A search for the Higgs boson in $H \rightarrow ZZ^{(*)} \rightarrow 4l$ mode

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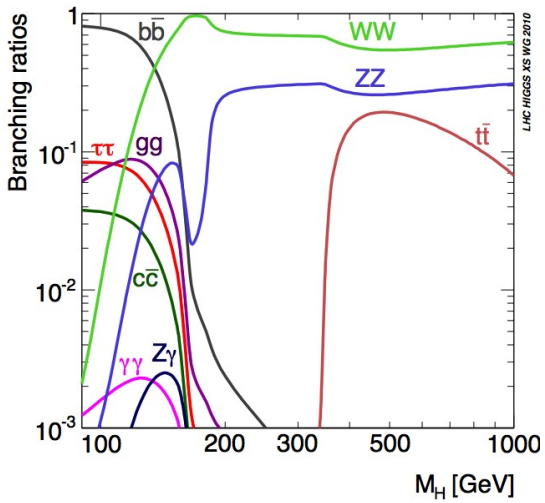
Introduction

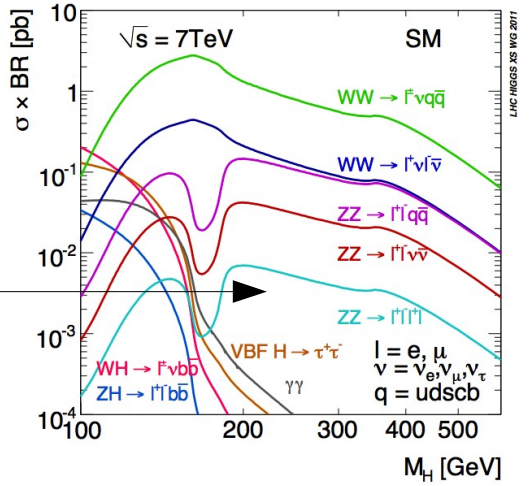
$H \rightarrow ZZ(*) \rightarrow 4l$ is a key decay mode for Higgs searches:

- Clean experimental signature: four, isolated, prompt leptons
- A narrow peak in the invariant mass distribution



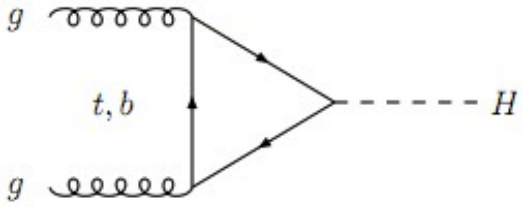
It also has its own challenges:

- Pure leptonic final state penalized by low branching ratio
- Leptons reach low p_T region



Backgrounds

Our signal:



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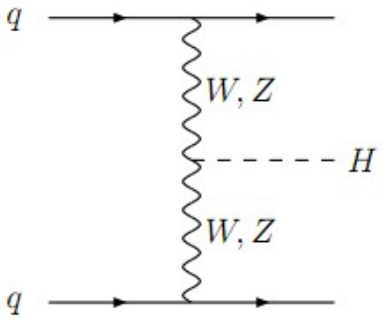


(+ associated production)

Irreducible background:

$pp \rightarrow ZZ$

Reducible backgrounds:

$Zb\bar{b}$

$t\bar{t}$

WZ

This search is performed in the mass range: 110 – 600 GeV/c^2

Selection criteria

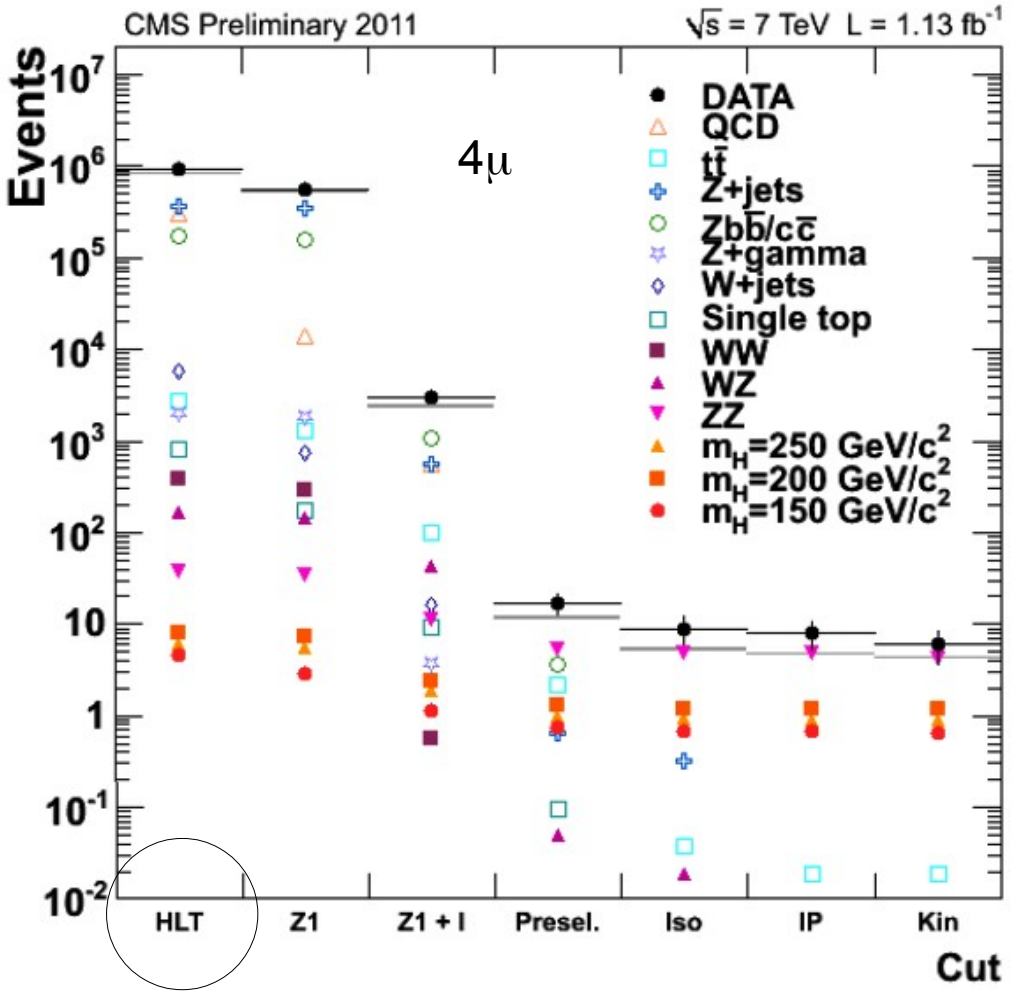
At trigger level we require:

