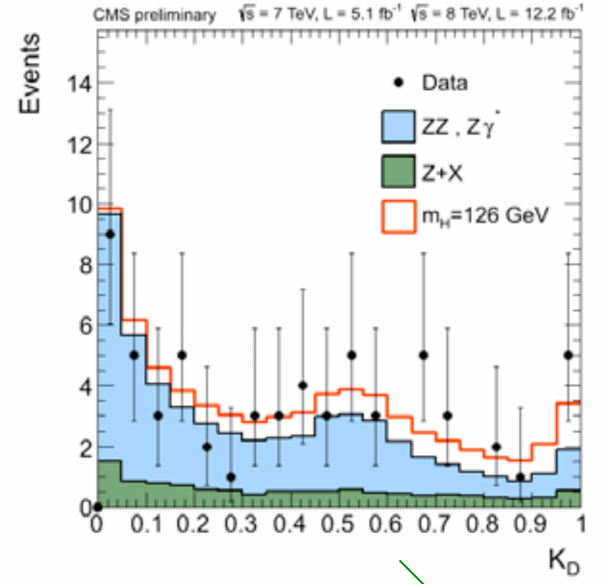


Cuts on MELA variable improve S:B ratio

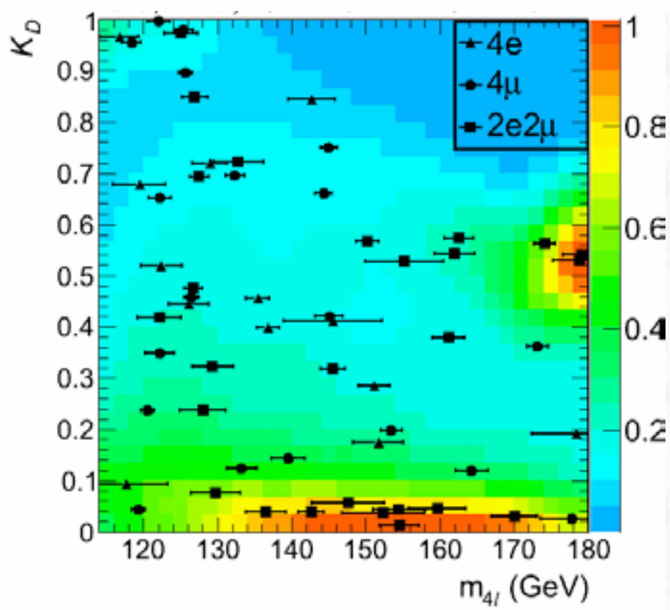
2D analysis using {m_{4l},MELA}

signal

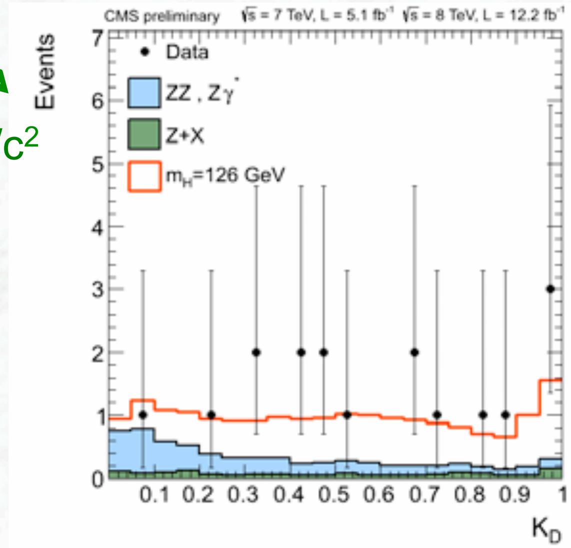




background



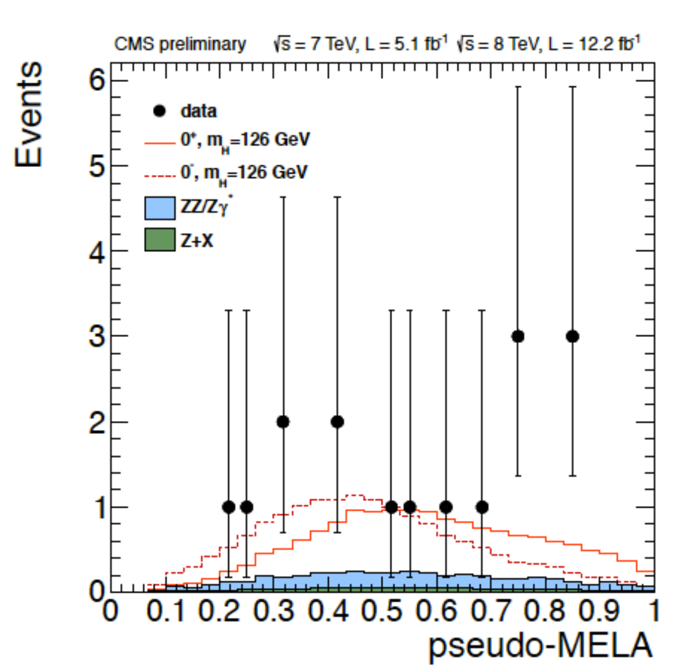
$121.5 < m_{4l} < 130.5$ GeV/c^2

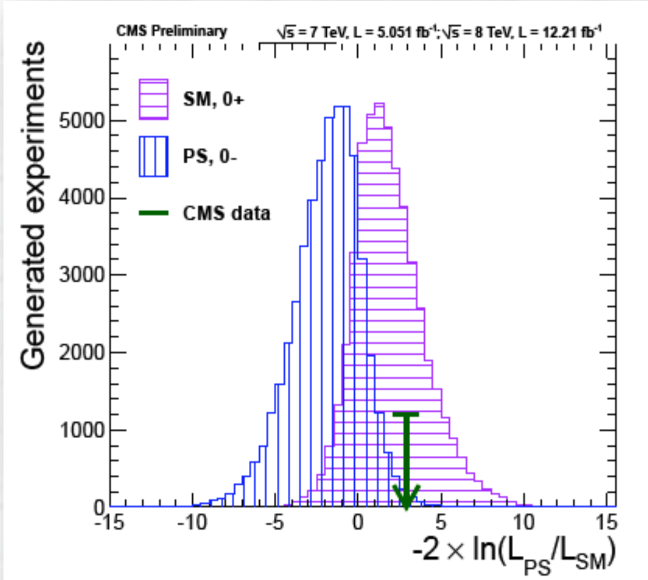


Data favour $J^P = 0^+$ versus 0^-

- Construct MELA-discriminant for SM (0^+) and 0^- hypotheses
- Tight cuts on background

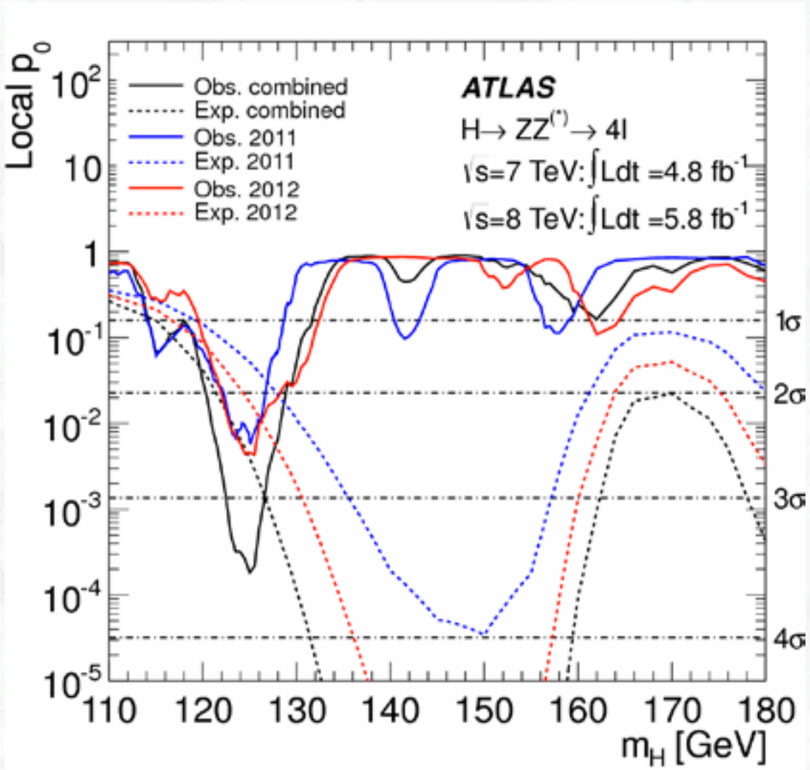
$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{SM}}{\mathcal{P}_{SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_1, m_2, \vec{\Omega} | m_{4\ell})}{\mathcal{P}_{SM}(m_1, m_2, \vec{\Omega} | m_{4\ell})}\right]^{-1}$$

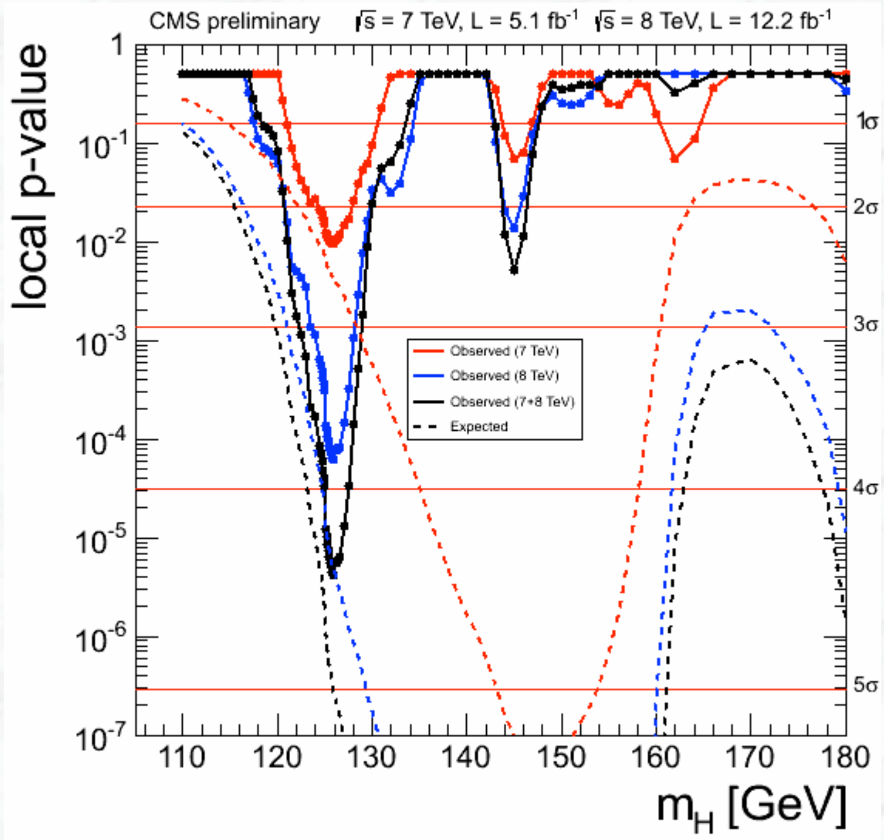




Scalar / pseudoscalar separation: 1.9 σ

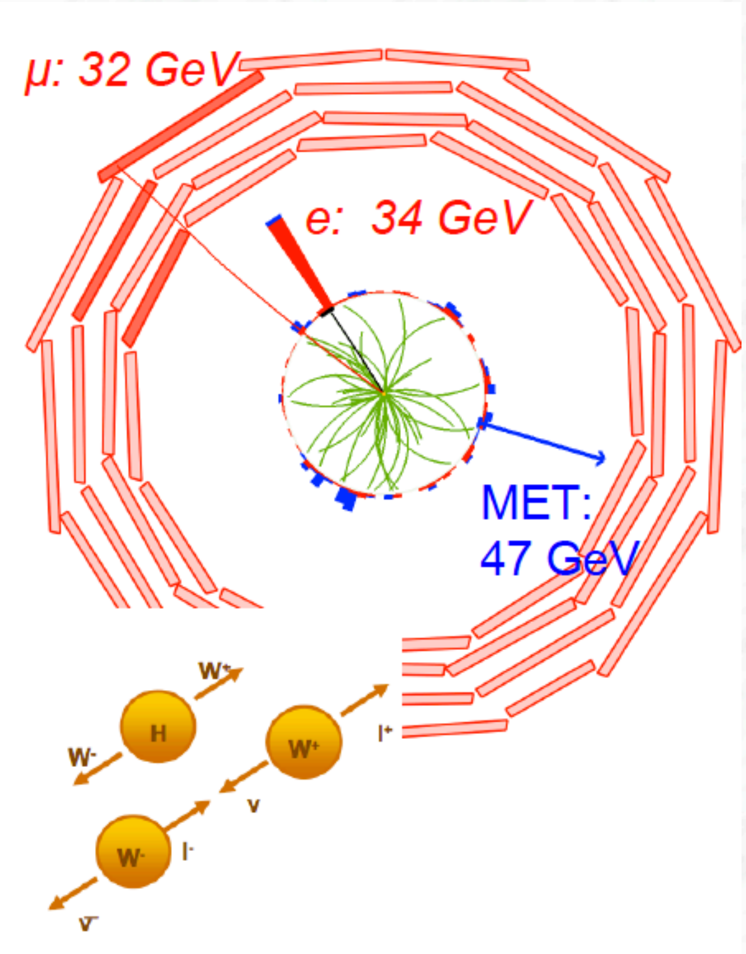
H → ZZ → 4ℓ: compatibility with background hypothesis





Significant for H → 4ℓ channel alone now above 4σ in CMS, including the new data

Search for H → WW → ℓν ℓν decay



- 2 leptons (e or μ) with large transverse momenta

  Leptons from Higgs decay (spin-0 particle) are expected to have a small angular separation

- 2 neutrinos

  → large missing transverse energy

  → Higgs boson mass cannot be reconstructed, use transverse mass

- Highest sensitivity around 160 GeV/c^2

  (nearly 100% H → WW branching ratio)

