Study of Standard Model Scalar Production in Bosonic Decay Channels in CMS

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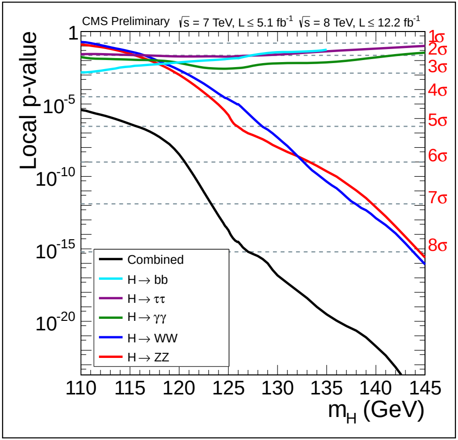
$H \to VV$ Modes

- Most sensitive channels
- Very good mass resolution: $\mathrm{H} \to \mathrm{ZZ}$ & $\mathrm{H} \to \gamma\gamma$
- Large yield: $\mathrm{H} \to \mathrm{WW}$
- Selection criteria defined before looking at the signal region
- Large number of cross-checks and independent analyses
- Today's talk: paying attention to low mass region and updated analyses w.r.t. last year



$17.3\ \mathrm{fb}^{-1}$ dataset only, figure for illustration

Key Points in the Object Id (just a few words)

- Trigger: single/double lepton/photon paths
- μ, e, τ, γ: relatively high p_{T} isolated objects
  - identification & isolation
  - momentum scale & resolution
- Jet reconstruction:
  - reject backgrounds and/or select VBF events
  - particle Flow-based, pile-up Id and pile-up subtraction of the energy
- b-tagging:
  - reject top backgrounds and/or select b-jets
  - based on displaced tracks and soft leptons
- $E_{\mathrm{T}}^{\mathrm{miss}}$:
  - select events with neutrinos and/or reject backgrounds
  - based on all particles pointing to primary vertex
- Systematics, data-driven methods

Analyses

Color code:

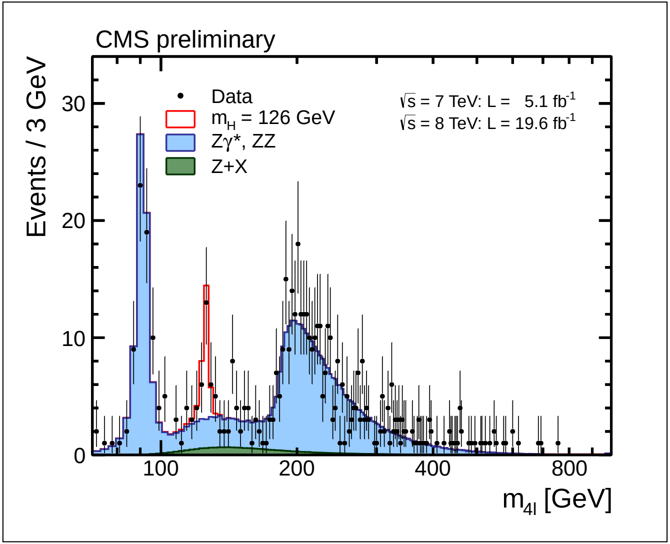
- Red: new update, shown today
- Blue: no new update, briefly shown today
- Green: no new update, some information in back-up slides

- High sensitivity analyses:
  - $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$
  - $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$
  - $\mathrm{H} \to \gamma\gamma$
- Other analyses at low masses:
  - $\mathrm{WH} \to \mathrm{WWW} \to 3\ell 3\nu$
  - $\mathrm{W/ZH} \to qq' 2\ell 2\nu$
  - $\mathrm{H} \to \mathrm{Z}\gamma$
- High mass analyses:
  - $\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu$
  - $\mathrm{H} \to \mathrm{ZZ} \to qq' 2\ell$
  - $\mathrm{H} \to \mathrm{WW} \to qq' \ell\nu$
- Two analyses also very high performing at high mass:
  - $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$, including $H \to \mathrm{ZZ} \to 2\ell 2\tau$
  - $\mathrm{H} \to \mathrm{WW} \to \ell\nu\ell\nu$