- Two electrons with
  - $E_{T,1}$ > 17 GeV
  - $E_{T,2}$ > 8 GeV

OR

- Two muons with
  - $p_{T,1}$ > 13 GeV/c
  - $p_{T,2}$ > 8 GeV

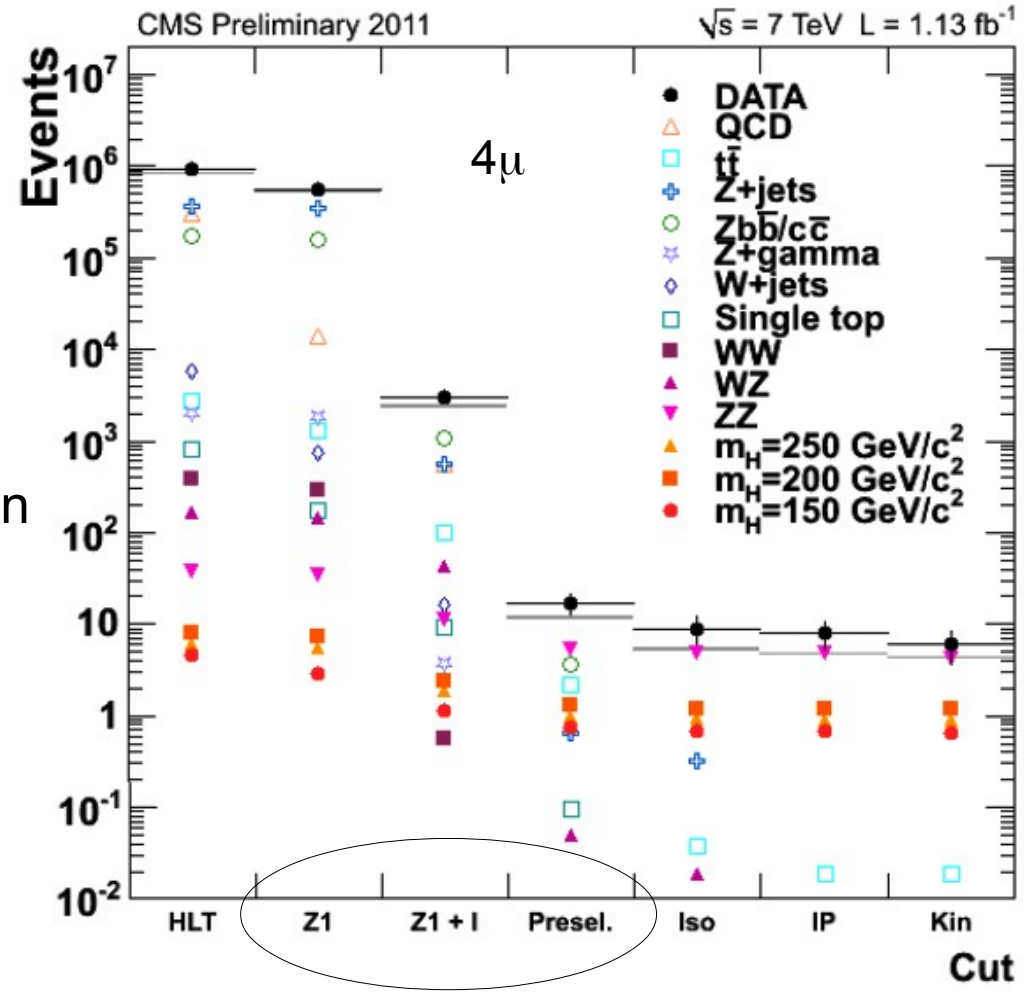
These requirements are 100% efficient wrt signal



Selection criteria

We require:

