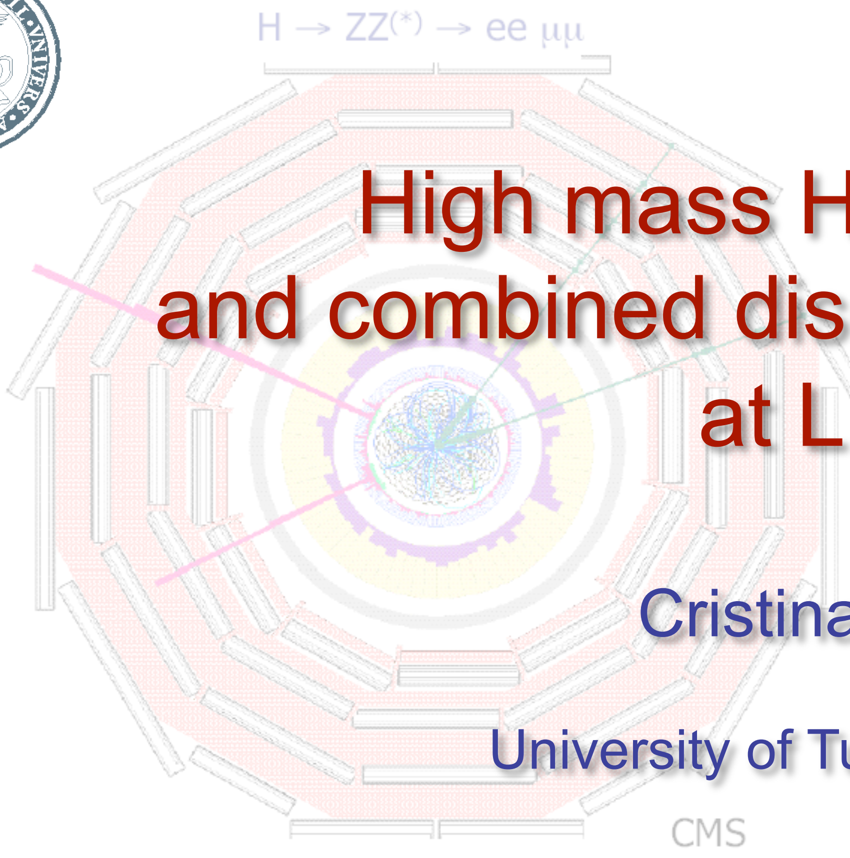


High mass Higgs search and combined discovery prospects at LHC

Cristina Botta

University of Turin and INFN

On behalf of CMS and ATLAS collaborations

The 2009 Europhysics Conference on High Energy Physics

16-22 July 2009 Krakow, Poland

Outline

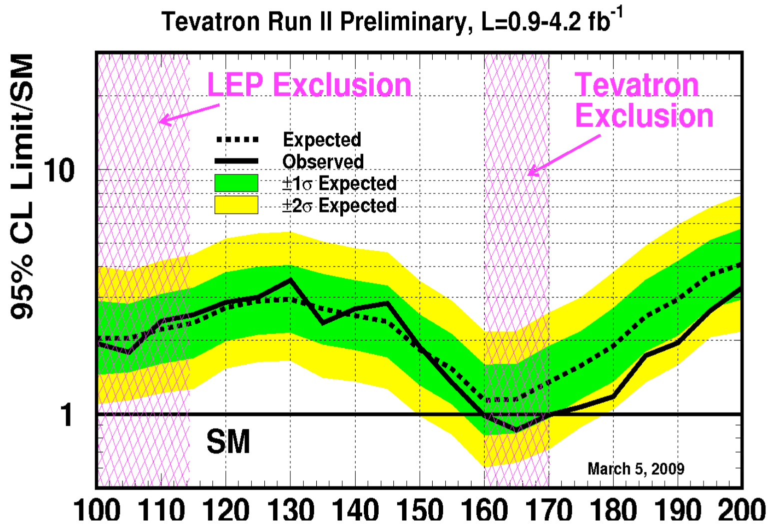
- Higgs Physics as of Today
- Higgs Physics at LHC
- High Mass Higgs search
- CMS and ATLAS Analyses: state of the art

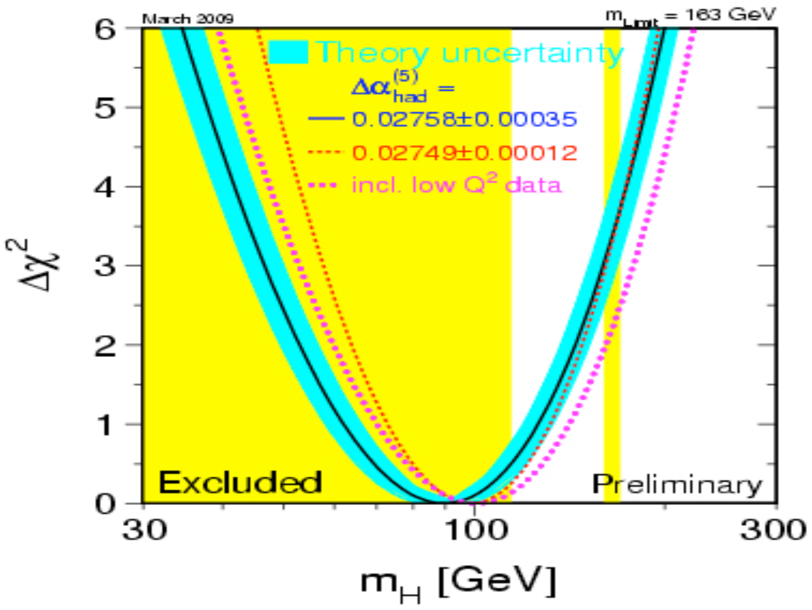
  $H \rightarrow ZZ \rightarrow 4l$

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

- Combined analyses results
- Conclusions

SM Higgs Physics as of today





Experimental Limits

- LEP → m_H ≥ 114.4 GeV at 95% CL
- TEVATRON Run II → 160 ≤ m_H ≤ 170 GeV excluded at 95% C

as shown in the previous talk by Dr. Bjoern PENNING

Indirect Constraints

- Preferred fit value $m_H = 90_{-27}^{+36}$ GeV (68% CL)
- m_H ≤ 163 GeV (95%CL) and ≤191 GeV (with LEP results)

