Search for the Standard Model Higgs Boson in the Decay Channel H→ZZ→2l2q at CMS

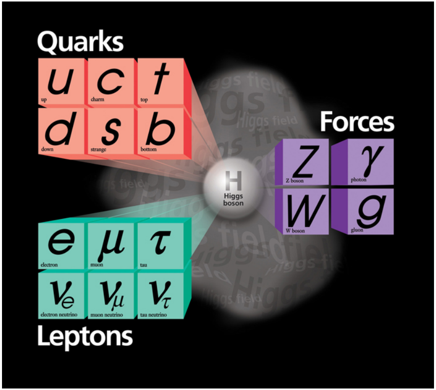
Matthew Kress

Adviser: Daniela Bortoletto
Ph.D. Defense
April 11, 2014

Outline

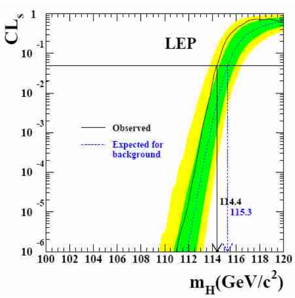
Outline

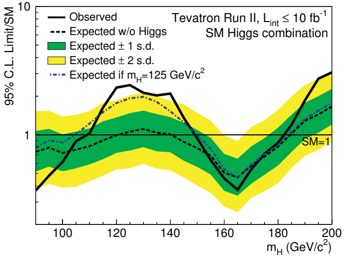
The Standard Model is the compilation of over 100 years of scientific discoveries and is in excellent agreement with a wide range of experimental observations.



- In the Standard Model the simplest solution for the nature of the electroweak symmetry breaking is the introduction of the Higgs field.
- At the comencement of the LHC the only free parameter of the Standard Model was the Higgs mass.

Source: http://www.fnal.gov/pub/presspass/press_releases/2013/Higgs-Boson-20130314.html





Source: http://tevnphwg.fnal.gov/

Experimental constraints:

- LEP excluded with $CL_{95\%}$

  $m_H < 114.4$ GeV.

- The latest measurments from Tevetron (July 2013) exclude with $CL_{95\%}$ at:

  90 GeV $< m_H <$ 109 GeV
  149 GeV $< m_H <$ 182 GeV.

Why search for a Higgs at high mass?

Discovery

In 2012 ATLAS and CMS announced the discovery of a new boson at 126 GeV. In 2013 is was confirmed that this new particle is consistant with a Standard Model Higgs boson.

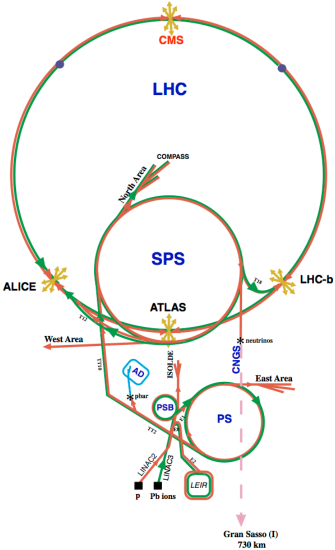
This analysis is sensative in the 250 to 650 GeV range so why search there?

- When we started this analysis in 2011 we didn't know where the Higgs boson would be. (Needed to look everywhere)
- Is the new particle THE Standard Model Higgs boson.
- Are there other Higgs bosons?

Beyond the Standard Model

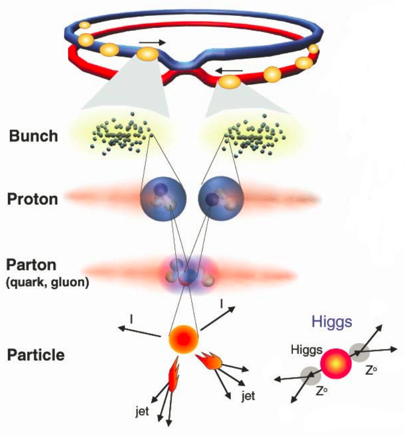
Many Beyond the Standard Model (BSM) theories extend the simple Higgs sector of the Standard Model and lead to more complicated particle spectrum. Very often one of the new particles has properties similar to the Standard Model Higgs.

LHC Environment



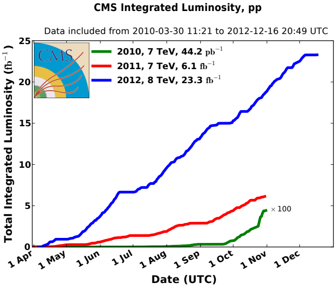
Source: http://www.quantumdiaries.org/2011/10/24/the-25-ns-pumpkin-teeth/

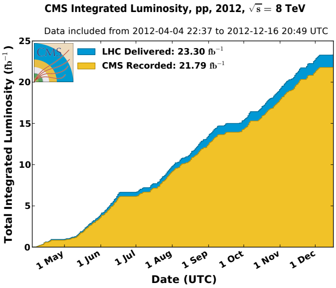
In 2012 $\sqrt{s} = 8$ TeV



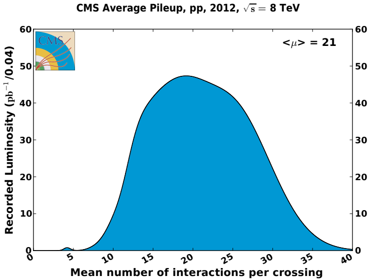
Source: HaijunYang, ColloquiumShanghaiJianTongUniversity, Sept12, 2012

LHC Delivered Data



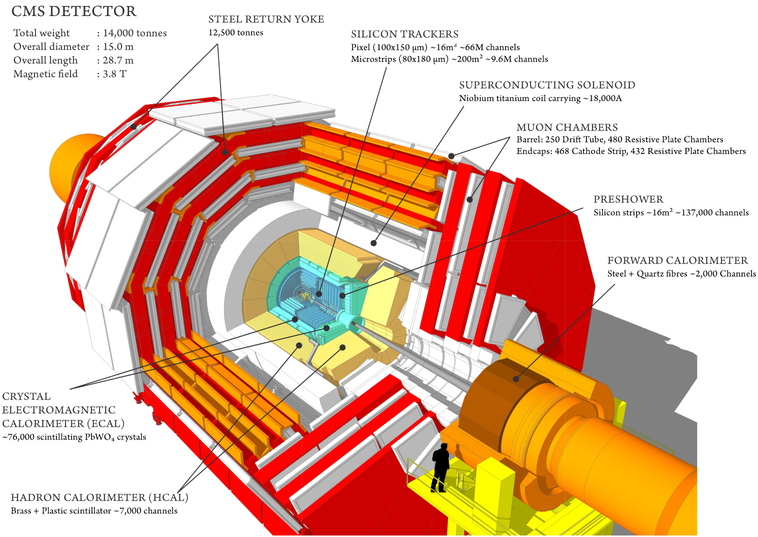


- CMS has done extremely well during Run I (2010-2012).
- Data-taking efficiency was very high (95%)
- Main challenge of the 2012 was how to deal with pileup.



