EW Symmetry Breaking at LHC

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On behalf of the **ATLAS** and **CMS** Collaborations

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Simplest mode of EW symmetry breaking…

Revealing the physical mechanism responsible for the breaking of electroweak symmetries is one of the most important open questions of contemporary particle physics; and therefore, is **one of the main physics goals for the LHC**.

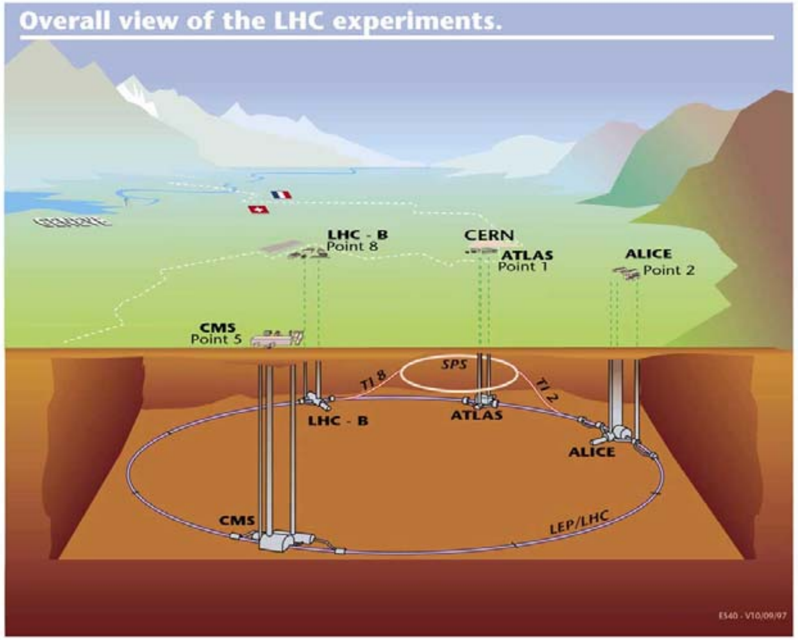
A simple mechanism for the breaking of the EW symmetry can be incorporated to the Standard Model (SM) → **Higgs Mechanism**

The Higgs Mechanism:
- Leaves the Standard Model mostly untouched
- Adds a scalar, the Higgs boson, which we can search for.
  → Its mass is a free parameter of the theory

There are many proposed breaking mechanisms of the EW symmetry (multiple higgses, technicolor…), the LHC data will help to discriminate among them.

But in this talk, I will concentrate in some of the prospective searches that will take place at LHC's experiments oriented to find a SM Higgs boson (and they are many…).

The Large Hadron Collider



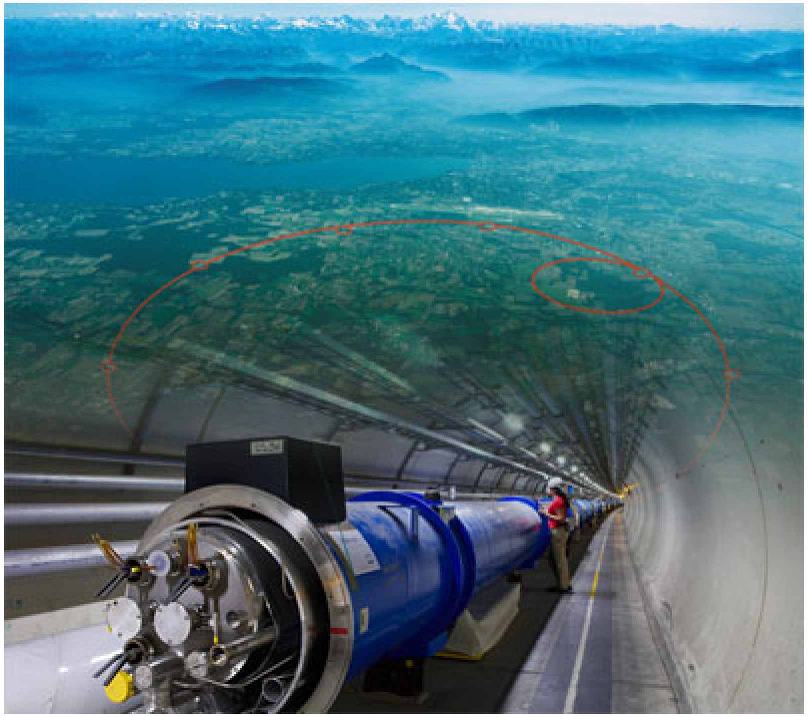
The Large Hadron collider is a **26 Km** long circular accelerator built at **CERN**, near Geneva, in **Switzerland**.

The magnetic field is created by 1232 superconducting dipole magnets (plus hundreds of focusing and correction magnets) arranged in a ring in the tunnel.

It has 4 big experiments (**ALICE, ATLAS, CMS, LHCb**), two of them (CMS and ATLAS) are intended for general purposes.

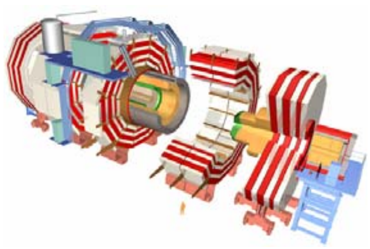
The design (proton-proton) collision energy is the highest ever: **14 TeV**
(~10TeV intended for the first data)

It's set up to re-start this fall! (cross-fingers)



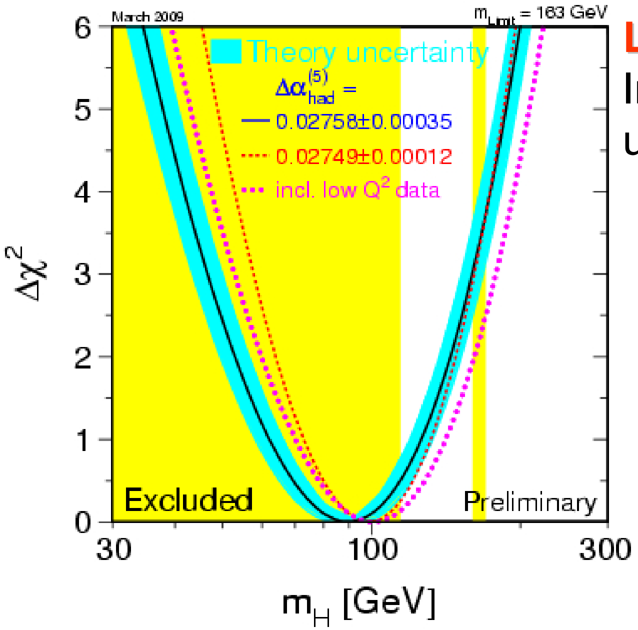
ATLAS Vs. CMS

	ATLAS (A Toroidal LHC ApparatuS)	CMS (Compact Muon Solenoid)
Dimensions	Width: 44m Diameter: 22 m Weight: 7.000 t	Width: 22 m Diameter: 15 m Weight: 14.500 t
Magnetic Field	2T solenoid + 3 toroid (0.5T barrel, 1T endcaps)	4T solenoid + return yoke
Tracker	Si pixels, strips + TRT	Si pixels, strips
ECAL	Pb + LAr (Liquid Argon Calorimeter) (Optimized towards background rejection)	PbWO4 crystals (Crystal calorimeter) (optimized towards precise measurements)
HCAL	Fe + scint. / Cu + LAr (10λ)	Cu + scintillator (5.8λ + catcher)
Muon System	Air core spectrometer	Iron core spectrometer
Trigger	3 – Level (region-of-interest 2-Level)	2 - Level



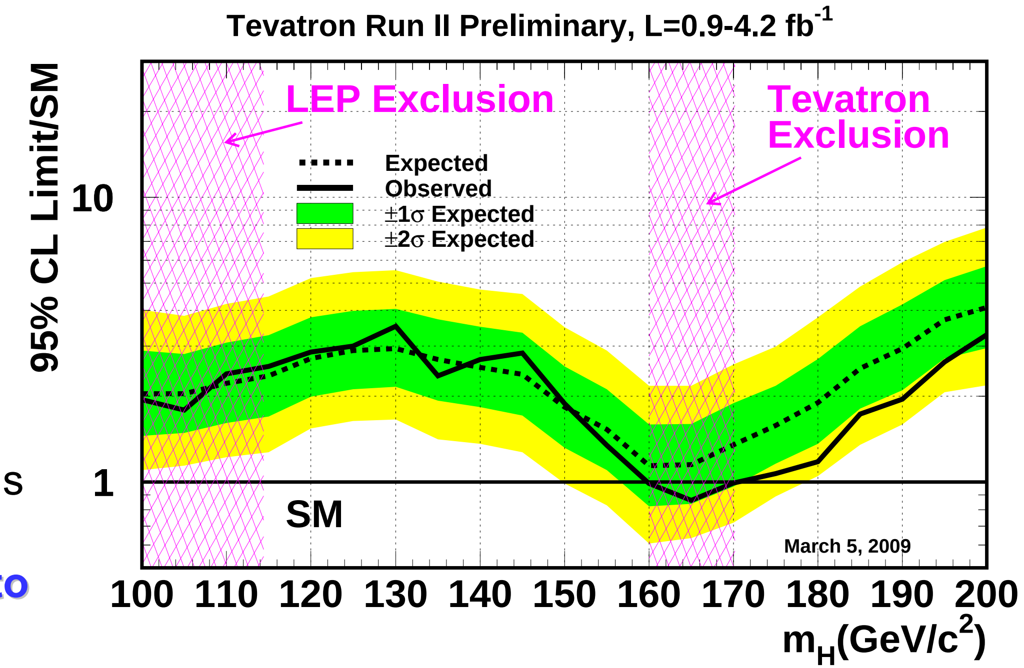
Similar concepts, different execution, detector technologies, design emphasis…

Searching for a SM Higgs: Direct searches



LEP experiments have set a 95% CL lower limit of **$m_H \geq 114$ GeV.** In addition to that, the **precision electroweak measurements** tell us that the mass of the Standard-Model Higgs boson is lower than **~163 GeV.**

This limit increases to **191 GeV** when including the **LEP-2** data.