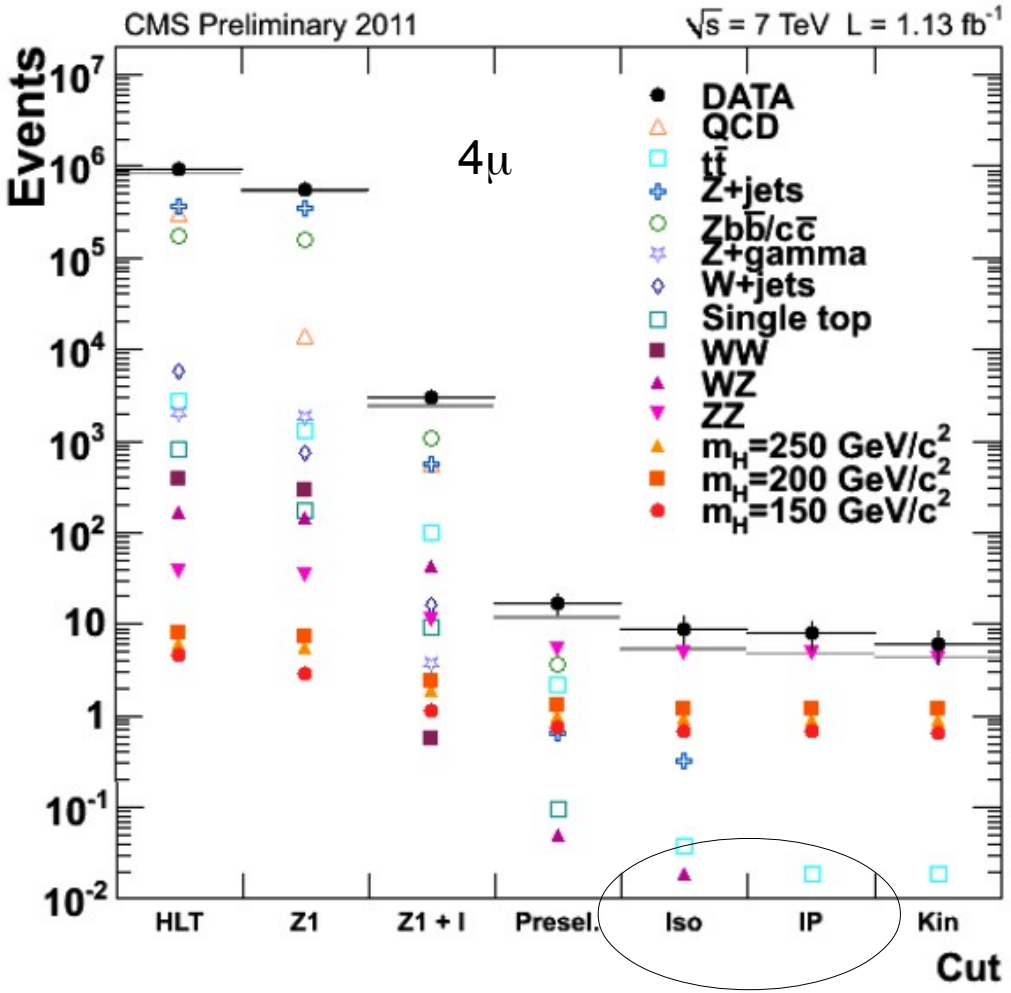
- A pair of leptons (Z_1) with $m_{ll} > 60$ GeV/c^2
  - $p_{T,l1} > 20$ GeV/c
  - $p_{T,l2} > 10$ GeV/c
  - Candidate with mass closest to Z chosen
- A second lepton pair (Z_2) such that
  - $m_{ll} > 12$ GeV/c^2
  - $m_{4l} > 100$ GeV/c^2
- Choose the second Z with leptons with highest p_T



Selection criteria

To remove the reducible background we cut on:

- Isolation of the leptons
- Significance of the impact parameter to the event vertex



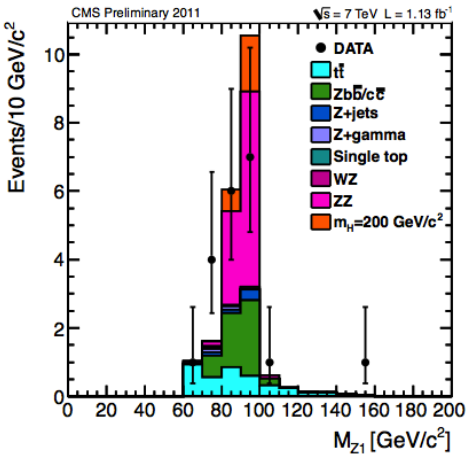
$ZZ^{(*)}$ kinematic regions

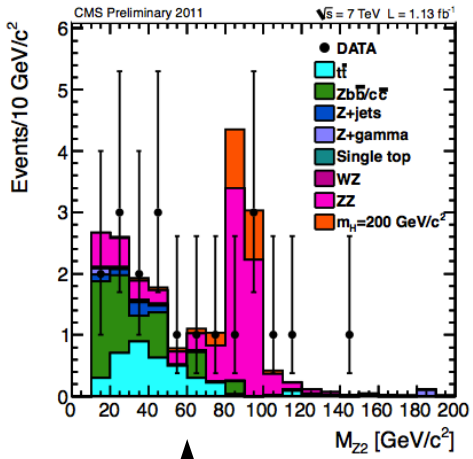
Identify two selections for $ZZ^{(*)}$:

- Baseline selection: $20 < m_{Z2} < 120$ GeV/c^2

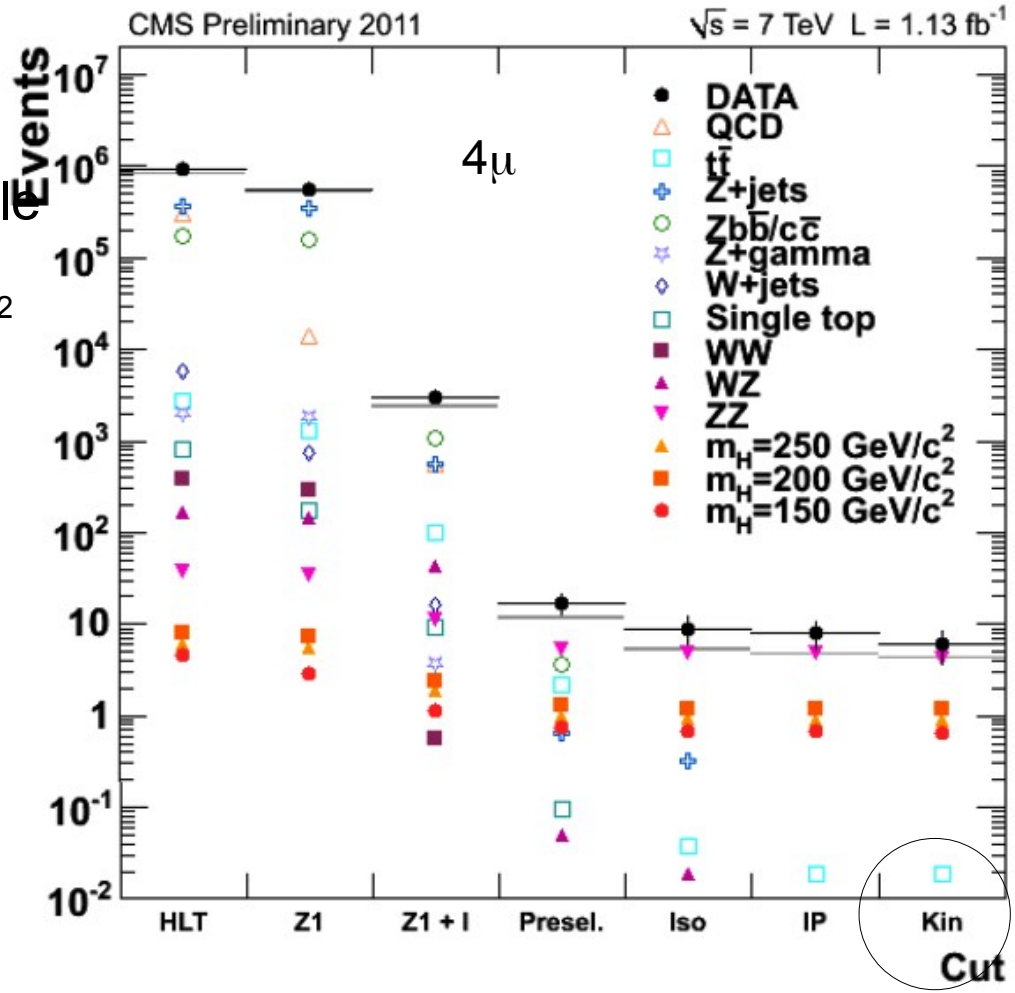
  Used for the Higgs search along the whole mass spectrum
- High mass selection: $60 < m_{Z2} < 120$ GeV/c^2