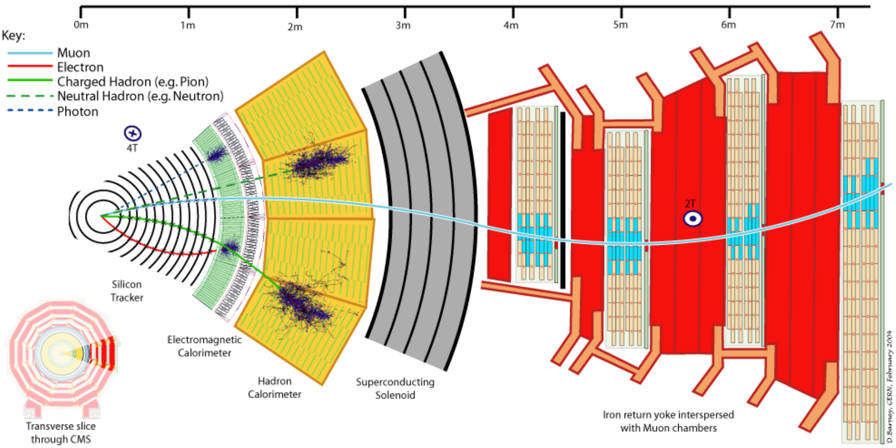
Source: http://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

Compact Muon Solenoid



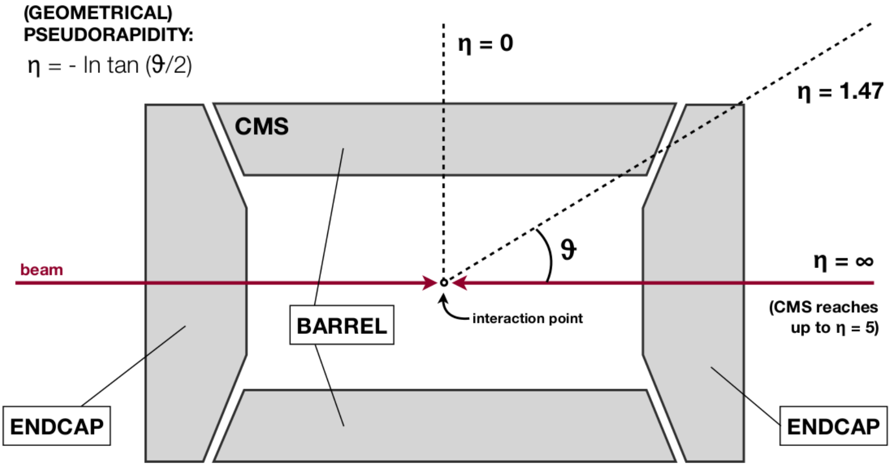
Source: `http://www.fnal.gov/pub/presspass/press_releases/2013/Higgs-Boson-20130314.html`

CMS Slice

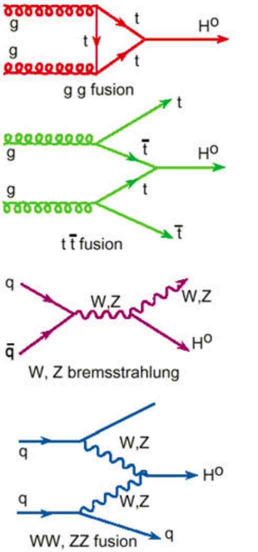


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

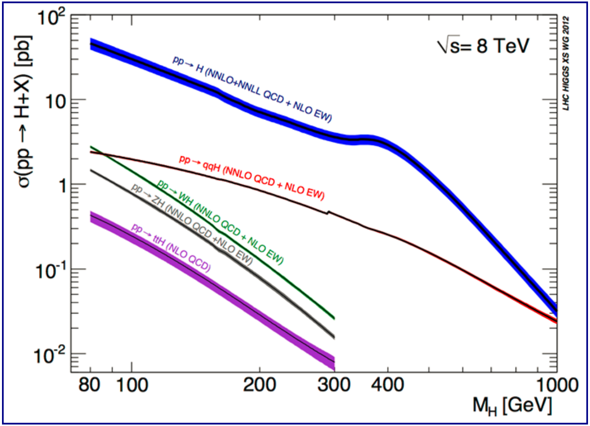
CMS Detector Glossary



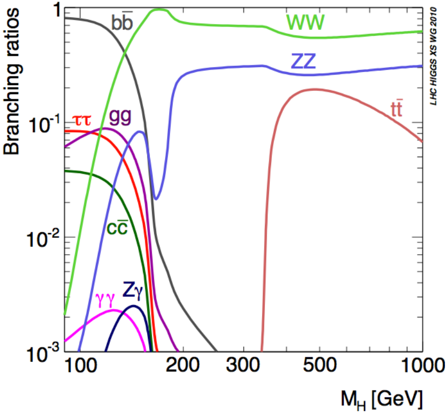
Higgs Production



Gluon-gluon fusion ($gg \rightarrow H$) and vector-boson fusion ($qq \rightarrow qqH$) are dominant



- Discovery strategy depends on the available decay channels.
- Decays with leptons provide clean signatures.



Main Discovery Channels

- $H \rightarrow \gamma\gamma$
- $H \rightarrow W^+W^-$
- $H \rightarrow ZZ$

The Heavy Higgs Decay

For a heavy (m_H > 200 GeV) Higgs boson the Higgs decays predominantly to vector boson pairs.
The fully leptonic decay modes are:

$$H \to WW \to \ell^+\nu\ell^-\overline{\nu}$$
$$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$$
$$(\ell = \mathrm{e}, \mu)$$

$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ (The "golden" Channel)

Pros:

- Decay chain can be fully reconstructed.
- High precision lepton measurements gives a narrow invariant mass peak.

Cons:

- The branching ratio of $Z \to \ell^+\ell^-$ is only 3.37% so less than 0.5% of the $H \to ZZ$ events will end up in the "golden" channel.

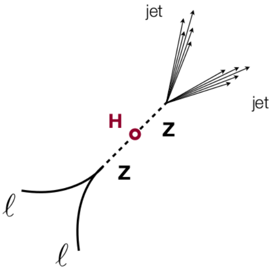
The $H \to ZZ \to llqq$ Channel

When a Z decays to quarks they hadronize and form "jets." These are complex objects and challenging to reconstruct.
If we allow one Z to decay leptonicly and the other to quarks we get.

$$H \to ZZ \to \ell^+\ell^- q\bar{q}$$
$$(q = u, d, c, s, b)$$

Pros:

- Large branching ratios
  - BR($Z \to qq$) = 70%
  - BR($ZZ \to 2l2q$) = 20 $\times$ $BR(ZZ \to 4l)$
- Fully decay is reconstructed (closed kinematics)



Cons:

- Resolution of jet momentum reconstruction is worse than for leptons.
- Large background coming from Z production in conjunction with QCD jets ($\sim 10^5$ > signal).

Traditional Jet Approach: Caloremeter Jets

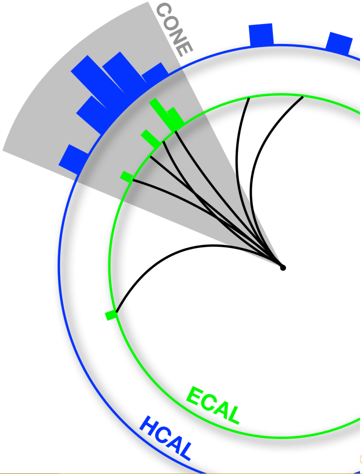
For CaloJets we assume most particles will reach the calorimeters close to each other. So all we have to do is cluster the energy deposits in the calorimeters.

Pros:

- straightforward
- fast and unaffected by event complexity

Cons:

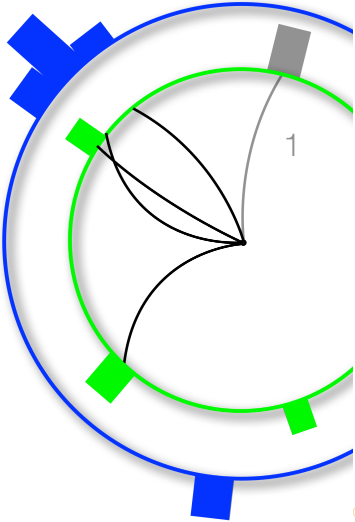
- response is p_T-dependent
- lose low p_T charged particles
- HCAL resolution



Particle Flow

The particle flow algorithm attempts to reconstruct all stable final state particles using all of the CMS sub-detectors.