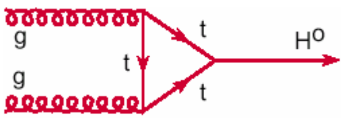


The Tevatron experiments **CDF** and **DØ** also search for the Standard-Model Higgs boson; the most recent combined result **excludes the mass range of 160 GeV to 170 GeV at 95%CL**.

Directly measured: m_H > 114 GeV and outside the **[160, 170]** interval
Indirect (precision fit): **m_H < 163 GeV**; including LEP2 **m_H < 191 GeV**

http://lepewwg.web.cern.ch/LEPEWWG/

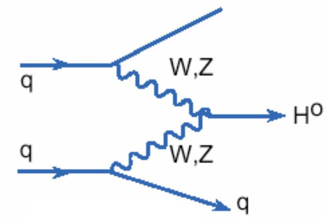
SM Higgs production at LHC

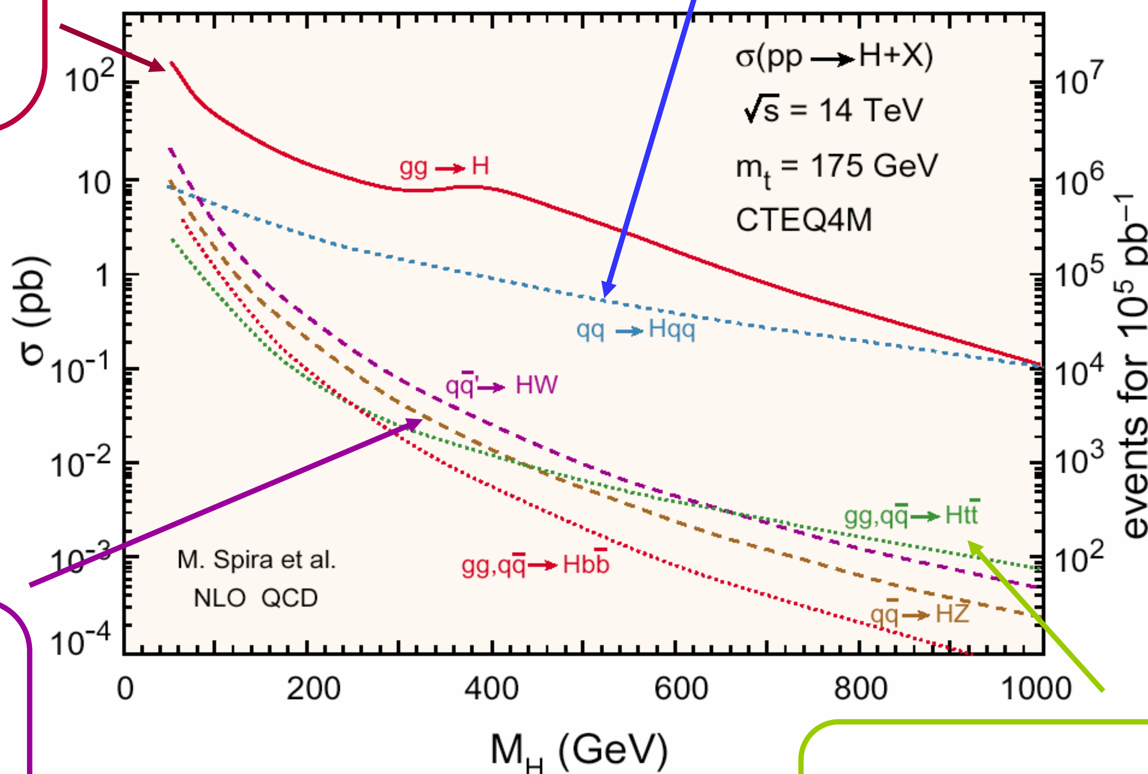


gluon-gluon fusion
K ~ 2
Unc. NNLO 10-20%
Large backgrounds at low mass

gg fusion dominates

(VBF) W,Z fusion
< 10% unc. NLO
K ~ 1.1
increasingly important at high masses

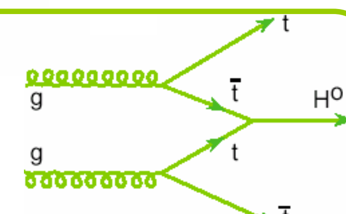




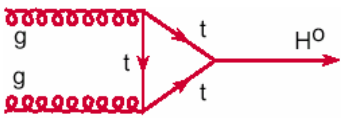
< 5% unc. NNLO
K ~1.4

associated production in the low mass region ('easy' triggering)

tt-fusion
~10% unc. NLO
K ~1.2



SM Higgs production at LHC



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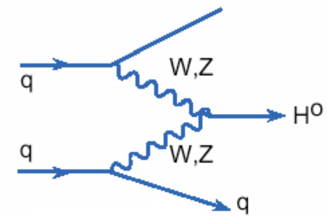