$\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ (I) - Introduction

- Four isolated leptons from the same vertex
- Good mass resolution
- Very small signal rate, but high signal-to-background ratio
- Backgrounds:
  - ZZ continuum: almost irreducible, different mass shape
  - $Z + jets$, Zbb & $\mathrm{t\bar{t}}$: lepton isolation and impact parameter, to reject $b \to \ell X$ decays
- Additional help from kinematic discriminants
  - $(m_{4\ell}) \to (m_{4\ell}, K_D) \to (m_{4\ell}, K_D, V_D - p_{\mathrm{T}}/m_{4\ell})$
- Public document: CMS-PAS-HIG-13-002
- New from last update:
  - use of full dataset ($\mathcal{L} \sim$ 24.7 fb^{-1})
  - updated kinematic discriminant variables
  - inclusion of VBF-like category to separate production modes
  - more detailed mass and spin separation studies

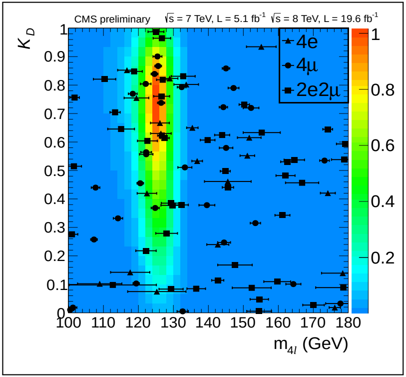
$H \rightarrow ZZ \rightarrow 4\ell$ (II) - $m_{4\ell}$ Distribution



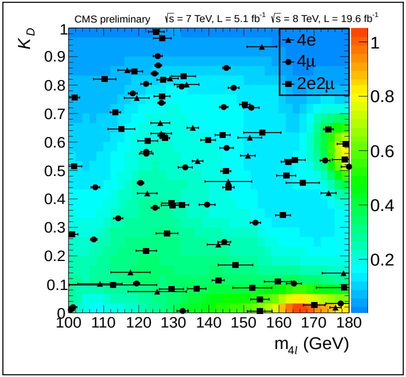
- Good description of ZZ continuum at high masses
- $Z \rightarrow 4\ell$ peak well visible
- Relatively clean mass peak at ~ 126 GeV

$H \rightarrow ZZ \rightarrow 4\ell$ (III) - Kinematic Discriminant(s)

H(126)



background

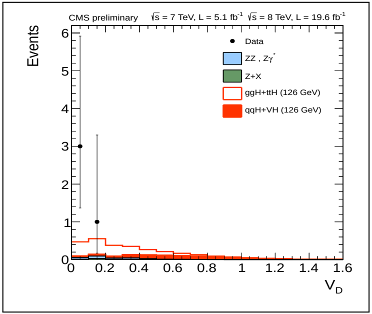


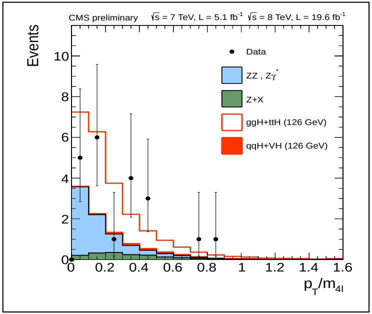
- Kinematic variable to further separate signal and background

$$K_D(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi, m_{Z_1}, m_{Z_2}) = \mathcal{P}_{sig}/(\mathcal{P}_{sig} + \mathcal{P}_{bkg})$$

- Matrix Element techniques used to build the discriminant variable
- Other approaches give similar performance

$\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ (IV) - Di-jet Analysis





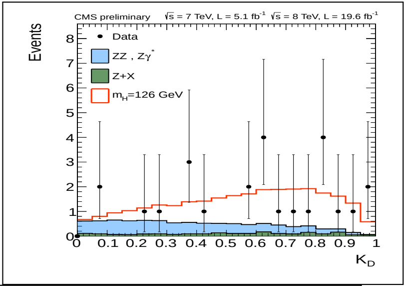
- First analysis able to separate production mechanisms in 4ℓ events
- Two categories: tagged and untagged events
  - tagged: events with at least two reconstructed jets with $p_T > 30$ GeV
  - untagged: otherwise
- Make use of a Fisher discriminant (V_D) in the tagged category using m_{jj} and $\Delta\eta_{jj}$ as input variables
- Make use of $p_T/m_{4\ell}$ in the untagged category as discriminant variable