  Used for the Higgs search at high mass and for ZZ cross section measurement





High mass selection



$ZZ^{(*)}$ normalization from data

We normalize the invariant mass shape of ZZ using data:

- Conside an inclusive $Z \rightarrow ll$ sample
- Calculate the ratio

$$R^{\sigma}_{\text{theory}} \times R^{\epsilon}_{\text{MC}} = \frac{\sigma^{q\bar{q}\rightarrow ZZ\rightarrow 4\ell}_{\text{NLO}} + \sigma^{gg\rightarrow ZZ\rightarrow 4\ell}_{\text{LO}}}{\sigma^{pp\rightarrow Z\rightarrow 2\ell}_{\text{NNLO}}} \times \frac{\epsilon^{ZZ\rightarrow 4\ell}_{\text{MC}}}{\epsilon^{Z\rightarrow 2\ell}_{\text{MC}}}$$

where:

- ZZ production cross section at NLO is calculated using MCFM
- The Z cross section at NNLO is calculated using FEWZ 2.0

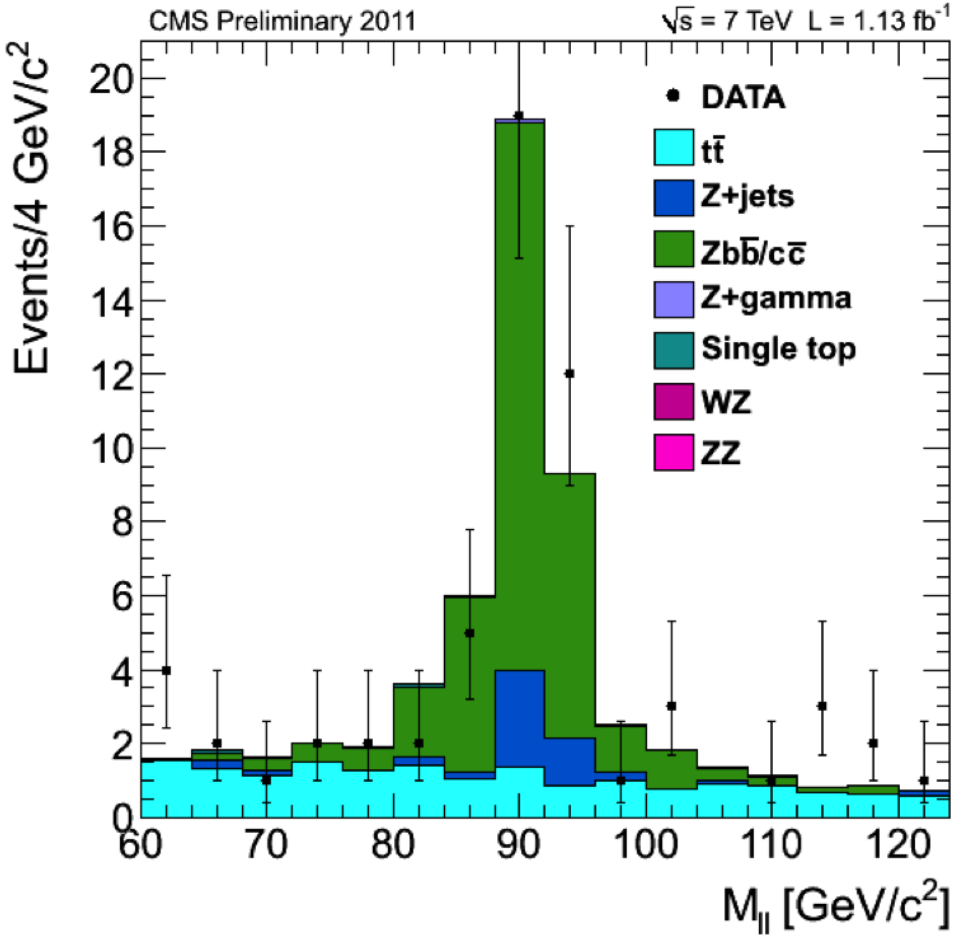
- We apply this normalization to the MC sample of ZZ

	channel	Normalization to Z rate	MC model simulation
baseline	$N^{ZZ\rightarrow 4e}$	2.76 ± 0.18	2.77 ± 0.26
	$N^{ZZ\rightarrow 4\mu}$	4.10 ± 0.27	4.24 ± 0.39
	$N^{ZZ\rightarrow 2e2\mu}$	6.72 ± 0.45	6.85 ± 0.63
high-mass	$N^{ZZ\rightarrow 4e}$	2.50 ± 0.17	2.52 ± 0.23
	$N^{ZZ\rightarrow 4\mu}$	3.55 ± 0.23	3.66 ± 0.33
	$N^{ZZ\rightarrow 2e2\mu}$	6.10 ± 0.40	6.22 ± 0.58