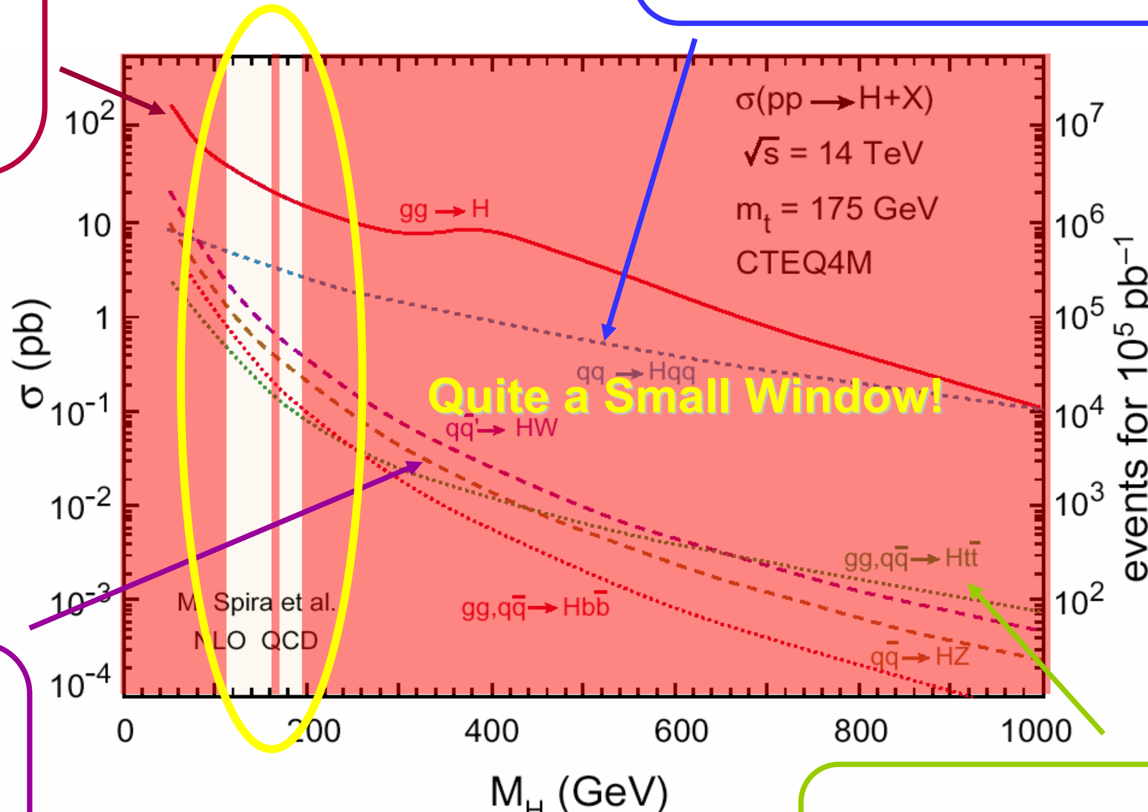

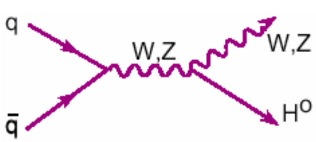

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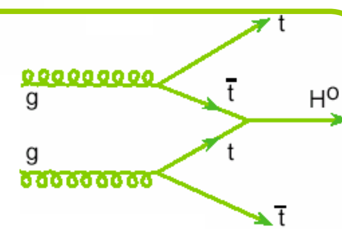
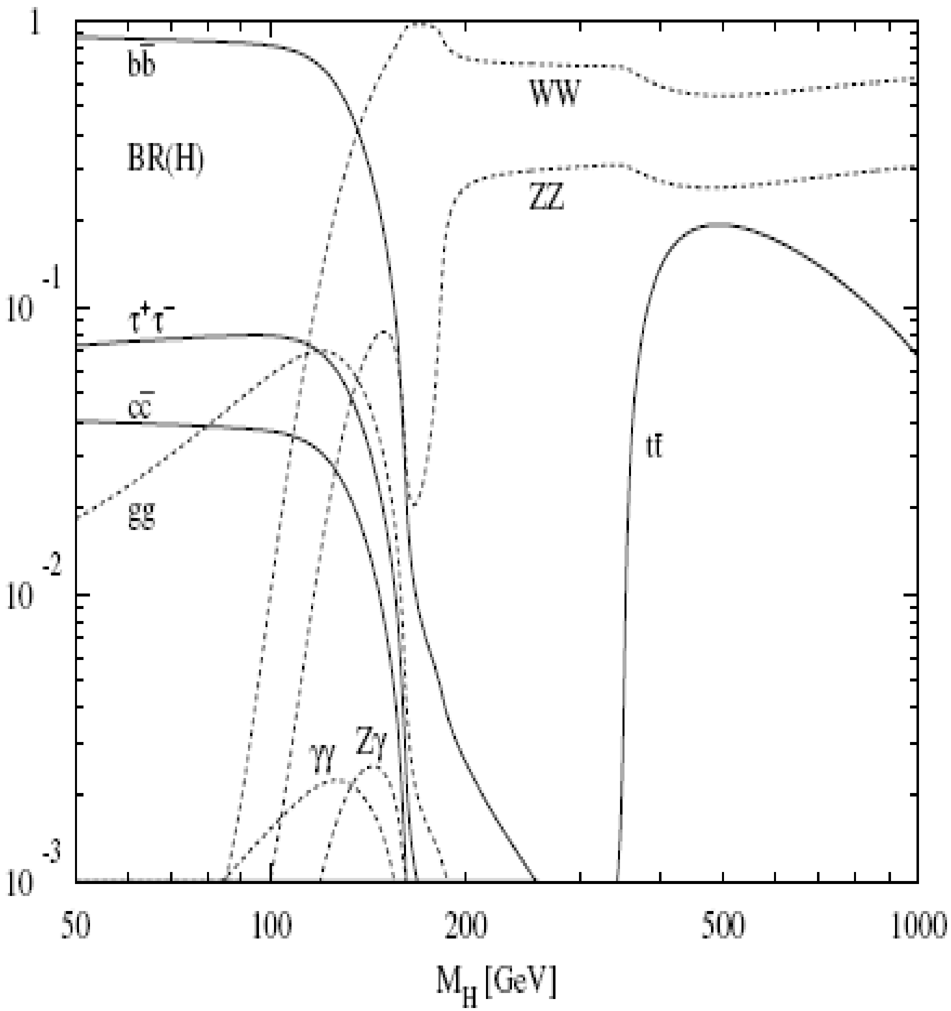


SM Higgs decays

Including quark mass uncertainties (t, b, c) and $\alpha_s(M_Z)$



Decay branching ratios at NLO :
Few % accuracy

At low mass (M_H< $2M_Z$)

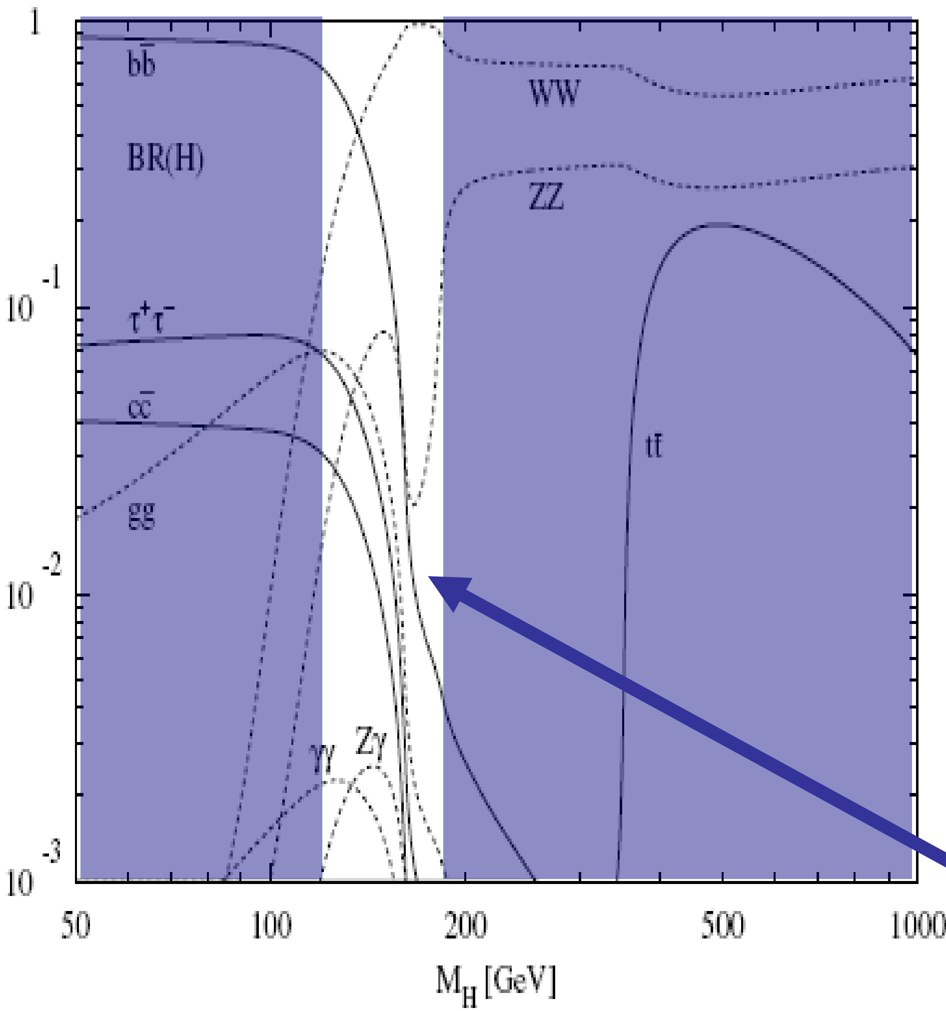
- Dominant bb; huge QCD background
- **H→ττ** accessible through VBF
- **H→WW(*)** accessible through gluon-gluon fusion and VBF
- **H→γγ** decays through top and W loops
- **H →ZZ*** also accessible

For higher masses

- **H→WW** and **H→ZZ**

SM Higgs decays

Including quark mass uncertainties (t, b, c) and $\alpha_s(M_Z)$



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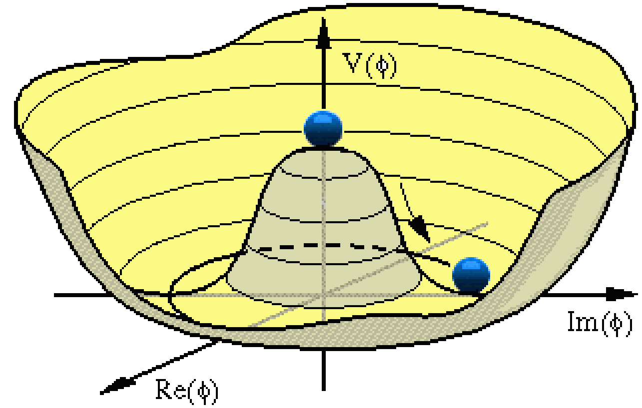
The mass window may be small, but a wide range of Higgs decay channels can be studied. Exciting times ahead!

