Search for the SM Higgs boson at LHC

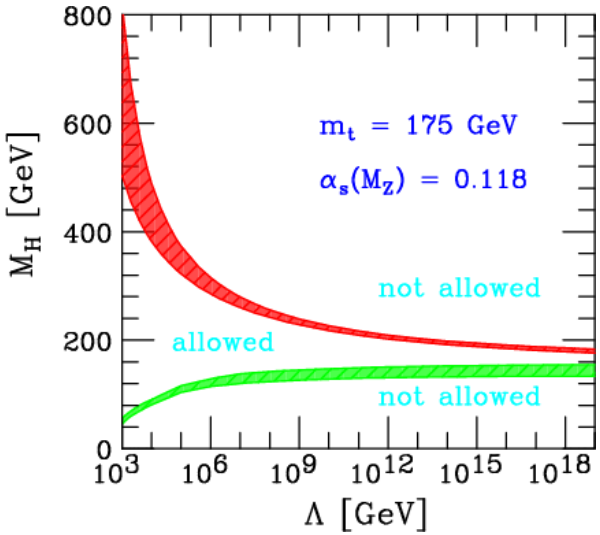
Patricia Lobelle Pardo
(Universidad de Cantabria)

On behalf of the ATLAS and CMS collaborations

XVII International Conference on Deep-Inelastic Scattering and Related Subjects

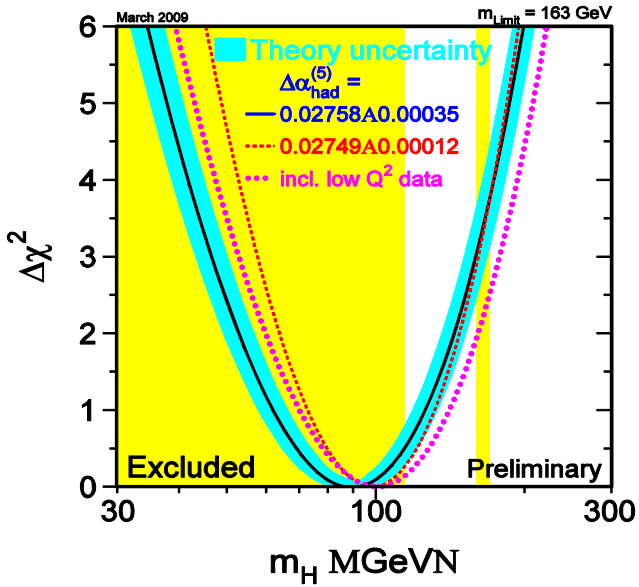
DIS09, 26th-30th April 2009, Madrid

Higgs current limits



- ***Theoretical limits***

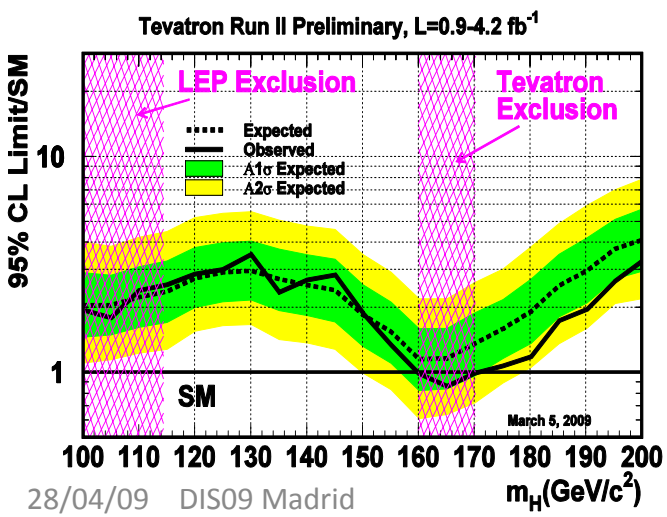
Finite and positive Higgs couplings



- ***Experimental limits***

❖ ***LEP*** : m_H > 114.4 GeV/c^2 at 95% CL

❖ ***Tevatron*** : Excluded the mass range of 160 GeV/c^2 to 170 GeV/c^2 at 95%CL



❖ ***Indirect constraints***

Derived from precise EWK measurements:

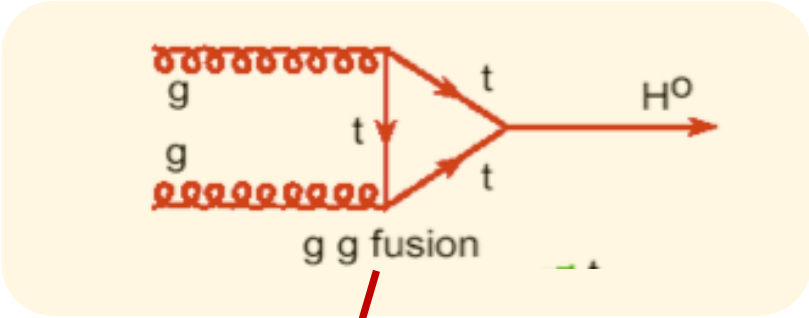
$m_H = 90\ ^{+36}_{-27}$ GeV/c^2

(m_H < 163 GeV/c^2) (m_H <191 GeV/c^2 if including LEP2 results)

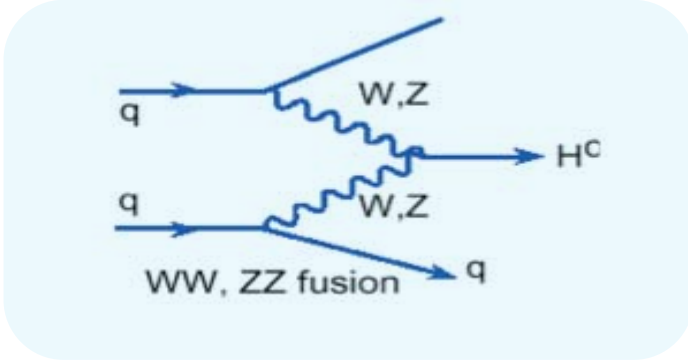
A light Higgs is favoured by measurements