Event candidates in the tagged category are likely to be $gg \to \mathrm{H}$ events

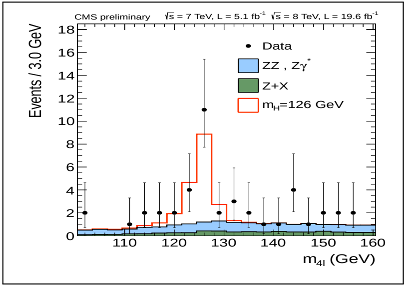
Events in figures within $121.5 < m_{4\ell} < 130.5$ GeV

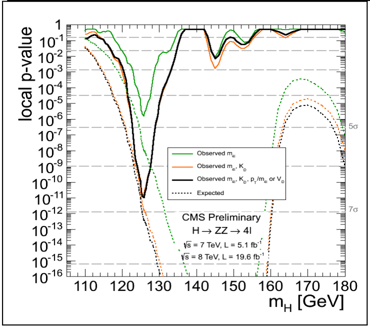
H → ZZ → 4ℓ (V) - Significance

$121.5 < m_{4\ell} < 130.5$ GeV



$K_D > 0.5$



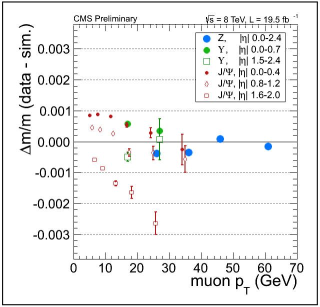


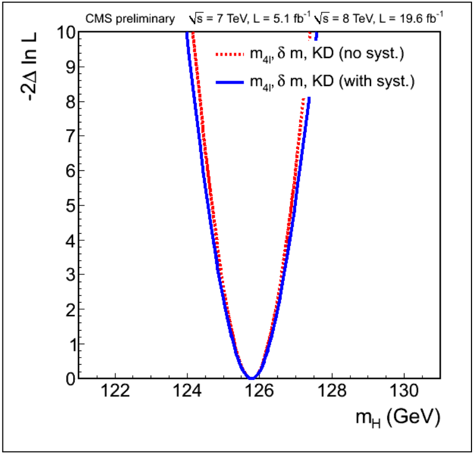
- Minimum p-value reached at $m_{\mathrm{H}} \sim 125.8$ GeV
- More than 5σ significance with this channel alone!

analysis	expected	observed
$1D(m_{4\ell})$	5.6σ	4.7σ
$2D(m_{4\ell}, K_D)$	6.9σ	6.6σ
$3D(m_{4\ell}, K_D, V_D - p_{\mathrm{T}}/m_{4\ell})$	7.2σ	6.7σ

$H \to ZZ \to 4\ell$ (VI) - Mass Measurement

- Momentum scale, studied and tuned in several di-lepton data control samples
- Event-by-event mass uncertainty built from lepton momentum uncertainties used to increase the mass measurement precision