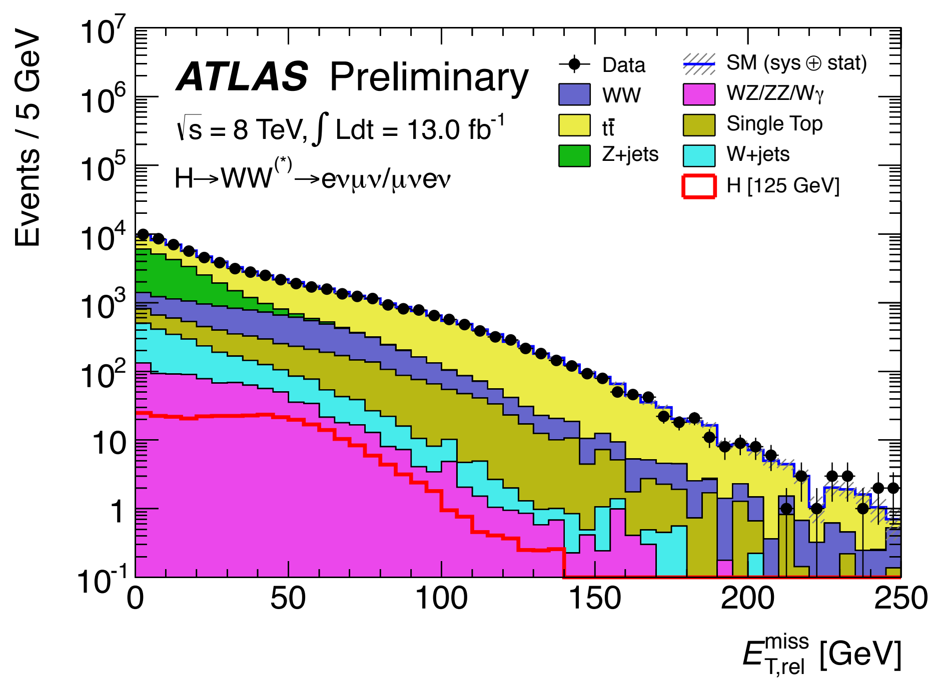
Search for H → WW → ℓν ℓν

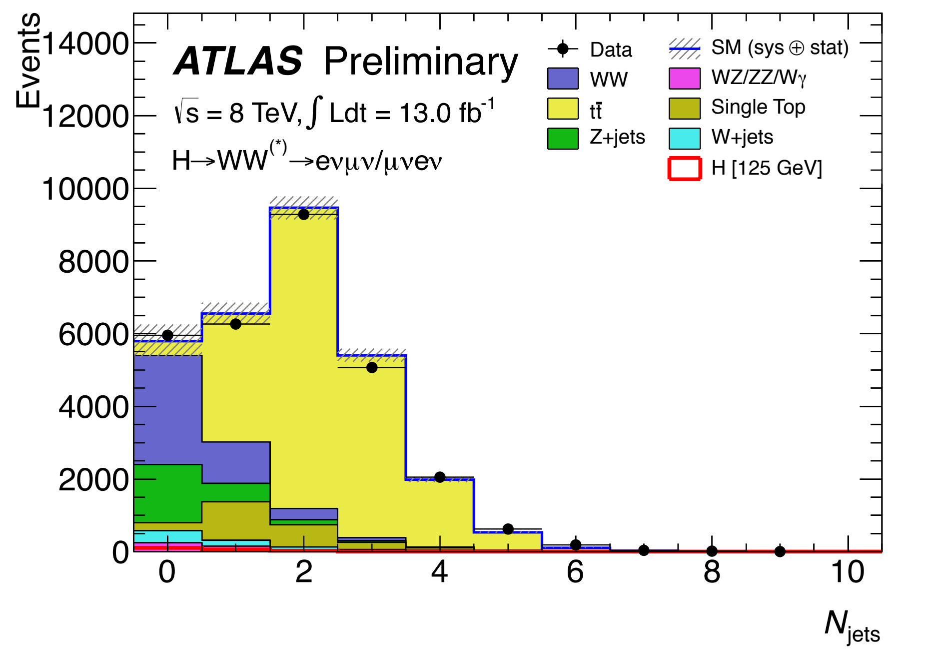
L_{int} = 13 fb^{-1}

- Comparison of a few distributions at an early cut stage

(i) Missing ET distribution after requiring two leptons

(ii) Jet multiplicity distribution after addition missing ET cut





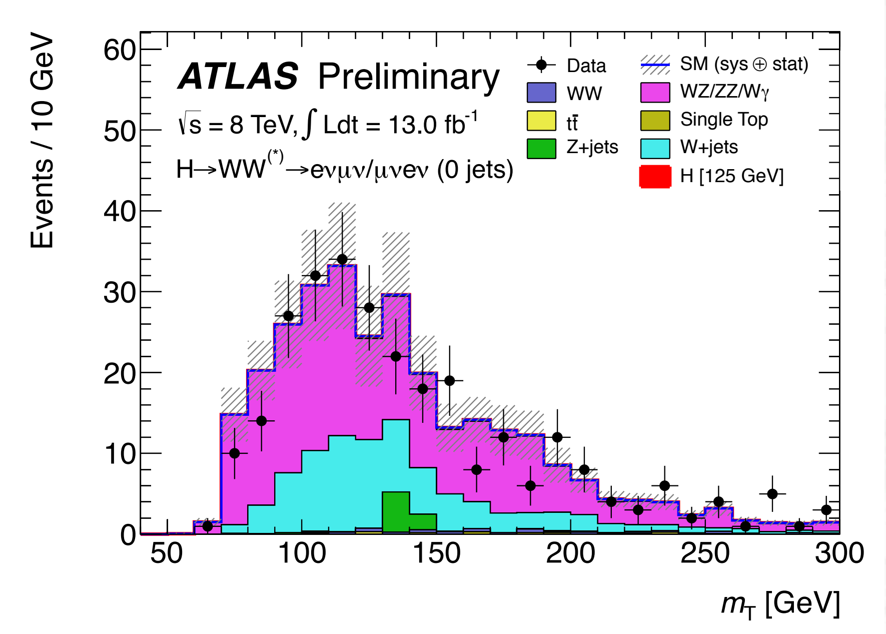
dominant background depends on the number of jets → split in jet classes

Search for H → WW → ℓν ℓν

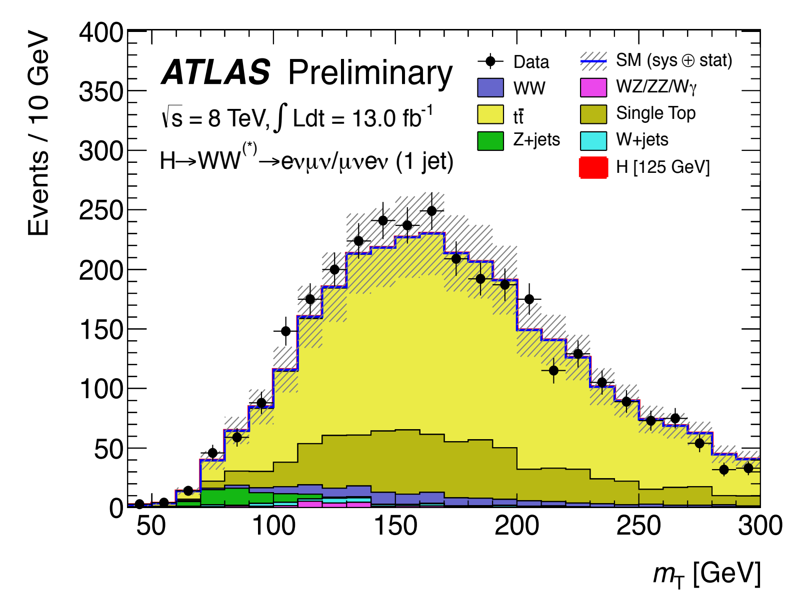
L_{int} = 13 fb^{-1}

- Background normalization in control regions with negligible signal contributions

(i) 0-jet control region: like-sign leptons, $m_{\ell\ell}$ > 80 GeV
(ii) Require b-tagged jet to define a "top control region"

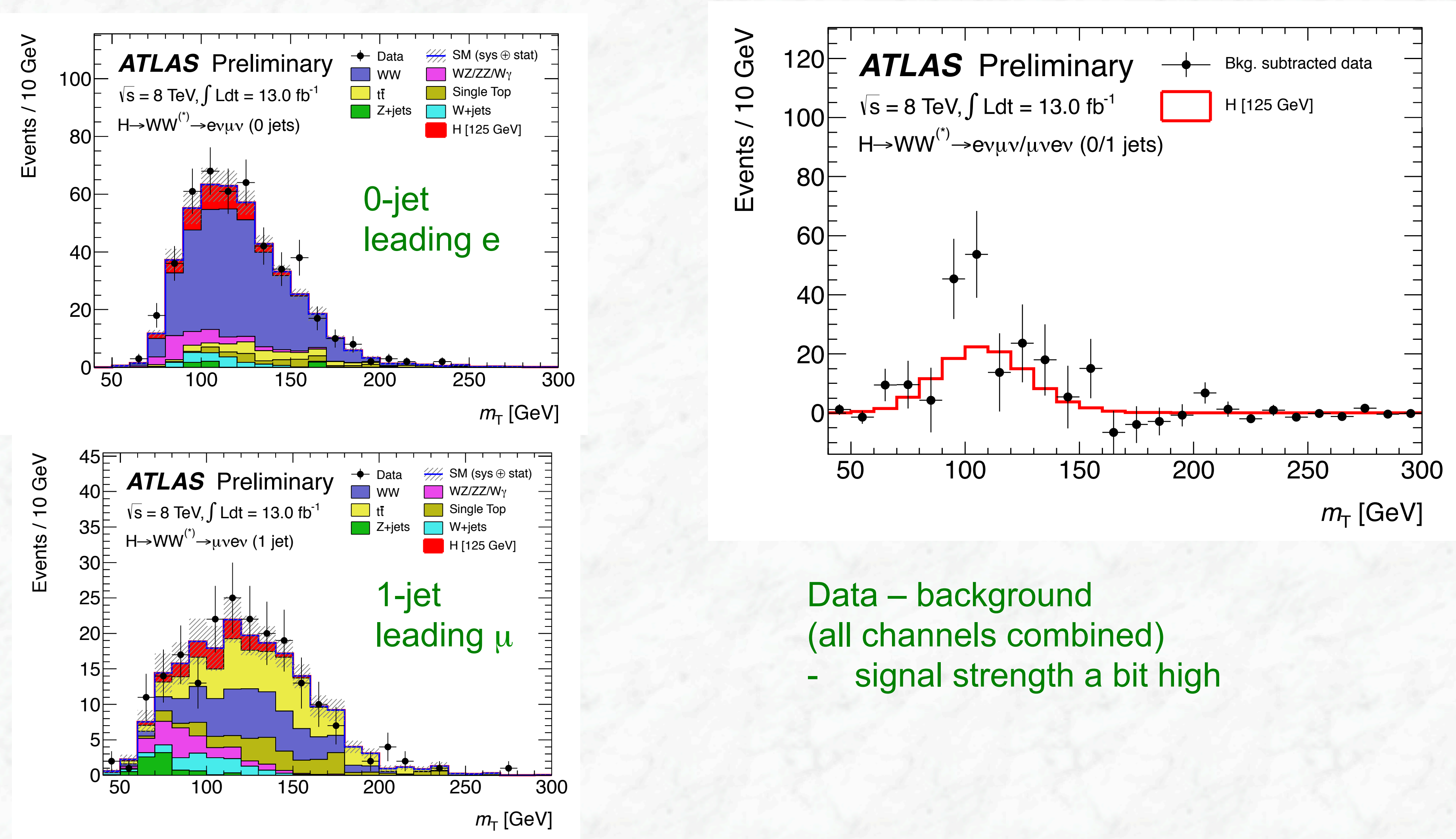


m_T in same charge validation region



m_T in 1-jet b-tag validation region
(before normalization)

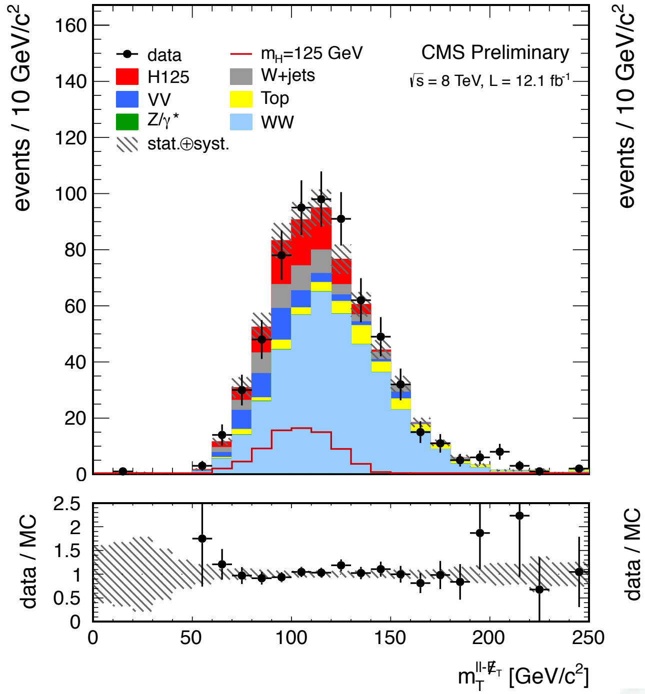
Transverse mass distributions after final cuts for the H → WW → ℓν ℓν search

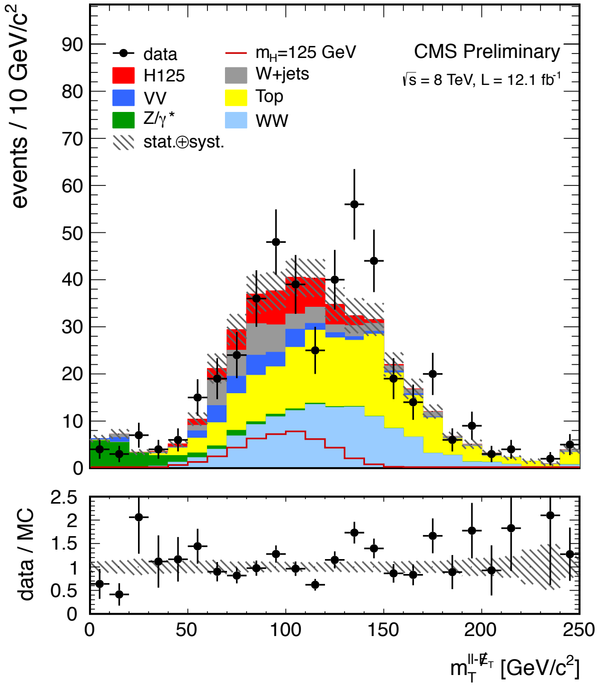


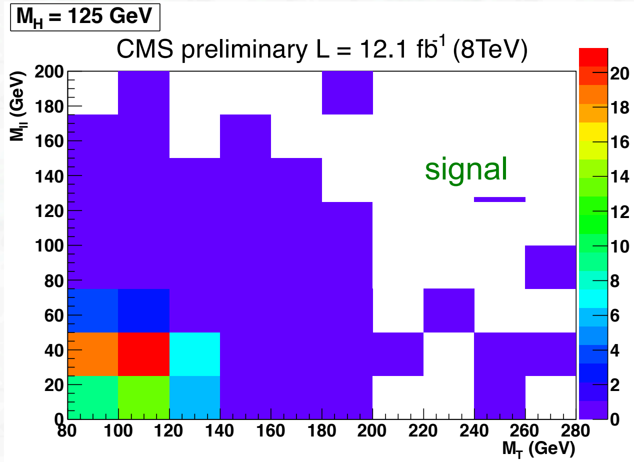
Data – background
(all channels combined)
- signal strength a bit high