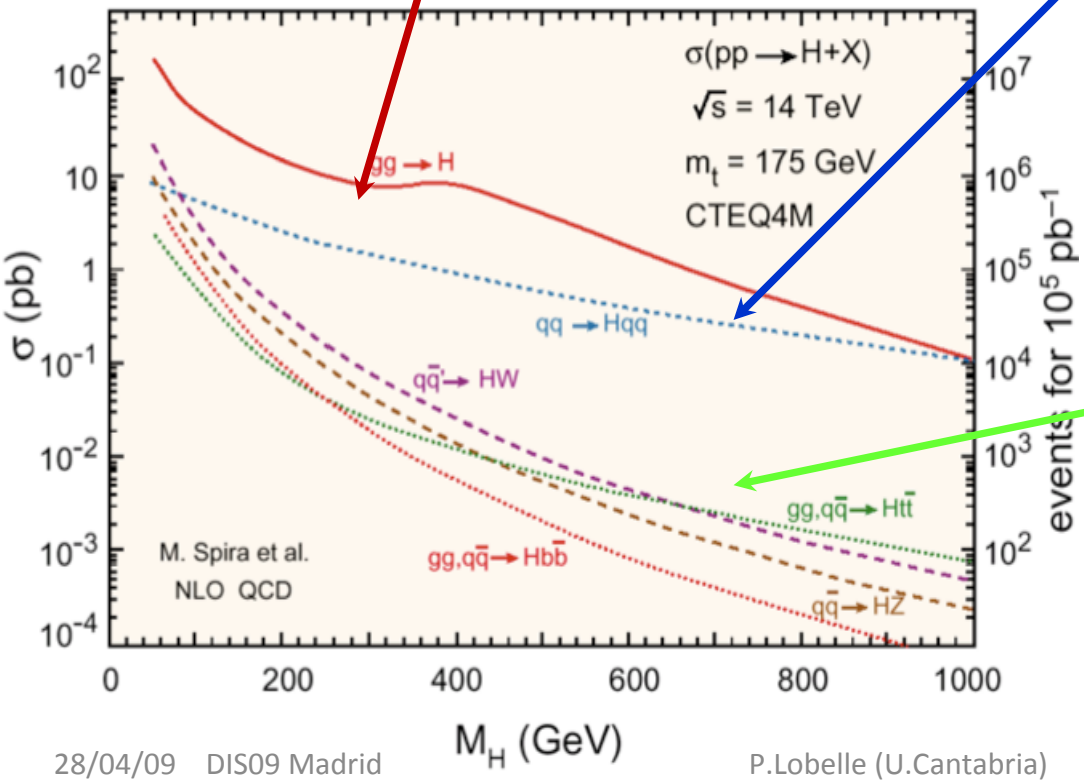
SM Higgs production at LHC

✓**Gluon-gluon fusion: dominant mode at LHC**

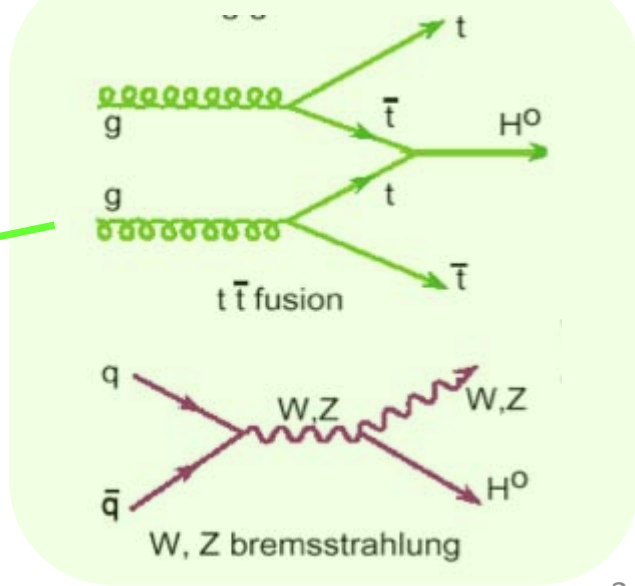


✓**Vector Boson Fusion**

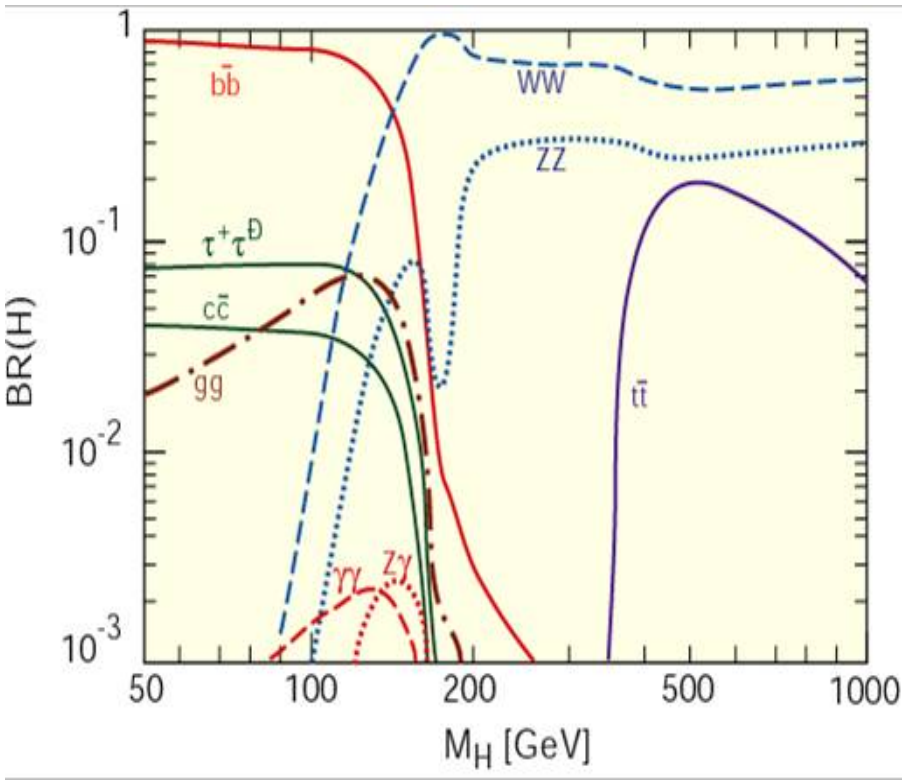




✓**Associated production**



SM Higgs decays



❖ ***At Low mass*** ***($m_H < 2m_Z$)***

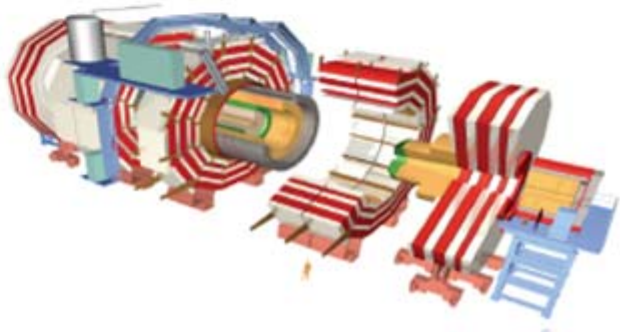
- **H→ bb : BR ~0.85 but huge QCD background**
- **H→ττ : accessible through VBF**
- **H→γγ : very important despite the low BR (~0.002) due to the excellent γ/jet separation and γ resolution**
- **H→WW*→2l2ν : accesible through gg fusion and VBF, BR~1 at m_H ~160 GeV/c²**
- **H→ZZ*→4l : also performant**

❖ **For Higher masses**

H→WW* →2l2v and **H→ZZ*→4l**

ATLAS and CMS

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\times10^{-4}p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\times10^{-4}p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)



State of the art

CERN-OPEN-2008-020
December 2008

Expected Performance of the ATLAS Experiment

Detector, Trigger and Physics

The ATLAS Collaboration

A detailed study is presented of the expected performance of the ATLAS detector. The reconstruction of tracks, leptons, photons, missing energy and jets is investigated, together with the performance of *b*-tagging and the trigger. The physics potential for a variety of interesting physics processes, within the Standard Model and beyond, is examined. The study comprises a series of notes based on simulations of the detector and physics processes, with particular emphasis given to the data expected from the first years of operation of the LHC at CERN.

NEW results with Full Simulation!

- **Better detector description and simulation: geometry, material budget, Geant4**
- **New approaches to match parton showers and matrix elements (ALPGEN + MLM matching, SHERPA etc.)**
- **New (N)NLO Monte Carlos for signals & backgrounds (MCFM, MC@NLO)**

Sensitivities at NLO!!

(NNLO maybe available before data taking , which will increase x-sections)

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J. Phys. G: Nucl. Part. Phys. 34 (2007) 995–1579 — doi:10.1088/0954-3899/34/6/S01

CMS Physics Technical Design Report, Volume II: Physics Performance

The CMS Collaboration

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Abstract

CMS is a general purpose experiment, designed to study the physics of pp collisions at 14 TeV at the Large Hadron Collider (LHC). It currently involves more than 2000 physicists from more than 150 institutes and 37 countries. The LHC will provide extraordinary opportunities for particle physics based on its unprecedented collision energy and luminosity when it begins operation in 2007.

The principal aim of this report is to present the strategy of CMS to explore the rich physics programme offered by the LHC. This volume demonstrates the physics capability of the CMS experiment. The physics goals of CMS are to explore physics at the TeV scale and to study the mechanism of electroweak symmetry breaking through the discovery of the Higgs particle or otherwise. To carry out this task, CMS must be prepared to search for new particles, such as the Higgs boson or supersymmetric particles, or for the Standard Model particles from the start-up of the LHC since new physics at the TeV scale may manifest itself with the largest data samples of the order of a few fb^{-1} or less.