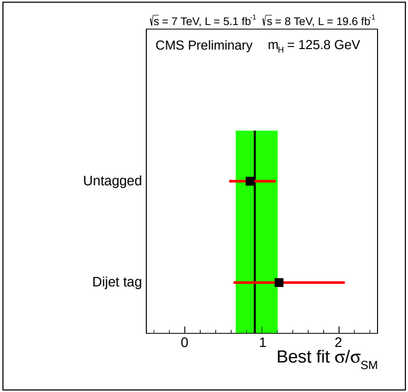


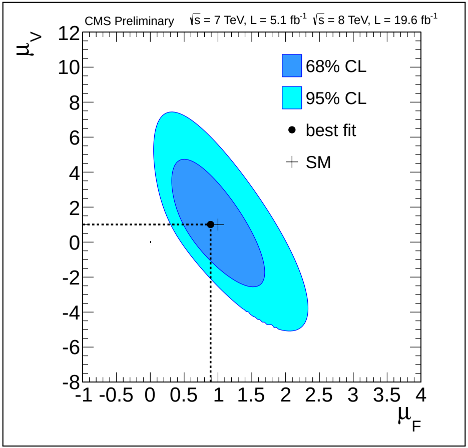


$$m_{\mathrm{H}} = 125.8 \pm 0.5(stat.) \pm 0.2(syst.)\ \mathrm{GeV}$$

- Still largely statistical limited

$H \rightarrow ZZ \rightarrow 4\ell$ (VII) - Production Mechanisms





- $\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$ $(m_{\mathrm{H}} = 125.8\ \mathrm{GeV})$

$\sigma/\sigma_{SM} \equiv \mu$

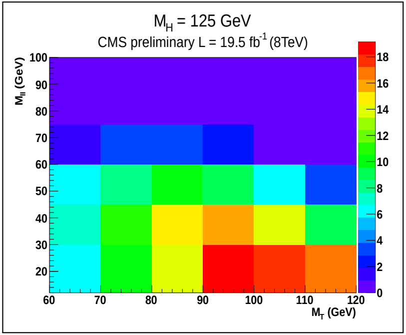
- $\mu_V\ (qq\mathrm{H},\ \mathrm{ZH},\ \mathrm{WH}) = 1.0^{+2.4}_{-2.3}$
- $\mu_F\ (gg \rightarrow \mathrm{H},\ \mathrm{t\bar{t}H}) = 0.9^{+0.5}_{-0.4}$

$\mathrm{H} \to \mathrm{W}^{+}\mathrm{W}^{-} \to 2\ell 2\nu$ (I) - Introduction

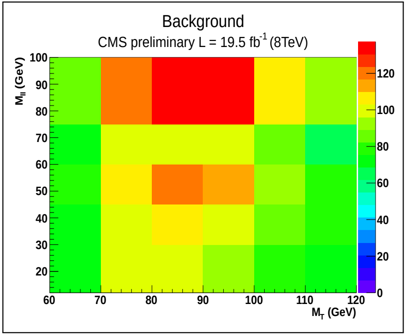
- Two high p_{T} isolated leptons and moderate $E_{\mathrm{T}}^{\mathrm{miss}}$
- Large $\sigma \times BR$ and clean final state
- No mass peak is the main drawback
- Controlling the background is the key
- Categories:
  - 0-jet, 1-jet (VBF not updated yet)
  - different-flavor (DF), same-flavor (SF)
- Public document: CMS-PAS-HIG-13-003
- New from last update
  - use of full dataset
  - 7 TeV dataset has been re-analized
  - further work in understanding all relevant backgrounds

$H \rightarrow W^+W^- \rightarrow 2\ell 2\nu$ (II) - Analysis Strategy

$m_H = 125$ GeV



background

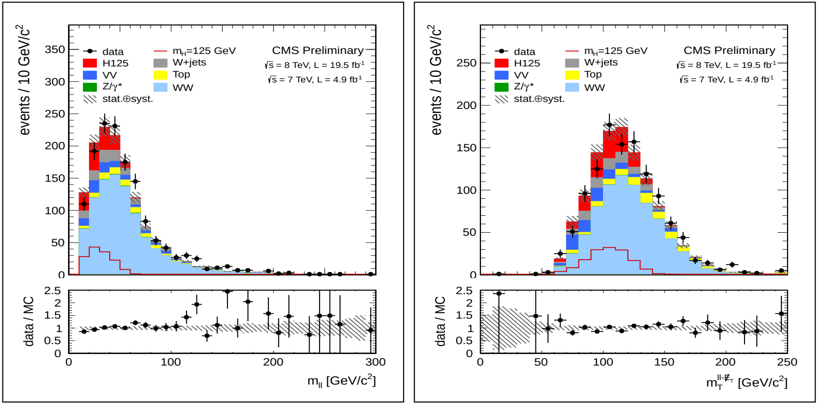


$$m_T = \sqrt{2 p_T^{\ell\ell} E_T^{\rm miss} cos(\Delta\phi_{\ell\ell - E_T^{\rm miss}})}$$

final state	cut-based approach	shape-based approach
DF 0-jet	counting	2D $m_{\ell\ell}$-m_T
SF 0-jet	counting	counting
DF 1-jet	counting	2D $m_{\ell\ell}$-m_T
SF 1-jet	counting	counting

