

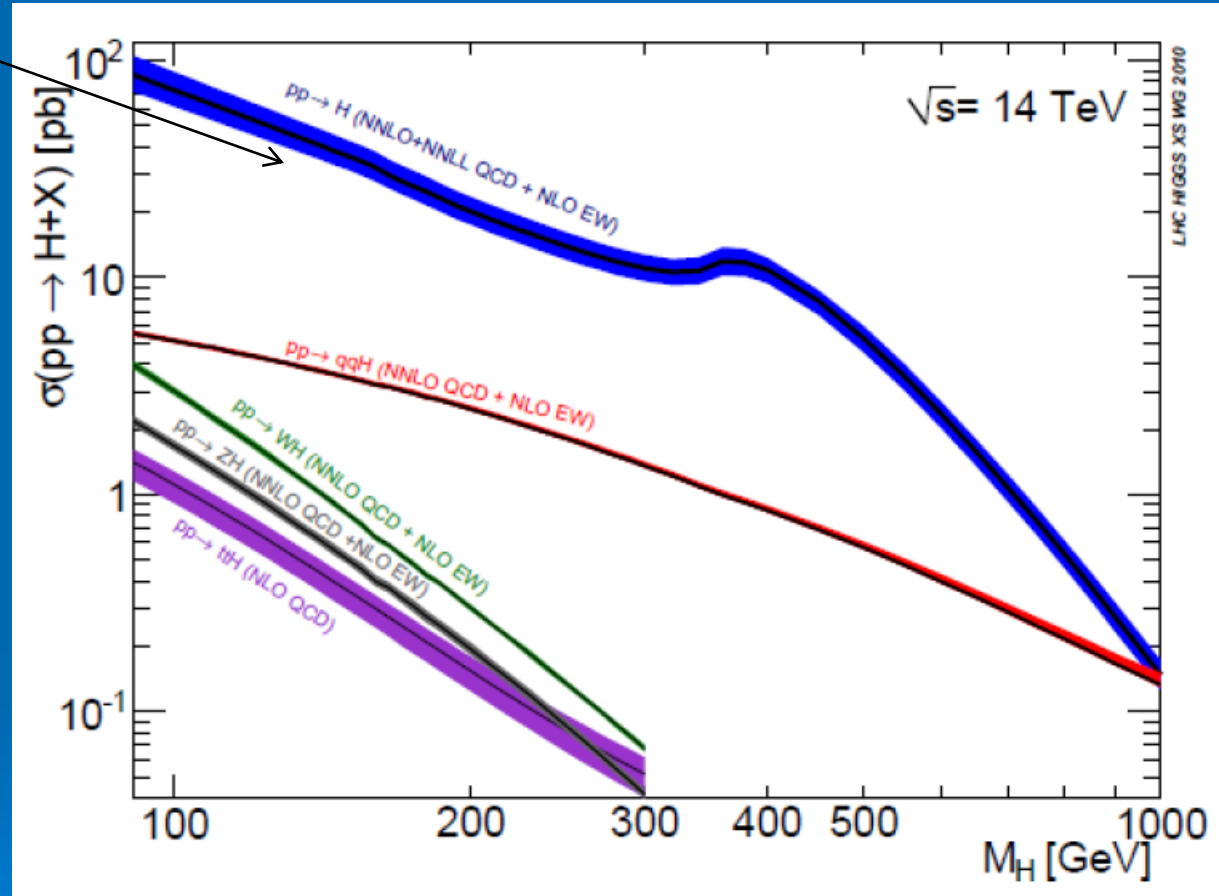
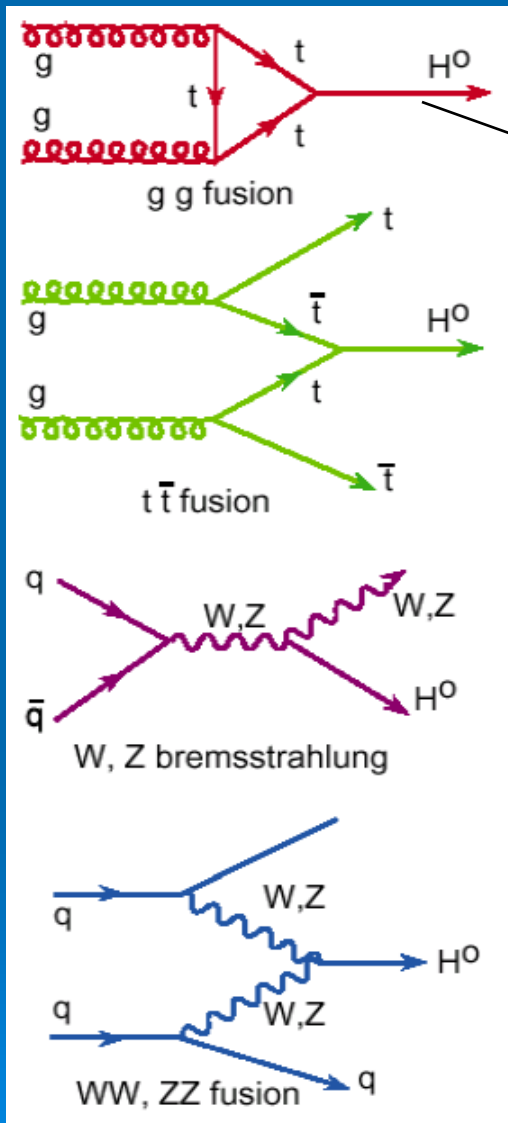
Search for the SM Higgs Boson in the $H \rightarrow ZZ \rightarrow 2l2j$ mode with CMS