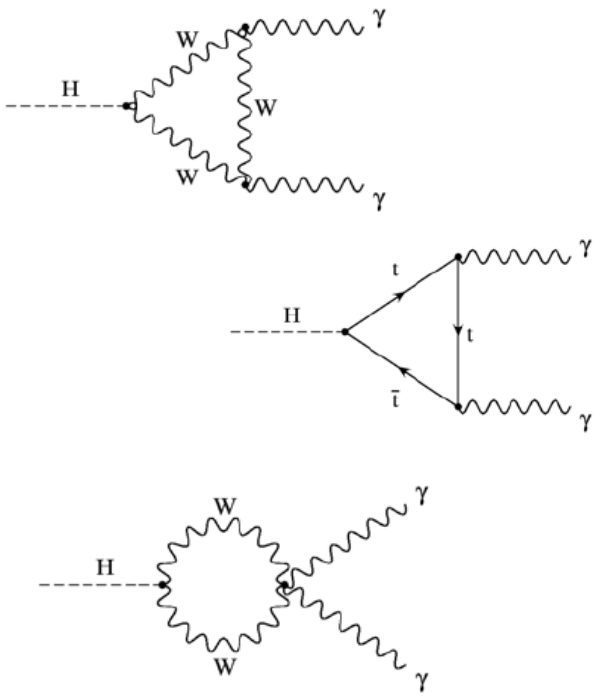
The analysis tools that have been developed are applied to study in great detail and with realistic modelling of performance analysis on CMS data specific benchmark processes, upon which depends the performance of CMS. These processes include several Higgs boson decay channels, the production and decay of new particles such as Z' and supersymmetric particles, B_s production and processes in heavy ion collisions. The simulation of these benchmark processes includes subtle effects such as possible detector miscalibration and misalignment. Besides these benchmark processes, the physics reach of CMS is studied for a large number of signatures arising in the Standard Model and also in theories beyond the Standard Model for integrated luminosities ranging from 1 fb^{-1} to 30 fb^{-1}. The Standard Model processes include QCD, *B*-physics, diffraction, detailed studies of the top quark properties, and electroweak physics topics such as the W and Z^0 boson properties. The production and decay of the Higgs particle is studied for many observable decays, and the precision with which the Higgs boson properties can be derived is determined. About ten different supersymmetry benchmark points are analysed using full simulation. The CMS discovery reach is evaluated in the SUSY parameter space covering a large variety of decay signatures.

0954-3899/07/060995+585$30.00 © 2007 IOP Publishing Ltd Printed in the UK 995

Plus recent updates of SM Higgs channels with new CMSSW software framework!!

- **More detailed, better understood reconstruction methods (partially based on test beam results), improved trigger simulation, event reconstruction and analysis tools**
- **Strategies to estimate backgrounds from data and express AlCa streams**
- **Improved statistical treatment (also including treatment of systematic uncertainties)**
- **Tevatron data are extremely valuable for validation, work has started**

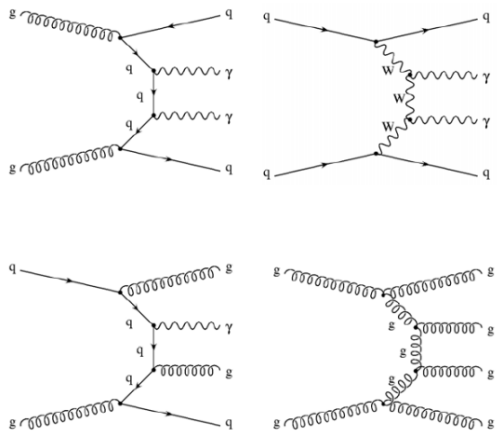
H→γγ



- ✓ Small branching ratio (0.002 at m_H =120 GeV/c^2)
- ✓ Final states produced through W, top and b loops
- ✓ Important channel for discovery at low mass (m_H<130 GeV/c^2)
- ✓ Very clear signature: 2 high Et isolated photons

- **Backgrounds**:
  - Irreducible: γγ, γγ+jets
  - Reducible: γ+jets, jets, DY

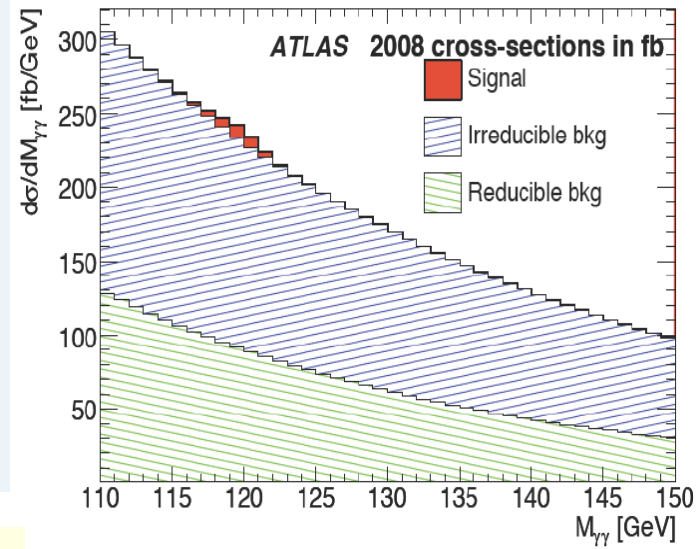
- **Requirements**
  - Good understanding of electromagnetic calorimeter performance and calibration
  - Excellent γ/jet separation
  - Good mass resolution
  - and Vertex reconstruction



$H \rightarrow \gamma\gamma$

❖ ATLAS

- Vertex determined from extrapolation using calorimeter samplings
- Converted photons used to improve vertex determination: 57% Higgs events have ≥1 conversion
- Signal divided into categories according to η_γ, #jets, #converted photons
- Inclusive analysis + search for di-photons with jets
- Unbinned maximum-likelihood fit



❖ CMS

Background reduction using photon isolation and kinematic information

$M_{\gamma\gamma}$ observed as a peak above background

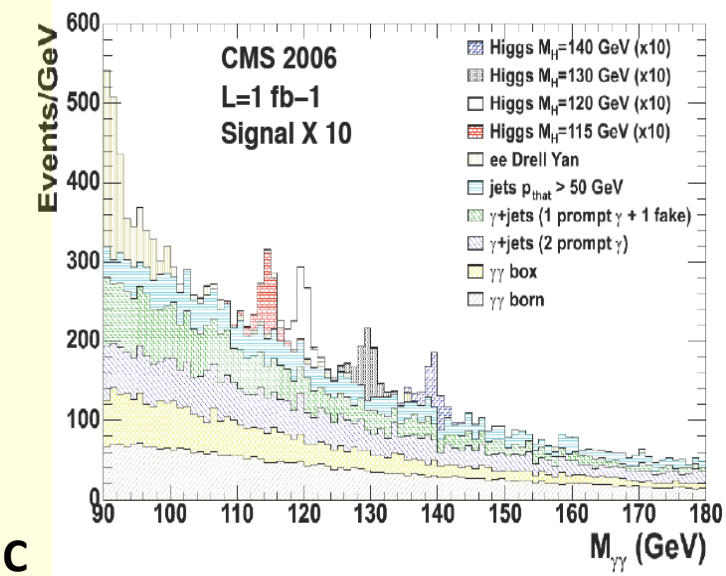
➢ ***Cut-based analysis***

– **Splitting in categories according to η_γ and lateral shower shape variable**

➢ ***Optimized analysis***

– **Loose sorting and additional kinematical variables**

– **Event-by-event kinematical Likelihood Ratio with background pdf taken from sidebands, signal pdf from MC**