http://lost-contact.mit.edu/afs/cern.ch/l3/lepewwg/Welcome.html

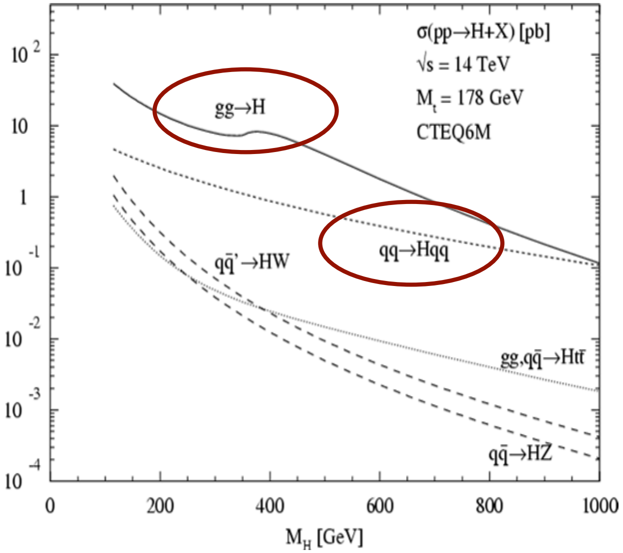
Theoretical Limits

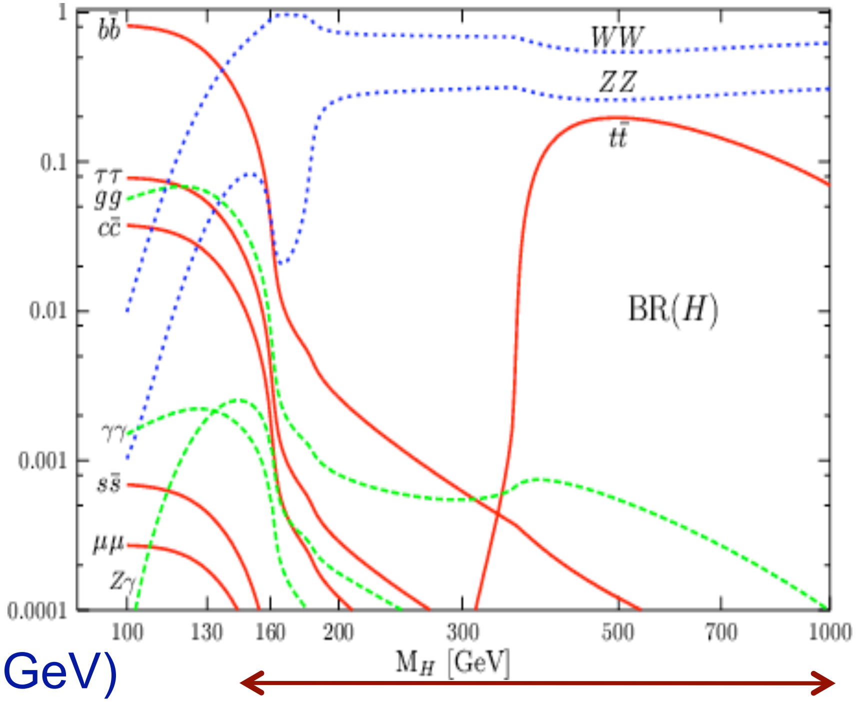
- m_H < 1 TeV from unitarity arguments
- If λ cutoff ≈ 1TeV weaker limits: 50≤ m_H ≤ 800 GeV

G.Ridolfi, hep-ph/0106300

SM Higgs Physics @ LHC

- Higgs Production: gg-fusion and VV-fusion





- Higgs Decays: high mass region ($M_H \geq 140$ GeV)

  - BR in $WW^{(*)}$ dominant (for $m_H \leq 2M_Z$, ≈1 @ $M_H = 160$)
  - BR in $ZZ^{(*)}$ < 1/2 of $WW^{(*)}$ BR (apart from $m_H = 2M_w$)

Both channels mainly accessible through vector boson leptonic decays

Most performant in 140-600 GeV : $H\rightarrow ZZ^{(*)}\rightarrow 4\ell$, $H\rightarrow WW^{(*)}\rightarrow 2\ell 2v$

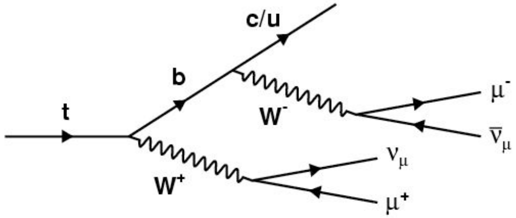
For masses >600 GeV in combination with $H\rightarrow ZZ^{(*)}\rightarrow \ell\ell vv$, $H\rightarrow ZZ^{(*)}\rightarrow \ell\ell qq$, $H\rightarrow WW^{(*)}\rightarrow \ell vqq$

High mass Higgs search

- **$H \rightarrow ZZ^{(*)} \rightarrow 4l \quad (l = \mu, e)$**
  - main discovery channel for its clean signature over a wide mass range

    4 isolated high p_t leptons emerging from the event primary vertex
  - ≈ 90 events with 4μ in the final state with 20 fb^{-1}

    (NLO cross section, M_H =190 GeV, leptons with p_t >3 GeV and η < 2.4)

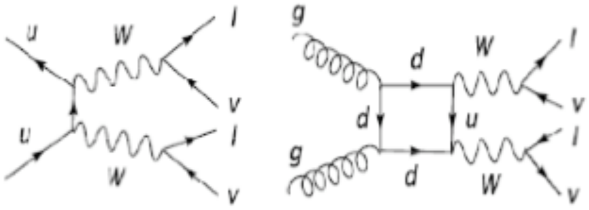


  - Main backgrounds: $ZZ^{(*)}/\gamma^{(*)} \rightarrow 4l$ (irreducible), $Zbb \rightarrow 2l bb$, tt (reducible)

- **$H \rightarrow WW^{(*)} \rightarrow 2l2\nu \quad (l = \mu, e)$**
  - Signal: 2 isolated high p_t leptons, MET and no hard jet

    signature highly sensitive in the mass range 150-180 GeV
  - ≈ 3000 events with 2e2v in the final state with 20 fb^{-1}

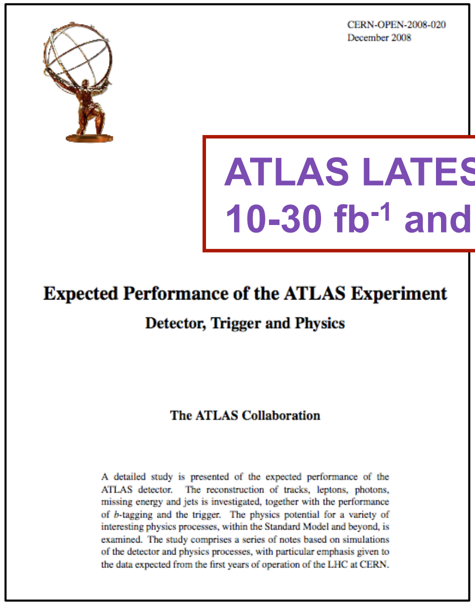
    (NLO cross section, M_H =190 GeV, leptons with p_t >3 GeV and η < 2.4)



  - Main backgrounds: $WW \rightarrow 2l2\nu$ (irreducible)

    tt, W+jets, DY, WZ, ZZ, tW (reducible)

Analyses: state of the art



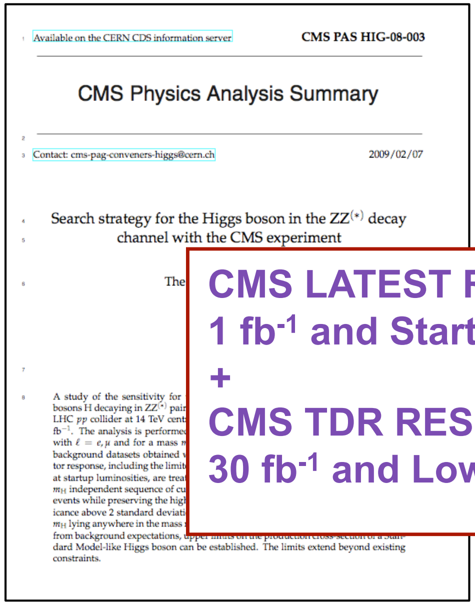
CERN-OPEN-2008-020
December 2008

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.

ATLAS LATEST RESULTS (2008)
10-30 fb^{-1} and Low Lumi 10^{33} cm^{-2} s^{-1}



Available on the CERN CDS information server
CMS PAS HIG-08-003

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch
2009/02/07

Search strategy for the Higgs boson in the $ZZ^{(*)}$ decay channel with the CMS experiment

The

A study of the sensitivity for
bosons H decaying in $ZZ^{(*)}$ pair
LHC pp collider at 14 TeV cent
fb^{-1}. The analysis is performed
with $\ell = e, \mu$ and for a mass
background datasets obtained
tor response, including the limit
at startup luminosities, are treat
m_H independent sequence of cu
events while preserving the high
icance above 2 standard deviati
m_H lying anywhere in the mass
from background expectations,
dard Model-like Higgs boson can be established. The limits extend beyond existing constraints.