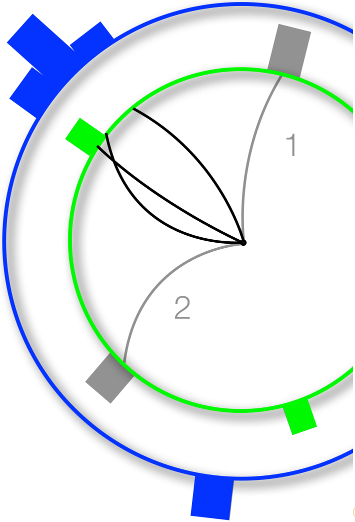
- 1. Get tracks linked to a single ECAL cluster if electron ID says OK create an electron.



Particle Flow

The particle flow algorithm attempts to reconstruct all stable final state particles using all of the CMS sub-detectors.

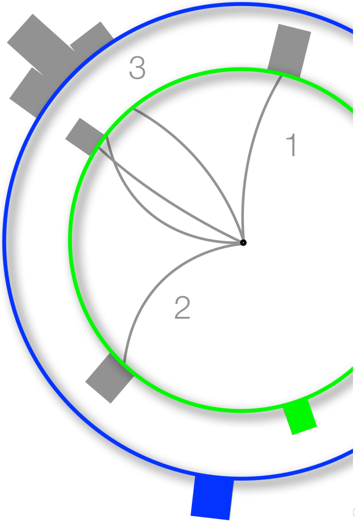
- 1. Get tracks linked to a single ECAL cluster if electron ID says OK create an electron.
- 2. If not then if there are compatible hits in muon chambers create a muon if not create a charged hadron.



Particle Flow

The particle flow algorithm attempts to reconstruct all stable final state particles using all of the CMS sub-detectors.

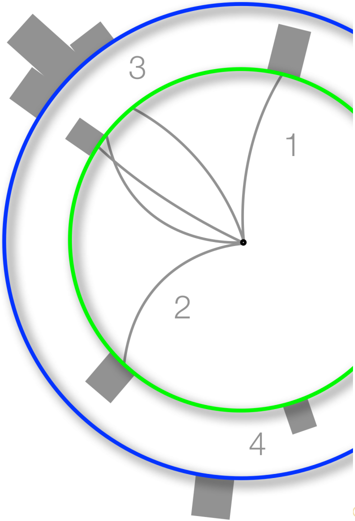
- 1. Get tracks linked to a single ECAL cluster if electron ID says OK create an electron.
- 2. If not then if there are compatible hits in muon chambers create a muon if not create a charged hadron.
- 3. For each HCAL cluster get all the linked tracks and all ECAL clusters linked to tracks. If the energy in the calorimeters is compatible with the tracks then create a charged hadron for each track. If the energy is greater than the tracks create photons or neutral hadrons equal to the missing calorimeter energy.



Particle Flow

The particle flow algorithm attempts to reconstruct all stable final state particles using all of the CMS sub-detectors.

- 1. Get tracks linked to a single ECAL cluster if electron ID says OK create an electron.
- 2. If not then if there are compatible hits in muon chambers create a muon if not create a charged hadron.
- 3. For each HCAL cluster get all the linked tracks and all ECAL clusters linked to tracks. If the energy in the calorimeters is compatible with the tracks then create a charged hadron for each track. If the energy is greater than the tracks create photons or neutral hadrons equal to the missing calorimeter energy.
- 4. For the remaining ECAL (HCAL) clusters that are not linked to tracks create a photon (neutral hadron).



Outline

Signal MC Samples

M_H GeV	$\sigma\times$ Br($H \to ZZ \to 2l2q$) [pb]
230	0.2278
250	0.2022
275	0.1751
300	0.1563
325	0.1478
350	0.1482
375	0.1360
400	0.1111
425	0.0914
450	0.7311
475	0.6000
500	0.4719
525	0.0380
550	0.0305
575	0.0250
600	0.0201

The signal samples, $H \to ZZ \to 2l2q$ ($\ell = \mathrm{e}, \mu, \tau$), were simulated with POWHEG then using PYTHIA to do the final parton showering and hadronization.

The cross section times branching fraction for each m_H value is listed in pb. Each sample was generated with 300,000 events.

Background Samples

Background

Process	generator	σ [pb]	luminosity [fb^{-1}]
Z+jets (inclusive)	madgraph	3503.71	8.7
Z+1 jet (exclusive)	madgraph	660.6	36.4
Z+2 jet (exclusive)	madgraph	215.1	101.6
Z+3 jet (exclusive)	madgraph	65.79	167.4
Z+4 jet (exclusive)	madgraph	27.59	232.1
$\mathrm{t\bar{t}}$	powheg-pythia6	23.38	461
ZZ	pythia6	17.654	549
WZ	pythia6	22.88	424
WW	pythia6	57.1097	168

Datasets (19.6 fb^{-1})

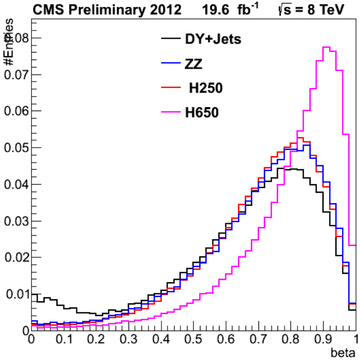
Double Electron and Double Muon datasets from a total of 19.6 fb^{-1} collected data in 2012 at $\sqrt{s}$ = 8 TeV.

Channel	Dataset	Luminosity [pb^{-1}]
$2\mu 2q$	/DoubleMu/Run2012A-13Jul2012-v1/AOD	808
	/DoubleMu/Run2012A-recover-06Aug2012-v1/AOD	82
	/DoubleMu/Run2012B-13Jul2012-v4/AOD	4429
	/DoubleMu/Run2012C-24Aug2012-v1/AOD	495
	/DoubleMu/Run2012C-EcalRecover_11Dec2012-v1/AOD	134
	/DoubleMu/Run2012C-PromptReco-v2/AOD	6394
	/DoubleMu/Run2012D-PromptReco-v1/AOD	7274
$2e2q$	/DoubleElectron/Run2012A-13Jul2012-v1/AOD	808
	/DoubleElectron/Run2012A-recover-06Aug2012-v1/AOD	82
	/DoubleElectron/Run2012B-13Jul2012-v4/AOD	4429
	/DoubleElectron/Run2012C-24Aug2012-v1/AOD	495
	/DoubleElectron/Run2012C-EcalRecover_11Dec2012-v1/AOD	134
	/DoubleElectron/Run2012C-PromptReco-v2/AOD	6394
	/DoubleElectron/Run2012D-PromptReco-v1/AOD	7274

PileUp and Isolation

$$\beta = \frac{\sum p_T \ CJP \ from \ Vertex}{\sum p_T \ all \ CJP}$$

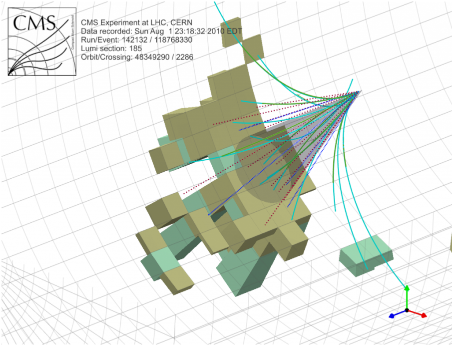
where CJP is charged jet particles.



Jets originating from pile-up interactions are removed by cutting on $\beta > 0.2$.