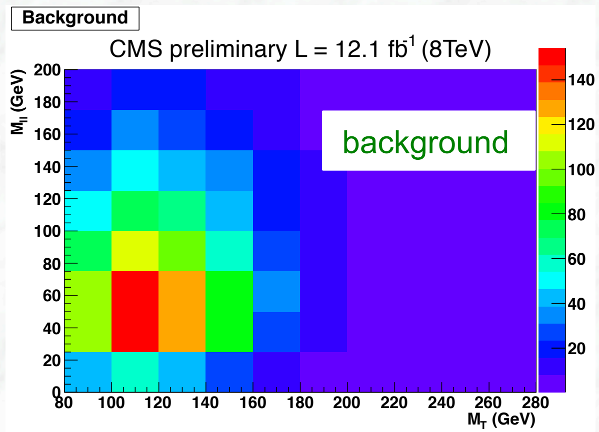
Clear excess visible in both channels

Transverse mass distributions after final cuts for the H → WW → ℓν ℓν search



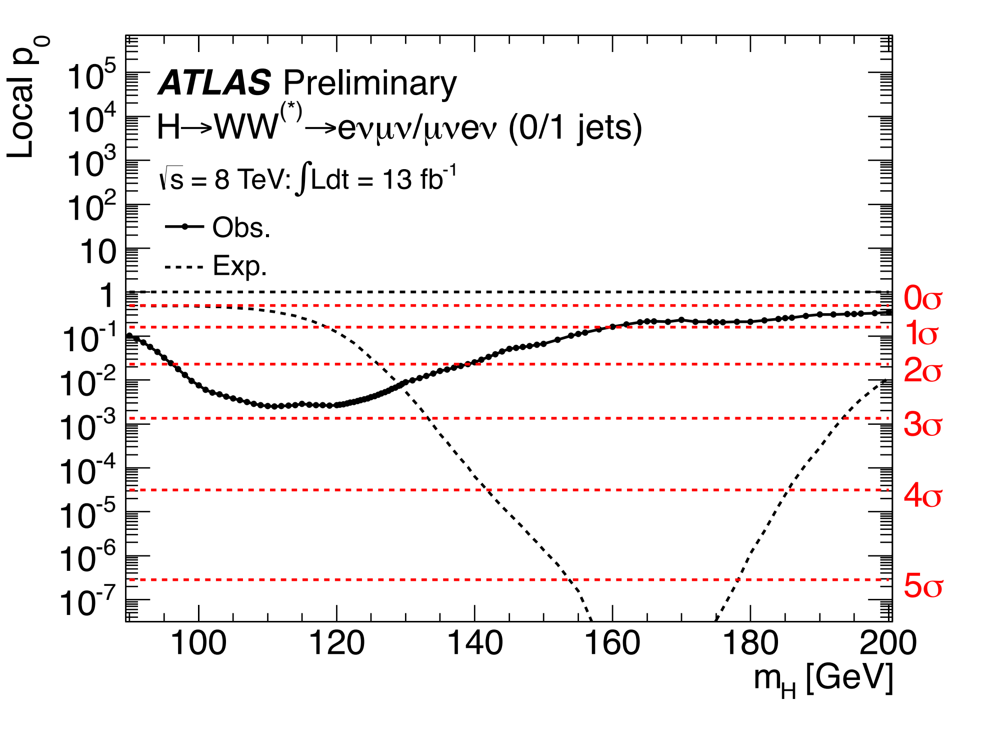


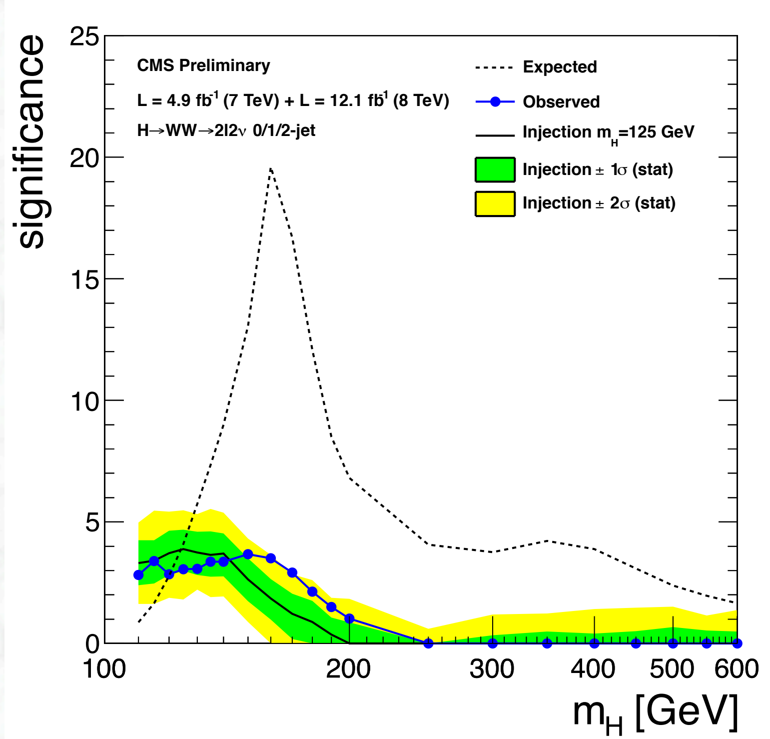




- Clear excess visible in both channels
- Exploit different correlations between signal and backgrounds for the final fit

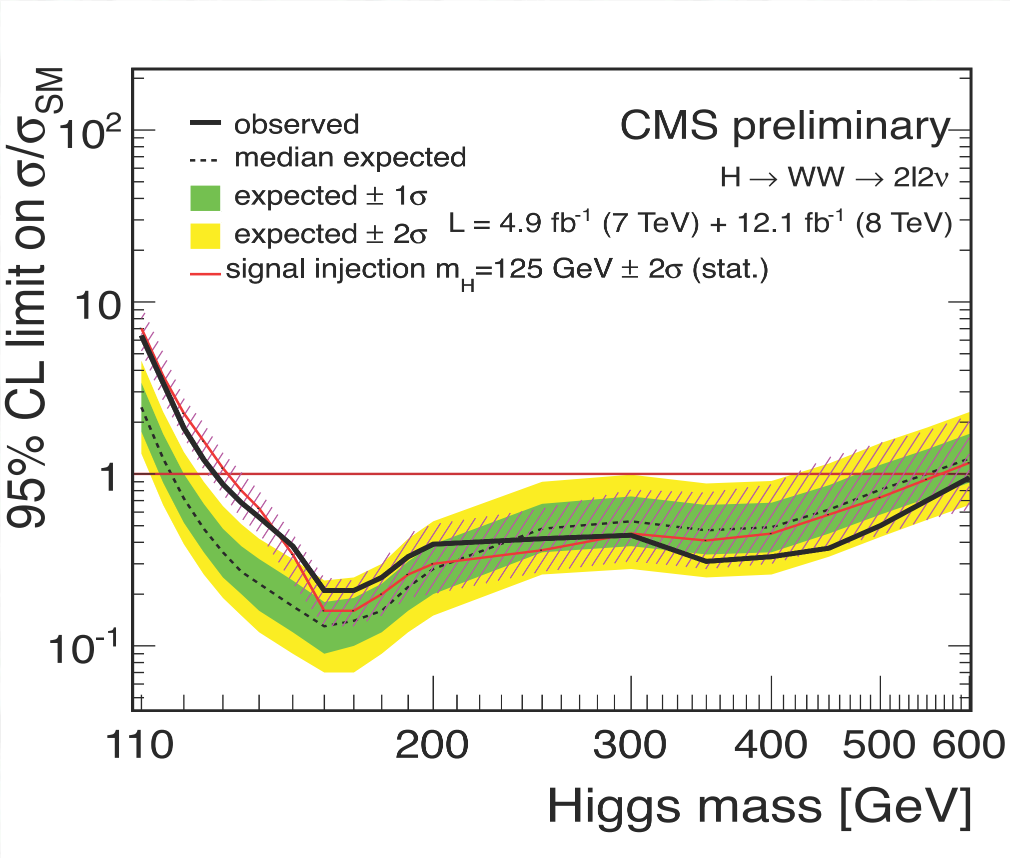
H → WW → ℓν ℓν: compatibility with background hypothesis





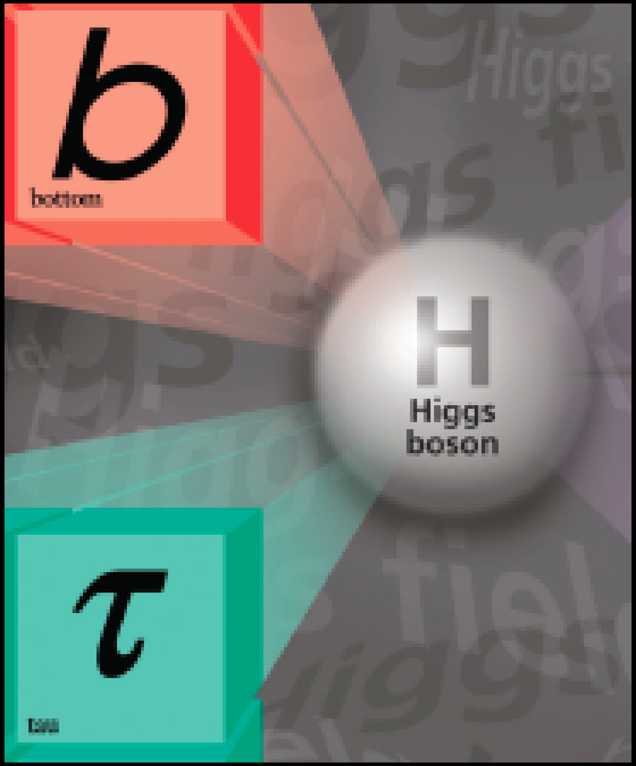
expected for m_H = 125 GeV:	4.1σ
observed at 125 GeV:	3.1σ

$H \rightarrow WW \rightarrow \ell\nu\,\ell\nu$: excluded cross sections



- WW channel alone excludes high mass SM Higgs boson up to masses around 600 GeV
- Background from “boson-126” visible in low mass region
- Smaller branching ratios (σ / σ_{SM}) excluded over significant mass range (important for “exotic Higgs model believers”)

Where are the τ and b decays ?

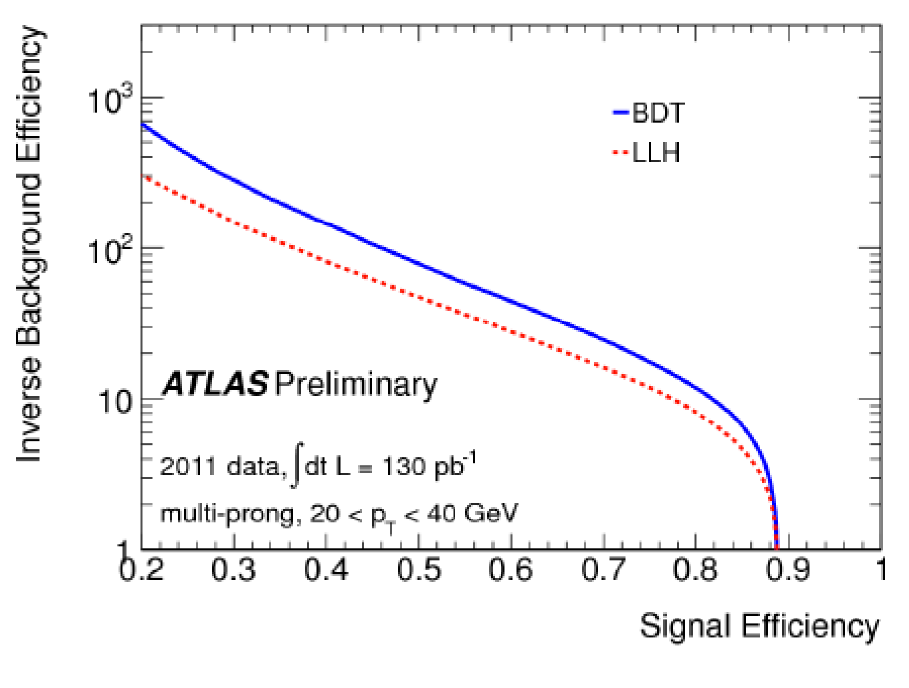


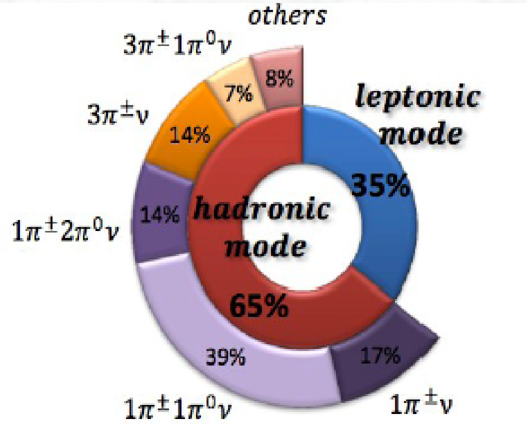
Why is the search in these decay modes so challenging?