CMS LATEST RESULTS (2009)
1 fb^{-1} and StartUp Lumi 2 * 10^{32} cm^{-2} s^{-1}
+
CMS TDR RESULTS (2007)
30 fb^{-1} and Low Lumi 10^{33} cm^{-2} s^{-1}

- Better detector description and simulation: material budget, geometry
- New approaches to match parton shower and matrix elements
  (ALPGEN+MLM matching + SHERPA)
- Sensitivities at NLO (NNLO maybe available before data taking)
- More detailed, better understood reconstruction methods, improved trigger simulation
- Data driven methods to control background rates from data
- Include statistical treatment of systematic uncertainties

H→ZZ→4ℓ: Main ideas

- The high performances on lepton reconstruction, identification and isolation and excellent lepton energy-momentum measurements are fundamental
  - against misidentification (“fake leptons”)
  - for a precise $m_{4\ell}$ measurement, single most discriminating variable for this search
- Both experiments show the power of a simple m_H -independent sequence of cuts
- Discriminating Variables for both analyses are:
  - **LEPTON ISOLATION**

    μISO (tracker + ECAL+ HCAL iso variable of the 2 least isolated muons)

    eISO (tracker + HCAL iso variable of the 2 least isolated electrons)
  - **LEPTON IMPACT PARAMETER**

    Significance of 3-dimensional IP (SIP_{3D})

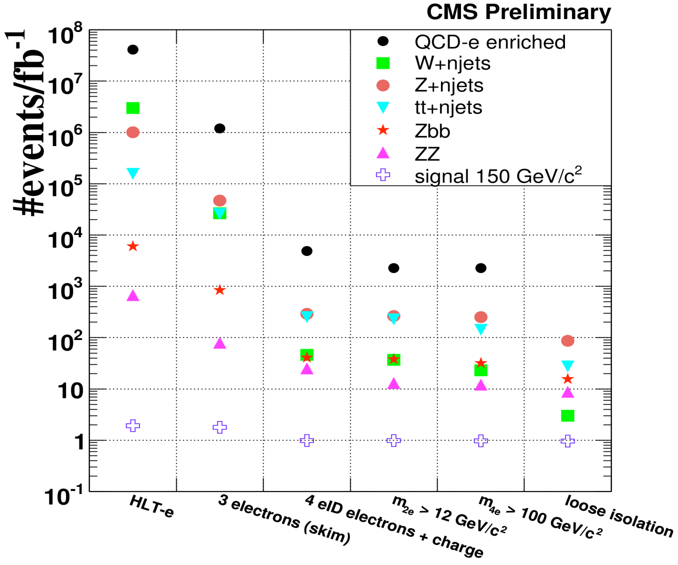
    Significance of transverse IP (SIP_{D0})
  - **LEPTON P_t**
  - **DI-LEPTON INVARIANT MASS**

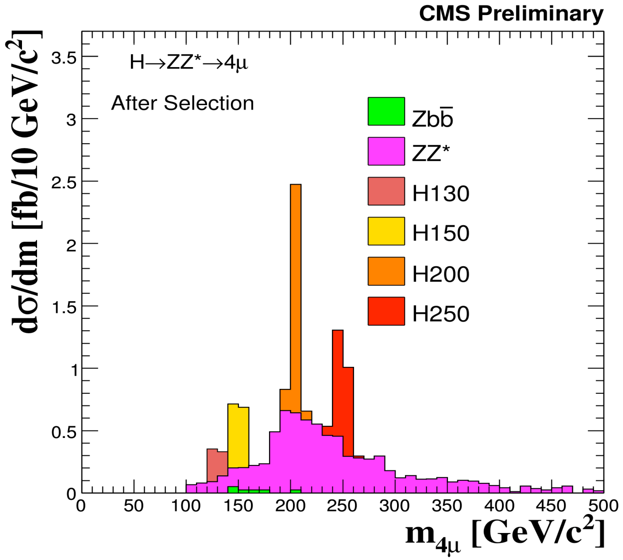
Leptons from H→ZZ decays are isolated, correctly associated to the primary vertex, have high P_t and if paired properly do reconstruct the Z_0 invariant mass

H→ZZ→4*l*: Strategies

CMS analysis: 1fb^{-1} and $\mathcal{L}=2\cdot10^{32}$ cm^{-2} s^{-1}

CMS PAS HIG-08-003





- TRIGGER

  combination of single- and di-leptons trigger: 99% 4μ, 95% 4e

- SKIMMING

  to reduce significantly QCD multijet events, Z+jets, W+jets

  2 leptons with p_t >10 GeV, 1 lepton with p_t > 5 GeV

- PRESELECTION

  mainly to suppress the contribution of “fake leptons” and lower QCD background largely under ZZ, Zbb, tt

  ≥ 2 *ll* pairs opposite charge and same flavor,
  at least two $m_{l^+l^-}$ > 12 GeV, at least one m_{4l} > 100 GeV

At this point the analysis is divided in 3 channels (4μ,4e,2μ2e)

- SELECTION (ex 4μ)

  focus to reduce the major reducible background Zbb and tt

  cut on μIso and eIso wrt Pt of the third μ/e (sorted by Pt)
  cut on Pt of the fourth μ/e
  cut on the highest value of S(IP_{3D})
  cut on M_Z and $M_{Z(*)}$

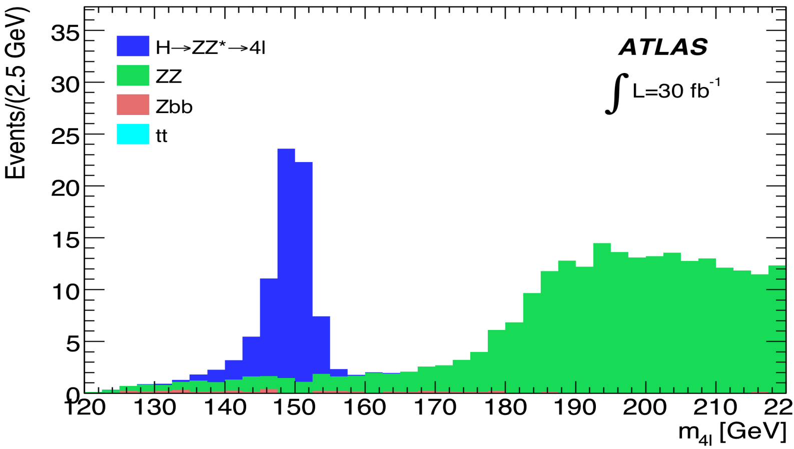
4μ channel: H(160) = 59% ZZ = 0.9% Zbb=0.01%

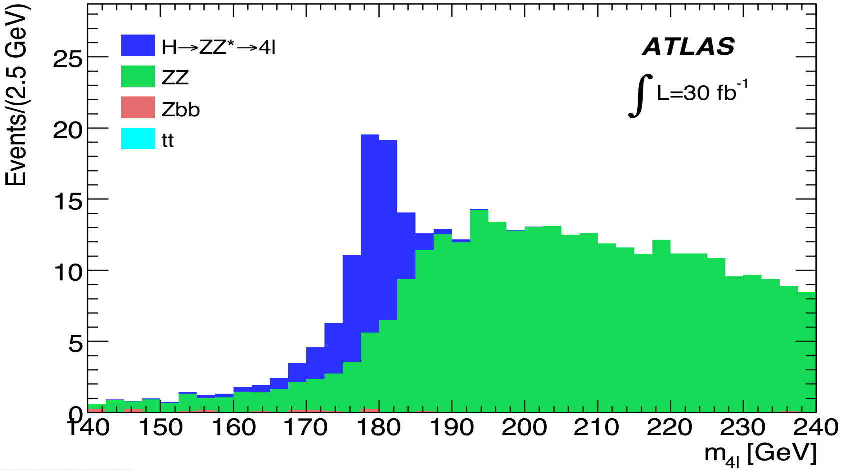
$H\to ZZ\to 4\ell$: Strategies

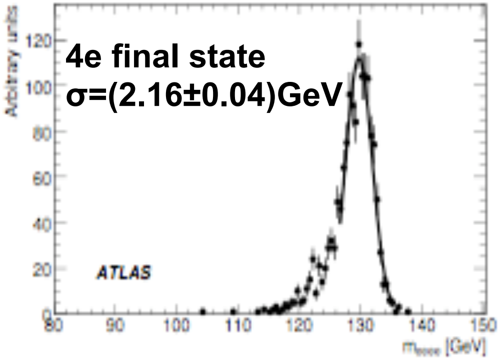
ATLAS analysis: 30 fb^{-1} and $\mathcal{L}=10^{-33}$ cm^{-2} s^{-1}