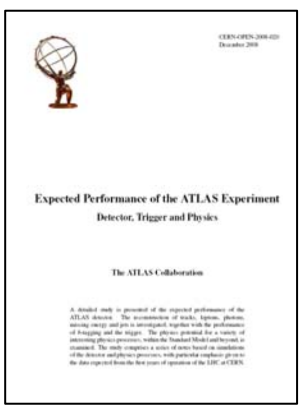
Decay branching ratios at NLO :
Few % accuracy

Prospective SM Higgs Searches ATLAS/CMS

ATLAS:
H → γγ
H → ZZ
H → WW
VBF H → ττ
ttH (H → bb)
ttH, H → WW*
WH, H → WW*
MSSM h/A/H → ττ
MSSM h/A/H →μμ
Invisible Higgs
Charged Higgs
…

CMS:
H → γγ
H → ZZ
H → WW
VBF H → WW/ZZ/invisible
H → ττ
Light charged Higgs
Heavy charged Higgs
Doubly charged Higgs
…




CERN-OPEN-2008-020
December 2008

Expected Performance of the ATLAS Experiment
Detector, Trigger and Physics

The ATLAS Collaboration


CMS Physics Technical Design Report,
Volume II: Physics Performance

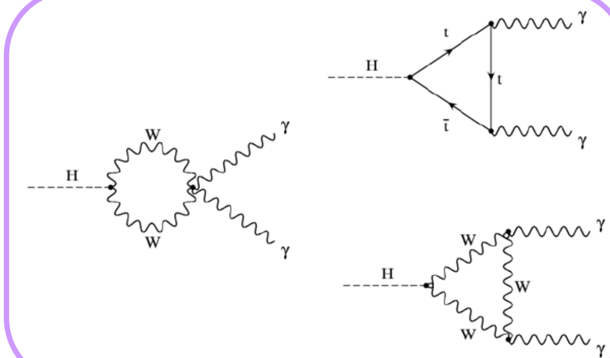
The CMS Collaboration

Both experiments work in a wide range of Higgs decay channels

ATLAS: CERN OPEN 2008-020

CMS: CERN / LHCC2006-021
(+ Updates!!)

$H \rightarrow \gamma\gamma$



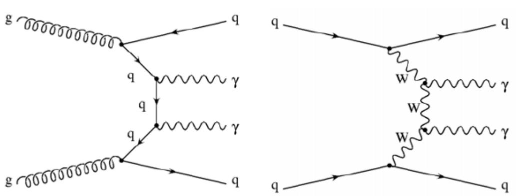
Promising channel for Higgs searches in the **low mass range (110 < m_H < 140 GeV)**
Small branching ratio but clear signature:

2 high E_T isolated photons

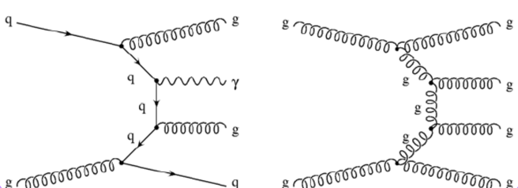
Signal:
Direct production (inclusive) or in association with hadronich high P_T jets

Background:
Coming from the production of two isolated photons (IRREDUCIBLE)
Coming from events with at least one fake photon (REDUCIBLE)

Irreducible: $\gamma\gamma$, $\gamma\gamma$**+jets**



Reducible: γ+jets, jets, DY

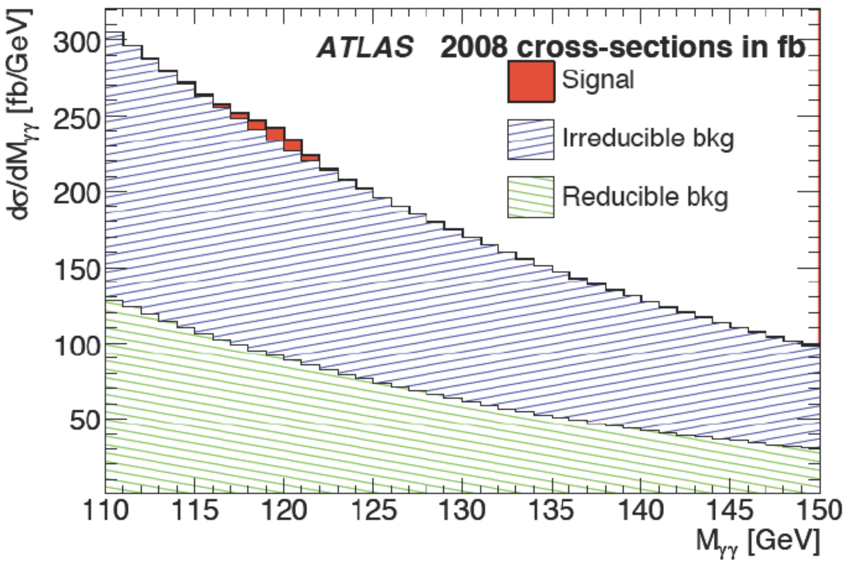


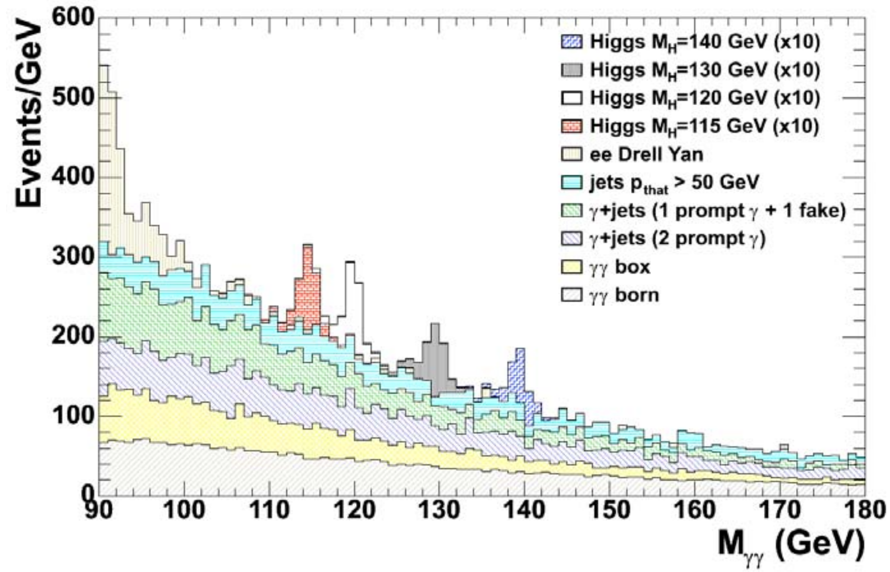
One of the benchmarks for the perfomance of the detectors.
Needs:

- ✓**Photon reconstruction/calibration/identification**
- ✓**Photon/jet separation**
- ✓**Conversion reconstruction**
- ✓**Vertex reconstruction**
- ✓**Good mass resolution**

And for the associated production channels
- ✓**jet tagging**

$H \to \gamma\gamma$





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

Search for **$H \to \gamma\gamma$** and **$H \to \gamma\gamma$ + jets**

Unbinned maximum-likelihood fit

CMS

Cut-based analysis:

Signal categories according to η_γ and lateral shower shape variable

Use of kinematics, isolation to reduce background

Reconstruction of the $M_{\gamma\gamma}$-peak

Optimized analysis

Loose sorting

Kinematical cuts

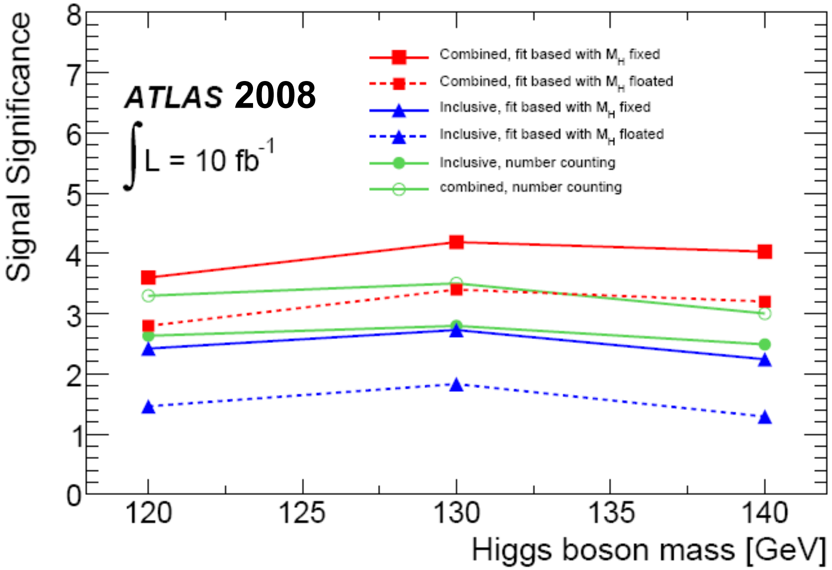
Event-by-event kinematical Likelihood Ratio