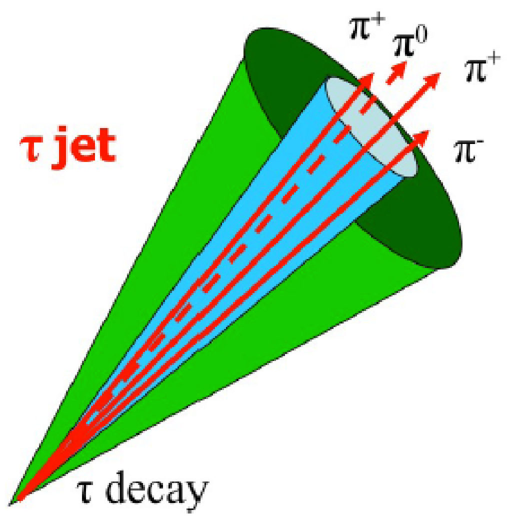
- The τ lepton is the heaviest lepton

  $m_\tau = 1.78$ GeV /c^2, lifetime 2.9 10^{-13} s

- Challenge: distinguish hadronic τ decays from hadronic jet activity

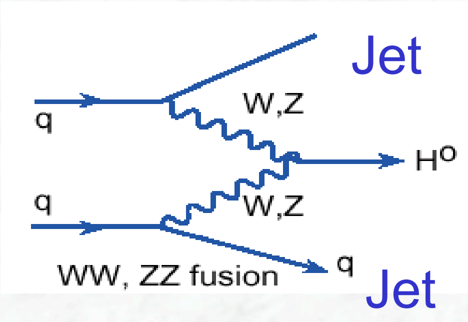




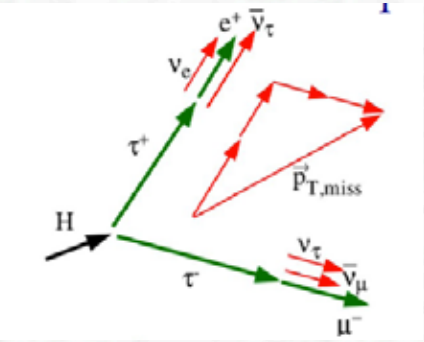


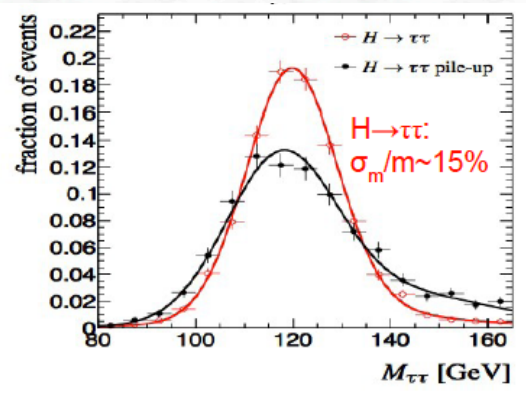
More complications with taus:

- Small signal rate, compared to large background from jet production via QCD processes
  → smaller vector boson fusion need to be used

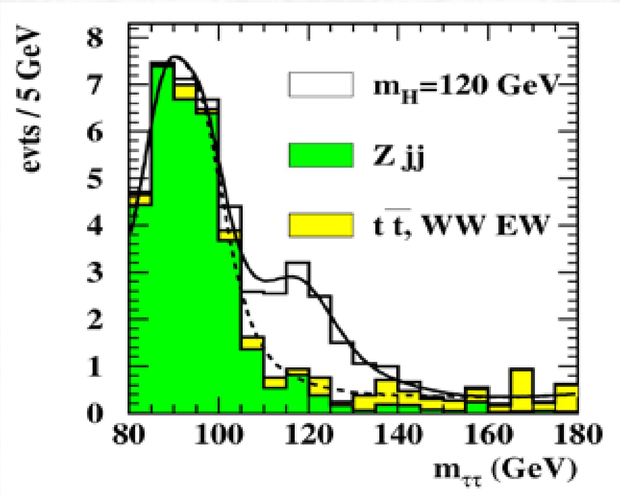


- Neutrinos in the final state
  → poor mass resolution





- Small signal in presence of a large $Z \to \tau\tau$ background



Expected signal

Monte Carlo Simulation !
~30 fb^{-1}

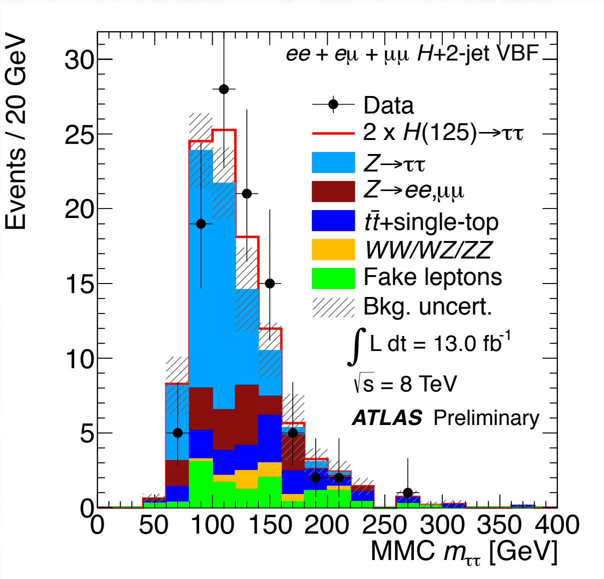
Results based on 13 fb^{-1} data at $\sqrt{s}$ = 8 TeV:

- Analysis is split into several sub-channels: - lepton-lepton decay mode
  - lepton-hadron decay mode
  - hadron – hadron decay mode

- and several topologies: - VBF topology
  - boosted τ (1 jet with high p_T)
  - 0 jet (low sensitivity)
- Domiant Z→ττ background via “embedding” technique from Z → μμ real events

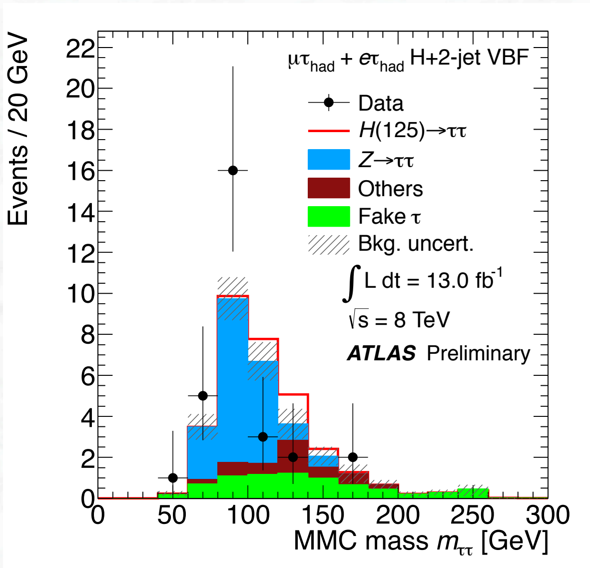
ττ mass distributions for the VBF topology

lep-lep



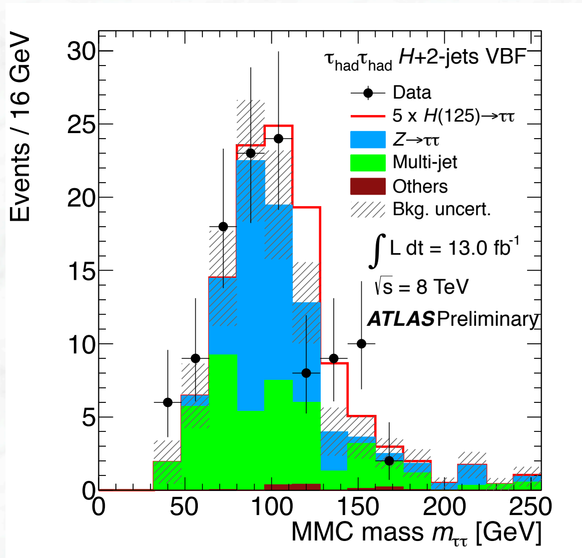
2 x SM Higgs signal

lep-had



1 x SM Higgs signal

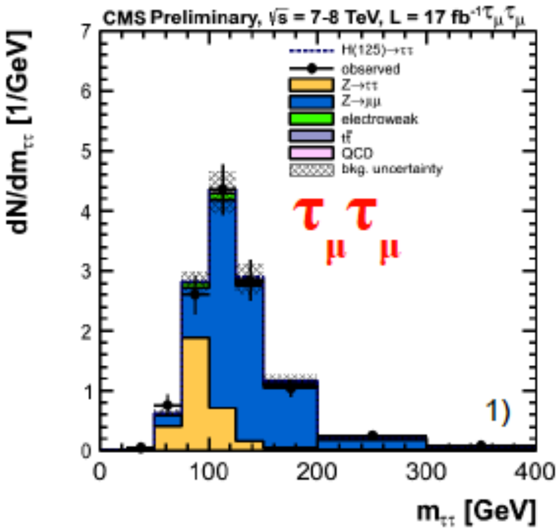
had-had

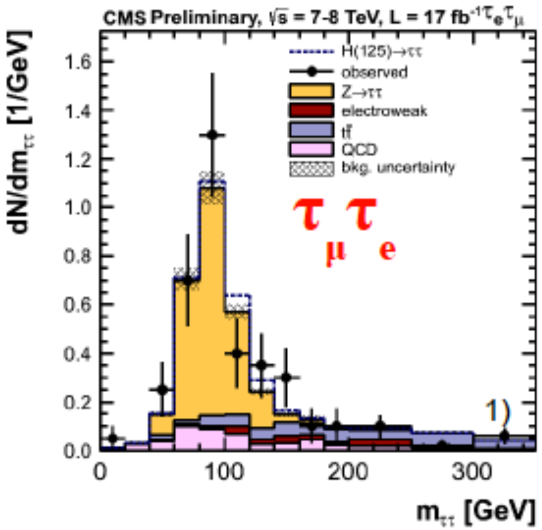


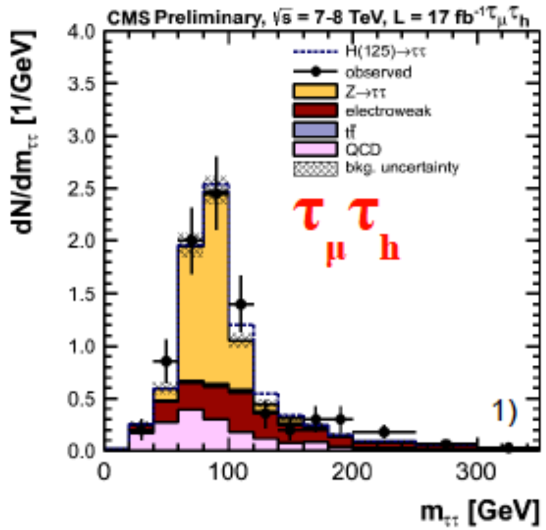
5 x SM Higgs signal

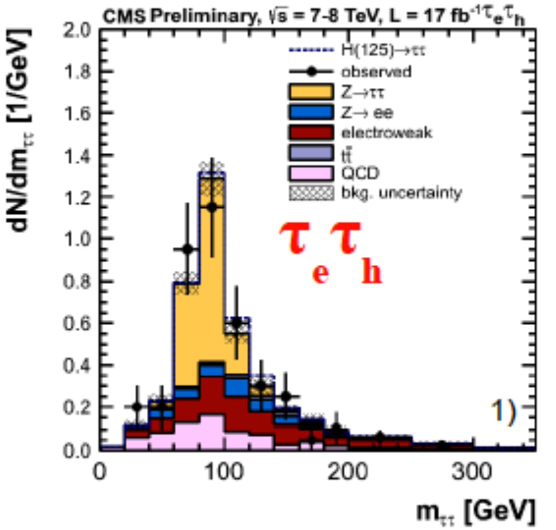
Results based on 17 fb^{-1} data:

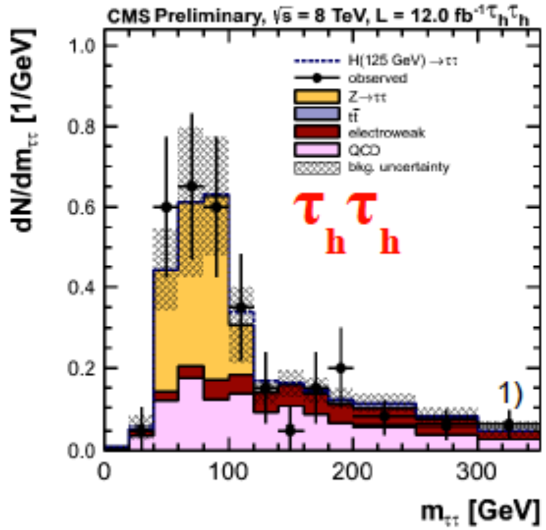
$\tau\tau$ mass distributions for the VBF topology







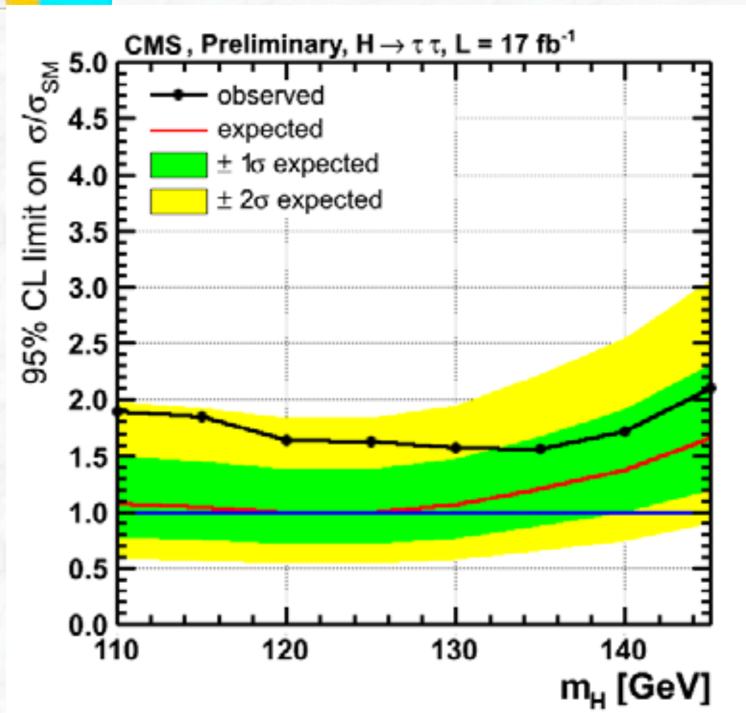


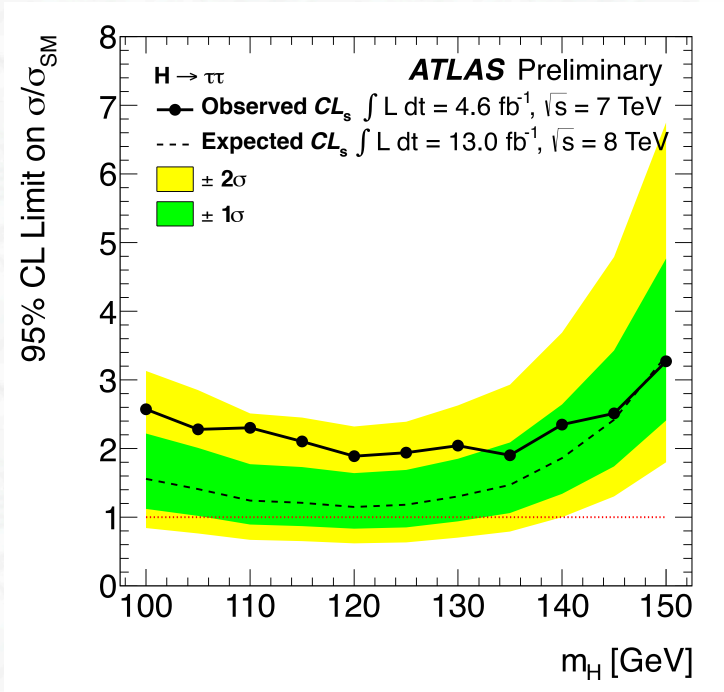


- After template fit (S+B hypothesis).
- Shaded bands: uncert's after fit.