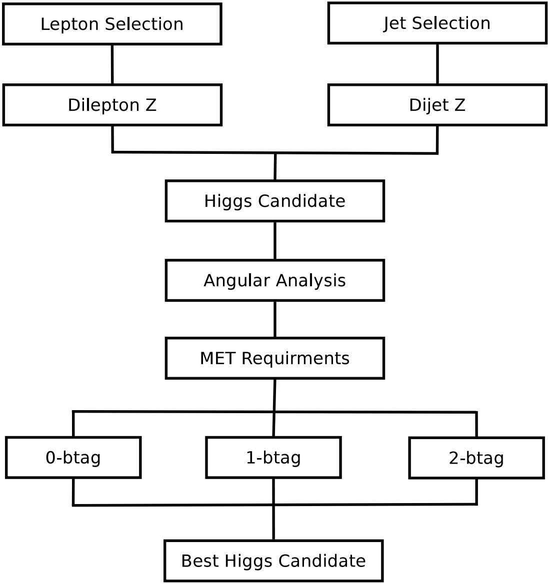
We also require that our objects are isolated by cutting on a cone around the primary vertex with radius:

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.5$$



Source: http://www.quantumdiaries.org/2011/06/01/anatomy-of-a-jet-in-cms/

Analysis workflow



Physics Objects and Preselection

Electrons
Physics Object

- Loose WP GSF Electron

Preselection

- $p_T > 40/20$ GeV
- $|\eta| < 2.5$

Muons
Physics Object

- Tight WP PF Muon

Preselection

- $p_T > 40/20$ GeV
- $|\eta| < 2.4$

Jets
Physics Object

- Anti-k_T 0.5 PF Jets

Preselection

- $p_T > 30$ GeV
- $|\eta| < 2.4$

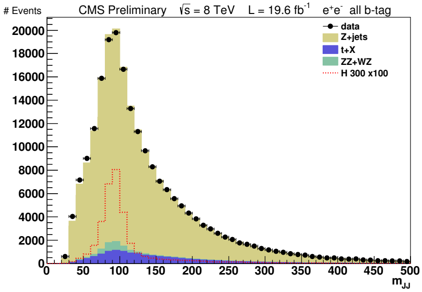
Triggers

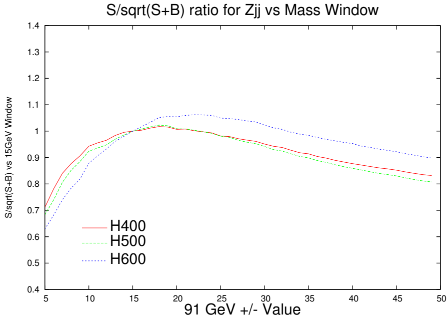
- HLT_Ele17_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL_Ele8_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL
- HLT_Mu17_Mu8

We are using the recomendations from the CMS physics object groups for lepton identification and isolation. These values can be seen in the backup slides.

After we have the objects, we apply additional preselection cuts to the leptons.

Our main background is Z+jets where the Z decays into leptons. For the signal the di-jet mass peak should be at the nominal Z boson mass of 91 GeV. We can cut on either side of this peak to reject a large amount of the Z+jets background. We optimized these cuts to maximize $\frac{S}{\sqrt{S+B}}$.





Signal and Sideband Regions

Optimal cuts around the Z_{ll} mass peak were also calculated. A side band region is defined in the Z_{jj} mass distribution. This side band region is used to get the Z+jets background from data.

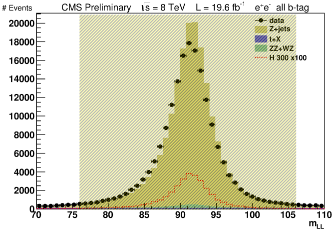
Signal:

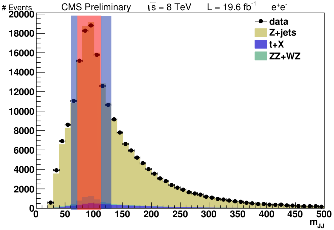
- $76 < m_{ll} < 106$ GeV
- $71 < m_{jj} < 111$ GeV

Sideband:

- $76 < m_{ll} < 106$ GeV
- $60 < m_{jj} < 71$ GeV
  $111 < m_{jj} < 130$ GeV

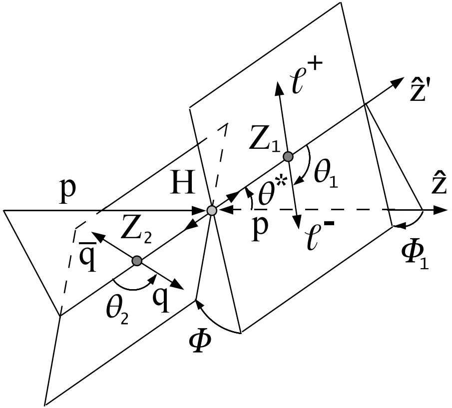
The muon distributions look similar and can be seen in the backup slides.





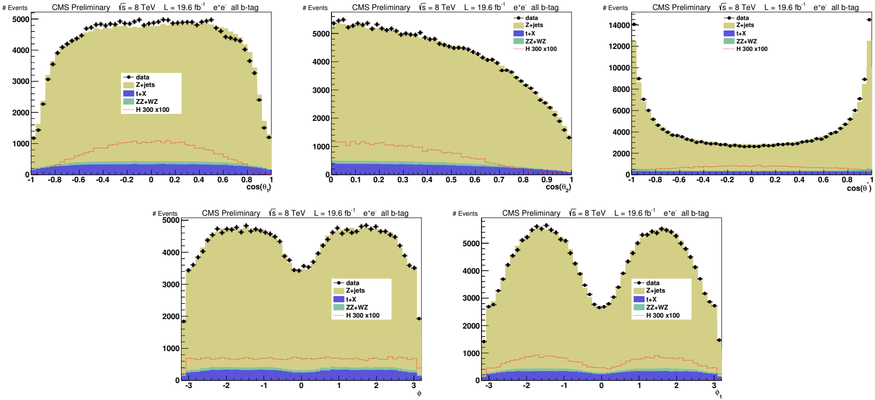
At this point we keep each combination that satisfy the previous criteria as a Higgs candidate. There can be multiple Higgs candidates per event at this stage.

Final state kinematics completely determined by 5 angles.