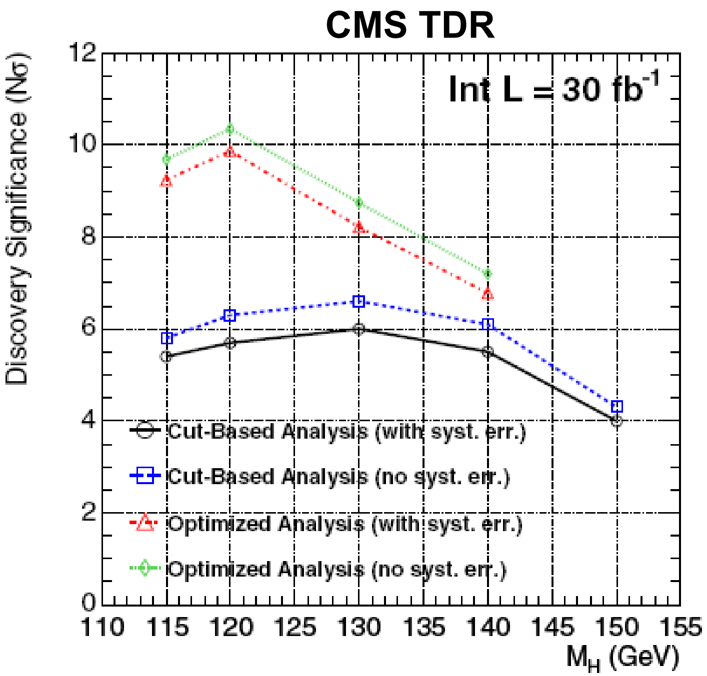
Results for H $\rightarrow \gamma\gamma$

ATLAS

For $\mathbf{m_H = 120\ GeV/c^2}$:

- **Event Counting :** σ= **2.6** (4.6) for **$10fb^{-1}$** ($30fb^{-1}$)
- **Fixed (floating) mass fit, combining 0j,1j,2j analyses:** σ = **3.6** (2.8) for **$10fb^{-1}$**



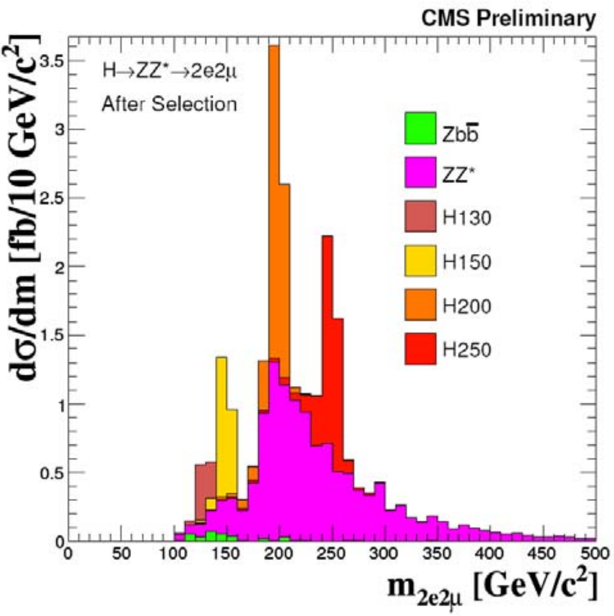


CMS

- **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 $\mathbf{m_H=120GeV/c^2}$ with **$7\text{-}8fb^{-1}$**

✓ CMS slightly higher sensitivity (older results)
✓ Improvements possible by using more exclusive $\gamma\gamma$ + jet topologies

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



'Golden' Higgs decay: experimentally cleanest signature for discovery.
Narrow 4-lepton (electrons or muons) **invariant mass peak** on top of a smooth background can be reconstructed.

Challenge: m_H between 120 and 150 **(one of the Z's on-shell)**

Signal:

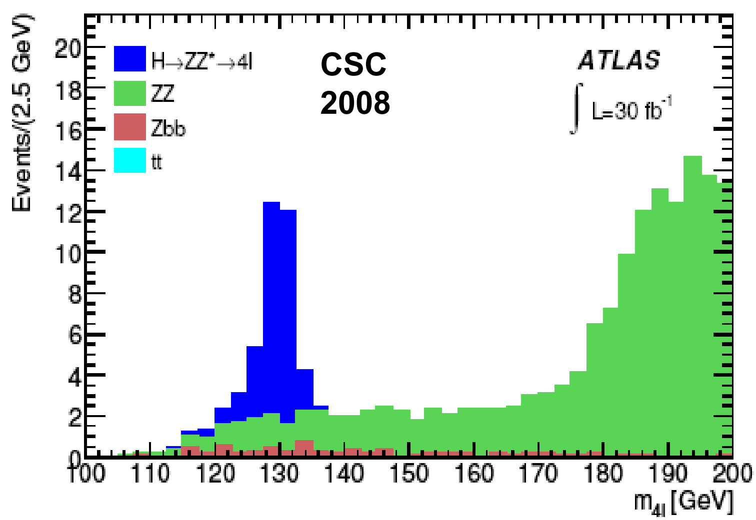
Very clean signal **($4e$, 4μ, $2e2\mu$)** with high branching ratio *except at $m_H \approx 2\,m_W$*
Excellent mass resolution
(1.5 – 2 GeV/c^2 for M_H= 130 GeV/c^2)
Powerful analysis in a wide mass range

Backgrounds:

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

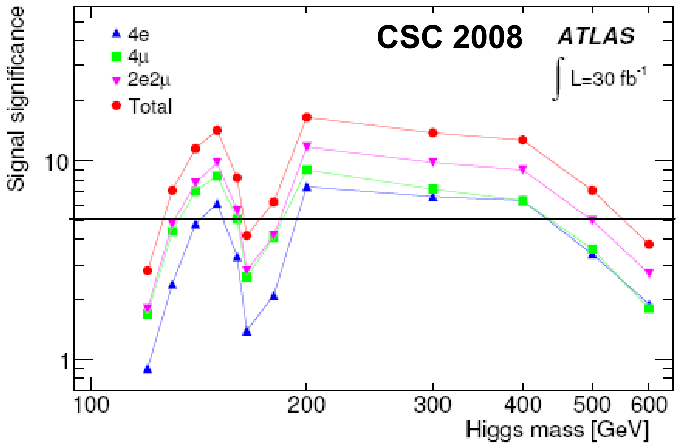
The analysis rely on a good lepton identification and isolation (tracker and calorimeters)

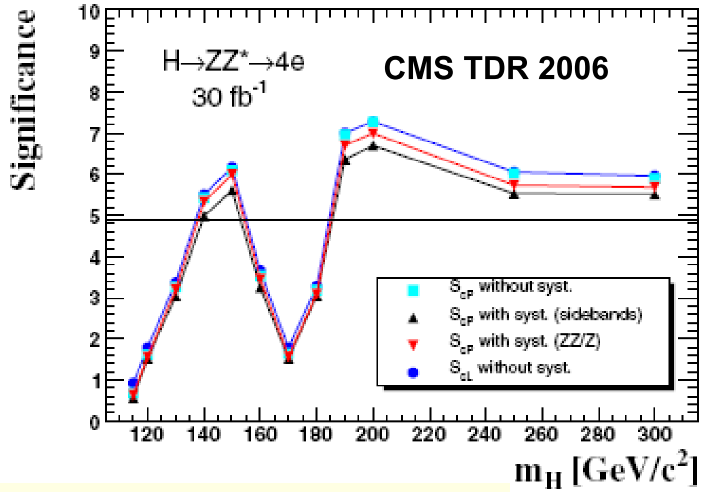
Quality cuts to reject Zbb, tt: isolation, lepton track, impact parameter, vertex reconstruction…



Results for H→ZZ*→4l

3 independent (final state) **channels + combined analysis** with several levels of systematic uncertainties treatment



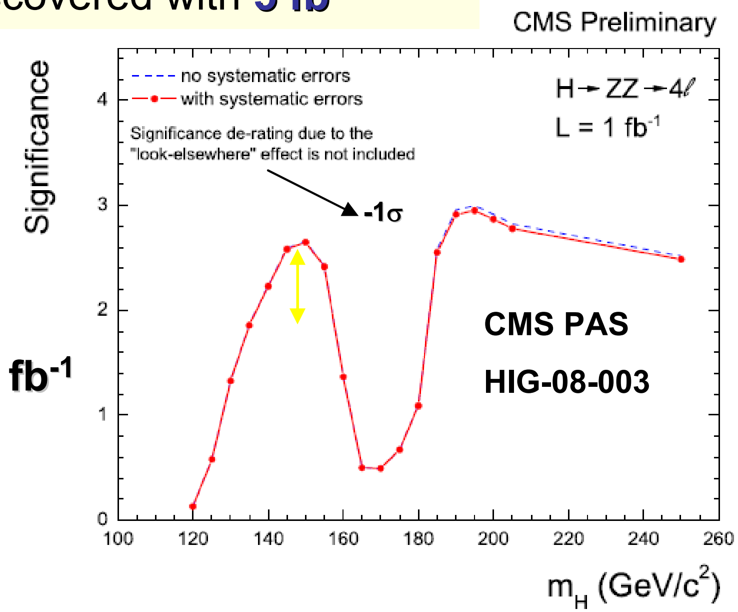


✓ Comparable significance
✓ Highly sensitive in the high mass region (**200 GeV/c² < m_H < 400 GeV/c²**) and in the **150 GeV/c²** region, where the Higgs boson could be discovered with **5 fb⁻¹**

CMS update:
- Cuts optimized for 1 fb^{-1}
- Data driven methods for bckg. optimization control