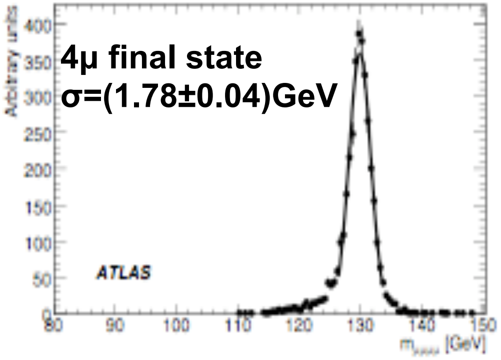
CERN-OPEN-2008-020

Selection cut		Signal			ZZ			Zbb		
		4e	4μ	2e2μ	4e	4μ	2e2μ	4e	4μ	2e2μ
Trigger	1	94.7	95.3	95.7	96.6	96.6	96.6	91.4	91.4	91.4
Preselection	2	57.0	73.8	66.8	13.8	17.6	31.4	2.6	9.4	12.0
Lepton quality and p_T	3	24.7	60.5	39.7	7.3	16.0	21.9	$1.1\cdot10^{-1}$	2.1	1.7
Z mass cuts	4	17.1	42.9	27.6	6.9	14.8	20.2	$4.7\cdot10^{-2}$	1.1	$8.4\cdot10^{-1}$
Calo Isolation	5	17.1	39.5	25.4	6.9	13.9	19.5	$4.7\cdot10^{-2}$	$8.5\cdot10^{-2}$	$1.2\cdot10^{-1}$
Track Isolation	6	16.5	38.1	24.7	6.8	13.6	19.2	$1.3\cdot10^{-2}$	$3.3\cdot10^{-2}$	$4.4\cdot10^{-2}$
IP cut	7	15.1	36.5	23.2	6.2	13.0	17.8	$5.6\cdot10^{-3}$	$1.1\cdot10^{-2}$	$1.8\cdot10^{-2}$
H Mass window	8	12.5±0.3	31.4±0.5	19.2±0.4	$5.2\cdot10^{-2}$	$11.3\cdot10^{-2}$	$12.0\cdot10^{-2}$	$1.6\cdot10^{-3}$	$1.2\cdot10^{-3}$	$3.0\cdot10^{-3}$









- Reconstructed 4ℓ mass after applying a Z mass constraint to the 2l pairs

- N_s and N_B to evaluate the final Significance = events in $m_{4\ell} \pm 2\sigma_{m4\ell}$ (extracted from the fit)

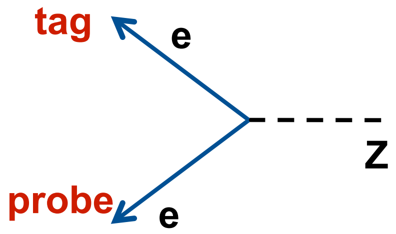
H→ZZ→4ℓ: Systematics

Main experimental uncertainties for lepton channels and their effect on the expected sensitivity are being considered (data-driven methods and extrapolation from MC when needed)

for the CMS analysis @ 1fb^{-1}

- Integrated luminosity (from Z or W production wrt theoretical cross section uncertainties from PDF and from the detector precision at early stages→ 5% with 1fb^{-1})

- Lepton Reco, ID and Iso efficiency (tag and probe method with Z→$\ell\ell$ high purity lepton sample electron efficiencies measured after 100 pb^{-1} with uncertainty < 2.5%)



- Lepton energy scale (after 100 pb^{-1} 1% for barrel electron, 2% for endcap electron, negligible for muons)

- Mis-calibration and mis-alignment (the tracking procedure takes into account the APE foreseen for a 100 pb^{-1} misalignment scenario → in the 4μ channel $M_{4\ell}$ increase of 2%)

ATLAS analysis also considered the Low-Luminosity pile-up effect: decrease of the final signal efficiency of 10%

H→ZZ→4l: Backgrounds Control

Data Driven methods to control the background rates proposed in the CMS analysis @ 1fb^{-1}

ZZ→4l background

- Normalization to sidebands: measure of the ZZ background in the m_{4l} spectrum outside the signal region (Δm)
- Normalization to Z: measure the Z→2l event count (qq-annihilation is the leading order diagram for both processes)

$$N_{ZZ}^{predicted}(\Delta m) = \rho(m_H) \cdot N_{CR}^{measured}$$

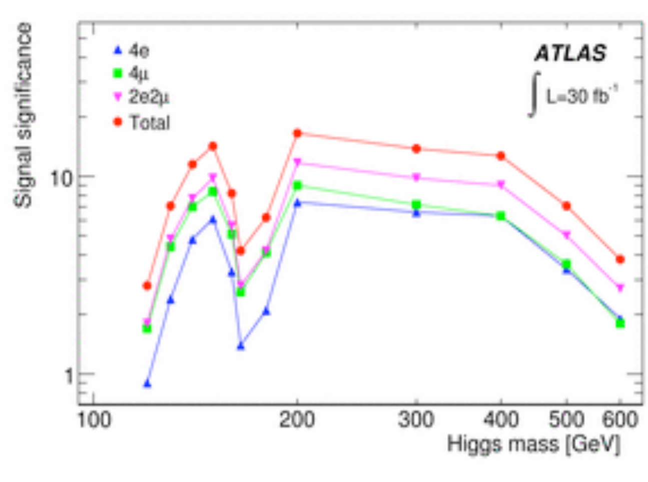
$$\rho(m_H) = \frac{N_{ZZ}^{theory}(\Delta m) \cdot \varepsilon_{ZZ}}{N_Z^{theory} \cdot \varepsilon_Z}$$

Uncertainties:

- Systematic errors on $\rho(m_H)$
- Statistical errors on N_{CR}

Source	Norm. to Z	Norm. to sidebands
Luminosity	0%	0%
Leptons: trigger/ID/reco/scale	6%	3%
Isolation	2%	2%
Miscalib. & misaling.	2%	2%
Theory (PDF&QCD sc.)	3%	3%
MC statistics	3%	3%
Statistical	~ 0%	20%
Total	8%	21%

H→ZZ→4*l*: Some Results

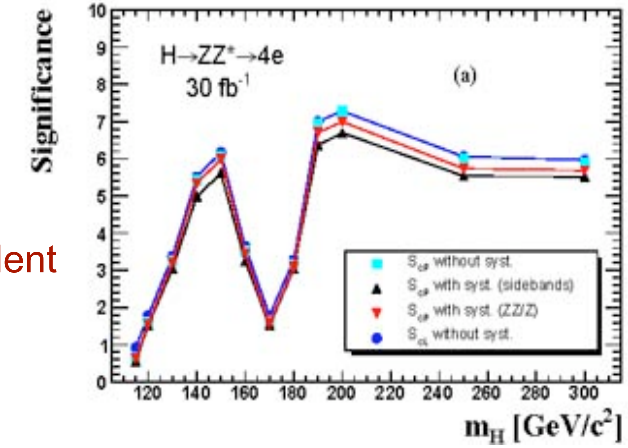


ATLAS 30 fb^{-1}

- 3 channel independent

- combined results

No systematics

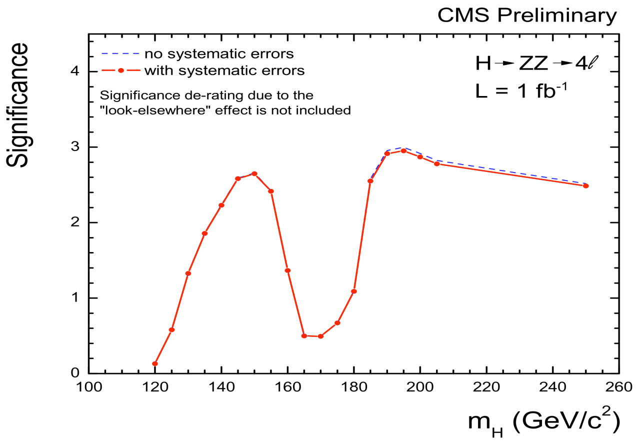


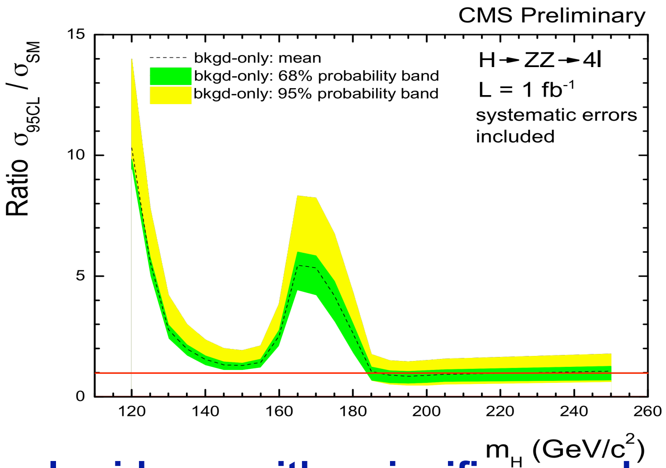
CMS 30 fb^{-1}

4e final state

With and without systematics

- **High sensitivity in the mass range 200 ≤ m_H ≤ 400 GeV and in the 150 GeV region where a significance of 5σ can be reached**