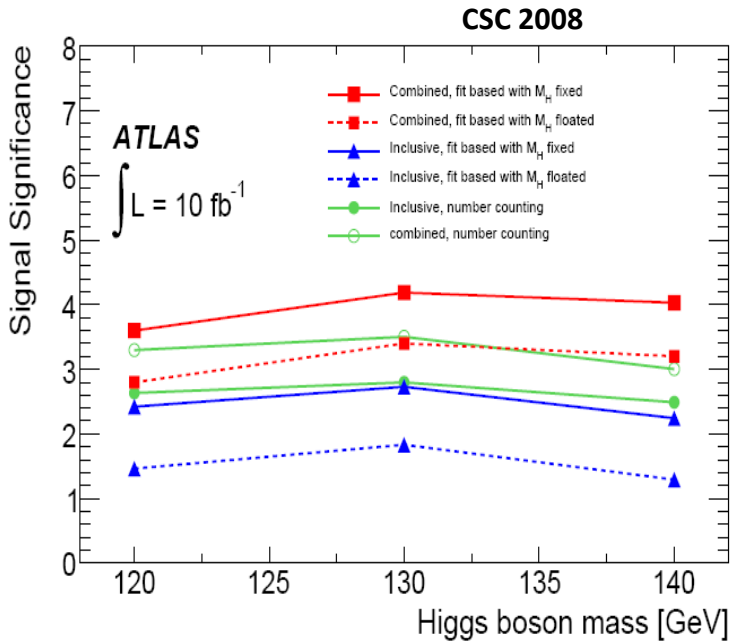


Results for H→γγ

ATLAS

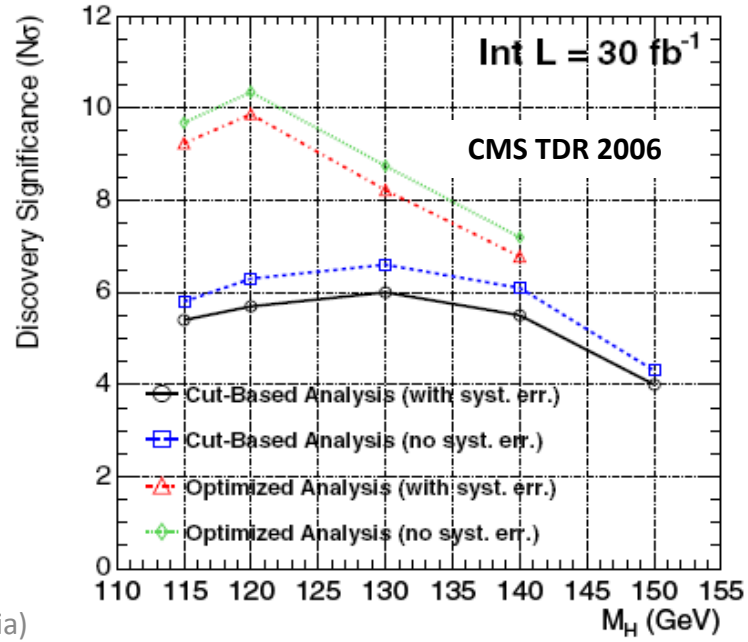
- For m_H=120 GeV/c^2 and 10 fb^{-1} :
- Inclusive analysis, using event counting **σ= 2.6**
- Combining the 0,1,2 jets analysis +using an unbinned maximum-likelihood fit:

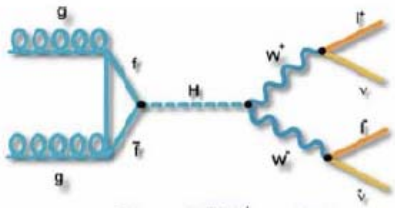
Floating (fixed) mass fit : **σ=2.8 (3.6)**



CMS

- 5σ discovery between LEP lower limit and 140 GeV/c^2 with less than 30 fb^{-1} of integrated luminosity
- 5σ discovery with event by event estimation of the S/B ratio possible at m_H=120 GeV/c^2 with 7-8 fb^{-1}



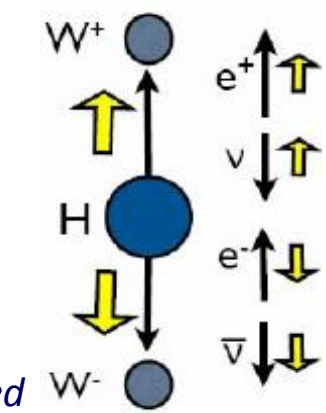


H→WW*→2l2ν

- ***Main search channel for range $140<m_H<2m_Z$***

-Highest branching ratio for m_H >140 GeV/c^2:

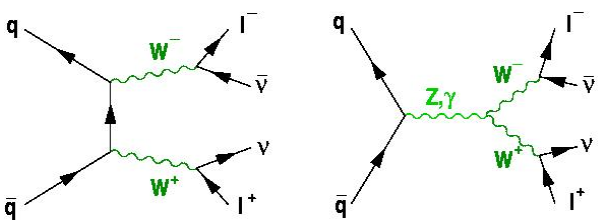
95% at m_H = 160 GeV/c^2

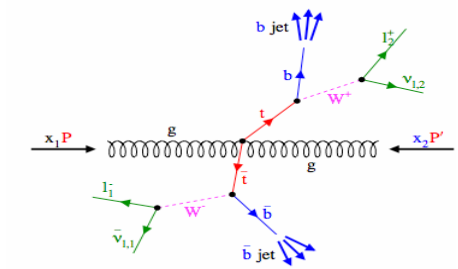


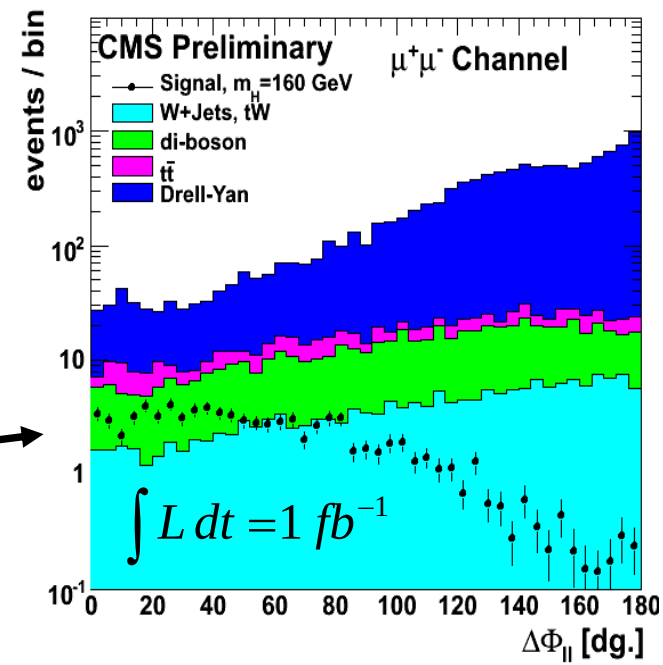
Signal: 2 high p_T isolated leptons, MET and no central jets

- **Backgrounds:**
  - WW, tt, W+jets, Z+jets, tW, WZ, ZZ…

No mass peak (undetected neutrinos) → Needs a good background understanding







Two main discriminants:

- **Angle between leptons in the transverse plane : main variable to reject WW (small opening angle for the signal due to spin correlations)**
- **Central Jet Veto for ttbar reduction**