Same strategy for 7 and 8 TeV datasets

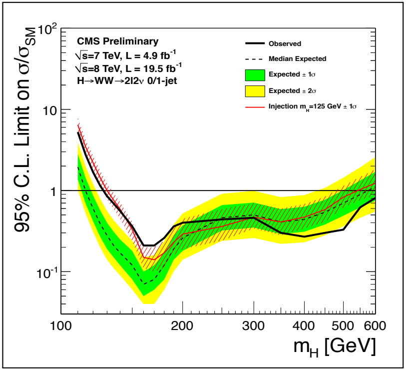
N-1 distributions, 0-jet bin different-flavor (7+8 TeV)



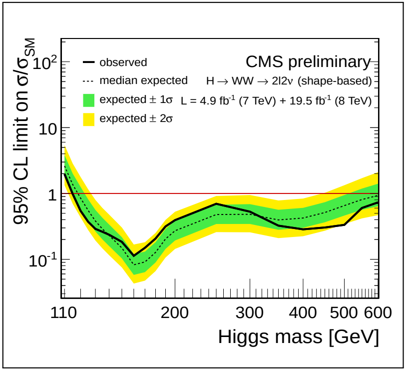
- Relatively large excess

$H \rightarrow W^+W^- \rightarrow 2\ell 2\nu$ (IV) - Upper Limits

standard analysis

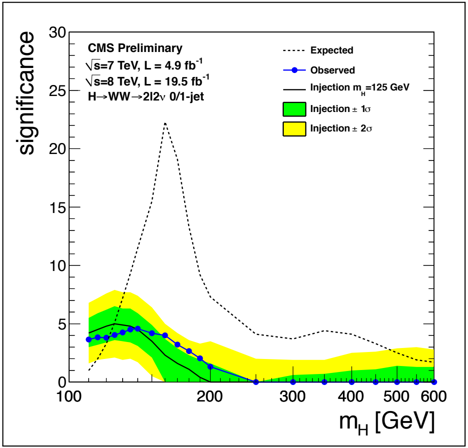


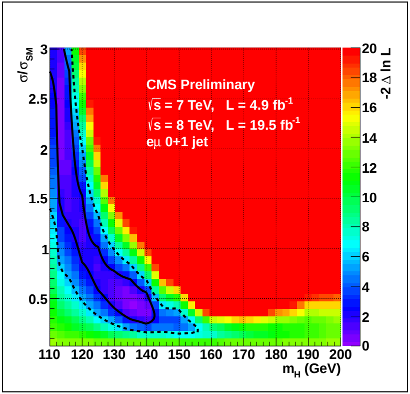
using $m_{\mathrm{H}} = 125$ GeV as background



- Exclusion at the 95% C.L. in the mass range 128-600 GeV
- Large excess in the low mass region makes the upper limits weaker than expected
- When including $m_{\mathrm{H}} = 125$ GeV as part of the background, no significant excess is seen over the entire mass range

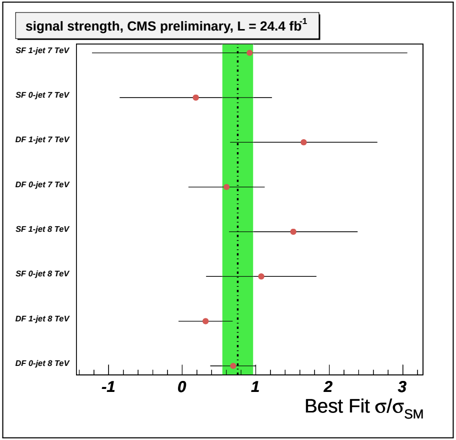
$H \to W^+W^- \to 2\ell 2\nu$ (V) - Significance & σ/σ_{SM}





- ~4.0(5.1) σ observed (expected) significance at $m_{\mathrm{H}} \sim 125$ GeV
- Low mass resolution gives a shallow likelihood profile as a function of m_{H}