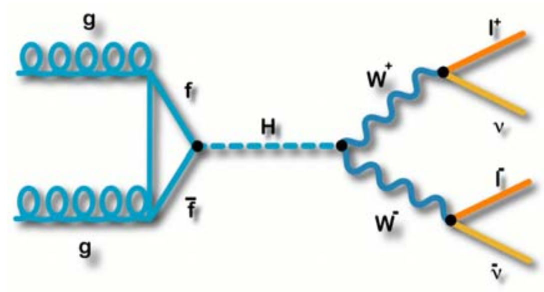
Significance of about **3σ** for **m_H ~ 200 GeV** at ∫Ldt = **1 fb^{-1}**
SM Higgs can be excluded for **m_H > 185 GeV** with ∫Ldt = **1 fb^{-1}**

"look-elsewhere" effect: in real search, significance to be de-rated by ~1σ



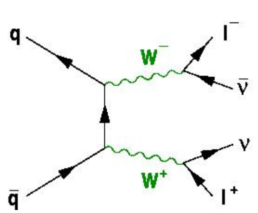
$H \rightarrow WW^* \rightarrow 2l2\nu$

$H \rightarrow WW$ is the discovery channel for a SM Higgs boson in the $\mathbf{2m_W < m_H < 2m_Z}$ range in the LHC.
Branching ratio close to 1 in this region + clear signature, on the other hand, no mass peak can be reconstructed due to the undetected neutrinos.

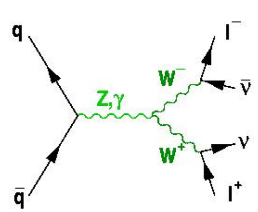


Backgrounds:
All sources of real or fake multi-lepton final states + missing ET:
ttbar (tW), WW (WZ, ZZ), Drell-yan, W+jets…
WW It is the 'Irreducible' background

Signal:
Two isolated leptons
No central jet activity
Significant missing E_T

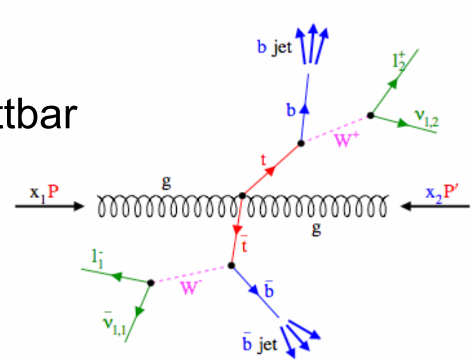


WW



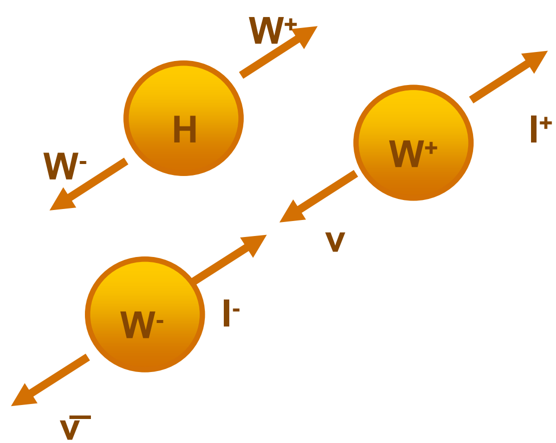
Drell-Yan

ttbar



$\Delta\varphi_{ll}$ (angle between the leptons in the transverse plane):

✓Small for Higgs (spin correlations)
✓Large for WW

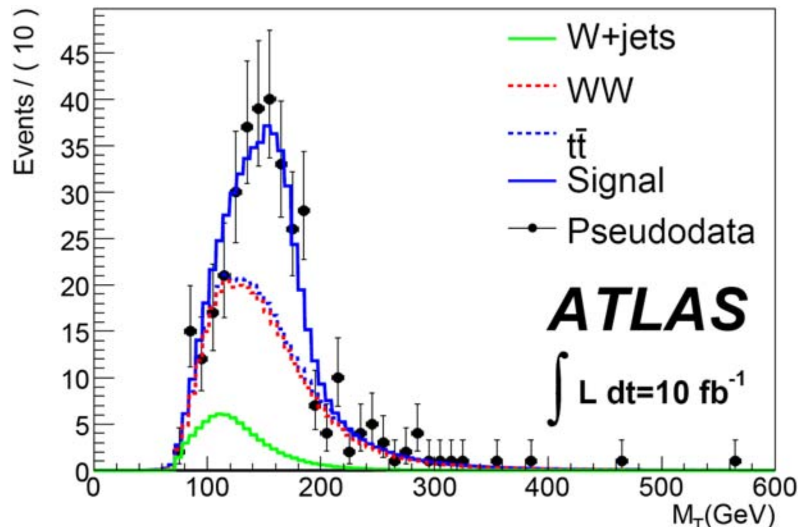


H→WW*→2l2ν

ATLAS (eμ final states; H+0j, H+2j)
- 2 isolated leptons
- Cuts on the transverse mass,e/μ kinematics, MET

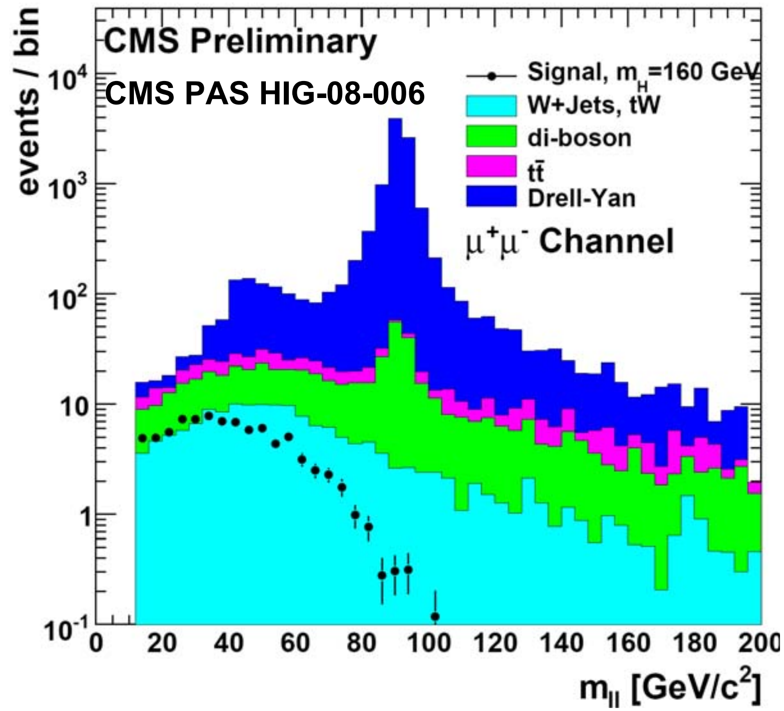
Two main discriminants:
- Angular correlation between lep. (WW)
- Veto on additional jets (ttbar)

Final selection: 2D fit on 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

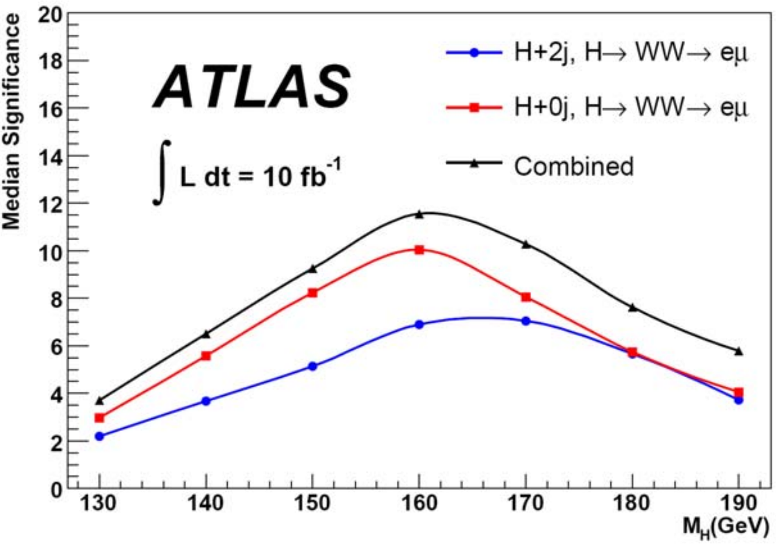


CMS (ee, μμ, eμ final states; H+0j)
- 2 opposite-sign isolated and identified leptons
- Kinematical and MET cuts
- No central jets
- **Final requirements**:

cut based & multivariate techniques
- Data driven techniques for background estimation: control regions, fake leptons study