1) divided by bin width

Results of updated H → ττ searches

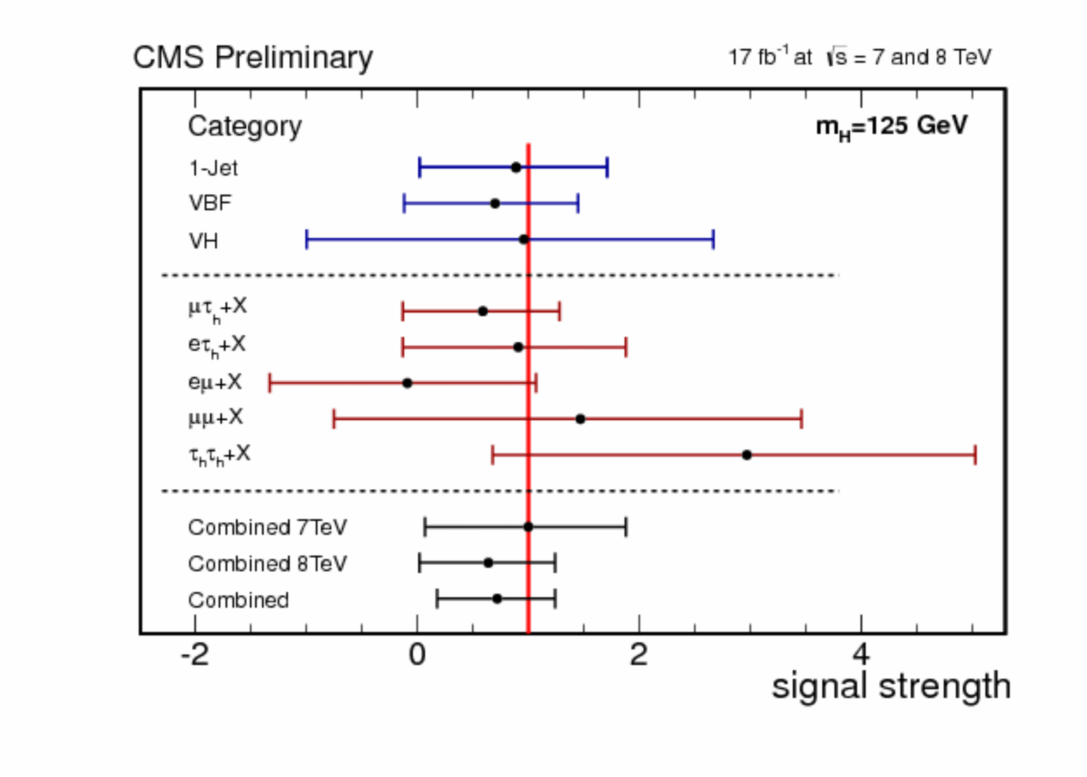




- Sensitivity (125 GeV) = 1.0 σ_{SM}
  Observed limit (125 GeV) = 1.6 σ_{SM}
- Sensitivity (125 GeV) = 1.2 σ_{SM}
  Observed limit (125 GeV) = 1.9 σ_{SM}

- The results of both experiments are compatible with a Higgs boson signal at 125 GeV, but also with the background only hypothesis.

Results of updated H → ττ searches

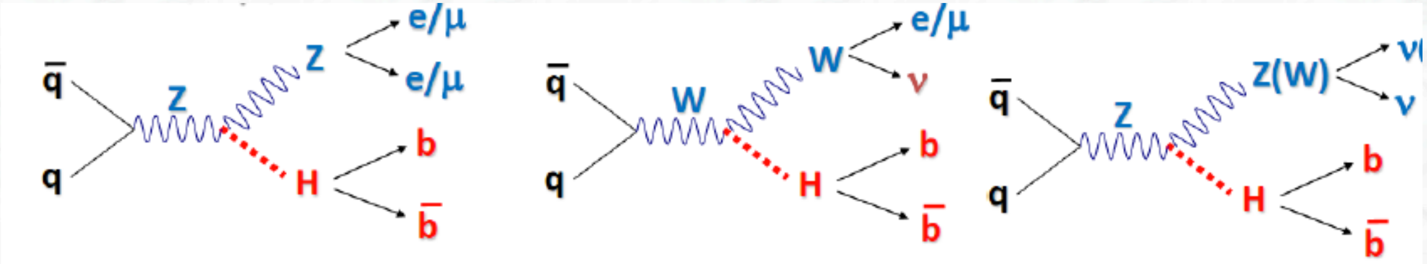


Combined signal strength

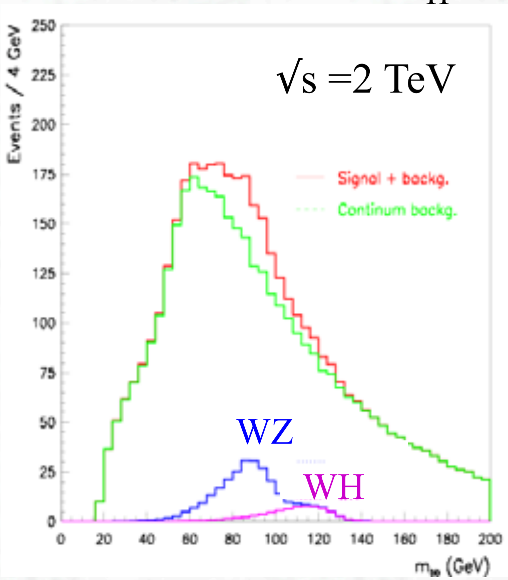
CMS: μ (H → ττ) = 0.72 ± 0.52

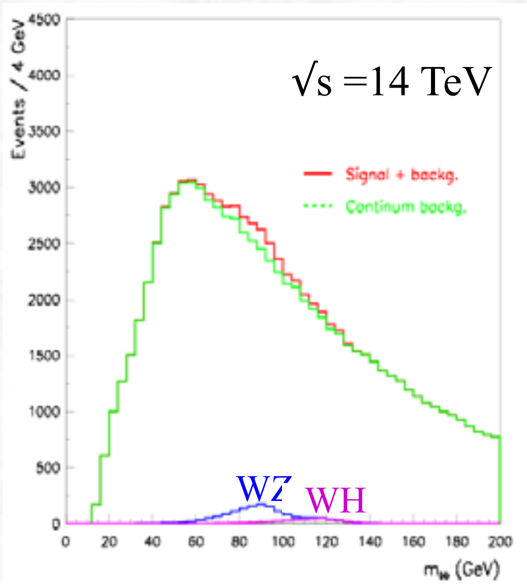
ATLAS: μ (H → ττ) = 0.7 ± 0.7

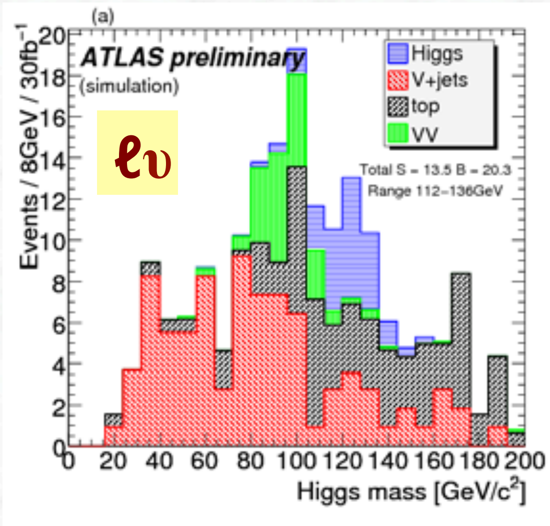
Search for VH, H → bb



m_H = 120 GeV, 30 fb^{-1}







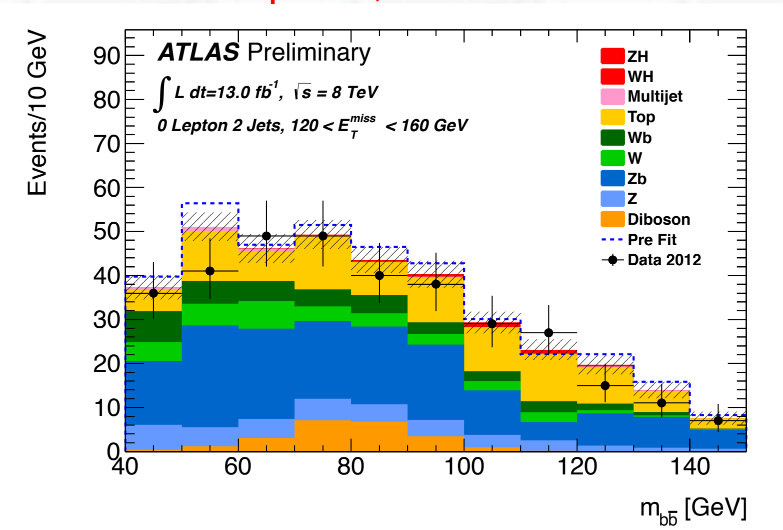
ATLAS simulation 2002

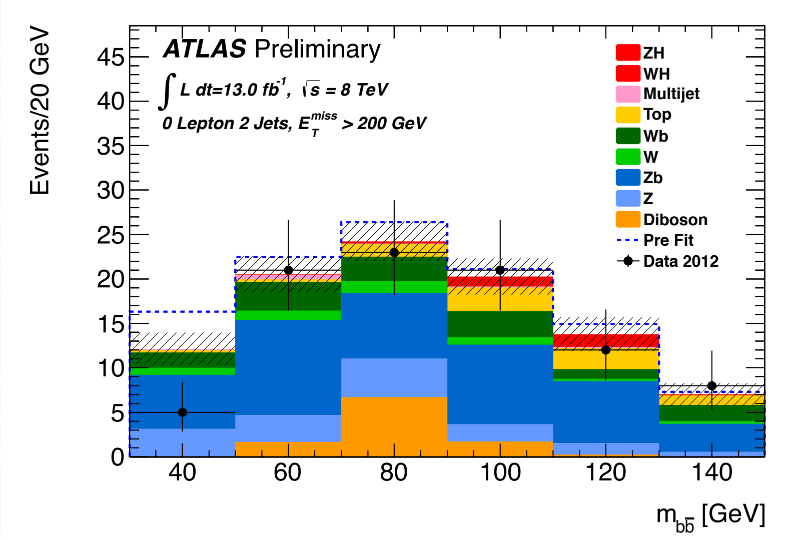
ATL-PHYS-PUB-2009-088

"boosted Higgs" (jet substructure)