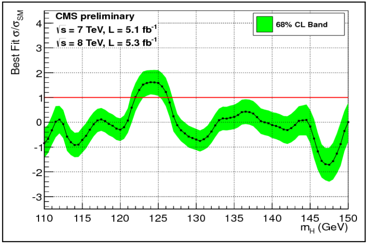
$\mathrm{H} \to WW \to 2\ell 2\nu$ (VI) - σ/σ_{SM} $(m_{\mathrm{H}} = 125\ \mathrm{GeV})$

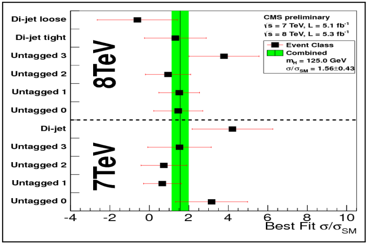


- $\sigma/\sigma_{SM} = 0.76 \pm 0.21$
- Consistent results among the different exclusive final states

$H \rightarrow \gamma\gamma$

- Two high p_T isolated photons
- Small $\sigma \times BR$, narrow mass peak on large continous background
- Main ingredients:
  - γ reconstruction, isolation and identification
  - energy resolution and primary vertex reconstruction
  - background modeling
- Additional categories help:
  - events with two high p_T jets with large $\Delta\eta_{jj}$ and m_{jj}
  - events with leptons
  - events with large E_T^{miss}
- Public document: arXiv:1207.7235

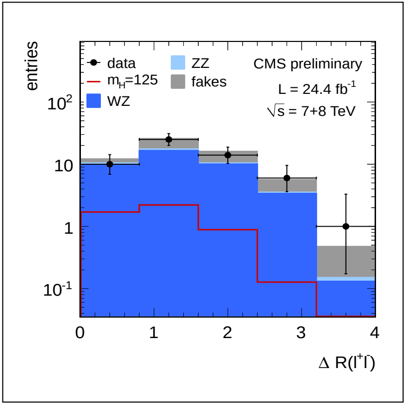


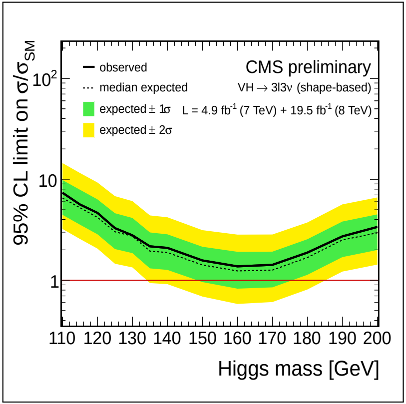


- Consistent with a boson with $m_H \sim 125$ GeV
- Still largely statistical limited

work in progress to update the analysis with the full dataset

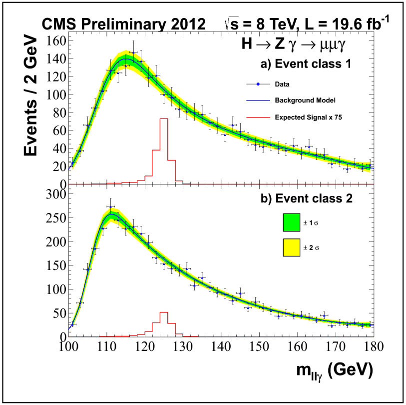
$WH \to WWW \to 3\ell 3\nu$

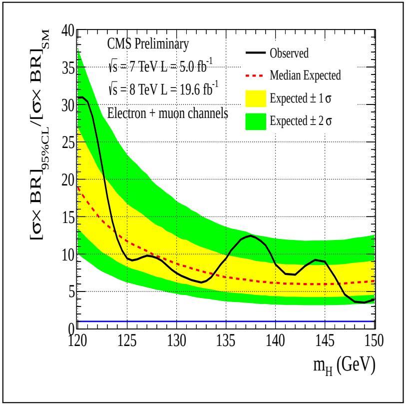




- Three high p_T isolated leptons with moderate E_T^{miss}
- Z veto and anti b-tagging to reject WZ and top events
- Two approaches: cut-based and shape-based (using $\Delta R_{\ell^+\ell^-}$)
- $\sim$20% better performance with shape-based approach
- Public document: CMS-PAS-HIG-13-009