Results for H→WW*→2l2ν

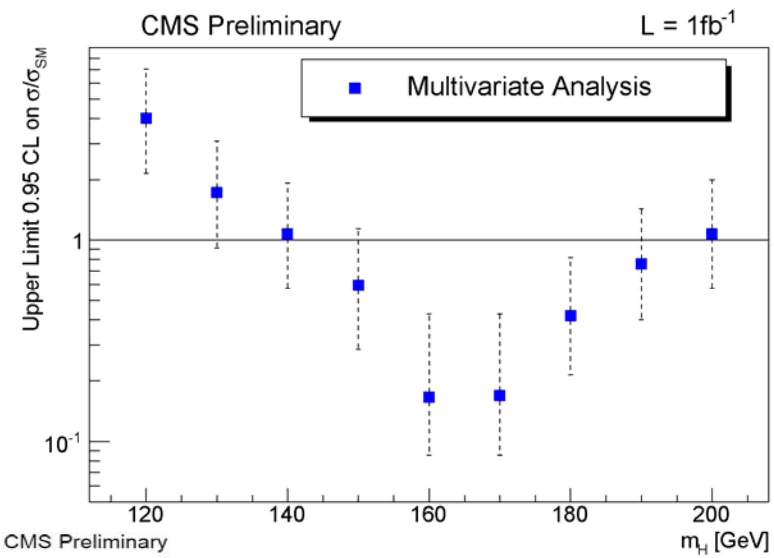


ATLAS

Main search channel for range: **~140GeV < m_H < $2m_Z$**

Significance above **5σ** for **m_H >140 GeV/c^2 (10fb^{-1})**

**Results to be scaled by √2 and to 1 fb^{-1}*



Updated CMS result:

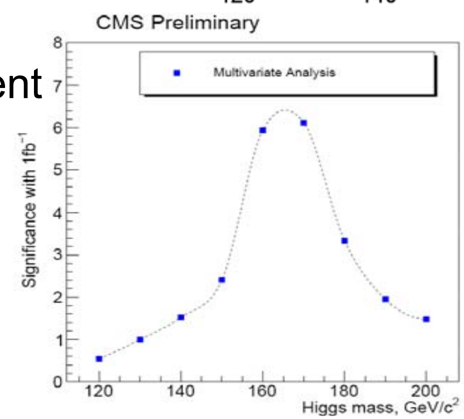
Using a mass-dependent **multivariate approach:**

5σ around **m_H = 160 GeV** for **1 fb^{-1}**

Analysis extended to other masses (mass dependent optimization) by **multivariate approach**

Improved lepton ID, mass dependent cuts, data driven methods

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

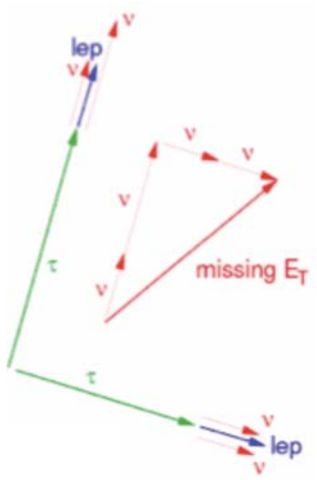


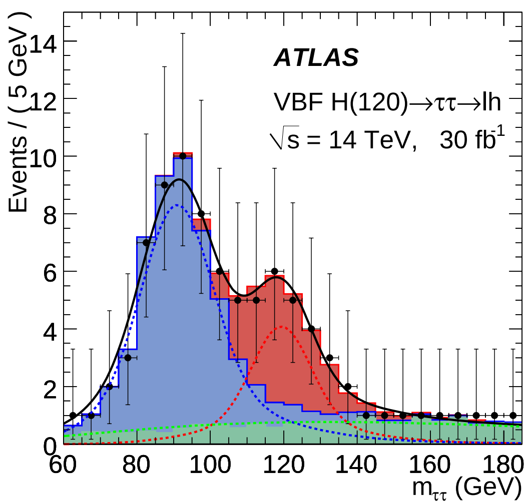
CMS PAS HIG-08-006

VBF H→ττ

Significant channel for **low masses** (115-145 GeV)
Important for studying the coupling of Higgs to leptons

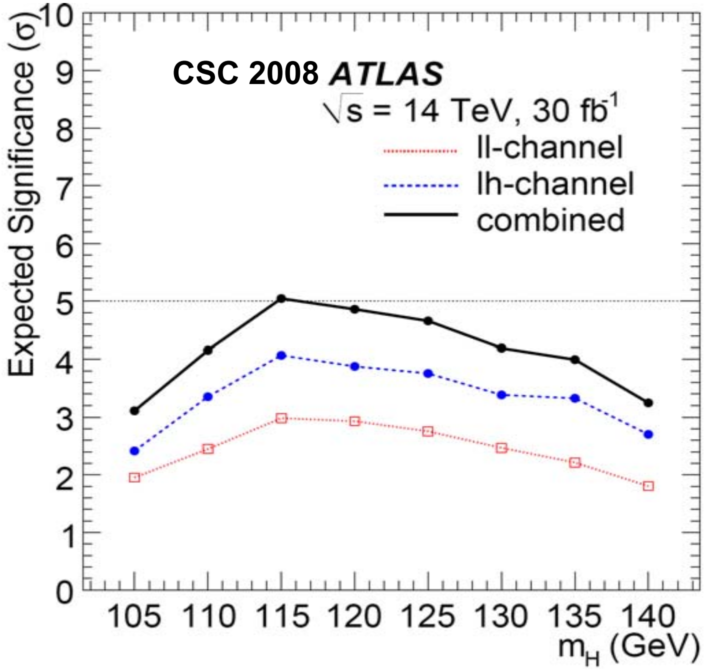
Three final states considered:
✓lepton-lepton
✓lepton-hadron (just CMS)
✓hadron-hadron
Backgrounds: *Zjj, tt, Z/γ → ττ*

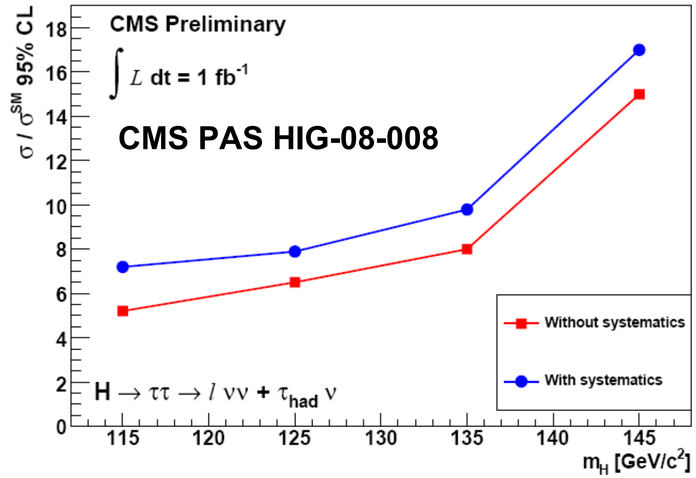




Invariant mass of the τ pair reconstructed via the collinear approximation (breaks down when the two taus are back-to-back)

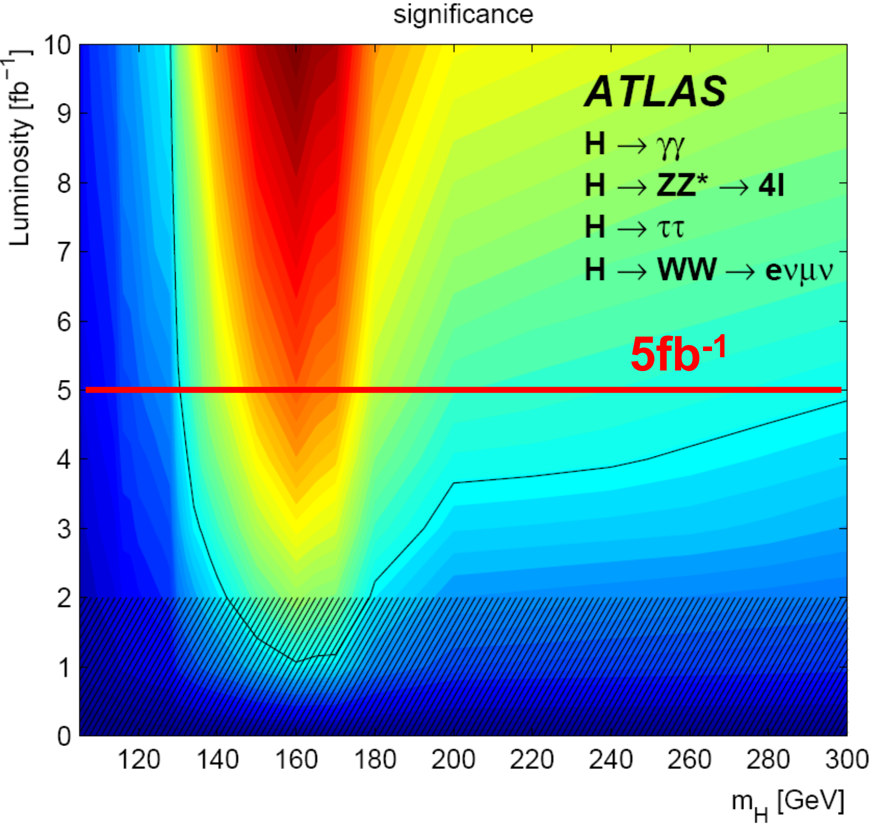
ATLAS: 5σ achieved for 115-120 GeV for 30fb^{-1}