CMS 1 fb^{-1}

Systematics Included

But statistical errors dominate

- **CMS analysis shows that a signal evidence with a significance above 2 is found unlikely for a Higgs anywhere in the mass range considered ("Look Elsewhere Effect" !!!)**
- **In absence of a significant deviation from SM background it can be excluded if M_H ≥ 185 GeV**

H→WW→2l2ν: Main ideas

- **CMS analysis: 1fb^{-1} and $\mathcal{L}$=2·10^{32} cm^{-2} s^{-1}**
  Mass dependent cut based analysis as well as multivariate analysis

  ATLAS analysis: 10 fb^{-1} and $\mathcal{L}$=10^{33} cm^{-2} s^{-1}
  Mass independent cut based analysis (published results only for eμ final state)

- Due to undetected neutrinos in the final state no Higgs mass peak could be reconstructed → a discovery/exclusion of a Higgs for a certain mass hypothesis relies on a COUNTING EXPERIMENT
  main backgrounds (irreducible WW, W+jets, tt) precise rate control from data is crucial

- Discriminating Variables for both analyses are:

  - **CENTRAL JET VETO**
  - **ANGULAR CORRELATION BETWEEN LEPTONS**
  - **LEPTON P$_t$ and DI-LEPTON INVARIANT MASS**
  - **MET**

$H \rightarrow WW \rightarrow 2\ell 2\nu$: Strategies

CMS analysis: $1 fb^{-1}$ and $\mathcal{L}=2 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

CMS PAS HIG-08-006

- TRIGGER

  combination of single-lepton trigger: 96% 2μ, 83% 2e

- SKIMMING

  highest possible signal efficiency

  very effective on QCD multijet and DY (p_t 10-40 → 0.5%)

  common to the 3 channels: 1 lepton with p_t>10, 1 lepton with p_t >20

- PRESELECTION
  - exactly one lepton pair with opposite charge
  - both with p_t >10 and at least one with p_t >20 and both with $|\eta|$ <2.4

    (H(160) with 2l in the accessible η range: 85%, high rejection power against ZZ and WZ)
  - MET > 30 GeV
  - $m_{\ell\ell} \geq 12$ GeV

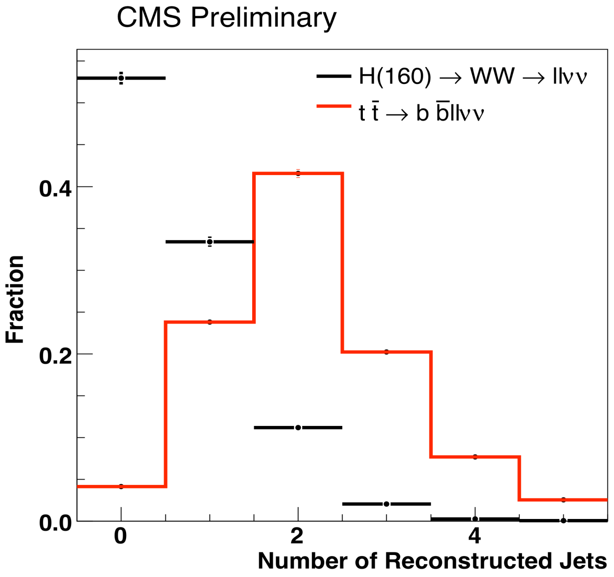
At this point the analysis is divided in 3 channels and a set of M_H dependent cuts is applied

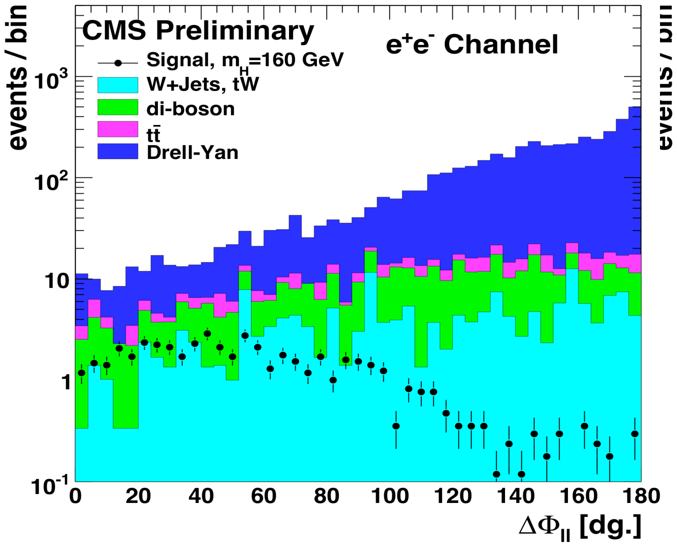
The outcome of the three independent analyses are then combined to give a single result

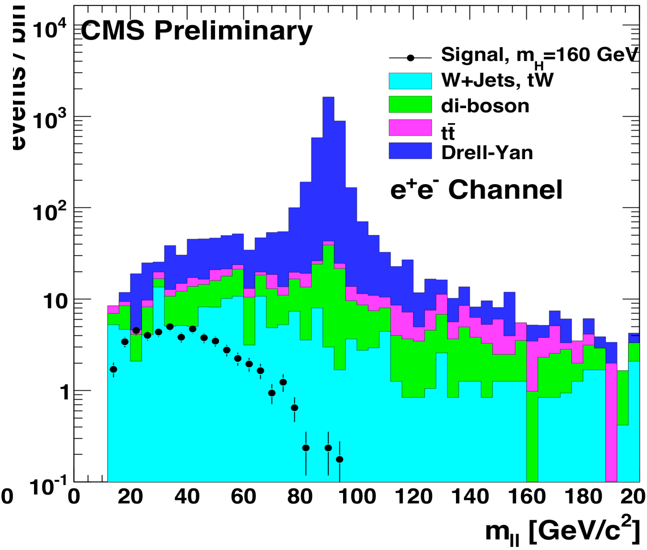
H→WW→2ℓ2ν: Strategies

CMS analysis: 1fb^{-1} and $\mathcal{L}=2\cdot10^{32}$ cm^{-2} s^{-1}

- FINAL SELECTION VARIABLES (2e channel):







CENTRAL JET VETO: veto applied to events with central jets $|\eta_{jet}|<2.5$

against tt where central jets are slightly favored (it also reduces QCD, DY+jets and other backgrounds with misidentified primary leptons such as W+jets)

$\Delta\varphi_{\ell\ell}$ angle between the isolated leptons in the transverse plane

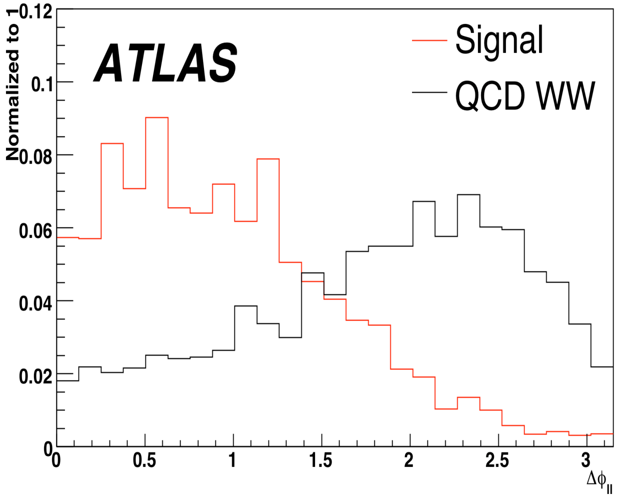
against the WW continuum background (larger $\Delta\varphi_{\ell\ell}$)

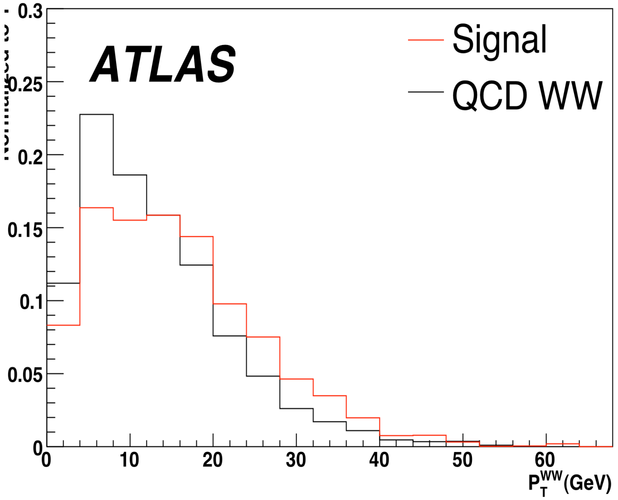
M_{ll} (for ee, μμ cases): upper cut to reduce the contamination from leptons coming from Z bosons