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SM Higgs Production at the LHC



Gluon fusion dominates at LHC at all m_H

$H \rightarrow ZZ \rightarrow 2l2j$

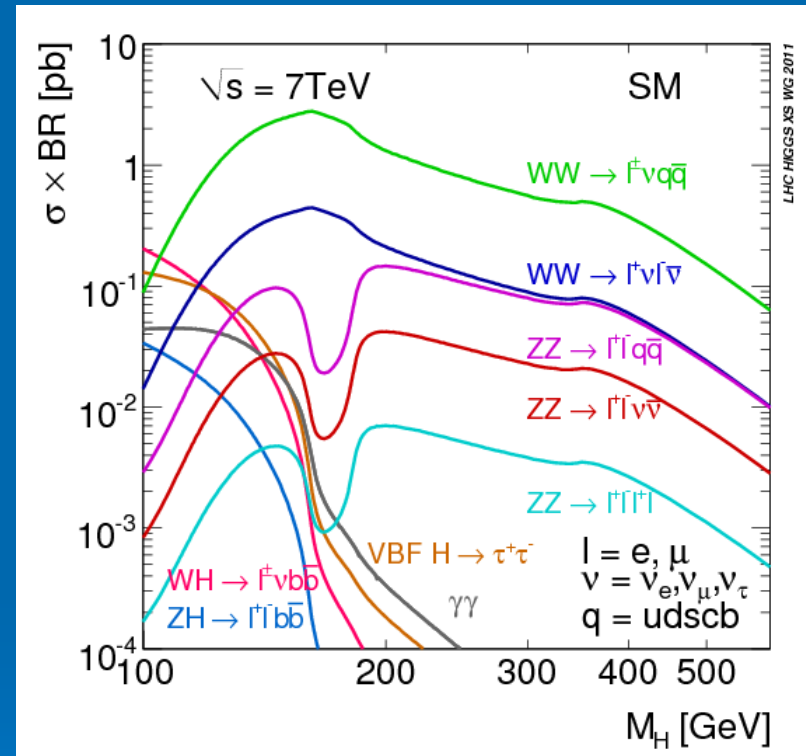
- Historically, focus on 4l final state because of clean reconstruction and low background.

Advantage:

- Better sensitivity, $BR(H \rightarrow ZZ \rightarrow 2l2q) \sim x20$ than 4l!

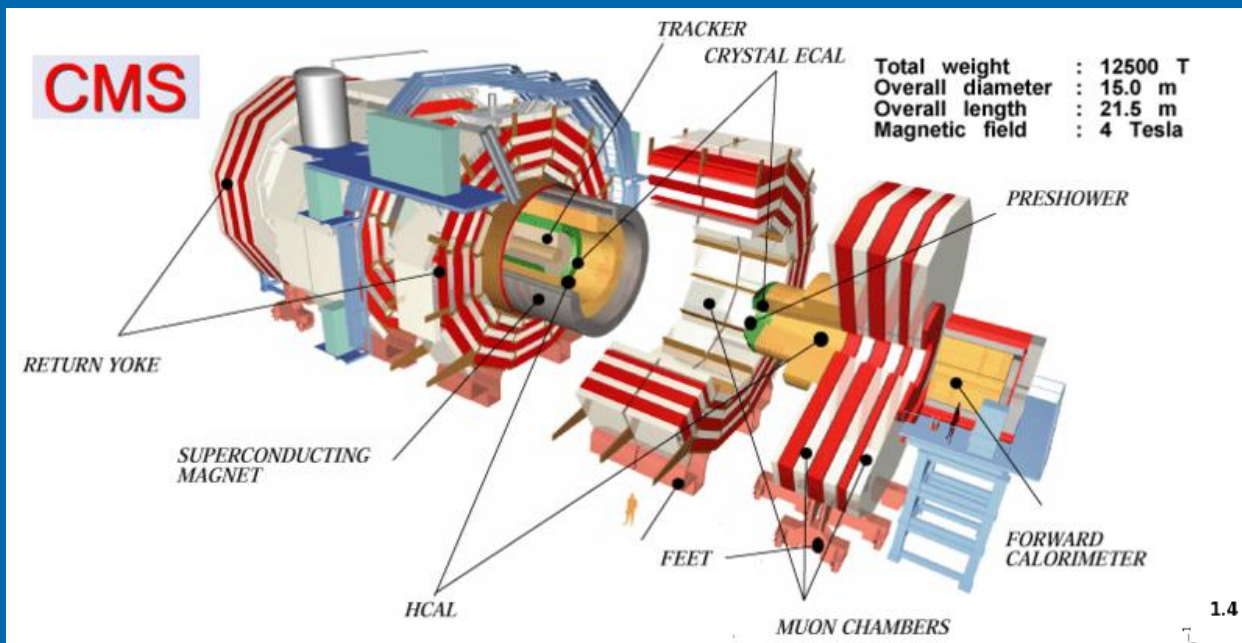
Challenges:

- Worse resolution from jets
- Large backgrounds dominated by Z+jets. Small contributions from tt, diboson and QCD multi-jet.
- Nevertheless, much higher BR wins in sensitivity at higher masses, where Z+jets background is not very high.