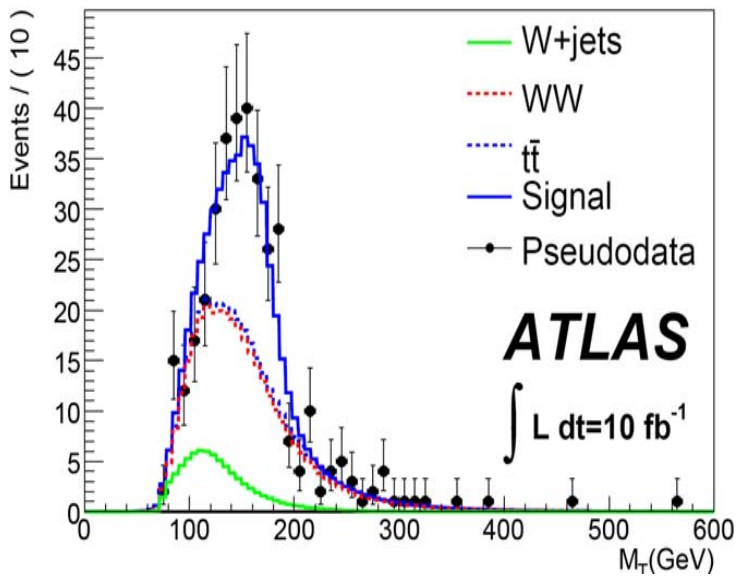
$H \rightarrow WW^* \rightarrow 2l2\nu$

❖ ***Analysis strategy***

ATLAS (eμ final state, H+ 0j, H+2j analysis)

- **Preselection** :
- 2 opposite-sign isolated and identified leptons
- Cuts on m_{ll}, MET, $\Delta\varphi_{ll}$, $Z_{\tau\tau}$ removal
- Central Jet veto & b-tag veto
- **Final selection:**

2D Fit of transverse mass and Higgs candidate p_T in 2 bins of di-lepton azimuthal angle $\Delta\varphi_{ll}$ to extract S/B ratio in signal region



CMS (ee, μμ, eμ final states, H+0j analysis)

- **Preselection**:
- 2 opposite-sign isolated and identified leptons
- Cuts on m_{ll}, MET
- Central Jet Veto
- **Variables used to reduce background :**

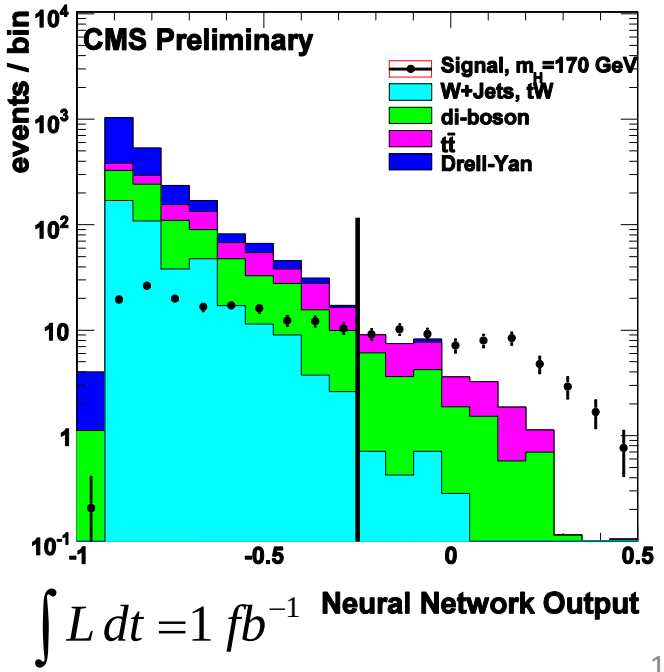
  p_T of the leptons, m_{ll} , $\Delta\varphi_{ll}$, MET

- **Final selection**:

Mass dependent cut based & multivariate analysis (optimization for 1fb^{-1})

- Control regions: fake leptons, background normalization

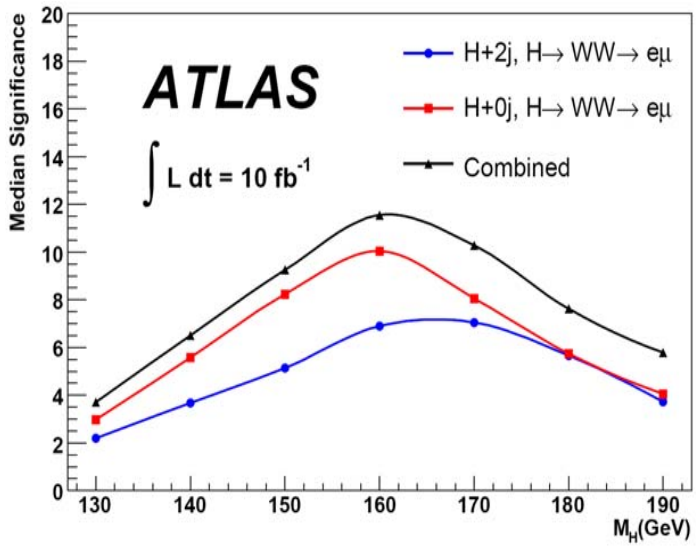
CMS PAS HIG-08-006



Results for H→WW*→2l2ν

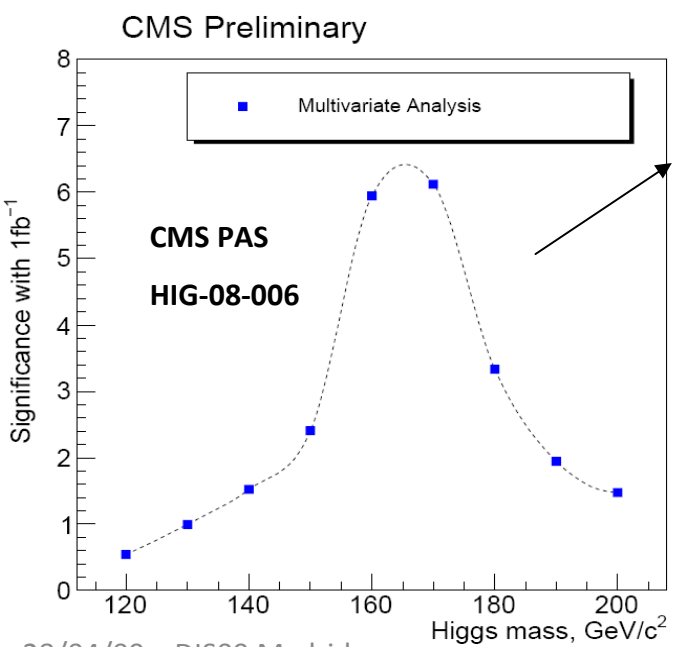
ATLAS

– **Combined significance** above the **5σ** level **for ~ m_H >140 GeV/c^2**



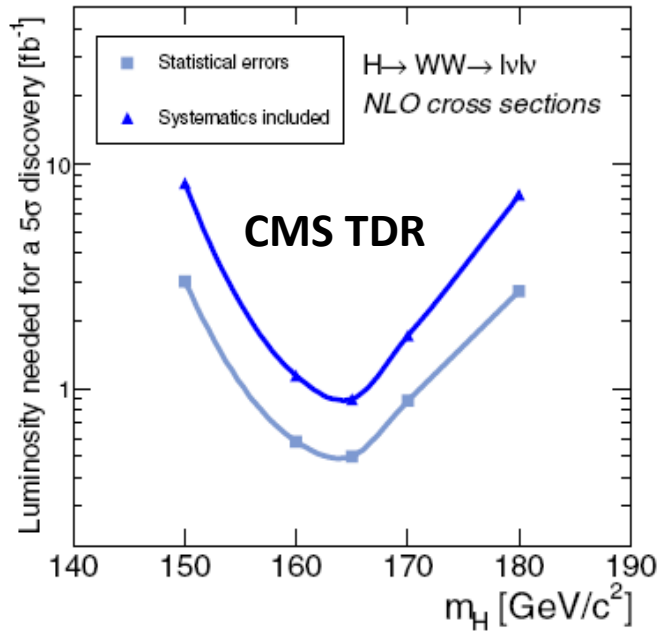
Updated CMS result:

Sensitivity to a SM Higgs improved using a **mass dependent multivariate analysis**