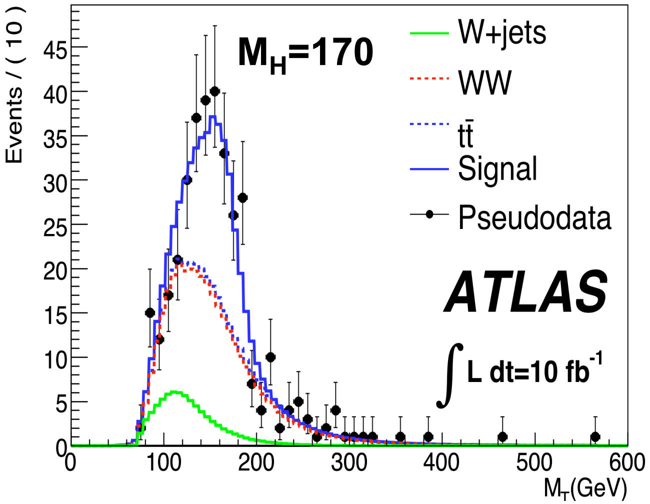
H→WW→2l2ν: Strategies

ATLAS analysis: 10 fb^{-1} and $\mathcal{L}=10^{33}$ cm^{-2} s^{-1} **CERN-OPEN-2008-020**

After a very similar TRIGGER+PRESELECTION the final mass-independent selection in based on:







Δφ$_{ll}$ angle between the isolated leptons in the transverse plane

Transverse Mass M$_t$ of the WW system defined as:

$$M_T = \sqrt{(E_T(ll) + E_T(\nu\nu))^2 - (P_T(ll) + P_T(\nu\nu))^2}$$

$$E_T(ll) = \sqrt{M(ll)^2 + P_t(ll)^2}$$

$$E_T(\nu\nu) = \sqrt{M(ll)^2 + P_t(\nu\nu)^2}$$

P$_t$ of the WW system

(which tends to be slightly larger for signal because gluon-initiated processes tend to have more initial-state radiation than quark-initiated processes)

H→WW→2l2ν: Backgrounds Control

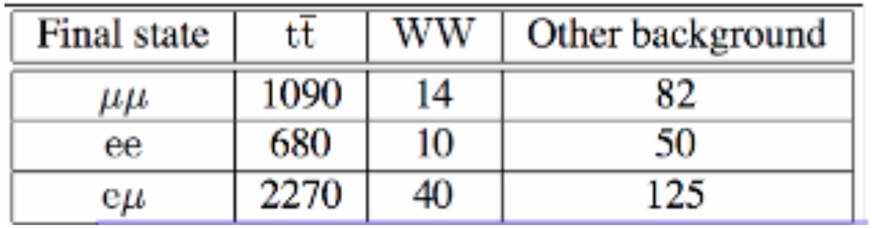
- A precise rate control of the main backgrounds (WW, tt) from data is crucial

  performances of “Sideband methods” have been studied and applied to determine tt and WW contribution in the signal region

- Big effort also on Lepton Fake Rate control from data

  important to control W+jets background

CMS analysis: 1fb^{-1} and $\mathcal{L}$=2·10^{-32} cm^{-2} s^{-1}



Final state	$t\bar{t}$	WW	Other background
$\mu\mu$	1090	14	82
ee	680	10	50
eμ	2270	40	125

Ex: tt background normalization

- The control region is defined:

  applying all the lepton- and pre-selection cuts

  inverting the CJV requiring at least two hard jets

  adding additional cut against DY contamination on the variable $E_T^{miss} \cdot \sin(\min(\Delta\varphi_{E_T{}^{miss}\, l}, \pi\ /2))$

- Uncertainties:

$$\frac{\Delta N_{tt}^{S}}{N_{tt}^{S}} = 16.5\% \ominus 1.5\% \oplus 2\% = 16.7\%$$

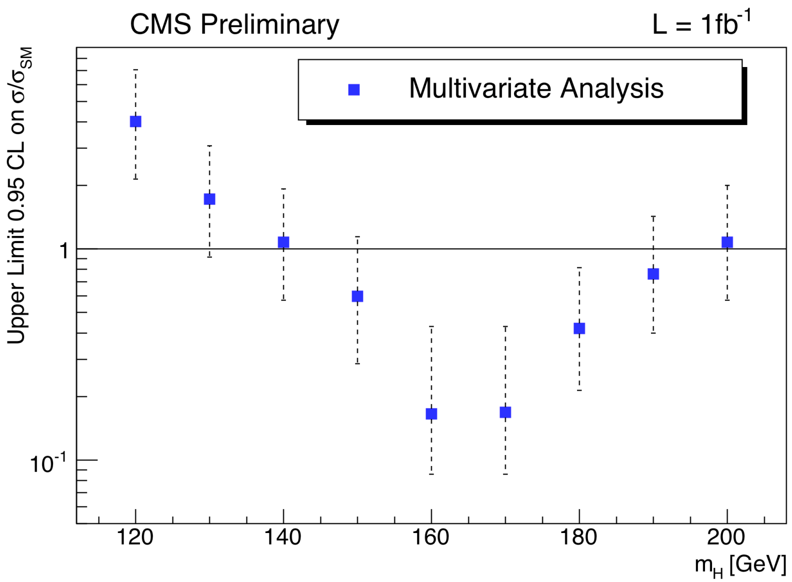
Jet energy scale

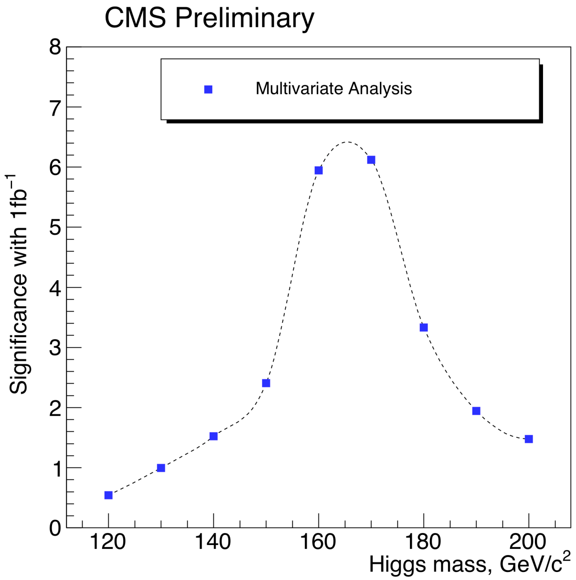
Observed statistic

Sample Contamination

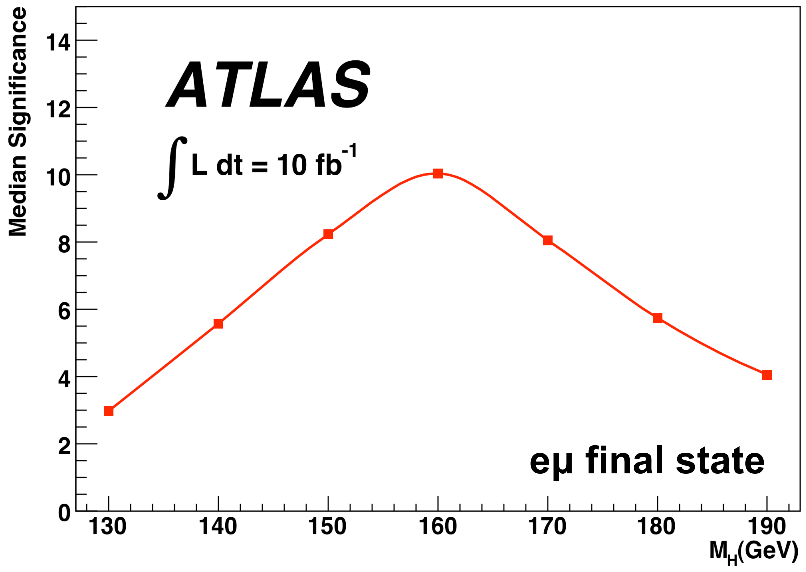
Considered as a statistical error in computing the final significance