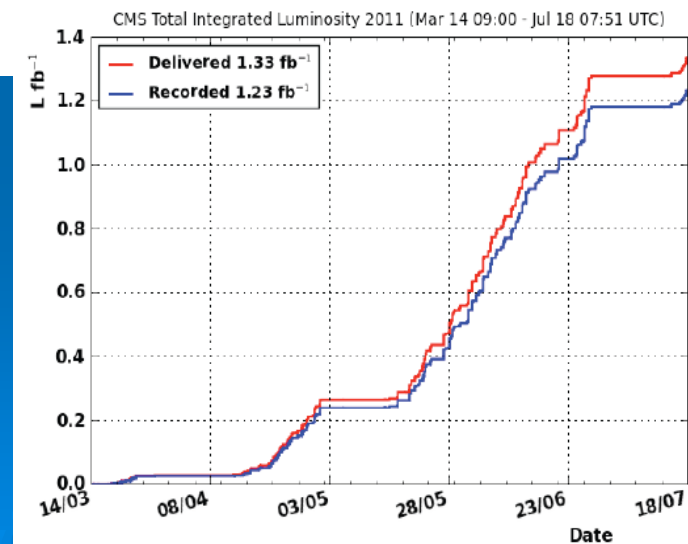


Dominant discovery channels at LHC are two gauge bosons : $\gamma\gamma$, WW , ZZ

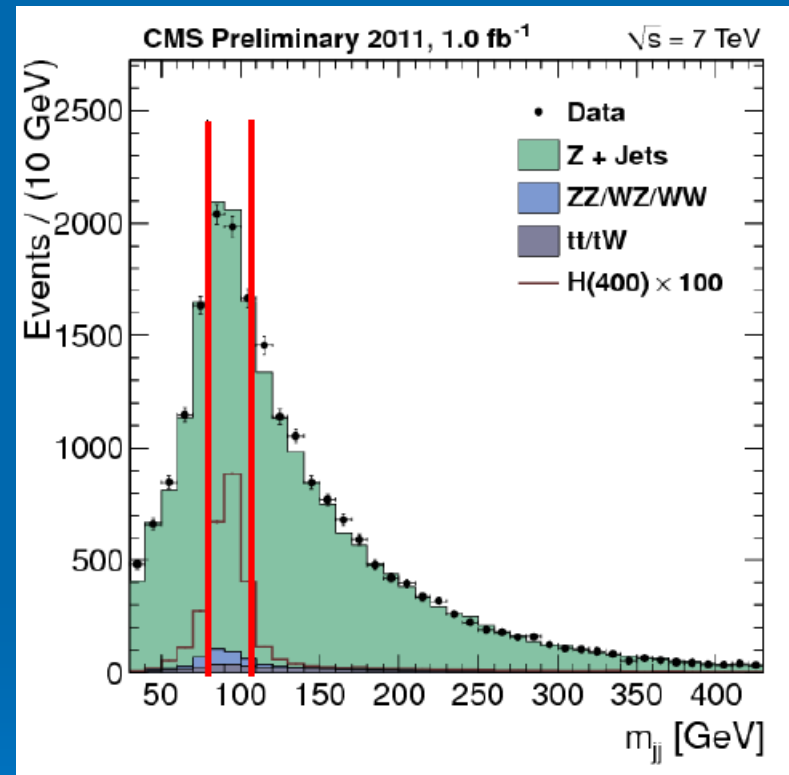
The CMS Detector



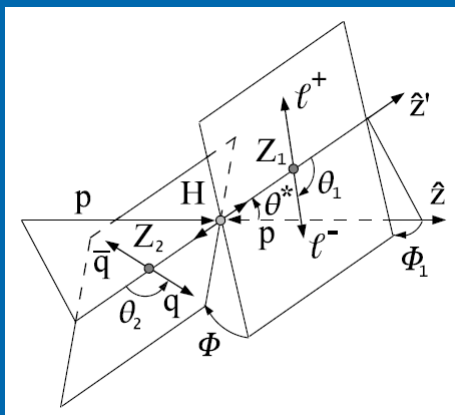
The current analysis uses 1.0 fb^{-1} of data



- Fully reconstruct the decay chain $H \rightarrow ZZ \rightarrow l^+l^-qq$
- e/μ
 - Two opposite-sign Same-Flavor isolated leptons
 - $p_{T,1/2} > 40/20 \text{ GeV}/c$
 - $|\eta_\mu| < 2.4$, $|\eta_e| < 2.5$
- **Jets**
 - anti- k_T clustering algorithm with $R=0.5$, PF objects
 - at least 2 jets
 - $p_T > 30 \text{ GeV}/c$, $|\eta_j| < 2.4$
- **Background suppression**
 - $70 < M_{ll} < 110 \text{ GeV}$
: reduce bkgd without real Z such as $t\bar{t}$.
 - $75 < M_{JJ} < 105 \text{ GeV}$
: effective against Z + jets and $t\bar{t}$