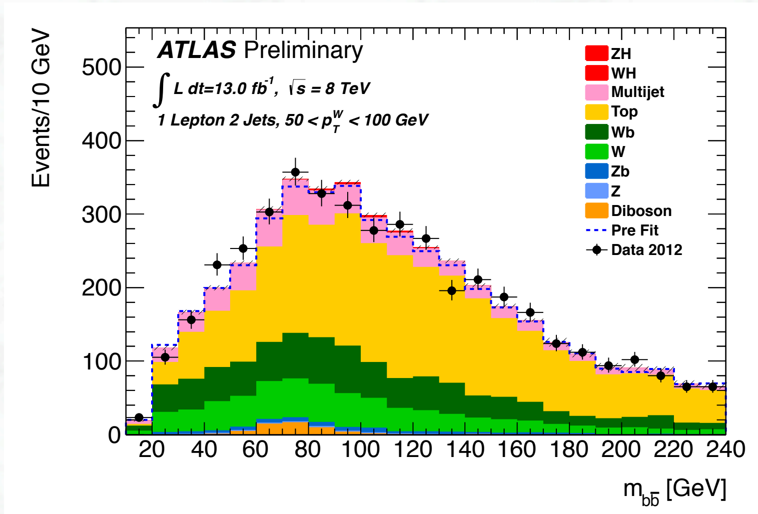
Results on H → bb from ATLAS

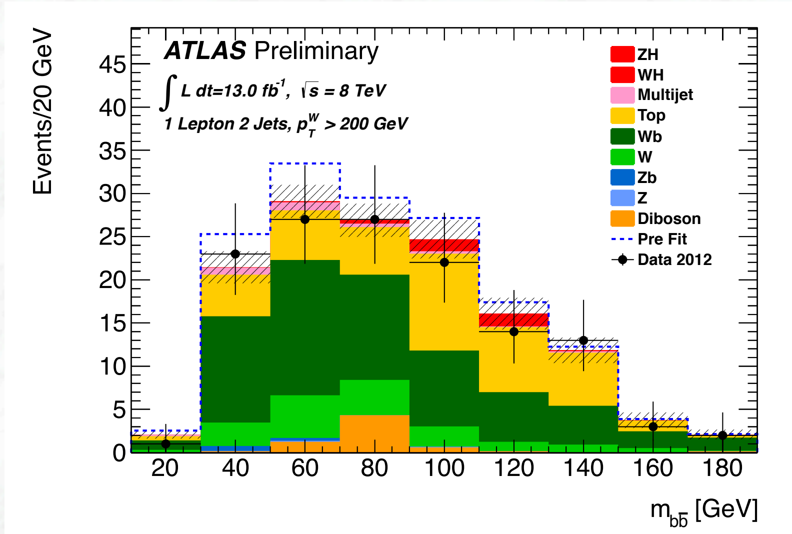
0 Leptons, Z → νν channel



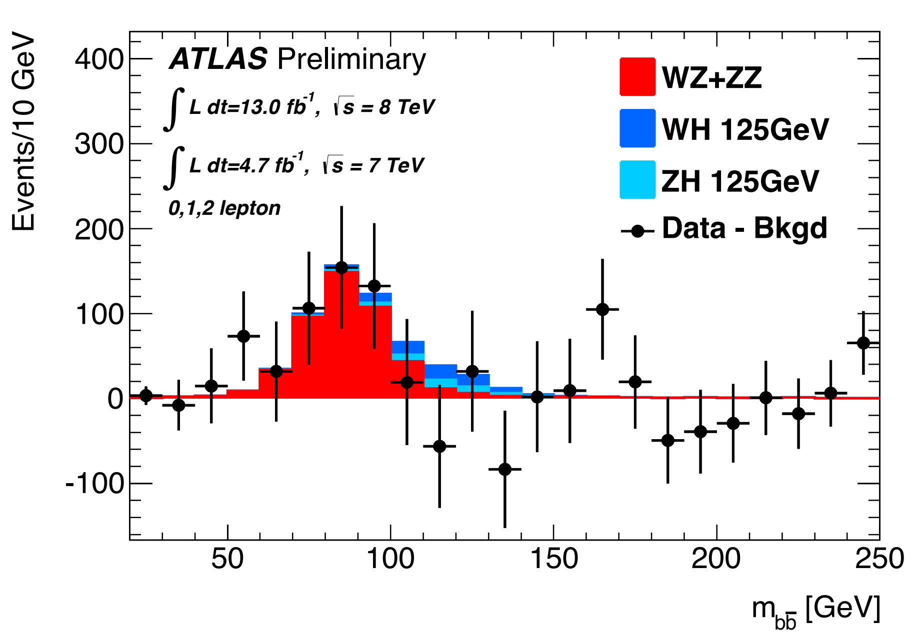


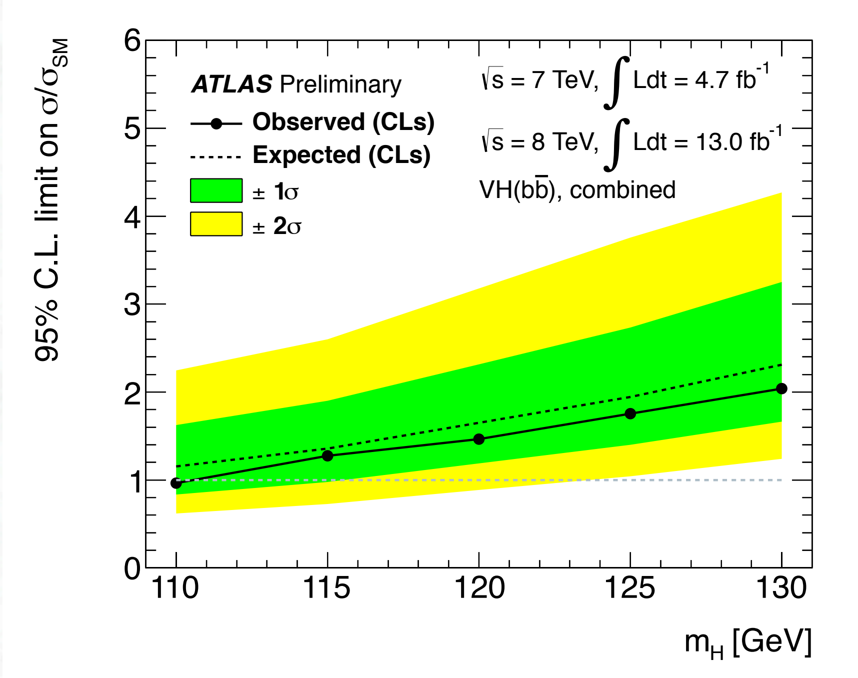
1 Lepton, W → eν channel





Results on H → bb from ATLAS



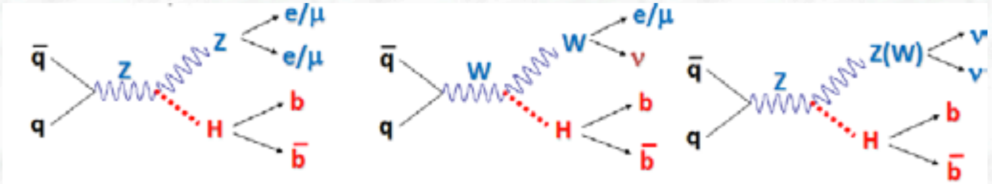


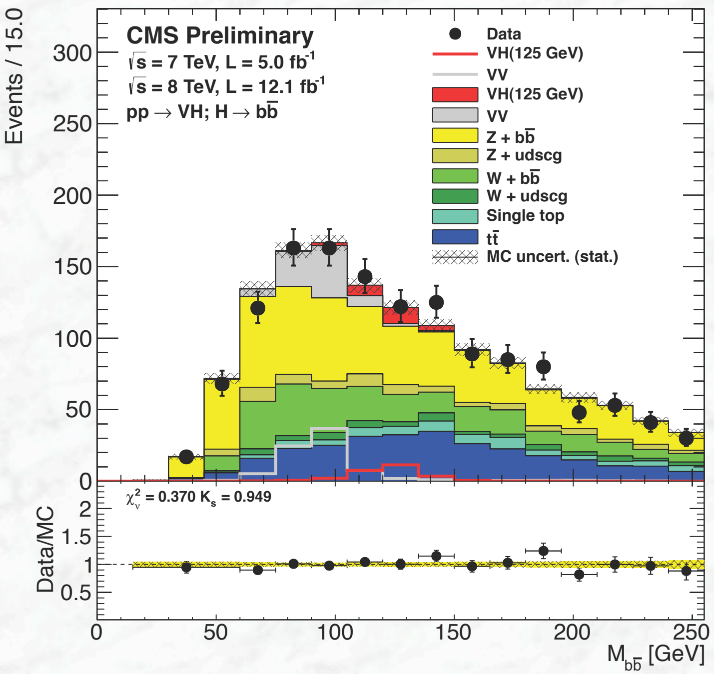
- No excess visible around 125 GeV
- Signal from di-boson production VZ, Z → bb seen

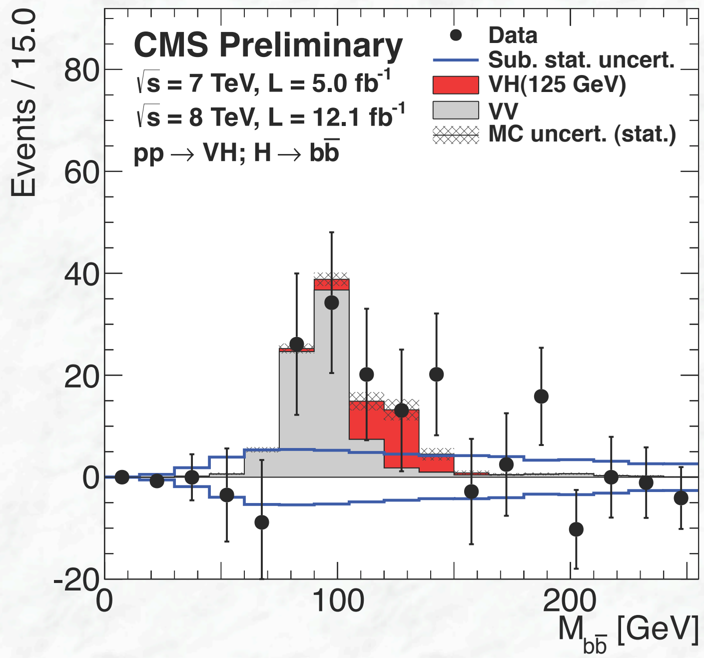
Combined signal strength

μ (H → bb) = -0.4 ± 1.1

Results on H → bb from CMS

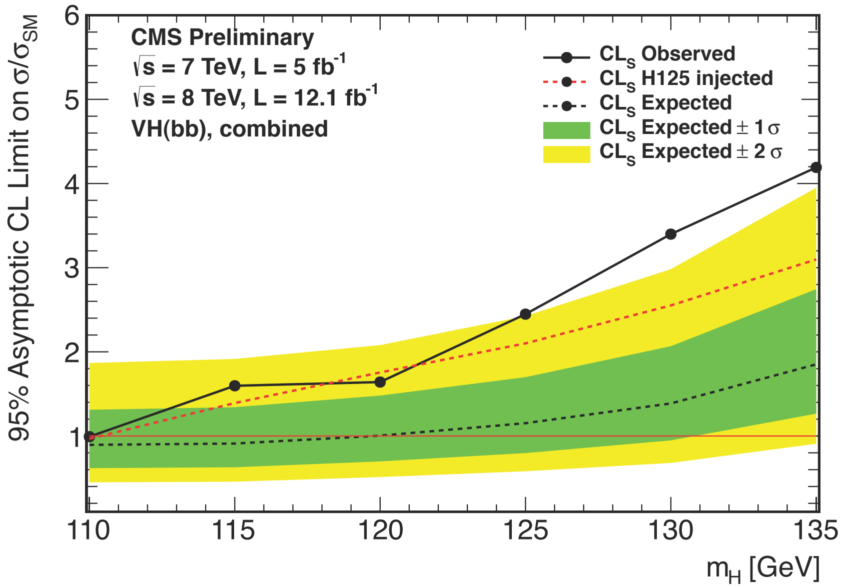


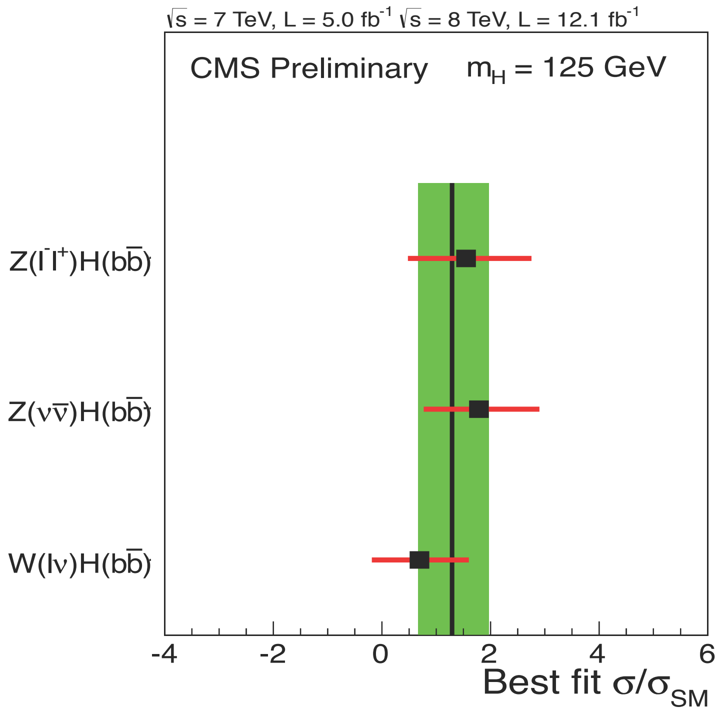




- Small excess is showing up around 125 GeV
- Signal from di-boson production VZ, Z→ bb seen and well described

Results on H → bb



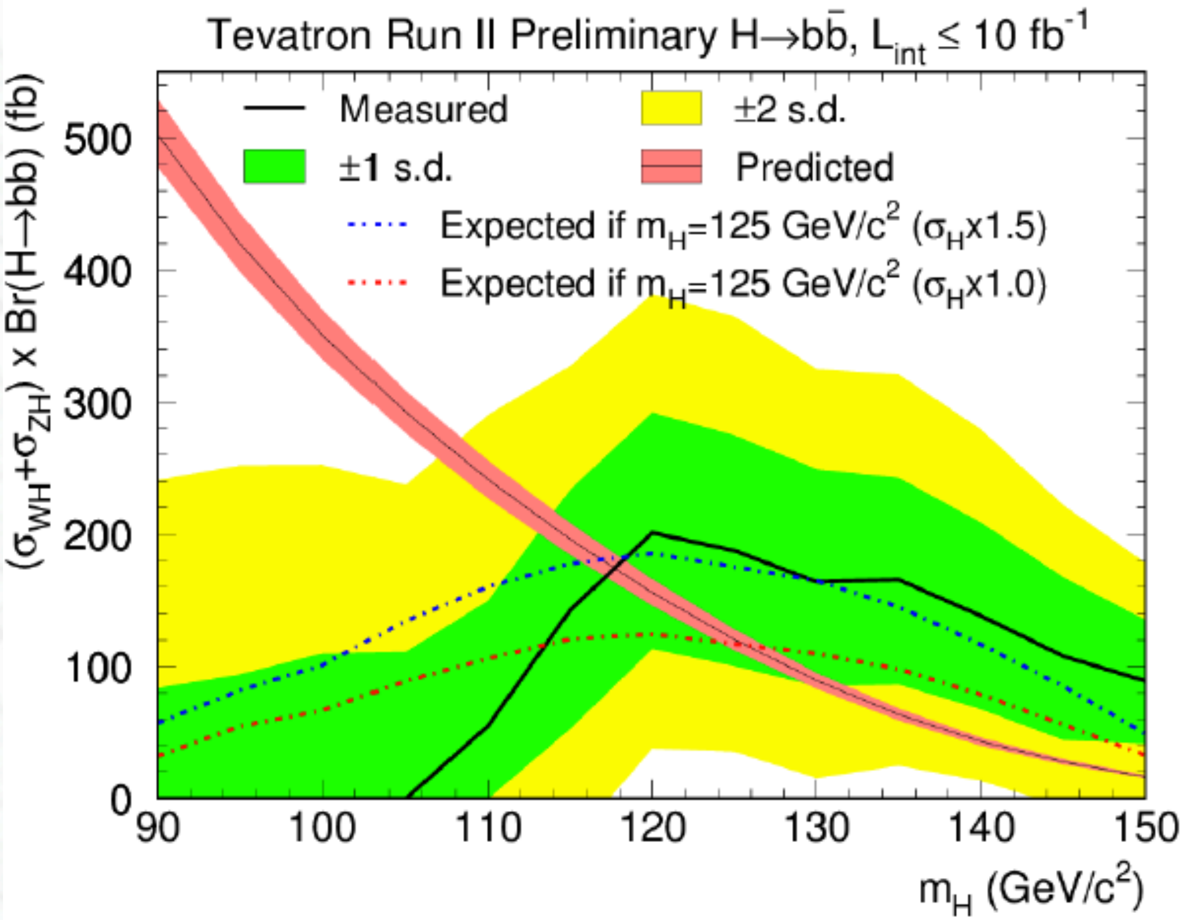


- Observed excess (125 GeV) = 2.2 σ
  Expected (125 GeV) = 2.1 σ
- Compatible with Higgs boson signal at 125 GeV but also with background only hypothesis.