Reducible background

Estimate of $Zb\bar{b}$ and $t\bar{t}$ shapes:

- Relax isolation cut
- Invert the cut on significance of the impact parameter



In order to determine the number of $Zb\bar{b}$ and $t\bar{t}$ events in the signal region, we estrapolate the normalization in the background region using the impact parameter distribution for the leptons

	baseline	high-mass
$N^{Zb\bar{b}/c\bar{c},t\bar{t}\to 4e}$	0.01 ± 0.02	-
$N^{Zb\bar{b}/c\bar{c},t\bar{t}\to 4\mu}$	0.01 ± 0.01	-
$N^{Zb\bar{b}/c\bar{c},t\bar{t}\to 2e2\mu}$	0.02 ± 0.02	-
$N^{Z+\text{jets}\to 4e}$	0.37 ± 0.07	0.14 ± 0.06
$N^{Z+\text{jets}\to 4\mu}$	0.06 ± 0.01	0.004 ± 0.004
$N^{Z+\text{jets}\to 2e2\mu}$	0.39 ± 0.07	0.15 ± 0.06

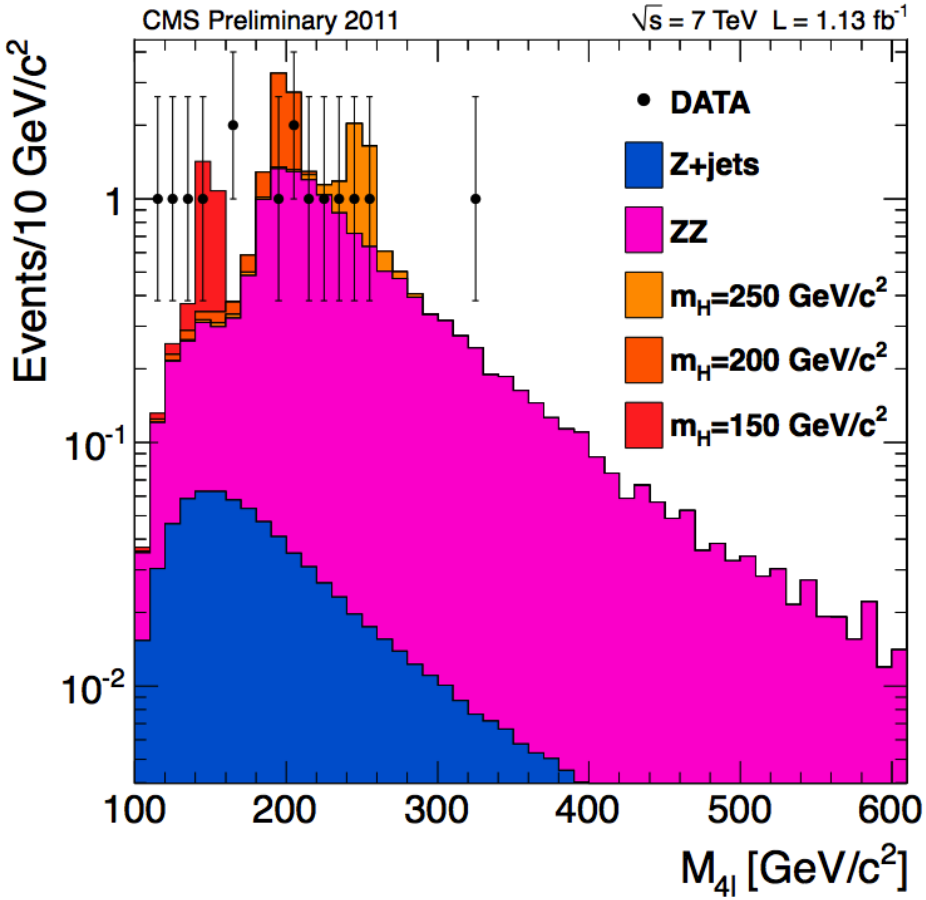
Invariant mass distribution

Baseline selection

$60 < m_{Z1} < 120$ GeV/c^2

$20 < m_{Z2} < 120$ GeV/c^2

	baseline		
	$4e$	4μ	$2e2\mu$
ZZ	2.76 ± 0.18	4.10 ± 0.27	6.72 ± 0.45
Z+jet	0.37 ± 0.07	0.06 ± 0.01	0.39 ± 0.07
$Zb\bar{b}/c\bar{c}, t\bar{t}$	0.01 ± 0.02	0.01 ± 0.01	0.02 ± 0.02
WZ	0.006 ± 0.006	0.006 ± 0.006	0.024 ± 0.012
All background	3.13 ± 0.19	4.17 ± 0.27	7.14 ± 0.46
$m_H = 150$ GeV/c^2	0.368 ± 0.007	0.637 ± 0.009	0.996 ± 0.011
$m_H = 200$ GeV/c^2	0.816 ± 0.011	1.161 ± 0.014	1.907 ± 0.018
$m_H = 250$ GeV/c^2	0.656 ± 0.009	0.885 ± 0.010	1.533 ± 0.013
Observed	3	6	6