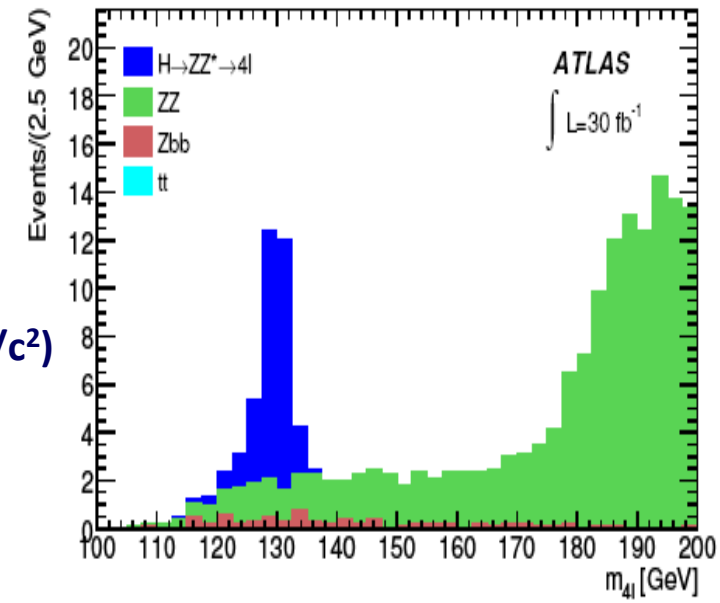
Improvements on Lepton ID , mass dependent cuts, more data driven approaches (compared to TDR)

Cuts have been optimized separately for 1fb^{-1} maximizing the expected statistical significance.

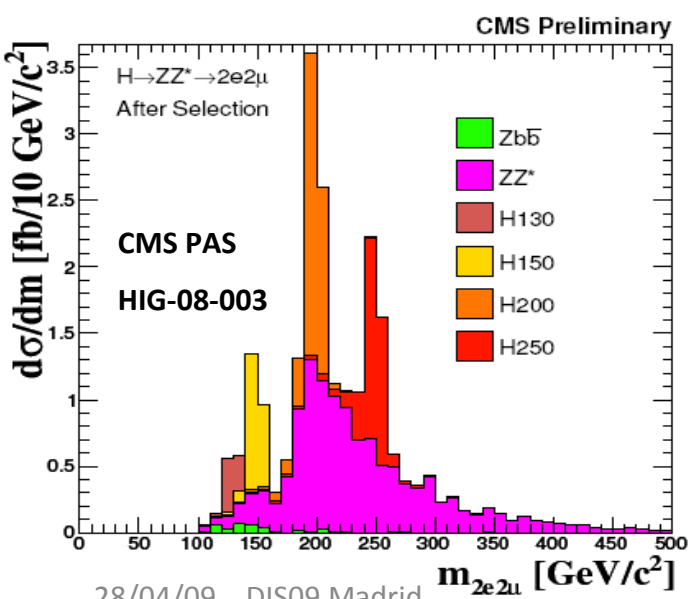


H→ZZ*→ 4l

- **Signal**: Very clean signature (*2 pairs of isolated leptons 4e, 4μ, 2e2μ)* with high branching ratio except at $m_H \approx 2\ m_W$
  - Excellent mass resolution (1.5 – 2 GeV/c^2 for M_H= 130 GeV/c^2)
  - Powerful analysis in a wide mass range



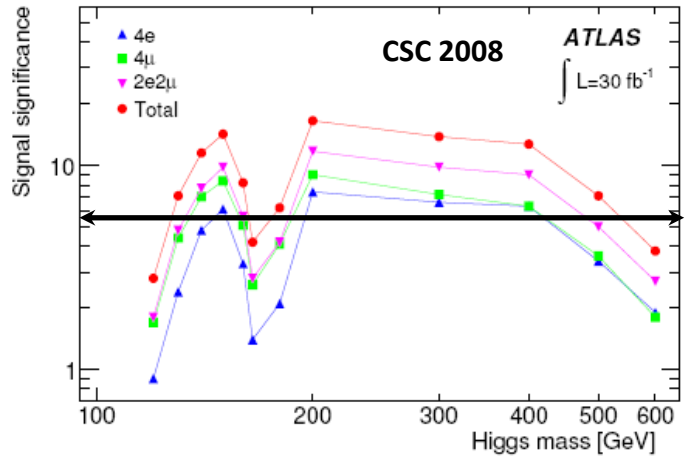
- **Backgrounds**:
  - **Irreducible:** ZZ* dominant
  - **Reducible:** Zbb, tt, ZW, Z + X

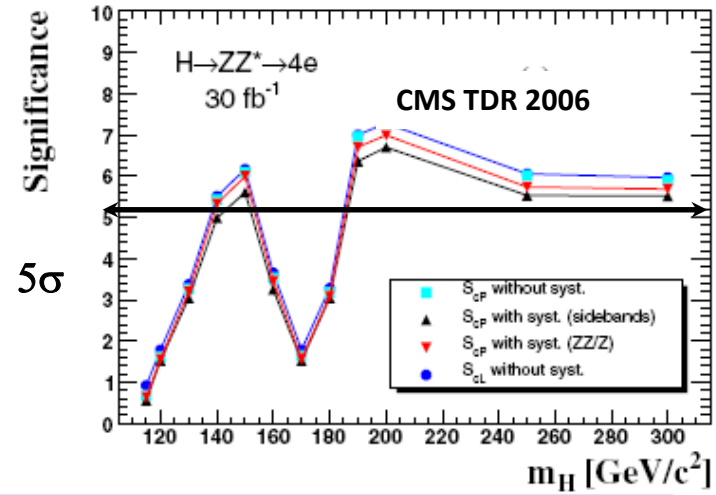


- **Selection of isolated (tracker + calorimeter) muon and electron pairs with opposite charge**
- **Isolation and Impact Parameter Significance main variables to reject Zbb, tt**
- **At least one Z→ll on shell** *(Mass of the leptons pairs some discrimination against the background)*
- **4-lepton mass reconstruction**
  Peak in the mass spectrum of the signal most discriminating variable against ZZ

Results for H→ZZ*→4l

➢3 channel independent +1 combined analysis with several levels of systematic uncertainties treatment



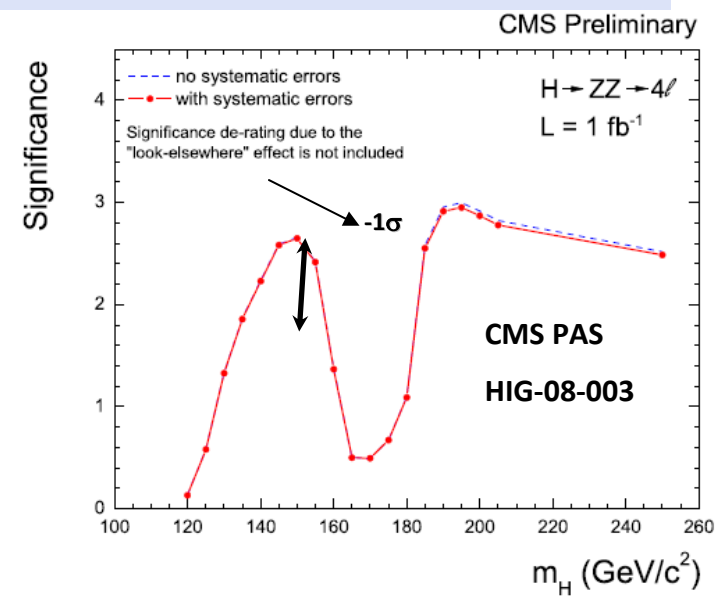


✓ **Comparable significance**

✓ Highly sensitive in the high mass region **(200 GeV/c² < m_H < 400 GeV/c²)** and in the **150 GeV/c²** region, where the Higgs boson could be discovered with **5 fb⁻¹**

CMS update:

- Cuts optimised for 1 fb^{-1} and data driven methods for background optimization control
- **Significance of about 3σ can be reached for m_H ~ 200 GeV/c² at ∫Ldt = 1 fb^{-1}**
- **SM Higgs boson can be excluded for m_H > 185 GeV/c² with ∫Ldt = 1 fb^{-1}**
- **"look-elsewhere" effect**: in real search, significance to be de-rated by ~1 sigma