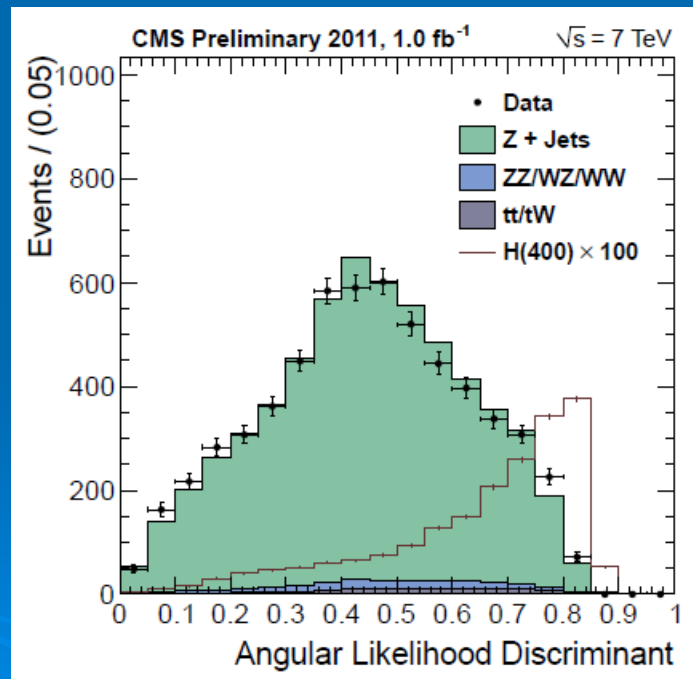
S/B Discrimination – Angular Analysis



- Final state kinematics fully described by five helicity angles (arXiv: 1001.3396v2)
 - They provide good discriminating power between signal and background.
 - Construct an angular likelihood discriminant based on the probability ratio for the signal and background hypotheses.

$$D(\theta^*, \phi_1, \theta_1, \theta_2, \phi) = \frac{P_{SIG}}{P_{SIG} + P_{BKGD}}$$

- All probabilities are parameterized as functions of m_{ZZ} .
- Thresholds of the discriminant are selected to optimize the expected sensitivity and depend on m_{ZZ} .



Parton flavor of jets provides an important handle

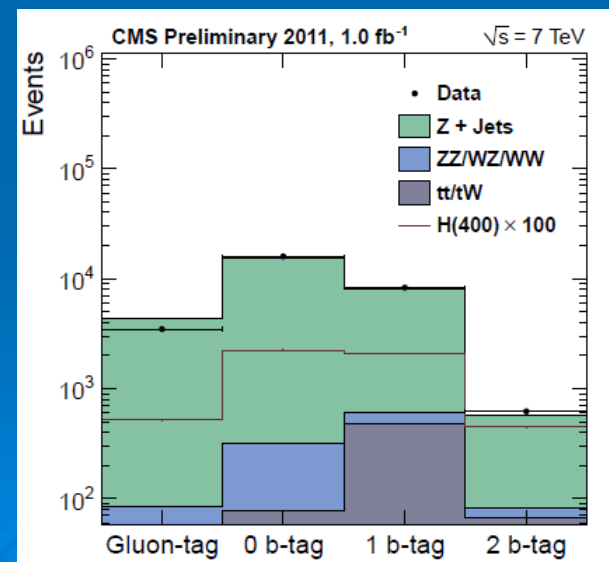
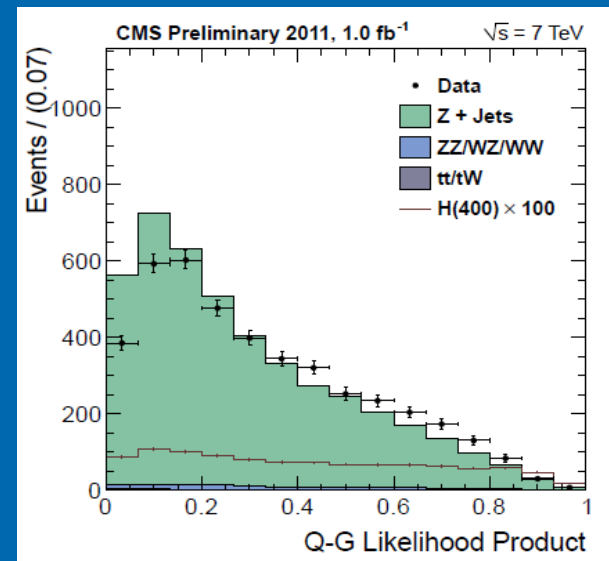
- Signal $Z \rightarrow qq$: primarily quark jets
- Z + jets : after gluons, u,d quarks dominate the jet production
 \Rightarrow Signal has relatively large contribution of heavy flavors (b,c) and absence of gluons.

Analysis takes advantage of both features

- Perform tagging of the b-flavor
- Use Q-G discriminant which separates gluon and quark jets on a statistical basis.