Invariant mass distribution

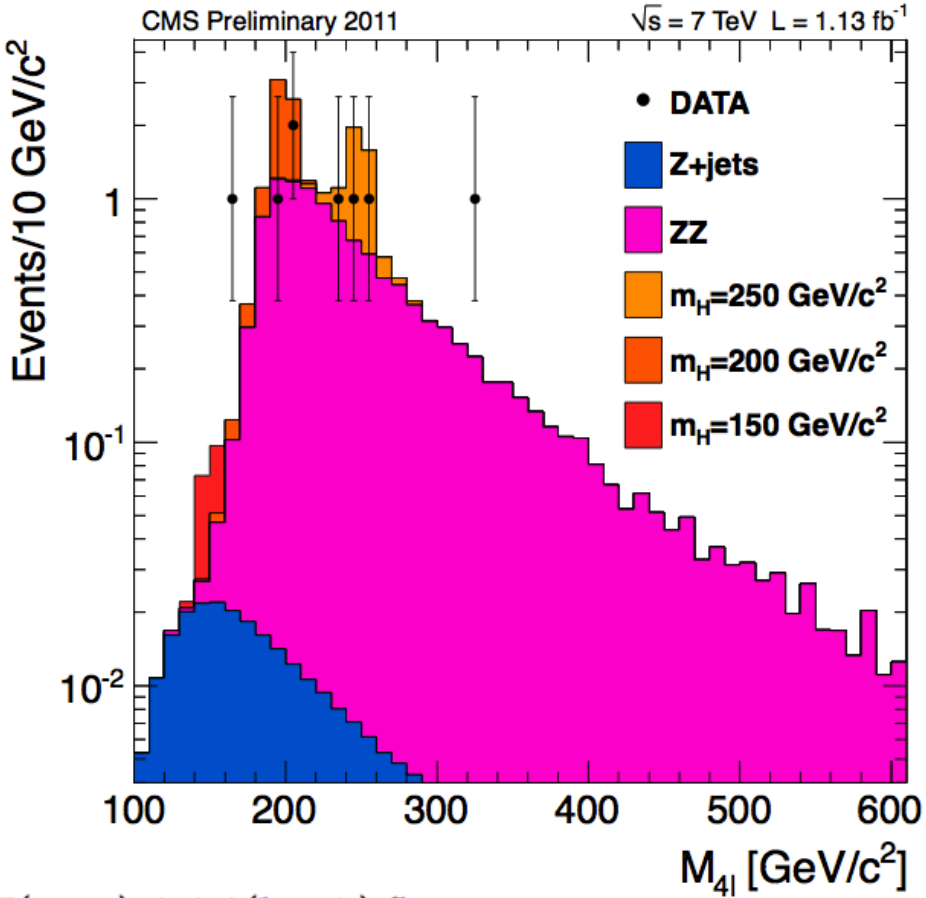
High mass selection

$60 < m_{Z1} < 120$ GeV/c^2

$60 < m_{Z2} < 120$ GeV/c^2

Same selection as ZZ cross section measurement

	high-mass		
	$4e$	4μ	$2e2\mu$
ZZ	2.50 ± 0.17	3.55 ± 0.23	6.10 ± 0.40
Z+jet	0.14 ± 0.06	0.004 ± 0.004	0.15 ± 0.06
$Zb\bar{b}/c\bar{c}, t\bar{t}$	-	-	-
WZ	-	-	0.006 ± 0.006
All background	2.64 ± 0.18	3.55 ± 0.23	6.25 ± 0.40
$m_H = 150$ GeV/c^2	0.018 ± 0.002	0.030 ± 0.002	0.045 ± 0.002
$m_H = 200$ GeV/c^2	0.765 ± 0.011	1.080 ± 0.013	1.801 ± 0.017
$m_H = 250$ GeV/c^2	0.621 ± 0.009	0.833 ± 0.010	1.442 ± 0.013
Observed	0	2	6



ZZ cross section measurement:

$$\sigma(pp \to ZZ + X) \times \mathcal{B}(ZZ \to 4\ell) = 17.5^{+6.3}_{-4.4}(\text{stat.}) \pm 0.7(\text{syst.}) \pm 1.1(\text{lumi.})\ \text{fb}$$

in agreement with SM predictions

Systematic uncertainties evaluation

We considered systematic variations arising from:

- Trigger efficiency
- Lepton reconstruction and identification
- Lepton isolation
- Energy/momentum calibation
- Limited statistics in background control regions
- Luminosity
- Higgs boson cross sections and branching ratios

	%
Luminosity	6
Trigger efficiency	1.5
Higgs cross section	17-20
Higgs B.R.	2
Lepton reco/ID eff.	2-3
Lepton isolation eff.	2
Electron energy scale	3