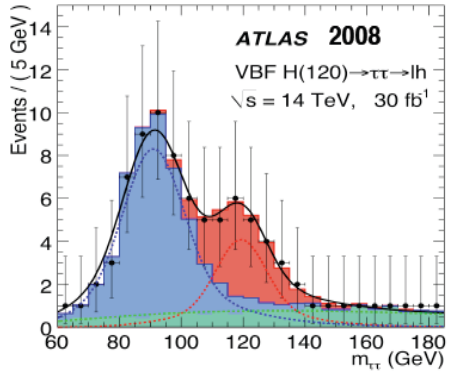
VBF H→ττ

➢ *Important channel for range 115-145 GeV/c²*

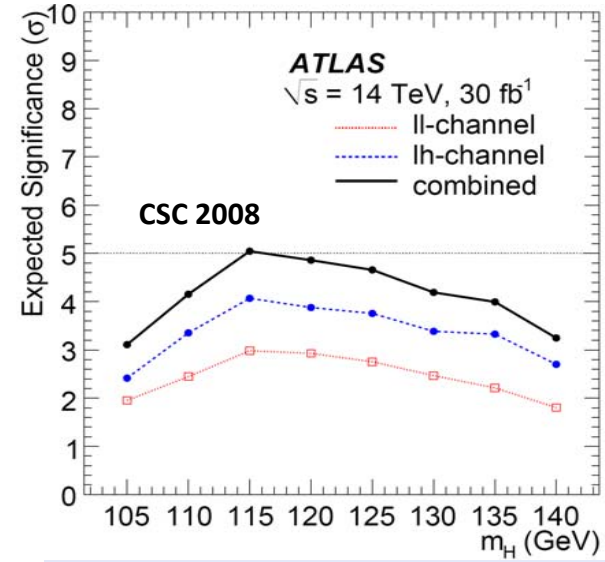
Signal: 2 leptons or τ-jets in central region, MET and 2 forward jets

- **Backgrounds:**
  - Zjj, tt, Z/γ*->ττ

3 final states :
- *Lepton-lepton*
- *lepton-hadron (CMS only this)*
- *hadron-hadron*

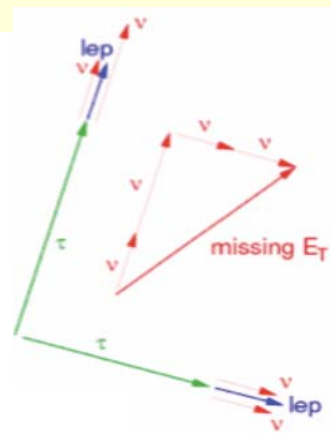


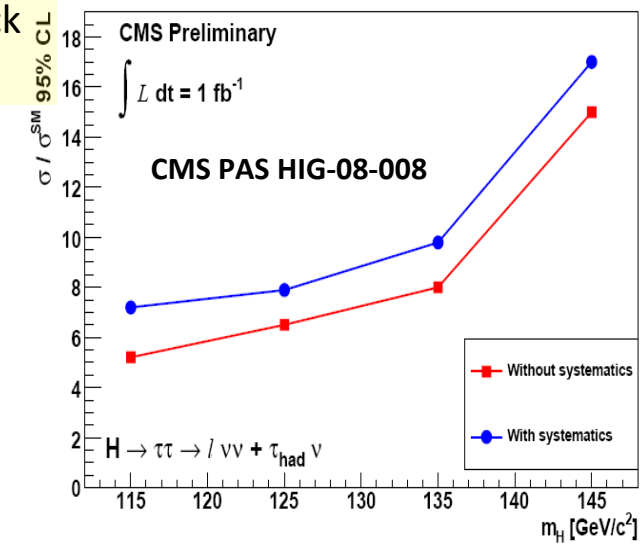
- Invariant mass of the τ pair reconstructed via the collinear approximation (breaks down when the 2 taus are back to back)



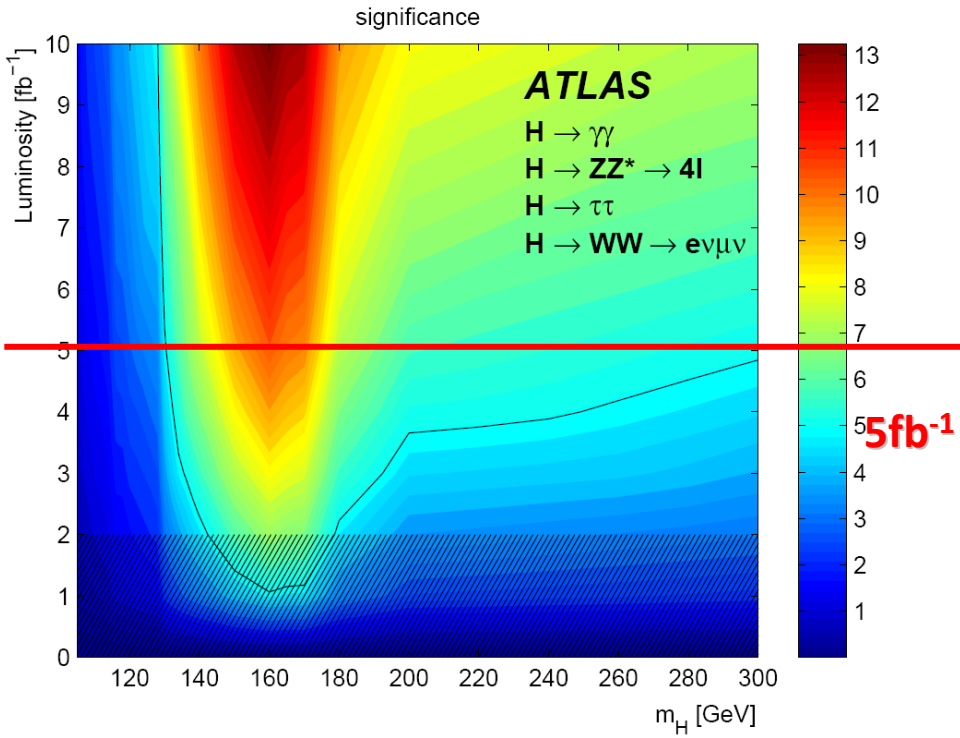
ATLAS lepton-lepton + lepton-hadron final states
→5σ achieved in the range 115-120 GeV/c² with 30 fb⁻¹

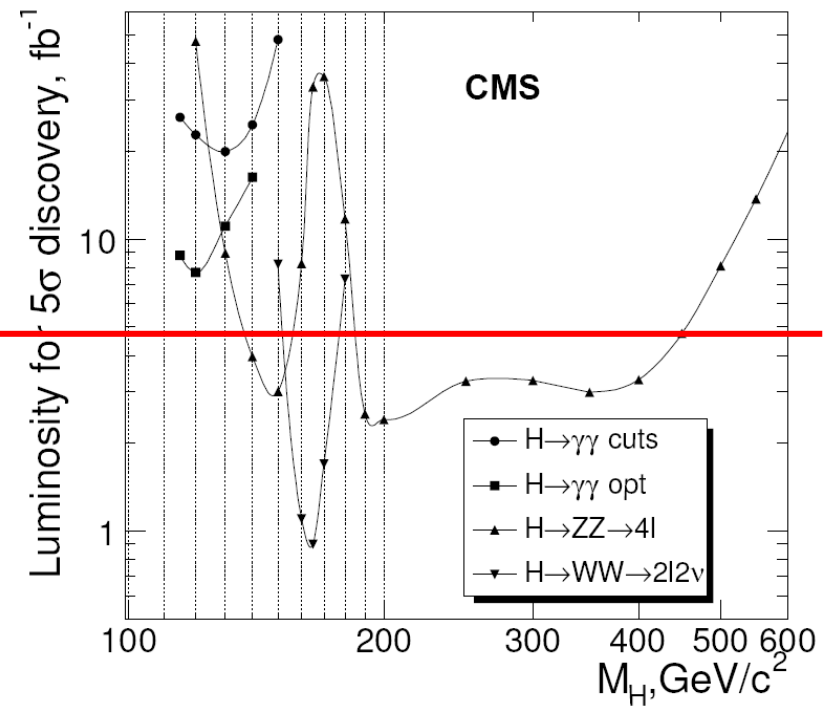
Important items:
- Tau tagging (Likelihood, NN methods)
- tt rejection (b-jet ID and veto for lepton-lepton)
- Z+jets background, especially at low masses