Separate events in three categories according to b-tag

- **2 b-tag**: high purity, low eff (include MET cut against $t\bar{t}$)
- **1 b-tag**: larger bkgd from Z+jets, eff > 2-btag
- **0 b-tag**: all other events, dominated by Z + jets bkgd, higher eff.
 Select gluon-tagged events and exclude them from further analysis.



Search for distinct peak over the continuum background in the invariant mass distribution of dilepton and dijet system m_{ZZ} . Proper estimates of the background is very critical.

Background estimation from the m_{jj} sidebands.

($60 < m_{jj} < 75$ GeV) \cup ($105 < m_{jj} < 130$ GeV)

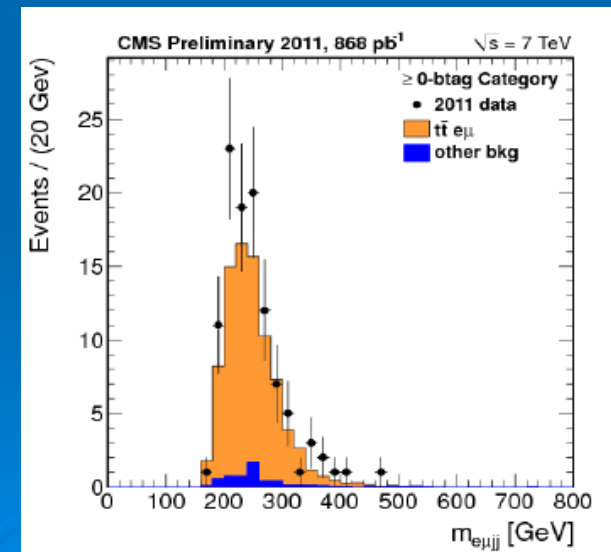
$$N_{\text{bkg}}(m_{ZZ}) = N_{\text{sb}}(m_{ZZ}) \times \frac{N_{\text{bkg}}^{\text{sim}}(m_{ZZ})}{N_{\text{sb}}^{\text{sim}}(m_{ZZ})} = N_{\text{sb}}(m_{ZZ}) \times \alpha(m_{ZZ})$$

Additional cross-checks

Use $e_{\mu jj}$ control sample for the estimation of $t\bar{t}b\bar{b}$ where the dominant Z +jets background is absent.

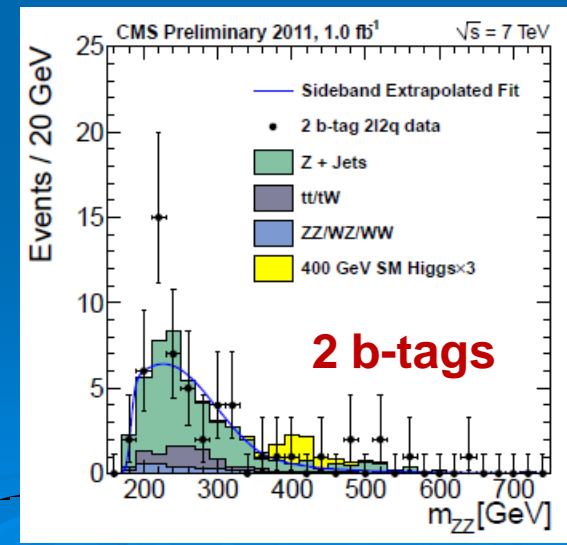
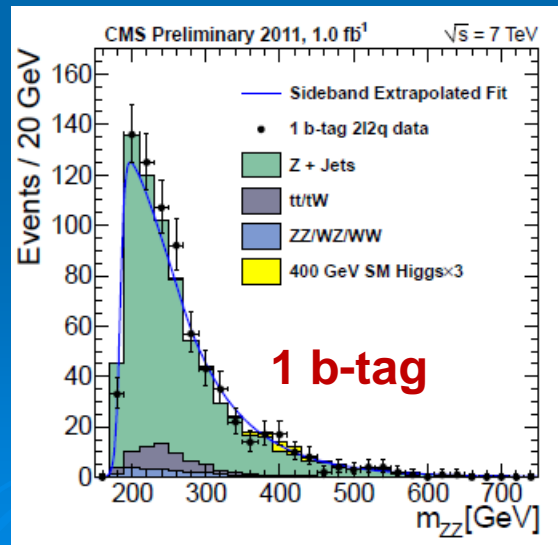
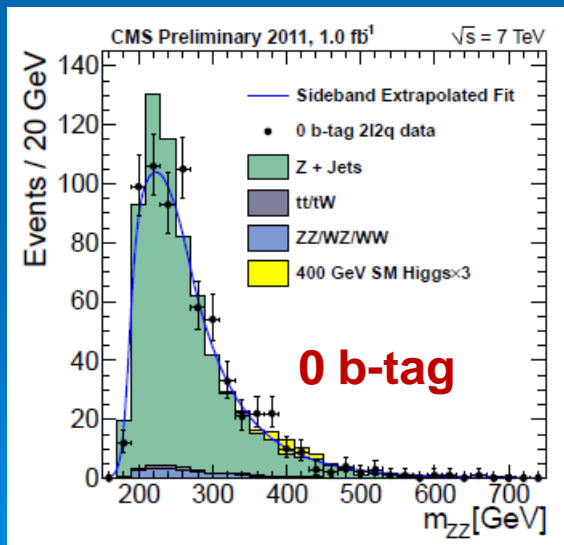
Use higher statistics γ +jets sample to validate Z +jets production.