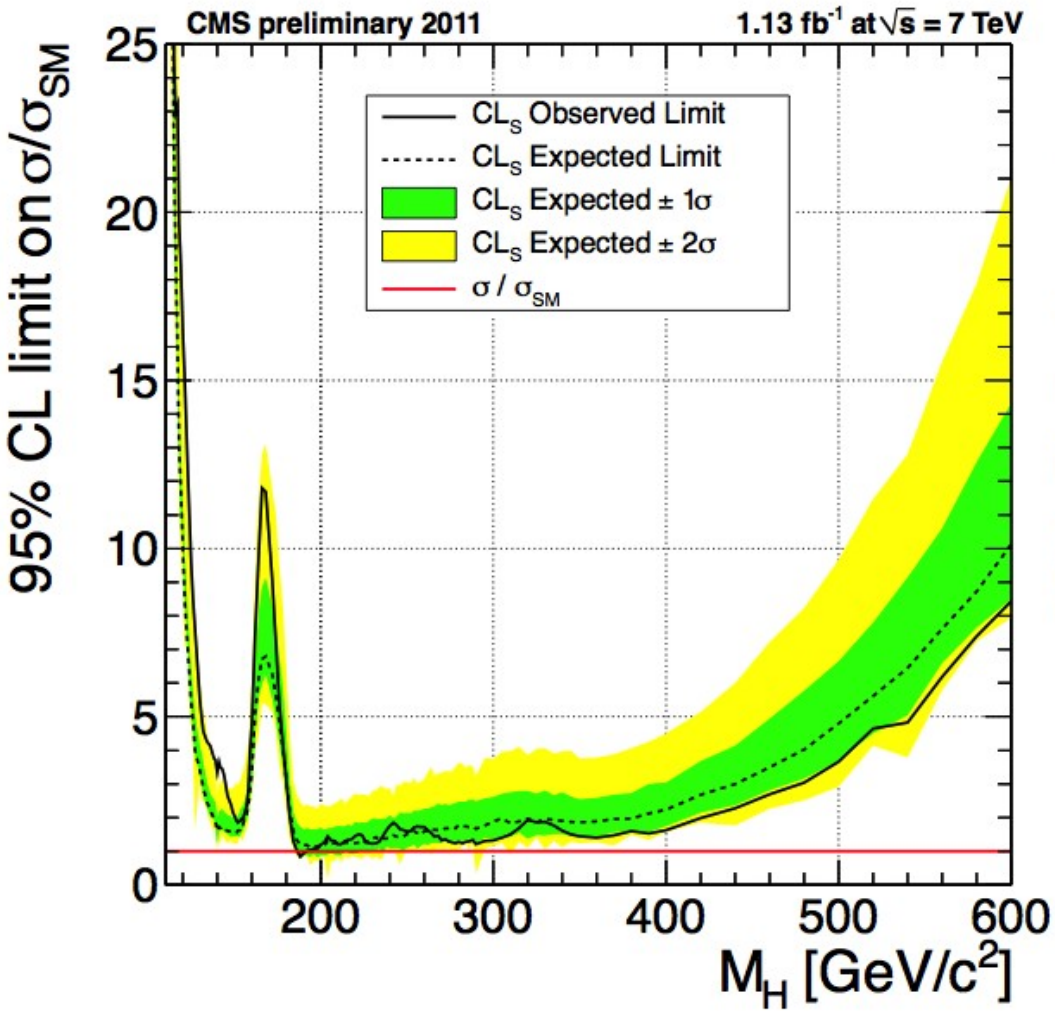
Upper limit measurement

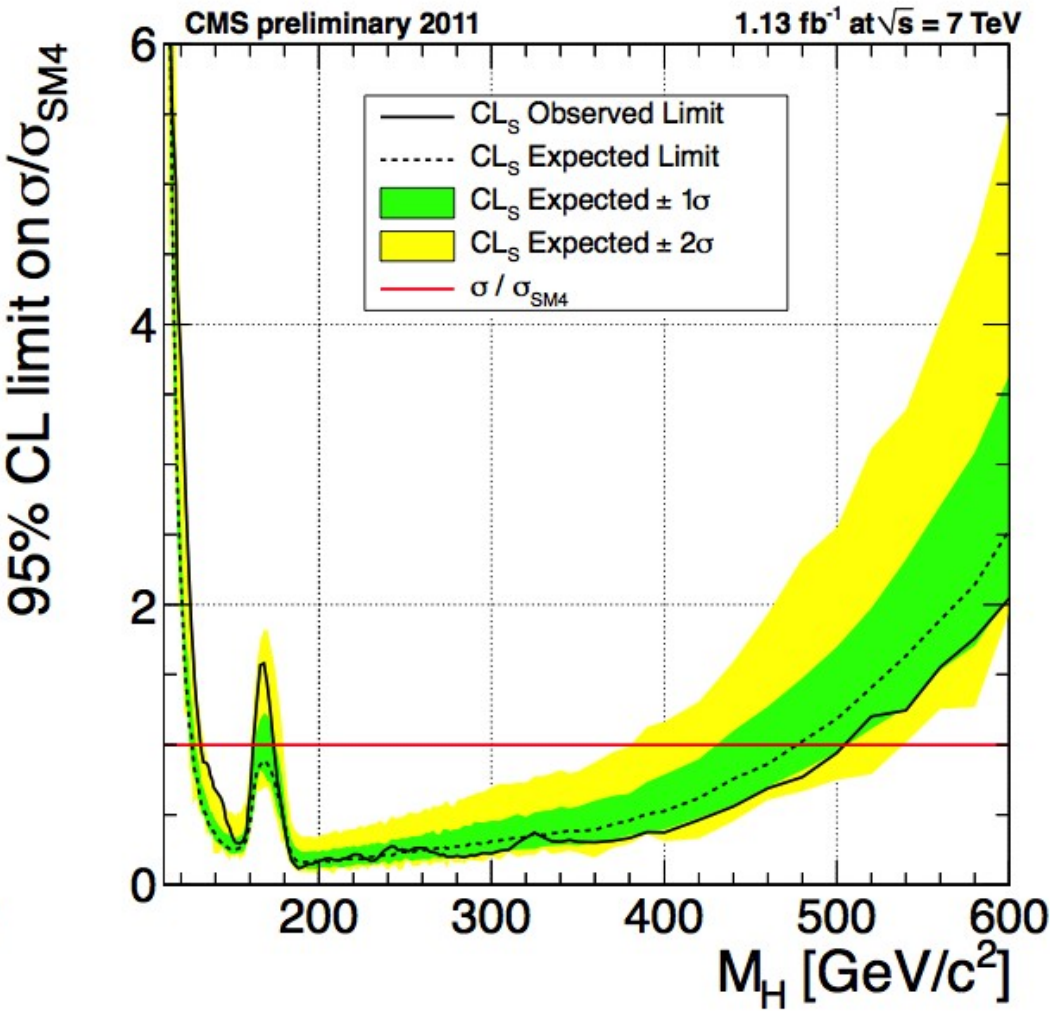
Shape based approach:

- Signal parametrized with a BW convoluted with a Crystall Ball function
- Signal parameters determined from MC generated in 17 mass points, and extrapolated to the rest of the spectrum
- ZZ background parametrized with an empirical density function. $Zb\bar{b}$, $t\bar{t}$, Zjets using distribution from data
- Cross-checked with a cut&count approach

Upper limit to H → ZZ → 4l

Baseline selection





Higgs with 4th fermion generation exluded at 95% CL in ranges 138-162 and 178-502 GeV/c^2