SM channel combination





- **With 10 fb^{-1} (*normally* considered as one LHC year at low luminosity), 5σ discovery for m_H in [~120, ~500] GeV/c^2**
- **With 5 fb^{-1} 5σ discovery for m_H in [~130, ~450] GeV/c^2**

Combining results from both experiments, around half of this luminosity

SM Higgs searches at $\sqrt{s}$<14TeV

LHC will start working with center of mass energy lower than 14 TeV around 10 TeV

► **Main Effect: cross section changes**

✓ **Different energy of LHC has two effects:**

- **Cross section for signals (and background) goes down**
- **Signal (Higgs production) goes down slightly faster:** ***Higgs is mainly produced from gg and backgrounds from qq***

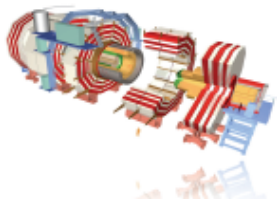
✓ **Efficiency and Acceptance:**

- **Higgs becomes relatively "heavier", i.e. decay products become relatively more central for smaller LHC energies**

Process	$\frac{\sigma_{\sqrt{s}=10\,TeV}}{\sigma_{\sqrt{s}=14\,TeV}}$	$\frac{\sigma_{\sqrt{s}=6\,TeV}}{\sigma_{\sqrt{s}=14\,TeV}}$
$t\bar{t}$	0.450	0.113
Wt	0.450	0.113
WW	0.650	0.320
WZ	0.650	0.320
ZZ	0.650	0.320
$Z \to \ell\ell$	0.681	0.371
$W \to \ell\nu$	0.681	0.371
$gg \to H$	0.540	0.190

Example : HWW + HZZ combined

$\int L$ for 5σ	14 TeV	10 TeV
m_H =200 GeV	0.6 fb-1	1.3 fb-1



PYTHIA for HZZ (LO) and MCFM for HWW cross section calculations, standard CMS MC Samples used for estimate

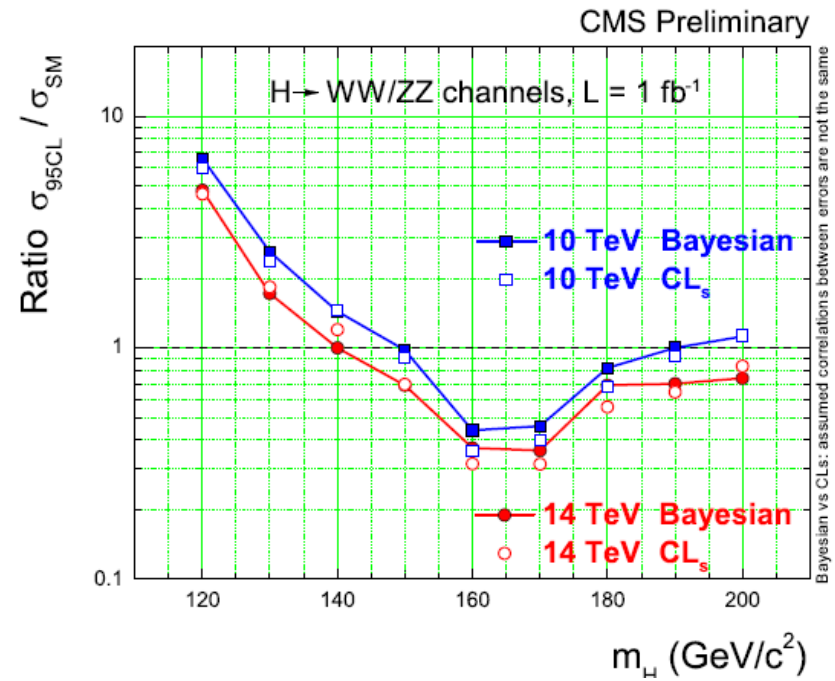
CMS projection for LHC@10TeV

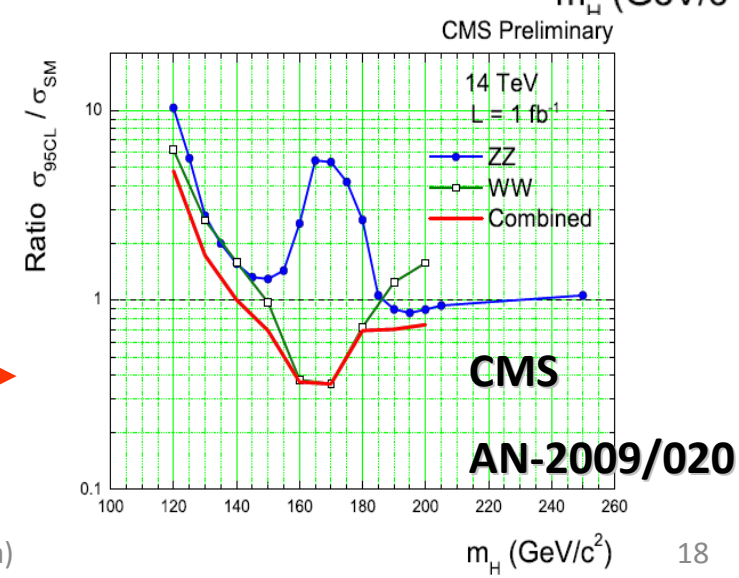
- **LHC 2009 - 2010 luminosity performance – estimate:**
  ~200 pb^{-1} of "good data"

- **Strategy:**
  - First understand detectors,
  - do SM measurements,
  - then search for the Higgs…

- **Signal and bkgd yields re-scaled 14→10 TeV**: loss of a factor of 1.5 in sensitivity, or a factor of ~2 in luminosity

- **With roughly ~200 pb^{-1}:**
  Reach sensitivity for a SM Higgs with m_H~160-170 GeV/c^2 *(comparable to the current Tevatron sensitivity)*
  (but region just excluded by Tevatron)





Conclusions

- **If the Higgs boson is there, ATLAS and CMS are ready to find it…**

…unless it is discovered or excluded first at the Tevatron!!!

- **For a SM Higgs, with a combination of ATLAS & CMS @14TeV, between ~ 1 and 5 fb^{-1} are needed depending on mass value. Benchmark luminosities:**
  - ***~0.1 fb^{-1} → exclusion limits will start carving into SM Higgs cross section***
  - ***~0.5 fb^{-1}- 1 fb^{-1} → discoveries start to become possible in the region near the one excluded by Tevatron (M_H~160-170 GeV/c^2)***
  - ***~5 fb^{-1}-10 fb^{-1} → SM Higgs could be discovered (or excluded) in full mass range (~110-500 GeV/c^2)***

- **LHC efforts focused to get as much luminosity as possible to get sensitivity to a SM Higgs boson.**

- **ATLAS and CMS are doing their best to commission and understand the detectors to be ready when collisions start**

- **Post-discovery questions that would need to be answered…**
  - Is it a Standard Model Higgs ?
  - What are the couplings to the rest of particles ?
  - Is there only one Higgs? **MSSM, other models?**
  - What is its precise mass, width, quantum numbers ?
  - Does it generate electroweak symmetry breaking *and* give mass to fermions?
  - **Higgs discovery also raises the "hierarchy" problem…**

- **Ready for Higgs discovery, but if it is not found, detectors are able to search for objects with similar signatures…**

LHC will answer these fundamental questions in the next years