Most of syst. uncert. on the bkgd cancel in the ratios, such as theoretical cross section prediction and b-tagging efficiency.



Event rates and Invariant Mass (m_{ZZ})

	0 b -tag	1 b -tag	2 b -tag
$\mu^- \mu^+ jj$			
observed yield	359	396	25
exp. background (data)	345.7 ± 17.8	376.4 ± 19.3	24.3 ± 3.7
exp. background (MC)	351.5 ± 5.6	371.2 ± 5.9	23.7 ± 1.6
$e^- e^+ jj$			
observed yield	307	352	30
exp. background (data)	286.4 ± 16.2	334.7 ± 18.2	20.3 ± 3.1
exp. background (MC)	304.3 ± 5.4	332.6 ± 5.8	23.6 ± 1.7



Signal Systematics

source	0 <i>b</i> -tag	1 <i>b</i> -tag	2 <i>b</i> -tag
muon reco	2.7%		
electron reco	4.5%		
jet reco	1–5%		
pileup	2%		
<i>b</i> -tagging	3%	1%	20%
gluon-tagging	4.6%	–	–
\cancel{E}_T	–	–	3%
acceptance (PDF)	3%		
acceptance (HQT)	2%	5%	3%
acceptance (WBF)	1-2%		
luminosity	6%		
Higgs cross section	13–18%		

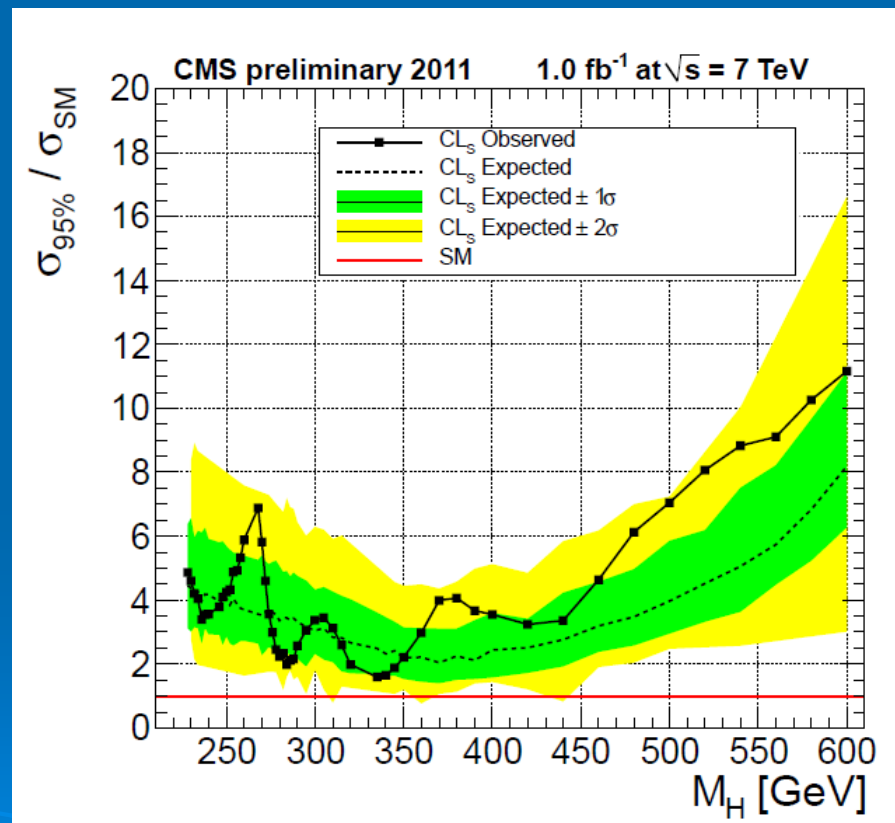
Background Systematics

Normalization uncert. dominated by statistics in sidebands : 0/1 *b*-tag ~ 5%, 2*b*-tag ~ 18%