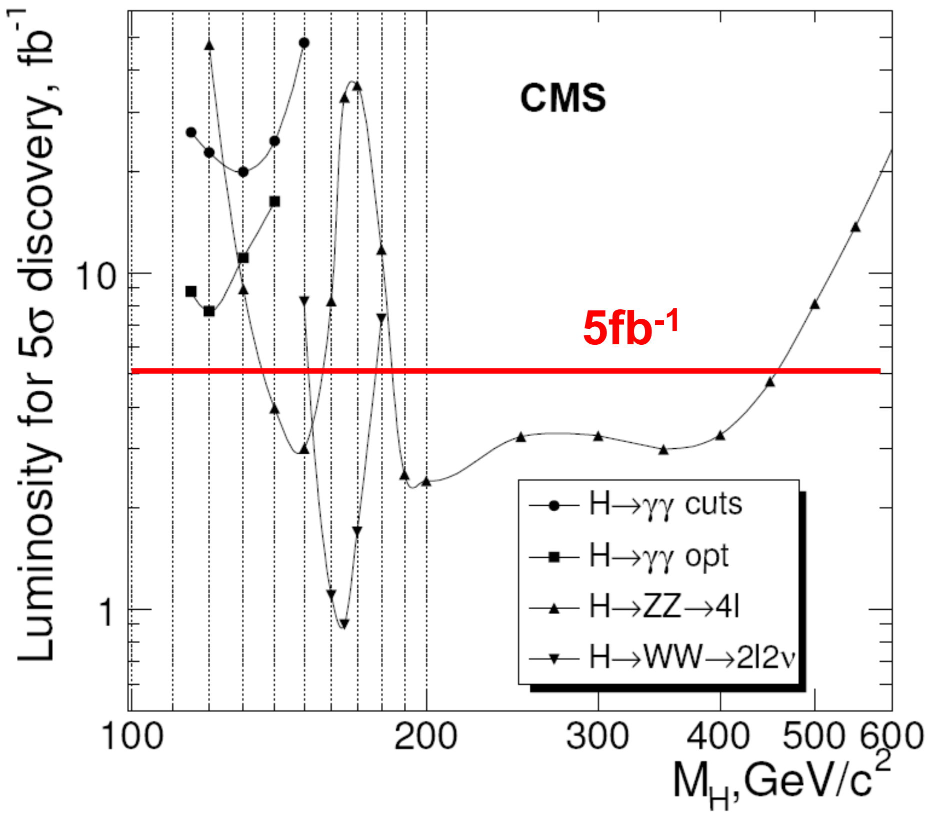




- **Tau tagging (Likelihood, NN methods)**
- **Z+jets background (especially for low masses)**
- **tt rejection (b-jet ID and veto for lepton-lepton)**

SM channel combination





With **10 fb^{-1}** (~ one LHC year at low luminosity)

5σ discovery for m_H in [~120, ~500] GeV

With **5 fb^{-1}**: **5σ discovery for m_H in [~130, ~450] GeV/c^2**

With **1-2 fb^{-1}**: **something can be said first with the H→ WW channel**

Combining results from both experiments, around half of this luminosity

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

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 backgrounds goes down**

- **Signal** (Higgs production) **goes down 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

- Therefore, the corresponding second order correction is larger than 1 (scaling factor)

Process	$\frac{\sigma_{\sqrt{s}=10TeV}}{\sigma_{\sqrt{s}=14TeV}}$	$\frac{\sigma_{\sqrt{s}=6TeV}}{\sigma_{\sqrt{s}=14TeV}}$
$t\bar{t}$	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

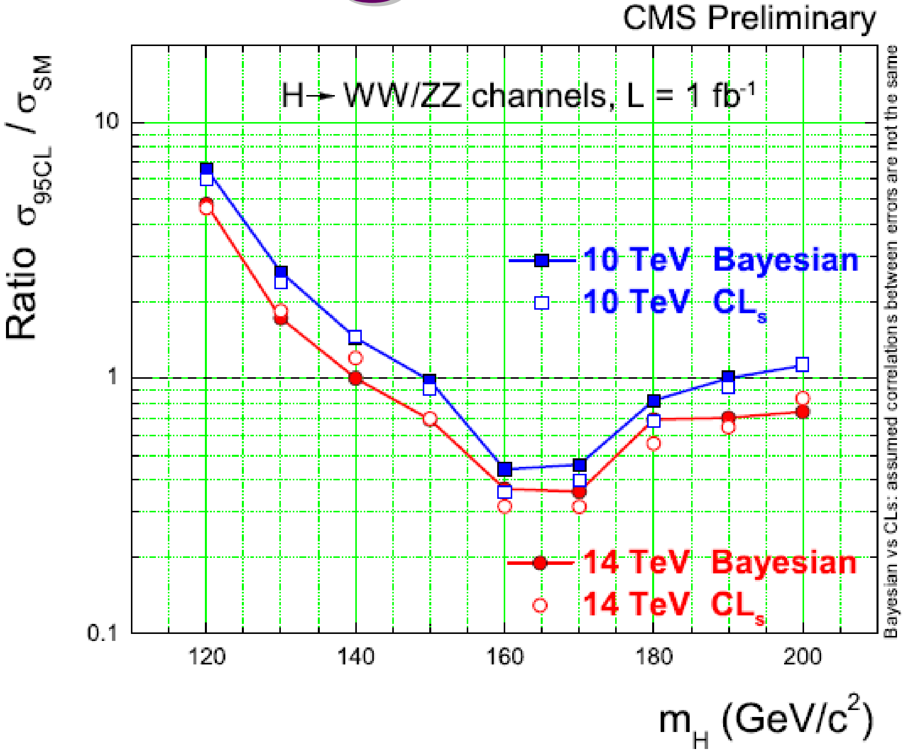
$\int$L for 5σ	14 TeV	10 TeV
m_H =200 GeV	0.6 fb-1	1.3 fb-1

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

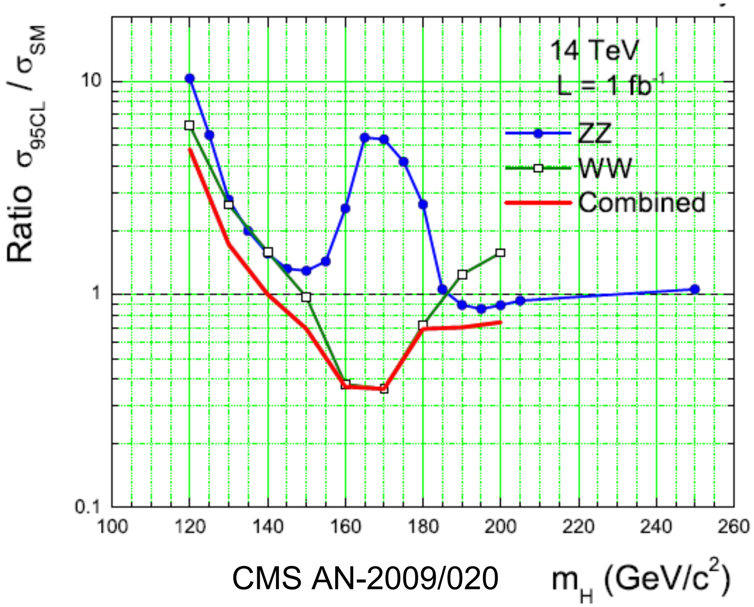
CMS projection for LHC@10TeV

- LHC 2009 - 2010 luminosity performance – estimate: ~200pb^{-1} of "good data"
- **Strategy:**
  - **First understand detectors,**
  - **do SM measurements,**

  → then search for the Higgs…
  Is that possible in the early running?



CMS: 10 TeV projection using the combination of HWW and HZZ results @ 14 TeV



CMS AN-2009/020

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)
☹ region <u>just excluded</u> by Tevatron!!!

Conclusions

EW Symmetry breaking is puzzling; but the **Large Hadron Collider** is in a very good position to shed light on this.

All the machinery is getting ready to start again this late fall
Not pushing (low energy, low luminosity).

With the first collision data we'll try to understand our detectors, but even in the early running, we'll be able to start doing some Higgs physics!

ATLAS and CMS are more than ready to start looking for the Higgs Boson.

For a SM Higgs, combining ATLAS & CMS @14TeV, between ~1 and 5 fb^{-1} are needed depending on mass value.

- **~0.1 fb^{-1}:** exclusion limits will start carving into SM Higgs cross section
- **~0.5 fb^{-1}:** 5σ sensitivity for M_H~160-170 GeV/c^2
- **~5 fb^{-1}:** SM Higgs is discovered (or excluded) in full range (~110-500)

Something has to happen, maybe it's a Higgs, maybe not, but at CERN, we're willing to start the hunting…

Thanks for listening!