H→WW→$2l2\nu$: Some Results





SYSTEMATICS INCLUDED



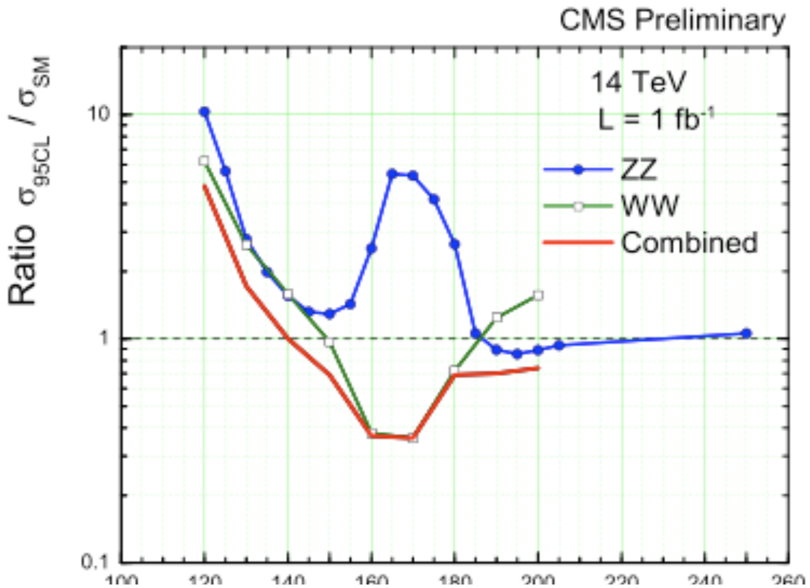
- The multivariate technique of CMS analysis at 1 fb^{-1} shows that:

  - combining all three final states (ee, μμ, eμ) a SM Higgs could be found at 5σ around 160 GeV

  - from the upper limit calculation the SM Higgs can be excluded in 150-190 GeV region

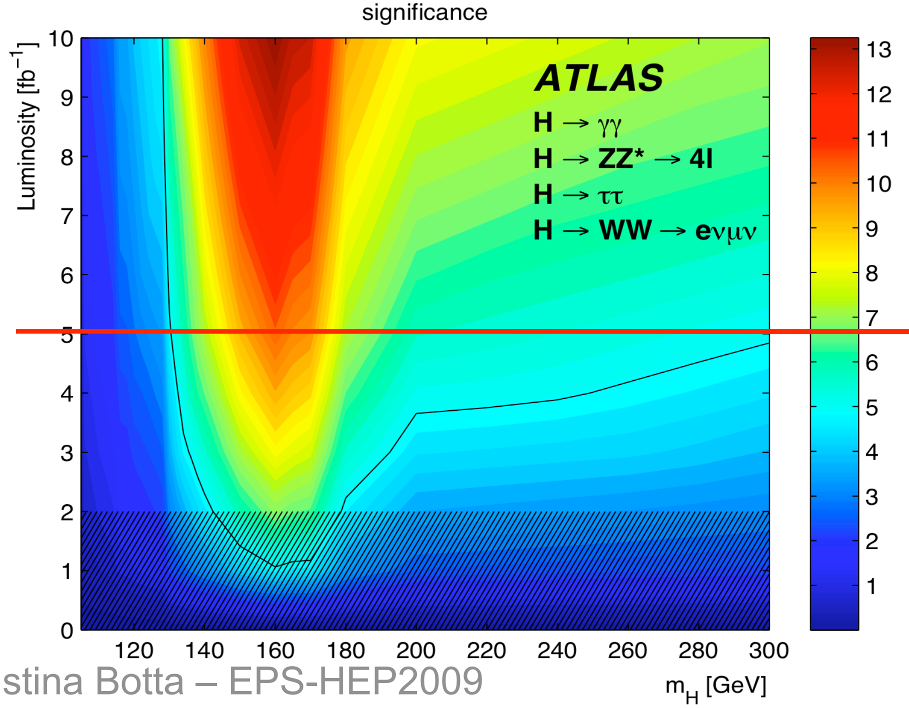
- The ATLAS analysis at 10 fb^{-1} shows that a SM Higgs could be found at 5σ in 140-180 GeV region

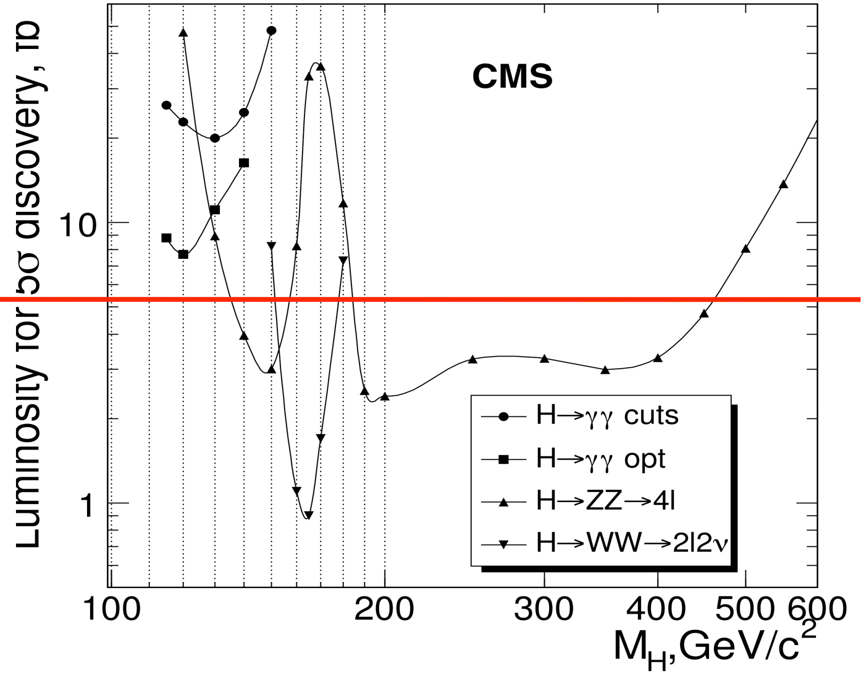
Combined Channel Results



- The statistical combination of the results of the CMS analyses (HZZ, HWW) @ 1fb^{-1} shows that a SM Higgs in the mass range 140-230 GeV can be excluded

- The ATLAS and CMS combination of all the main analysis results shows that with 5fb^{-1} a High Mass Higgs 140-450 GeV can be discovered with 5σ significance





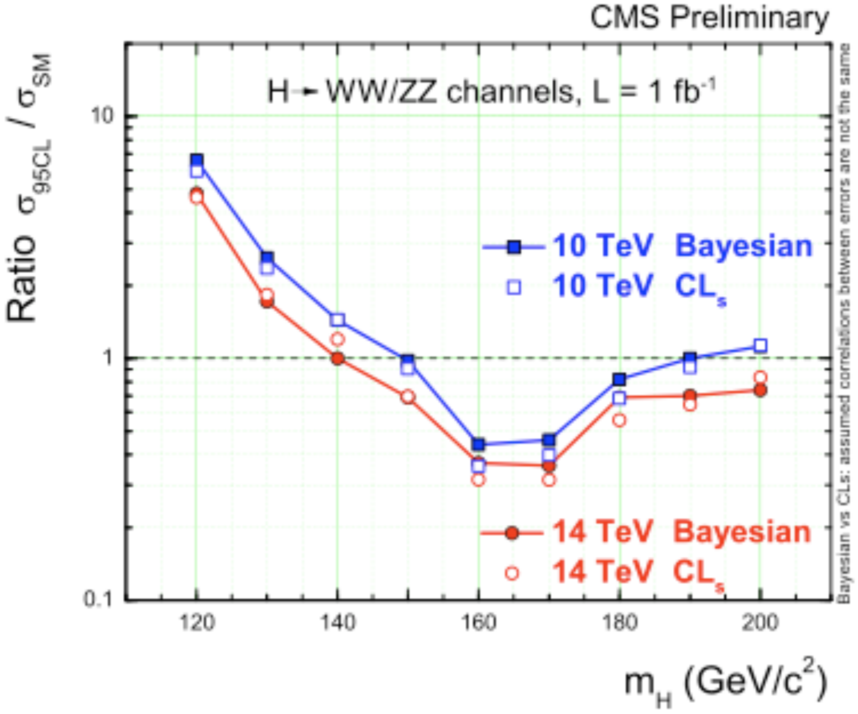
From 14 to 10 TeV

- The LHC will start working in 2009-2010 with a C.M. energy lower than the nominal one