Excluded Cross Sections

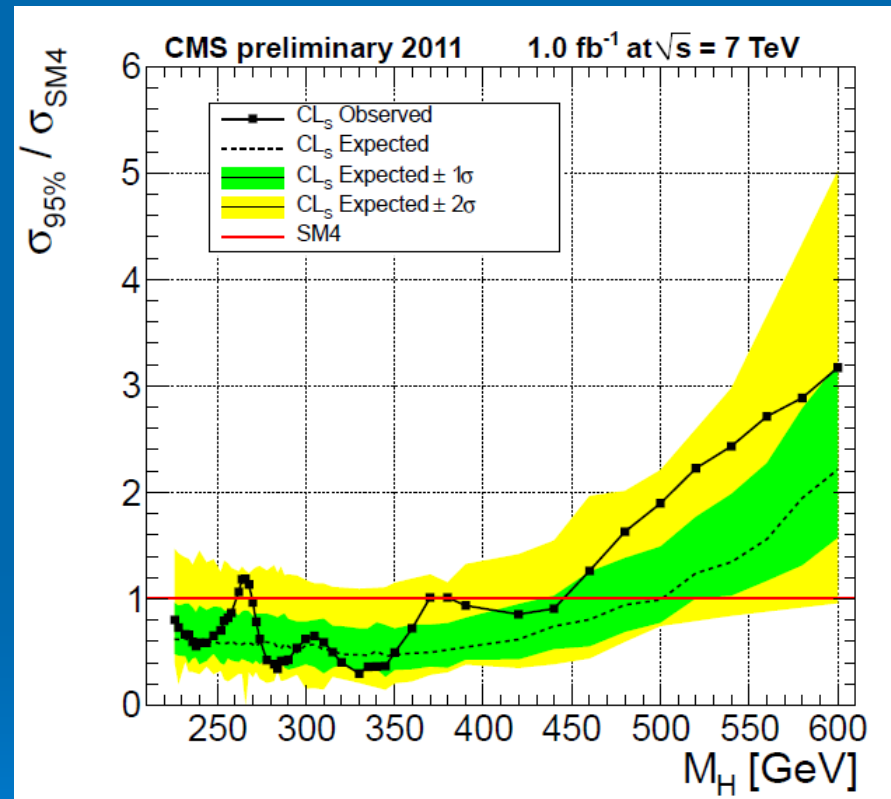
- No evidence of Higgs boson production. Setting exclusion limits on the SM and SM+4th generation with CLs technique
- All fluctuations within $\sim 2\sigma$
- Expected 95% exclusion limit: $\sim 2-4 \cdot \text{SM}$ in the 230-500 GeV range
- Observed 95% exclusion limit $\sim 1.6 \cdot \text{SM}$ at ~ 350 GeV
- Limited by statistics to make exclusion in this decay mode alone. Need to combine with other channels.

REF: CMS-PAS-HIG-11-006



- Enhancements of the production cross sections in the SM scenario with a 4th generation of high mass fermions
- The Higgs boson in SM4 can be excluded at 95% CL in the wide mass range [226-445] GeV except for two narrow windows, [261-270] GeV and [370-381] GeV.
- Large coverage for masses, important input for grand combination.

REF: CMS-PAS-HIG-11-006



Summary

- CMS has performed the search for $H \rightarrow ZZ \rightarrow 2l2q$ using 1 fb^{-1} of data.
- No evidence for SM Higgs has been found and upper limits on the production cross-section for the SM Higgs have been set in the range of masses between 200 GeV and 600 GeV.
- Large range of Higgs mass has been excluded in the model with the 4th generation SM-like couplings of the Higgs

Backup Slides

- Quark/Gluon discrimination
 - Gluons typically radiate more (higher PF multiplicity, broader cone)
 - Build discriminant for each jet, select $Z \rightarrow jj$ with product of discriminant > 0.1

The 0 b -tag category is dominated by the Z +jets background, and from these events we further select a “gluon-tagged” category, which is then excluded in further analysis. Therefore, we apply an additional requirement that the two jets are not consistent with being gluons, based on three measured quantities. These are the number of charged hadronic particle tracks, the number of photon and neutral hadronic PF candidates, and transverse momentum distribution $\sqrt{\sum p_T^2 / (\sum p_T)^2}$, where the sum is extended over all PF candidates in the jet. Gluons have a more intense coupling to the strong field than quarks; therefore, their hadronization favors the production of a larger number of stable particles. This translates into the observation of wider high-multiplicity jets when compared to those generated by final state quarks.

signal expectation (MC)				
Higgs	200 GeV/c ²	2.57 ± 0.37	3.43 ± 0.49	0.70 ± 0.19
	250 GeV/c ²	5.34 ± 0.75	4.75 ± 0.67	1.46 ± 0.38
	300 GeV/c ²	5.84 ± 0.83	4.97 ± 0.69	1.75 ± 0.46
	350 GeV/c ²	6.45 ± 0.94	5.61 ± 0.80	2.15 ± 0.56
	400 GeV/c ²	5.33 ± 0.76	4.83 ± 0.67	1.96 ± 0.50
	450 GeV/c ²	3.54 ± 0.53	3.38 ± 0.48	1.43 ± 0.35
	500 GeV/c ²	2.21 ± 0.34	2.21 ± 0.32	0.97 ± 0.24
	550 GeV/c ²	1.36 ± 0.22	1.41 ± 0.22	0.63 ± 0.16
	600 GeV/c ²	0.83 ± 0.21	0.86 ± 0.21	0.39 ± 0.15