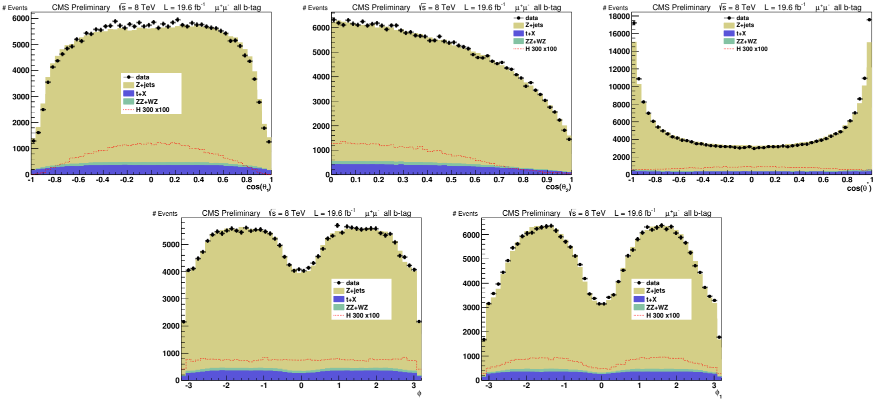


$$cos(\theta^*), cos(\theta_1), cos(\theta_2), \Phi, \Phi_1$$

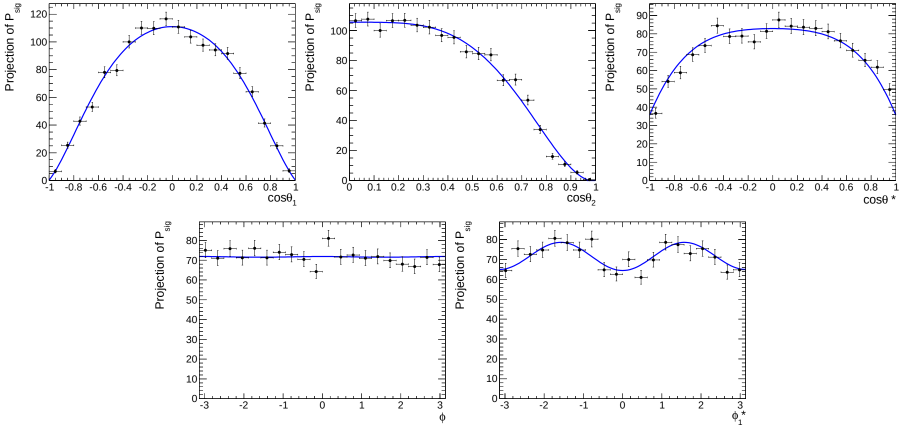
Electron Helicity and Production Angles



Muon Helicity and Production Angles

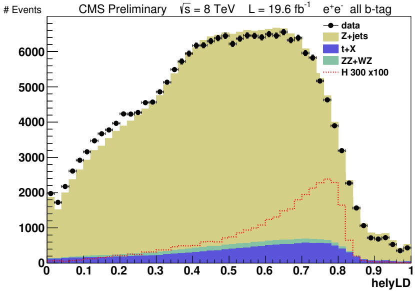


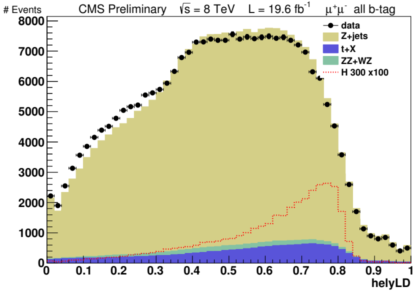
Example fits at for 500 GeV (475 - 550 GeV).



Helicity LD Distribution and Cuts

$$LD = \frac{P_{sig}}{P_{sig} + P_{bkg}}$$



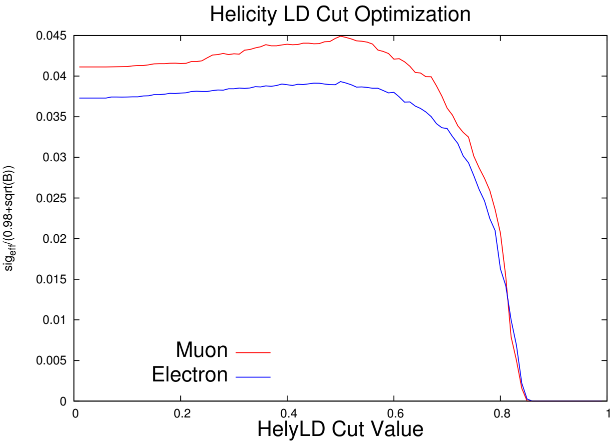


An explanation of the shape discrepancy is given in the backup slides.

HelyLD Optimization

We do an optimization for the cut on the HelyLD maximizing the Punzi equation:

$$\frac{\frac{\#\ signal}{\#\ total\ signal}}{0.98+\sqrt{B}}$$

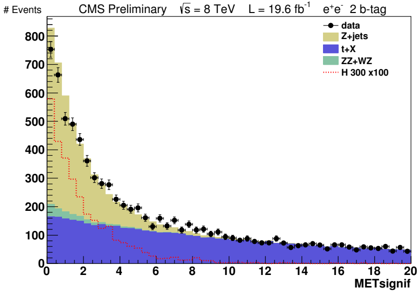


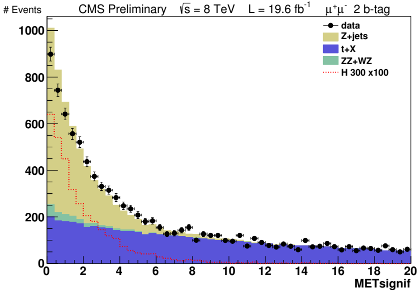
We cut on 0.5 which is within 5% of the optimal value for all Higgs mass values, b-tag regions, and lepton types.

Our signal should not have any Missing Transverse Energy (E_T^{miss}, MET) from neutrinos. MET significance is a measure of how likely the MET we see is real(not from detector effects).

$$MET\ Significance = 2ln\lambda(MET) = 2ln\frac{L(MET_{true} = MET_{measured})}{L(MET_{true} = 0)}$$

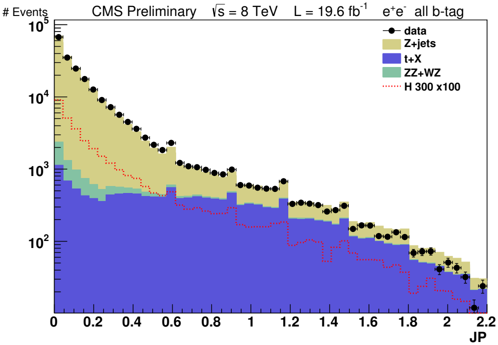
This is particularly useful to suppress the $t\bar{t}$ background in the 2-tag region (b-tagging on next slide), but we apply a cut on MET significance > 10 to all categories.





b-tagging

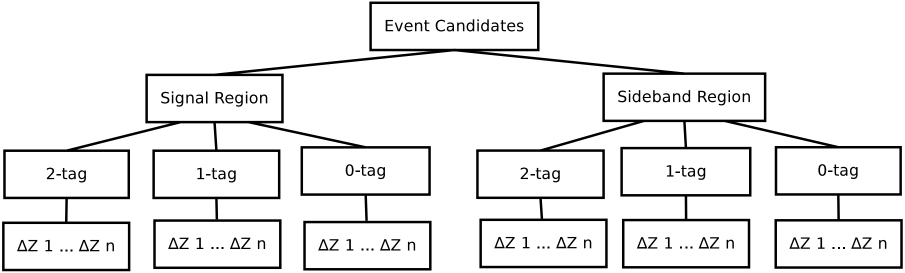
- Using **JP algorithm**
- We are looking for heavy quarks (b,c)
- There are “loose”(0.275) and “medium”(0.545) working points that are defined by the b-tag group that we use to classify our events.



0 - tag	Both Jets < Loose
1 - tag	> Loose and < Medium
2 - tag	> Loose and > Medium

Best Higgs Candidate

When there are multiple candidates in the same event we apply a string of logic to select which is the candidate that we are going to keep.



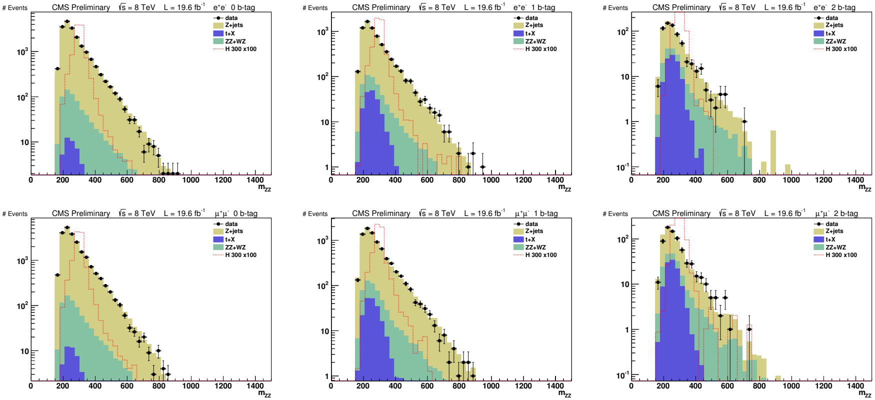
$$\Delta Z = |M_{\ell^+\ell^-} - m_Z| + |M_{JJ} - m_Z|$$

m_Z is the nominal mass of the Z boson

$\Delta Z1..Zn$ is the candidates sorted by ΔZ smallest to largest.