Conclusions

- We peformed the first search for the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay at CMS
- Both irreducible (ZZ) and reducible backgrounds ($Zb\bar{b}$,$t\bar{t}$,Zjets) have been accounted for with data-driven techniques
- We found 15 events in the three leptonic channels, compatible with an expectation of 14.4 ± 0.6 events from SM backgrounds
- In the low mass region ($<2m_Z$) we found 6 events with an expectation of 1.9 ± 0.1 events
- No clustering of events in a given mass region is observed
- In a scenario with a 4^{th} fermion family, the Higgs boson is excluded in the mass ranges 138-162 and 178-500 GeV/c^2 at 95% CL

Backup

The CMS experiment

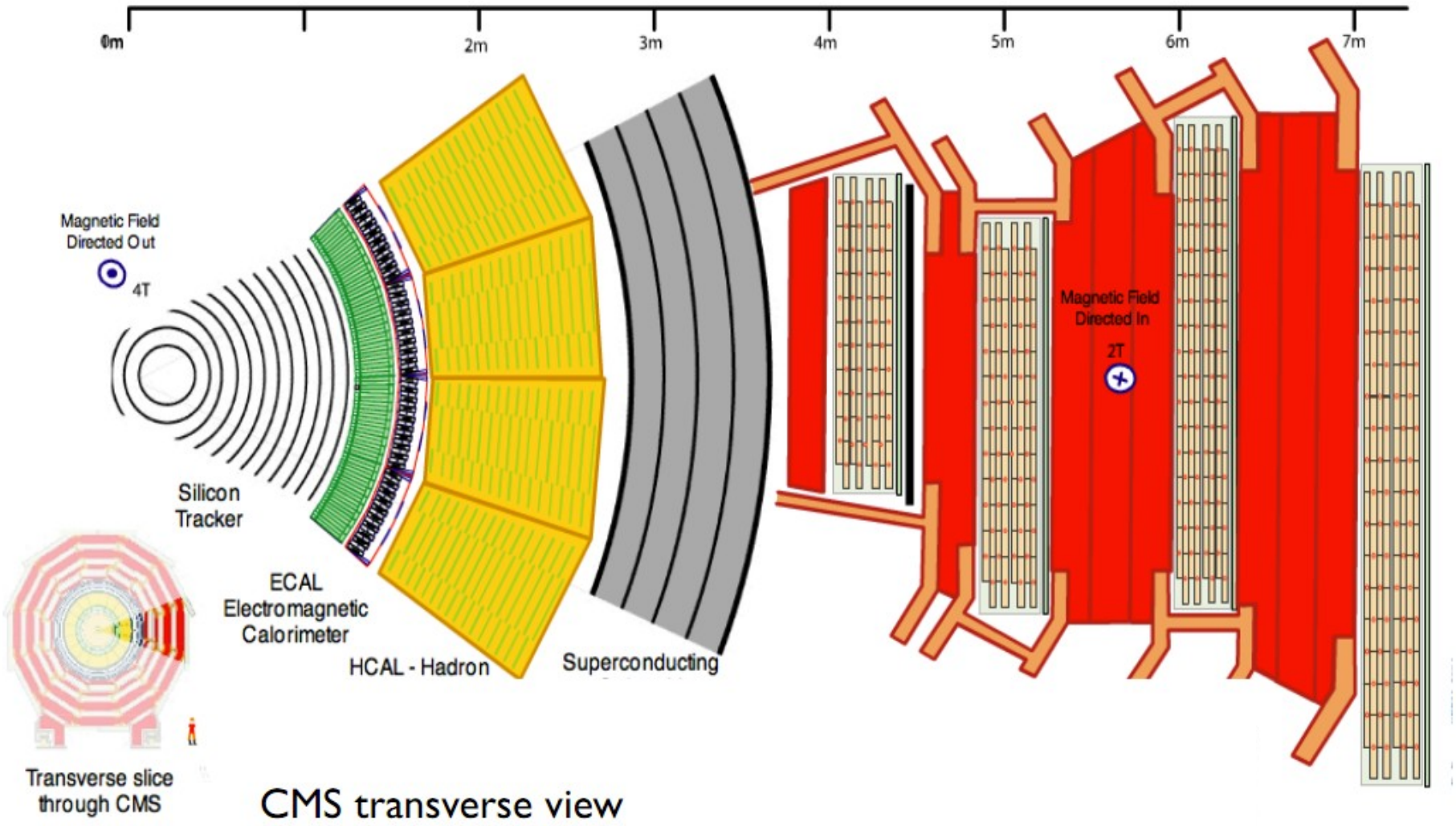


Table 6: Properties of the four-lepton combinations satisfying the baseline selection for the Higgs boson search.

Event	Run #	Event #	Channel	m_{Z_1}	m_{Z_2} (GeV/c^2)	$m_{4\ell}$	$p_{T,4\ell}$ (GeV/c)	$y_{4\ell}$
A	146511	504867308	4μ	91.4	92.6	201.2	2.9	0.18
B	147926	368148849	4μ	101.5	40.0	167.8	43.7	1.45
C	163334	286336207	$2e2\mu$	94.5	65.1	162.9	10.4	-0.53
D	163659	344708580	$4e$	93.3	28.8	139.3	24.9	0.39
E	163795	30998576	$2e2\mu$	91.9	82.3	207.1	5.0	1.84
F	163817	155679852	4μ	91.3	34.8	144.9	24.1	-0.36
G	165633	394010457	$2e2\mu$	91.2	92.8	243.7	11.6	-0.48
H	166408	917379387	$2e2\mu$	88.8	105.3	257.9	29.3	-1.21
I	166438	78213037	$4e$	94.5	44.6	216.7	22.9	0.04
J	166512	337493970	4μ	91.0	93.2	238.5	22.0	0.26
K	166950	1491724484	$2e2\mu$	92.4	93.9	194.6	14.2	0.82
L	167281	480301165	4μ	90.4	54.8	222.3	42.3	-0.64
M	167284	1038911933	4μ	77.8	29.7	119.0	43.9	0.58
N	167675	876658967	$4e$	92.6	27.1	125.7	15.3	0.07
O	167807	966824024	$2e2\mu$	90.2	93.4	323.0	40.9	-0.43