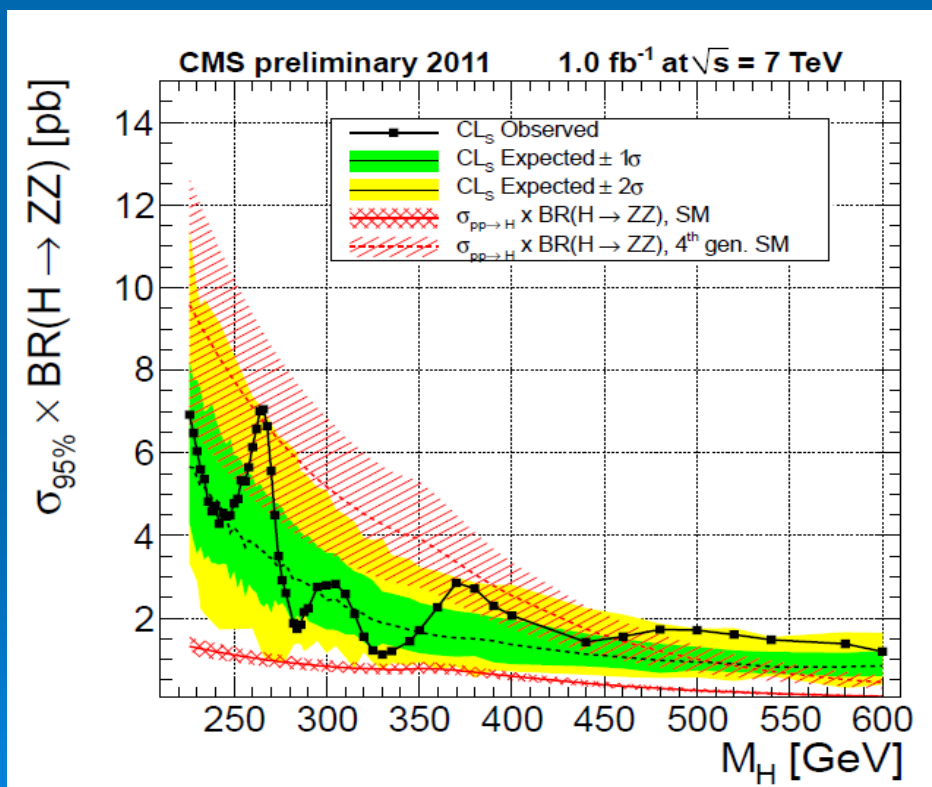


Table 1: Summary of optimized kinematic and topological selection requirements.

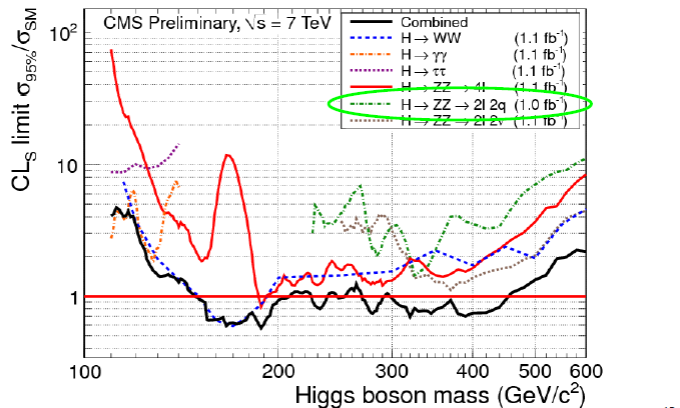
	preselection		
$p_T(\ell^\pm)$	lowest $p_T > 20 \text{ GeV}/c$, highest $p_T > 40 \text{ GeV}/c$		
$p_T(\text{jets})$	$> 30 \text{ GeV}/c$		
$ \eta (\ell^\pm)$	$(e^\pm) < 2.5, (\mu^\pm) < 2.4$		
$ \eta (\text{jets})$	< 2.5		
	0 b -tag	1 b -tag	2 b -tag
b -tag	none	one loose	medium & loose
angular LD	$> 0.55 + 0.00025 m_{ZZ}$	$> 0.302 + 0.000656 m_{ZZ}$	> 0.5
quark-gluon LD	> 0.10	–	–
$2 \ln \lambda(\cancel{E}_T)$	–	–	< 10
m_{jj}	$\in [75, 105] \text{ GeV}/c^2$		
$m_{\ell\ell}$	$\in [70, 110] \text{ GeV}/c^2$		
m_{ZZ}	analyzed within $[183, 800] \text{ GeV}/c^2$		

The overall combination is presented of six standard model (SM) Higgs boson searches performed by the CMS Collaboration using the following Higgs boson decay signatures: $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$, $H \rightarrow WW \rightarrow 2\ell 2\nu$, $H \rightarrow ZZ \rightarrow 4\ell$, $H \rightarrow ZZ \rightarrow 2\ell 2\nu$, and $H \rightarrow ZZ \rightarrow 2\ell 2q$. Depending on the analysis, the amount of data used corresponds to 1.0-1.1 fb^{-1} of integrated luminosity. The conclusion of this combination is that the SM Higgs boson is excluded at 95% C.L. in two mass ranges 149-206 and 300-440 GeV/c^2 , as well as several narrower intervals in between. The expected exclusion in the absence of a signal is 127-420 GeV/c^2 . At 90% C.L., we exclude the SM Higgs boson in the mass range from 145-480 GeV/c^2 . The same experimental search results, reinterpreted in the context of the standard model with 4 fermion generations (SM4), allow us to exclude the SM4 Higgs boson with a mass in the range 120-600 GeV/c^2 at 95% C.L.

Input to CMS combined limit



<http://cdsweb.cern.ch/record/1370076>



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