- The main effect is the change in the bkg and signal cross sections

  (signal goes down slightly faster because Higgs is mainly produced via gg and background from qq)

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



CMS projection for the exclusion limits with the combined HZZ and HWW channel @ 10 TeV

Conclusions

- ATLAS and CMS are ready for High Mass Higgs Boson searches

- The two most important channels for this search (the fully leptonic HZZ, HWW) have been described and their discovery/exclusion potential discussed

  - DISCOVERY POTENTIAL

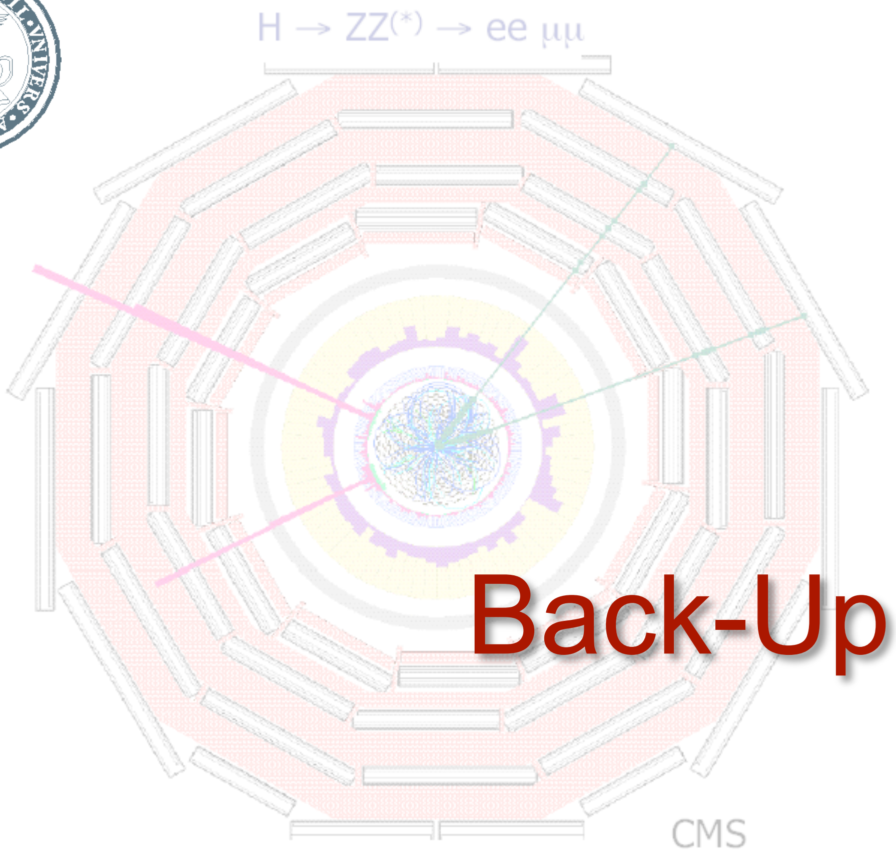
    the SM Higgs Boson can be discovered in the 140-450 GeV mass range by both experiments with 5fb^{-1}

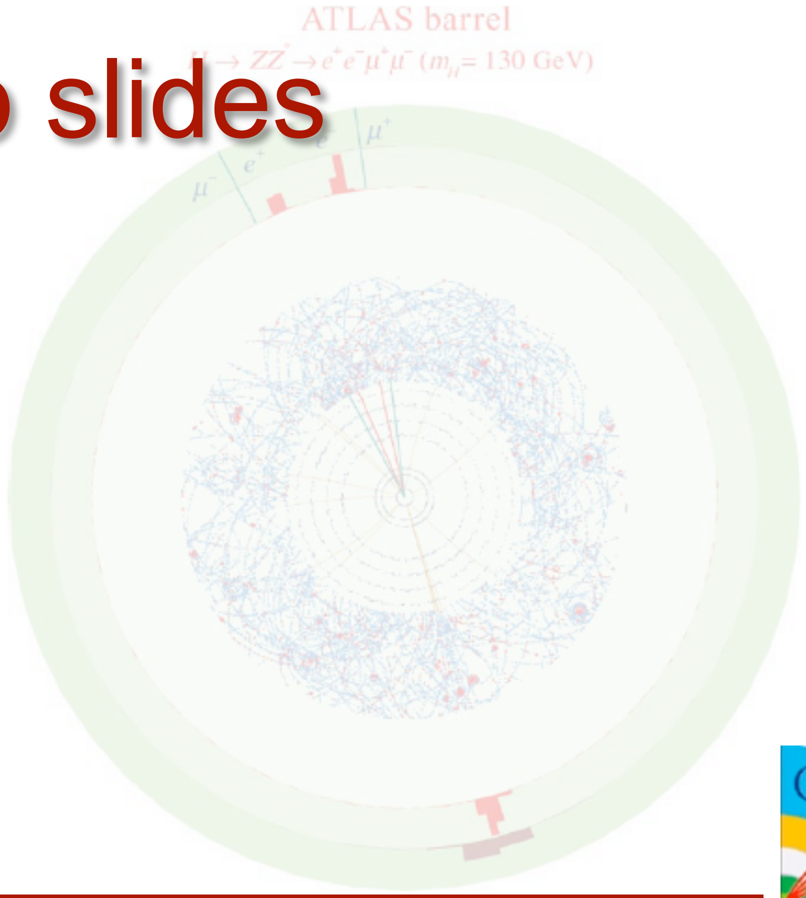
  - EXCLUSION POTENTIAL

    already at 1fb^{-1} the combination of the two channels allows to exclude the SM Higgs Boson in the 140-230 GeV mass range at 14 TeV (150-190 GeV at 10 TeV)

- Main effort is being done in developing methods to control background rate from data and to have a good estimation of systematics

- Waiting for data to come ATLAS and CMS are doing their best to commission and understand the detector responses



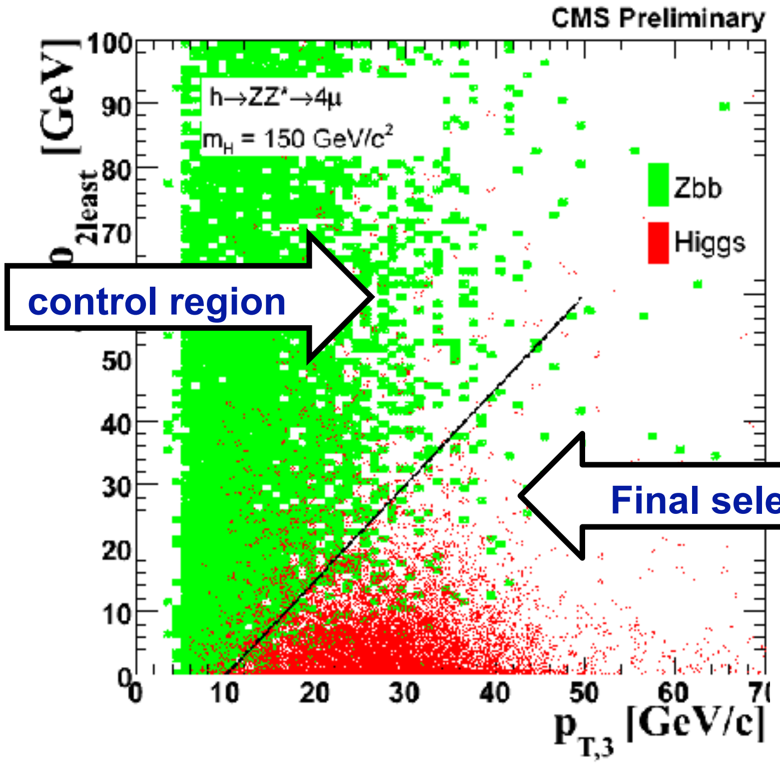


Back-Up slides

H→ZZ→4l: Backgrounds Control

Data Driven methods to control the background rates proposed in the CMS analysis @ 1fb^{-1}

Zbb→2lbb background



control region

Final selection region

- Normalization to sidebands: the control region is found exploiting the analysis strategy used to reject Zbb
- Discriminating power of combining the IsoVariable and the pt of the third lepton (sorted in decreasing order)
- Control Region contaminated with other background (mainly tt)
- A good control of tt background can be provided with the Z mass constrain
- Systematic @ 1fb^{-1}: the difference between the number of events under the Z peak from pseudo-experiment and from MC → 35% final uncertainty