Combined signal strength

μ (H → bb) = $1.3^{+0.7}_{-0.6}$

Results on H → bb from the Tevatron

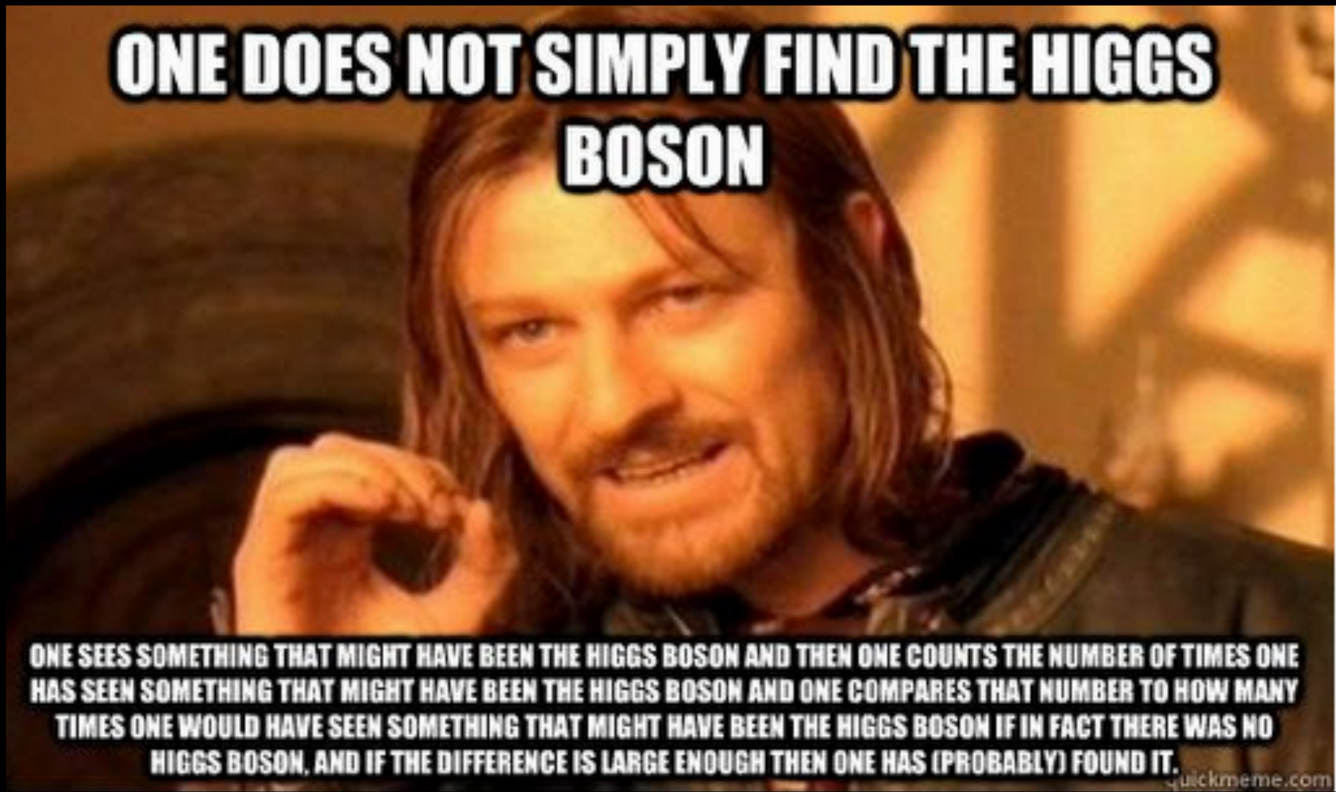


$\mu = 1.56 \pm^{0.72}_{0.73}$

$$(\sigma_{WH}+\sigma_{ZH})\times\mathcal{B}(H\rightarrow b\bar{b}) = 0.19\pm0.09\ (\mathrm{stat}+\mathrm{syst})\ \mathrm{pb}.$$

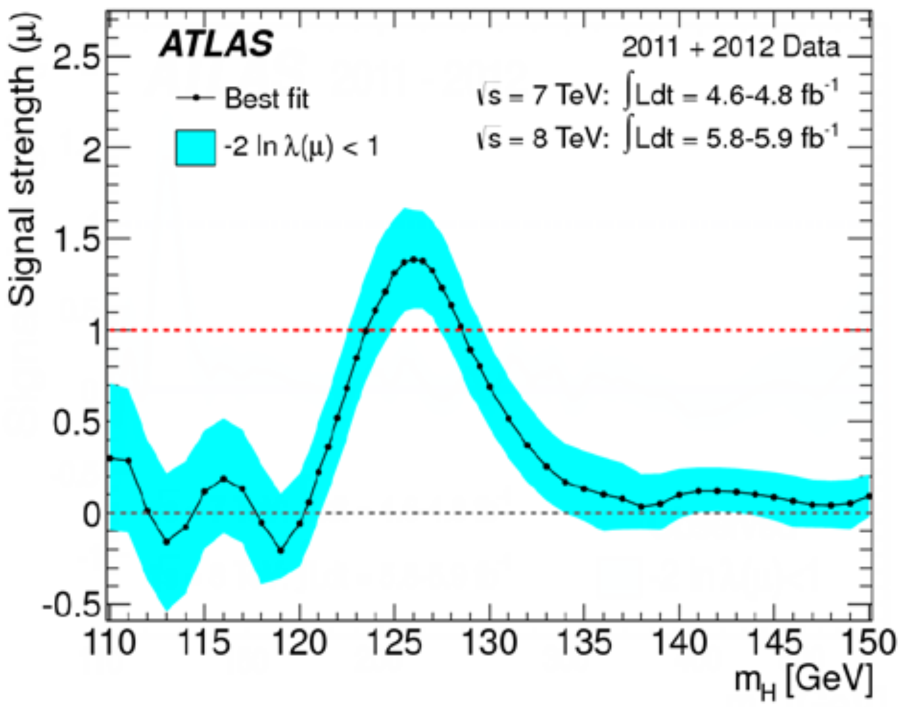
SM expectation : 0.12 ± 0.01 pb

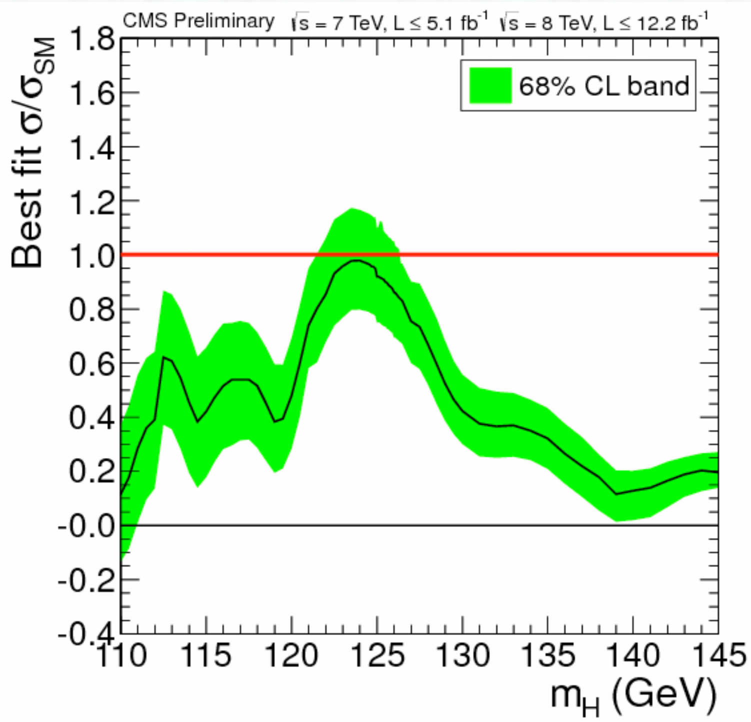
Is it the Higgs Boson ?



Signal strength of the new particle

Determination of „best“ signal strength $\mu = \sigma_{observed}/\sigma_{SM}$





Largest signal strength at m_H= 126.0 GeV

μ = 1.4 ± 0.3

μ = 1.3 ± 0.3 (incl. latest H → ττ and H → bb results)

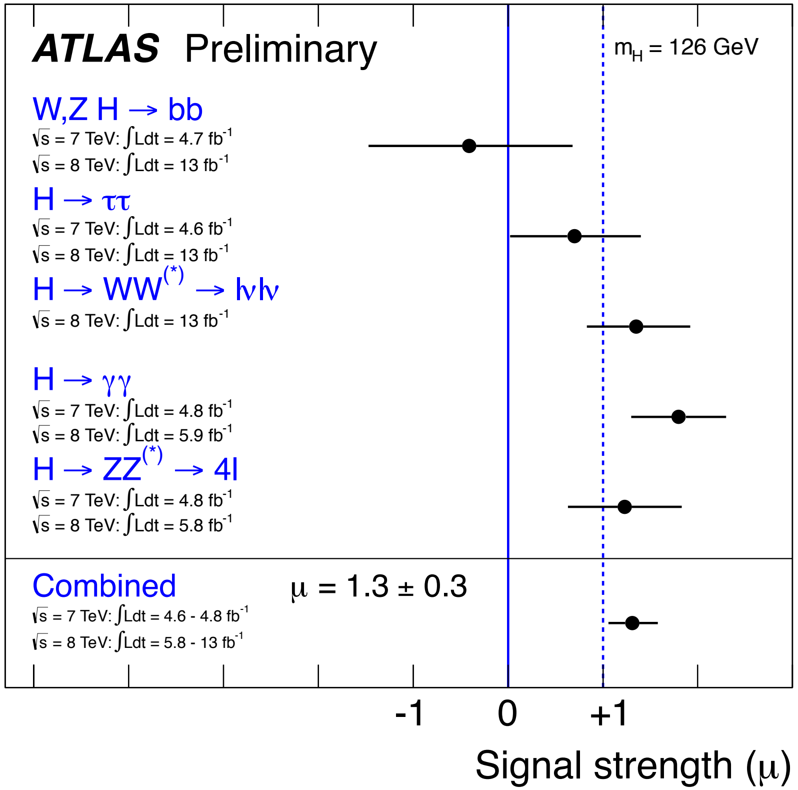
μ value for a mass of m_H= 125.8 GeV

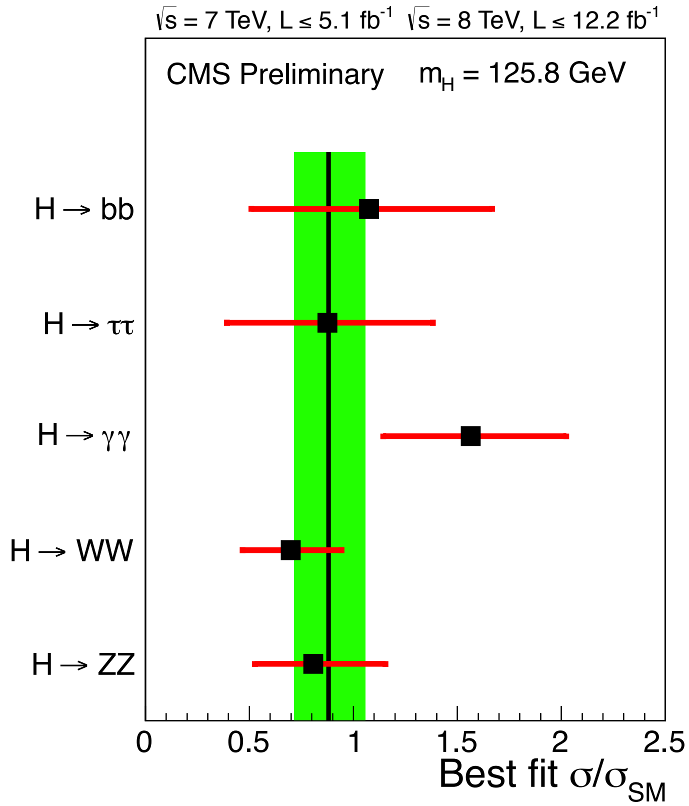
μ = 0.88 ± 0.21

Consistent with expectation in the Standard Model (μ=1)

Signal strength in individual decay modes

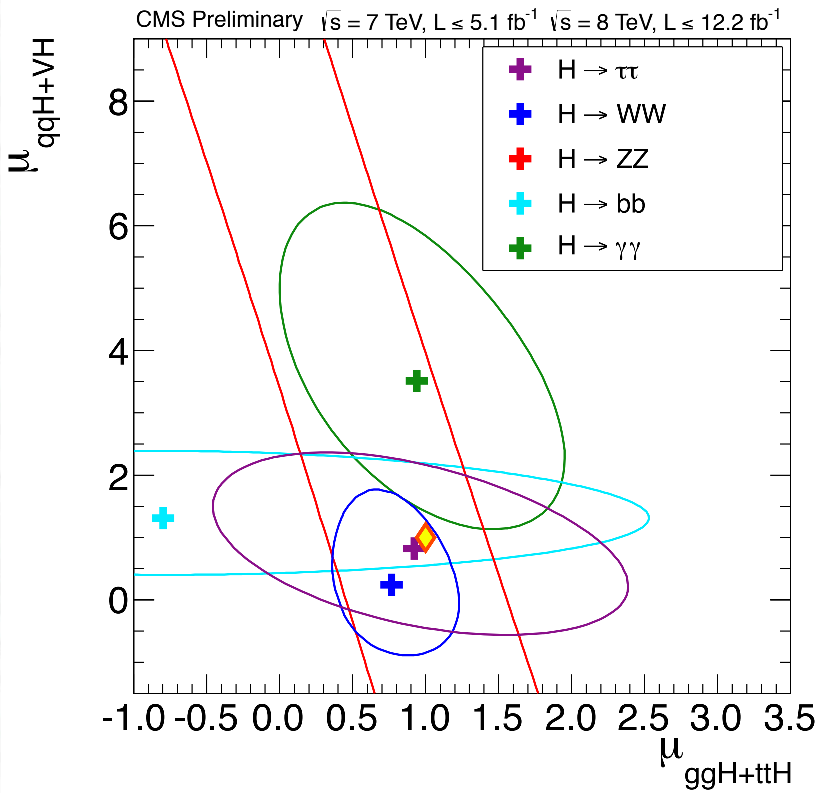
-including new data-

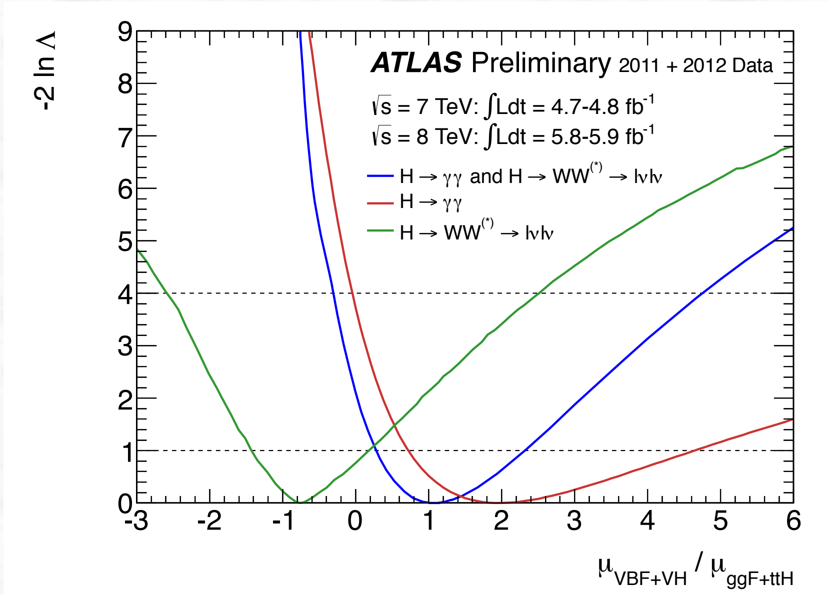




- Data are consistent with the hypothesis of a Standard Model Higgs boson !
- Experimental uncertainties are still too large to get excited about “high” γγ and “low” fermionic (ττ and bb) signal strength !