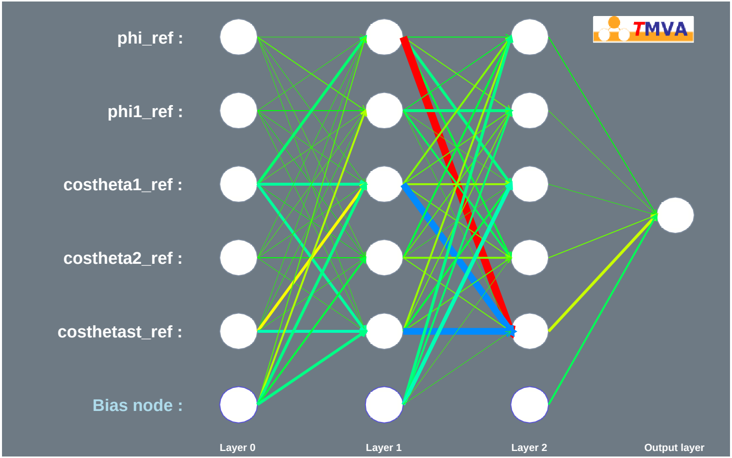
When all candidates are sorted we keep the candidate that is furthest to the left.

Final Region m_{ZZ} Plots



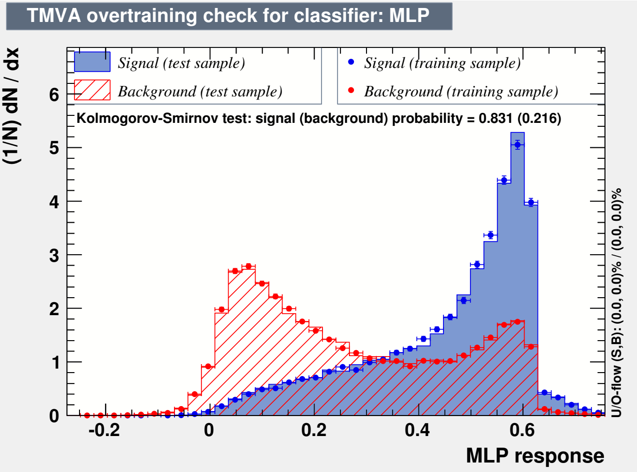
Outline

Neural Network with TMVA Package

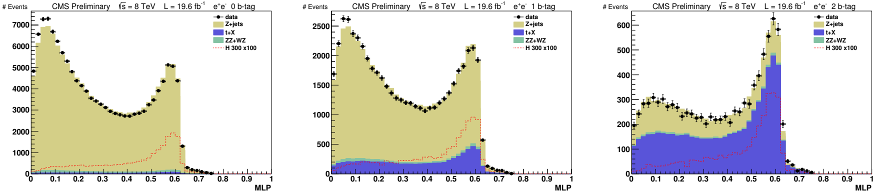


Neural Network Training and Testing

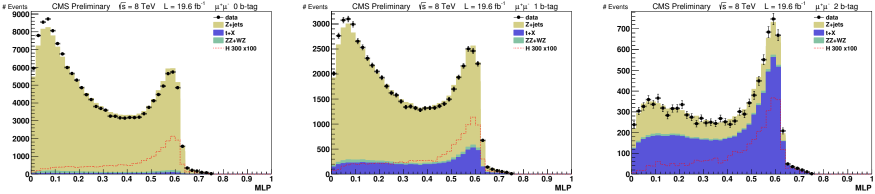
The trainings are done after preselection and additionally require at least one B-tagged Medium jet. (Trained on H 400 GeV)



Electrons (zero,one,two)

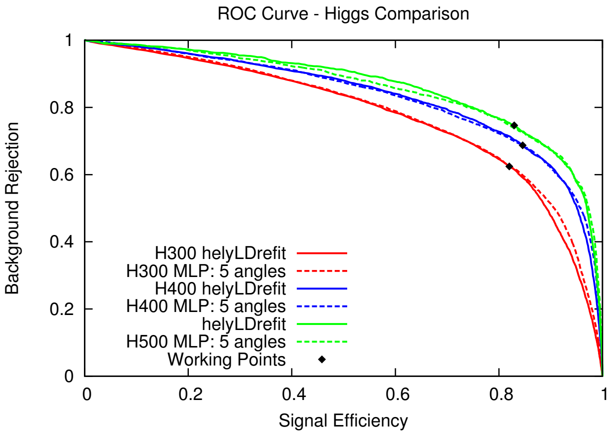


Muons (zero,one,two)



MLP vs Helicity LD

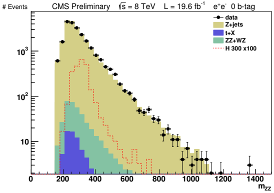
The working point is the background rejection point that we currently achieve in the two tag region in our analysis.



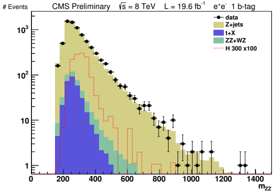
m_{ZZ} plots - Side Band Region

Electrons

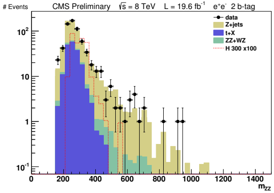
0-tag



1-tag

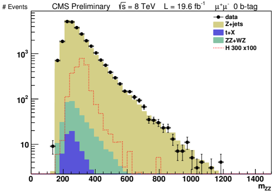


2-tag

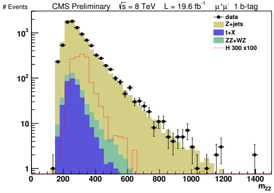


Muons

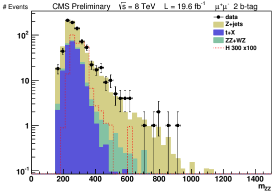
0-tag



1-tag

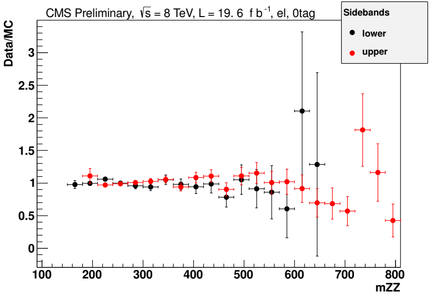


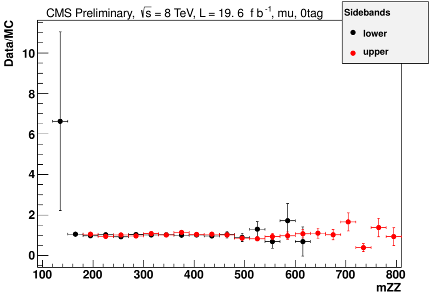
2-tag



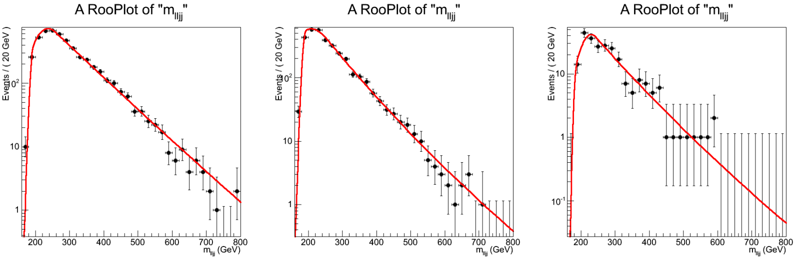
Upper vs Lower Sideband

We also have very similar performance between the upper and lower sidebands in the m_{ZZ} distribution so we are able to use them together.





- We use the mjj sideband in data to get the normalization and a MC shape correction.
- The fit is to a Fermi*CrystallBall function

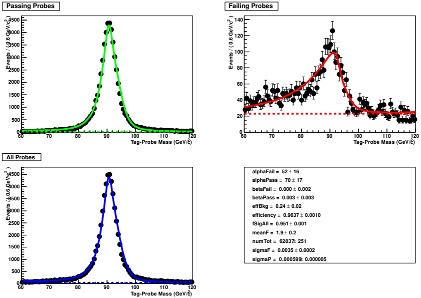


0-tag 1-tag 2-tag

Tag and Probe

- Method to use Z boson to calculate efficincy of Data and Monte Carlo.
- One lepton is “good” (tag) and the other is used for the calculations(probe).
- Compairing Monte Carlo to data gives us Scale Factors.

SuperCluster to GSF Electron



Signal Systematics

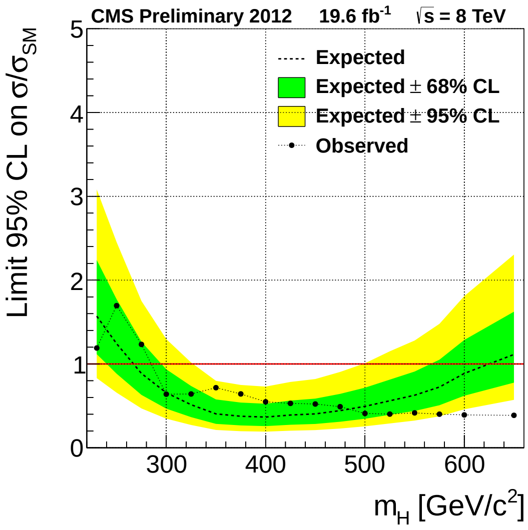
Source	0 *b*-tag	1 *b*-tag	2 *b*-tag
Muon trigger & ID		2.7%	
Electron trigger & ID		2%	
Electron energy scale		0.2%	
Muon momentum scale		0.1%	
Jet reconstruction		1-4%	
b-tagging eff. and mistag rate	1-4%	1-5%	5-8%
MET		$<1\%$	
Pile-up		1-2%	
Production mechanism (PDF)		1.5%	
Production mechanism (lineshape)		0-3%	
Luminosity		4.4%	
Higgs cross-section		13-15%	

Background Systematics

	Normalization			Shape		
Source	0 *b*-tag	1 *b*-tag	2 *b*-tag	0 *b*-tag	1 *b*-tag	2 *b*-tag
Muon trigger & ID		2.7%				
Muon momentum scale		0.1%				
Electron trigger & ID		2.0%				
Electron energy scale		0.5%				
Jet energy scale		5.5%			0-4%	
b-tagging efficiency SF	+0.4%	-0.8%	-4.5%			
Mistag SF	-1.9%	+7.8%	+6.2%			
MET		0.3%				
Pile-up		0.1%				
$p_{\mathrm{T}}^{\ell\ell jj}$ weighting		0.8%			0-3%	
Diboson cross section		15%				
Luminosity		4.4%				
Control Region				0-15%	0-30%	0-40%

Outline

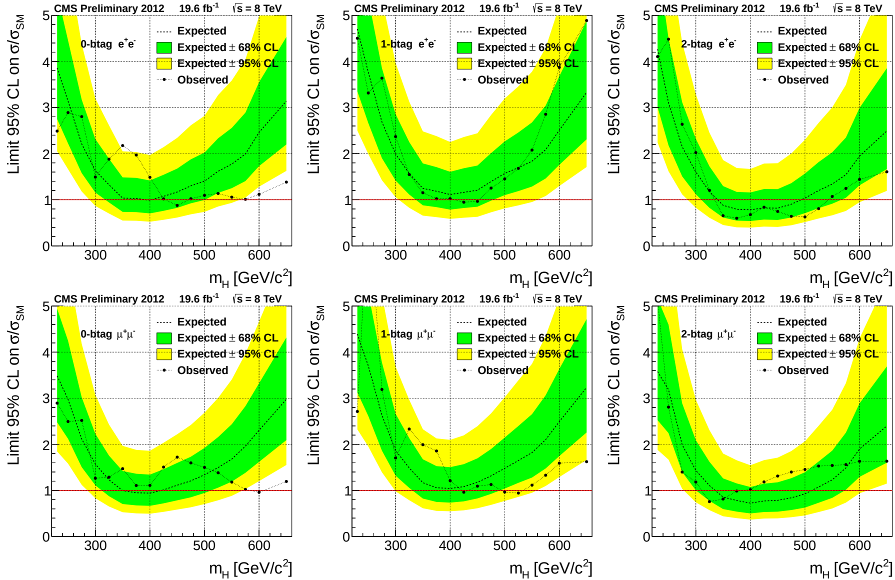
8 TeV Results

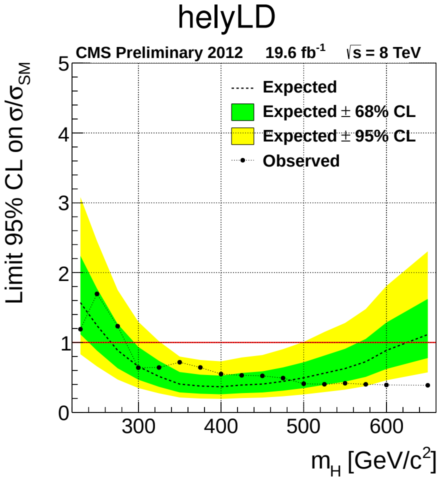


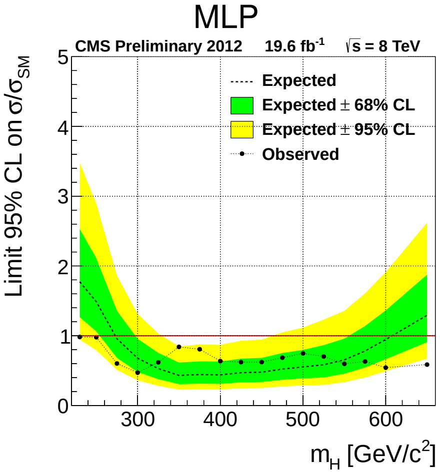
Observed (solid) and expected (dashed) 95% CL upper limit on the ratio of the production cross section to the SM expectation for the Higgs boson obtained using the $\mathrm{CL_s}$ technique.

The 68% and 95% ranges of expectation for the background-only model are also shown with green and yellow bands, respectively. The solid line at 1 indicates the expectation for a SM-Higgs-like boson.

8 TeV Individual Channel Results

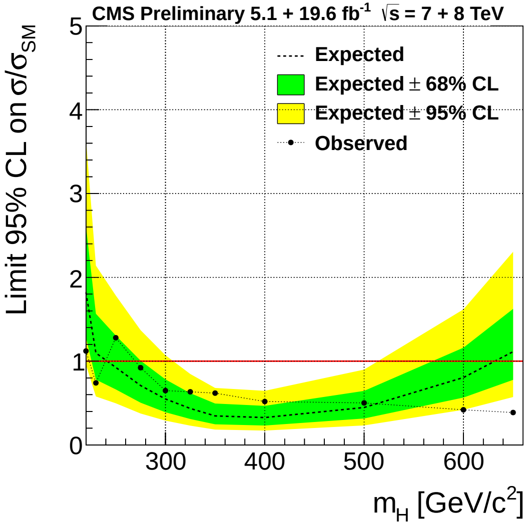






The helyLD and MLP discriminators give very similar results, with the helyLD doing about 5% better overall.

7 TeV and 8 TeV HelyLD Combined Results



The 7 TeV 2l2q group results are in the backup slides.

Outline

Summary

- No evidence of a Higgs boson signal is found.
- At $95\%_{CL}$ a Standard Model Higgs boson is excluded in the range of 285 GeV to 650 GeV.
- Similar Results are obtained using both the HelyLD and the MLP classifier using the kinematic information of the events.

Future Channel Plans

- Extend analysis to 1 TeV.
- Search for narrow width resonance Higgs.
- Extend analysis to search for the Graviton.