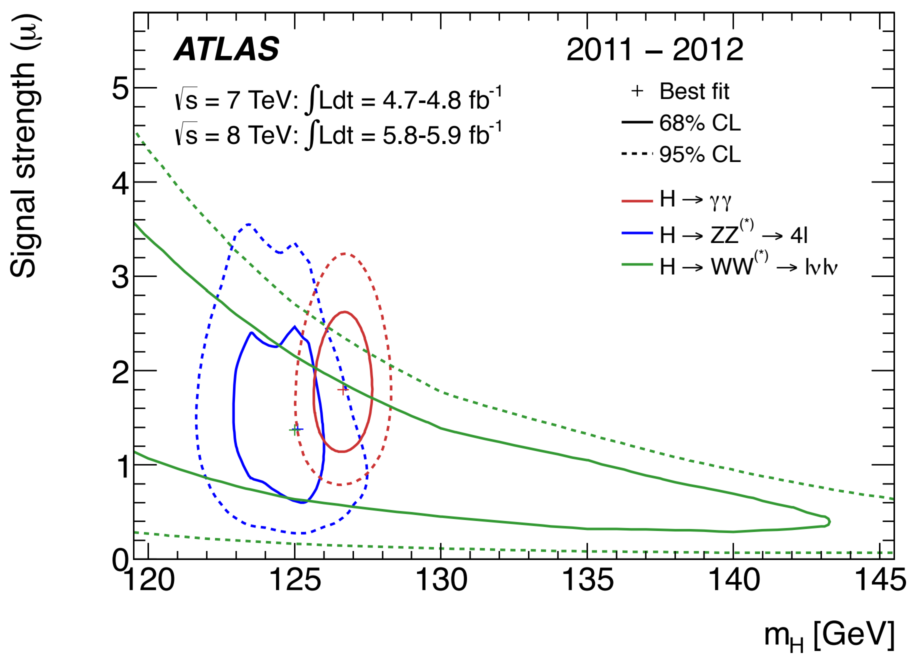
A first attempt to separate the production processes
-including new data-

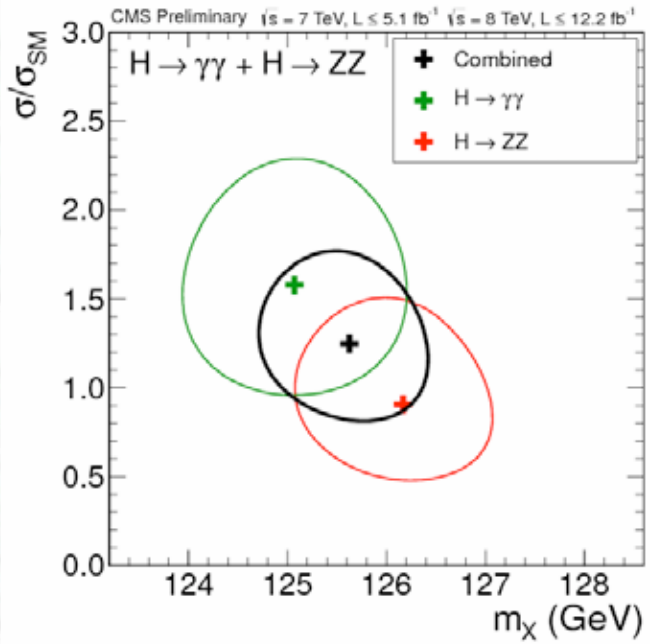




- Data are consistent with the hypothesis of a Standard Model Higgs boson !
- Experimental uncertainties are still too large to get excited about “high” $\gamma\gamma$ and “low” fermionic ($\tau\tau$ and bb) signal strength !

Determination of mass and signal strength





m_H = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV

m_H = 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV

Relative signal strength for the two decay modes are constrained to their SM expectations for a Higgs boson

Compatibility with a Standard Model Higgs boson

- Measurements / constraints on coupling scale factors
  (following the prescription as defined by the Higgs cross-section working group)

- Assumptions:

  - Allow for modifications of coupling strength (scale factors)
    The observed state is assumed to be CP-even scalar as in the SM

  - Signals observed in the different channels originate from a single narrow resonance

  - The width of the Higgs boson is assumed to be negligible

→ $$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

Compatibility with a Standard Model Higgs boson

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

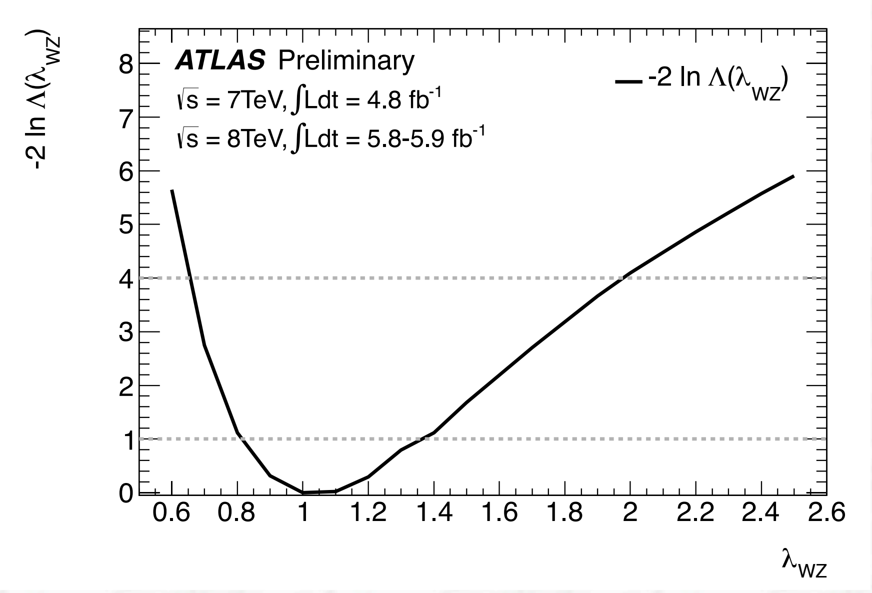
$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa_W^2$$

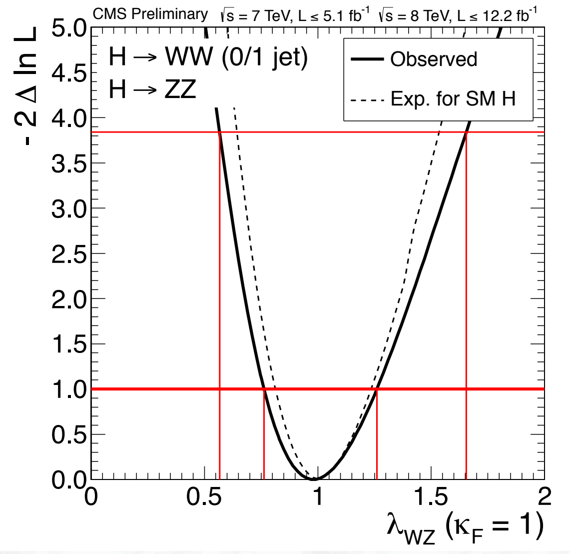
$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa_Z^2$$

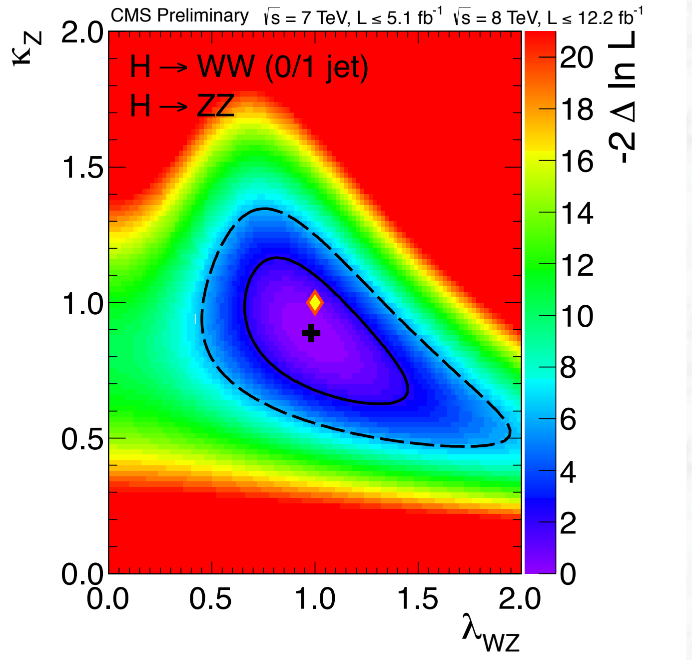
$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

Test of W/Z coupling strength

-test of custodial symmetry-

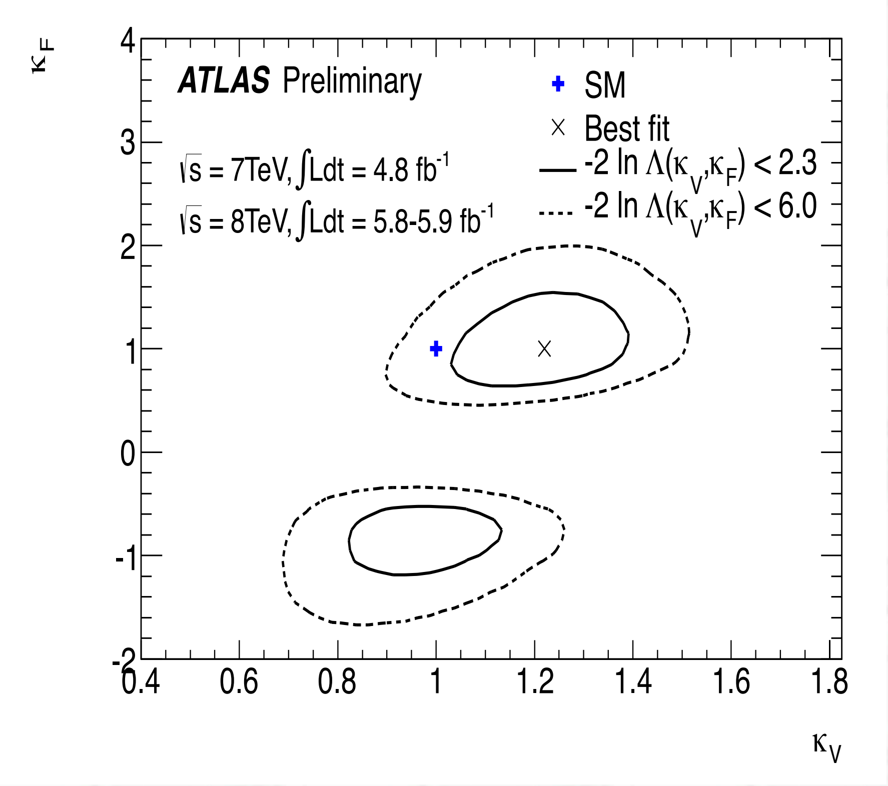


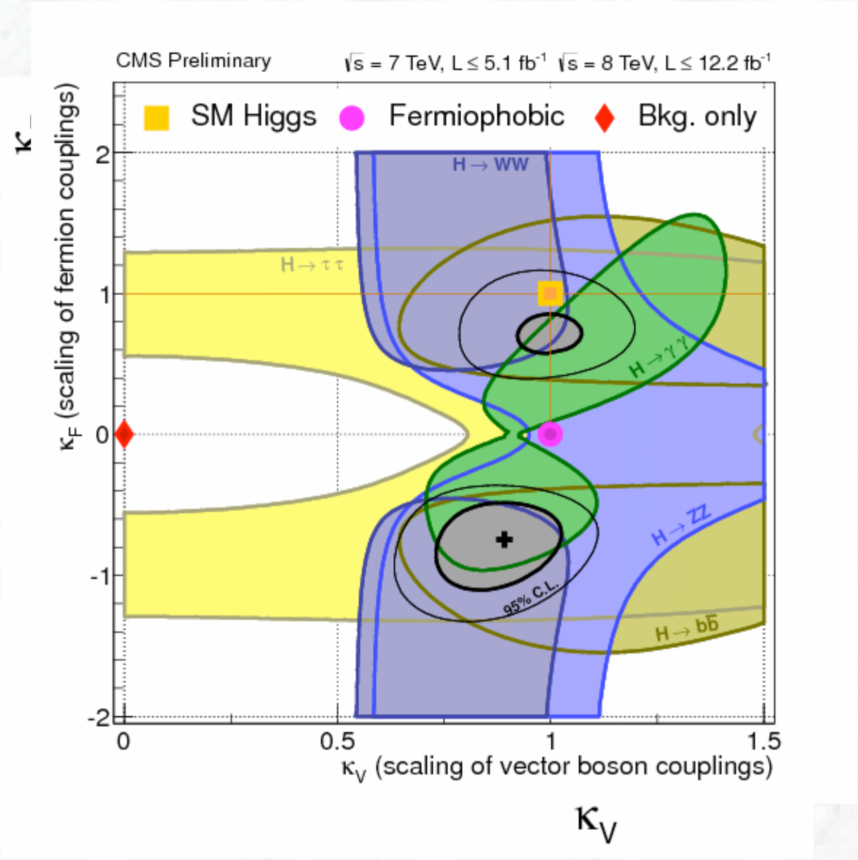




Fermion versus boson couplings

- Consider two scale factors: k_F and k_V
- Include all channels in a global fit, include two sectors in the fit





H → γγ loop is sensitive to sign, more statistics will help to solve the ambiguity

Conclusions

- With the operation of the LHC at high energies, particle physics has entered a new era

- Performance of the LHC and the experiments is superb

- A milestone discovery made in July 2012

  - Data are consistent with a Standard Model Higgs boson with a mass ~125 GeV, but also with many extended Models
  - Evidence for decays in Heavy Fermions ($\tau\tau$ and bb) is building up

- More data and a combination of the results of the two experiments are needed to determine the true nature of the new particle (Spin, CP, couplings to fermions and bosons)

- More conclusive and more precise results are expected in Spring / Summer 2013

- … and hopefully the discovery of the Higgs-like particle it a portal to other exciting discoveries at the LHC