Thank You

BACKUP

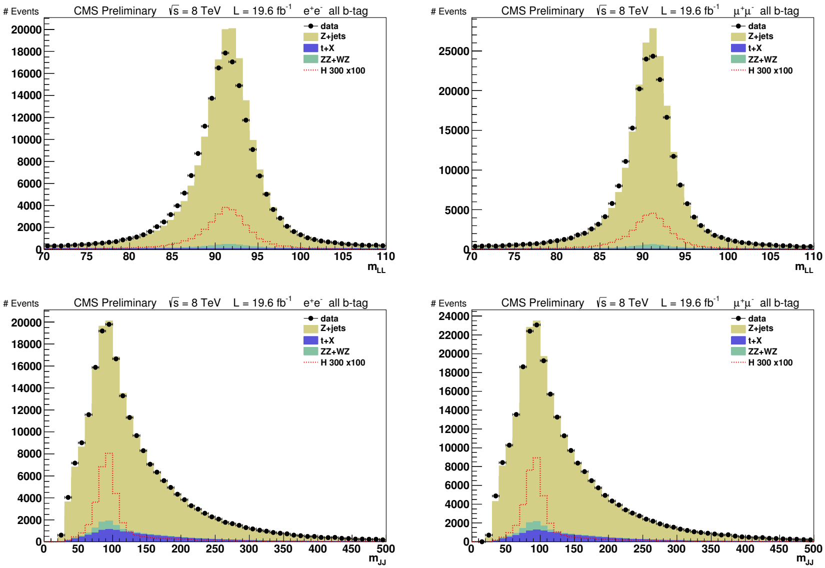
Electron requirements for the Loose working point

Variable	Barrel cut	Endcap cut
$\Delta\eta_{trk,supercluster}$	< 0.007	< 0.009
$\Delta\phi_{trk,supercluster}$	< 0.15	< 0.1
$\sigma_{i\eta,i\eta}$	< 0.01	< 0.03
H/E	< 0.12	< 0.10
d_0 (wrt primary vertex)	< 0.2 mm	< 0.2 mm
d_z (wrt primary vertex)	< 2 mm	< 2 mm
$\lvert 1/E - 1/p \rvert$	< 0.05	< 0.05
$I_{PF,\ corr}/p_T$	< 0.15	< 0.15
Missing hits	≤ 1	≤ 1
Conversion vertex fit prob.	$< 10^{-6}$	$< 10^{-6}$

Muon requirements for the Tight working point

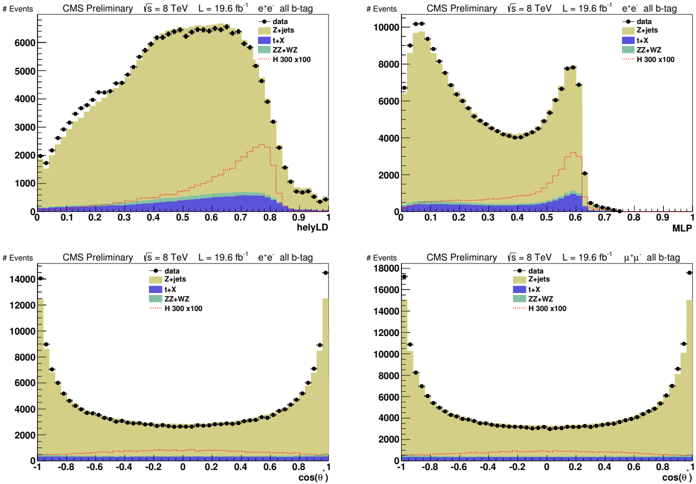
Variable	Cut
isGlobalMuon	True
isPFMuon	True
$\chi^2/ndof$ (global fit)	< 10
Muon chamber hits in global fit	> 0
Muon stations with muon segments	> 1
d_{xy} (from tracker, wrt primary vertex)	< 2 mm
d_z (from tracker, wrt primary vertex)	< 5 mm
Valid pixel hits (tracker track)	> 0
Tracker layers with hits	> 5
$I_{PF,\ corr}/p_T$	< 0.12

m_{ll} and m_{jj} distributions



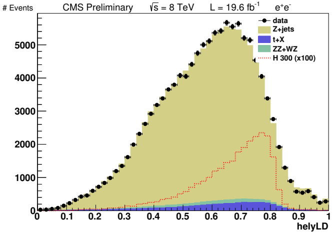
MLP and HelyLD Data/MC Discrepancy

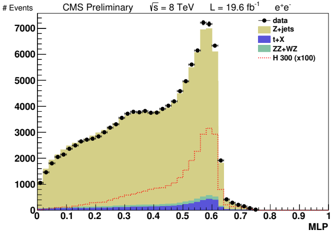
Both the HelyLD and the MLP don't agree in the background like regions between data and MC. This is because $cos(\theta^*)$ is not well modeled in MC.

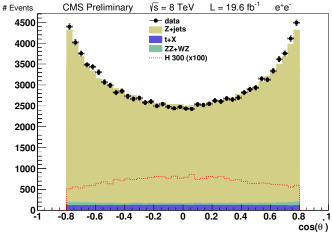


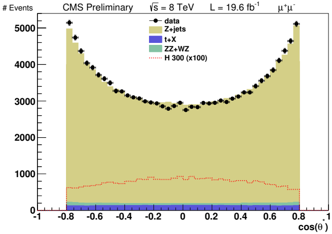
Solution

This is a MC issue that can be fixed by cutting on $|cos(\theta^*)| > 0.8$ or by refitting MC to data.



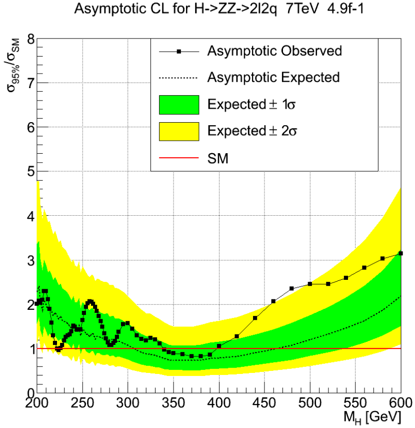






2011 Results

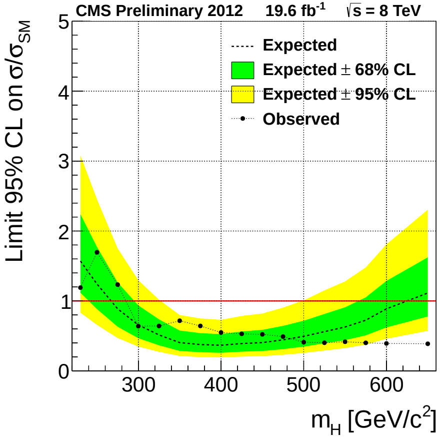
Limit on the expected 95% CL upper limit on the product of the Higgs boson production cross section and the branching fraction of H→ZZ (black dots.), for the recorded luminosity in 2011 of 4.9 fb^{-1} at 7TeV. Yellow and Green bands represent the 68% and 95% ranges of expectation.



CMS Collaboration, Search for a Higgs boson in the decay channel $H \to ZZ \to \ell^+\ell^-$ ~~qq~~, JHEP 04 (2012) 036, doi:10.1007/JHEP04(2012)036, arXiv:1202.1416.

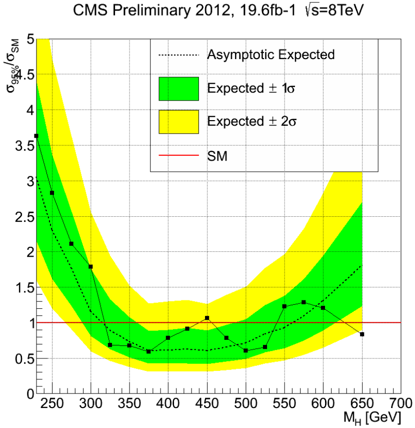
Shape vs Cut and Count

Shape



Cut and Count

-6% m_H +10%



The shape analysis does about 15% better than the cut and count, but both give very similar results.