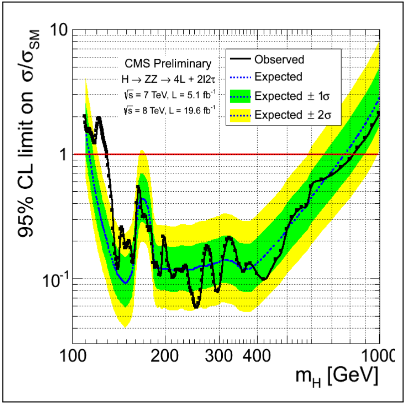
$H \to Z\gamma$

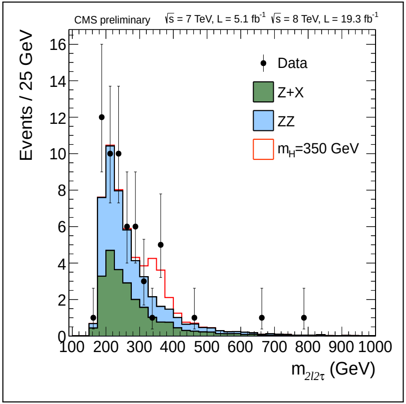




- Two leptons and one photon in the final state
- Relatively simple analysis, but very low expected signal yields
- Split in several categories to improve S/B and mass resolution
- No significance excess over the entire search region
- Public document: CMS-PAS-HIG-13-006

High Mass $H \rightarrow ZZ \rightarrow 4\ell/2\ell 2\tau$





- No significant excess at high mass
- data and background prediction agree in $2\ell 2\tau$ final state
- 130-827 GeV exclusion at 95% C.L.

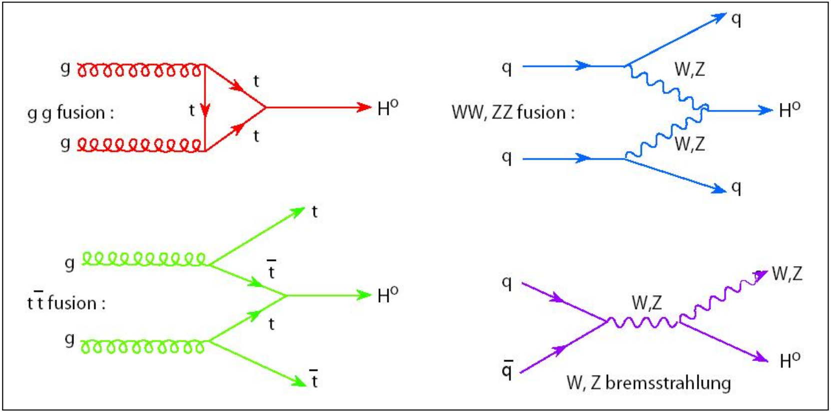
Summary

- SM Scalar candidate at $m_{\mathrm{H}} \sim 126\ \mathrm{GeV}$ growing
- So far, all measurements statistically consistent with SM Scalar prediction
- Spin [1], parity, couplings... will profit by increased data sample
- Search for additional scalar particles has just started
- All results are still preliminary, stay tuned
  - $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ & $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$ updated with full dataset
- $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ highlights:
  - $m_{\mathrm{H}} = 125.8 \pm 0.5\ (\text{stat.}) \pm 0.2\ (\text{syst.})\ \mathrm{GeV}$
  - 6.7 (7.2) s.d. observed (expected) significance
  - $\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$
    - $\mu_V\ (qq\mathrm{H},\ \mathrm{ZH},\ \mathrm{WH}) = 1.0^{+2.4}_{-2.3}$
    - $\mu_F\ (gg \to \mathrm{H},\ \mathrm{t\bar{t}H}) = 0.9^{+0.5}_{-0.4}$
- $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$ highlights:
  - 4.0 (5.1) s.d. observed (expected) significance
  - $\sigma/\sigma_{SM} = 0.76 \pm 0.21$

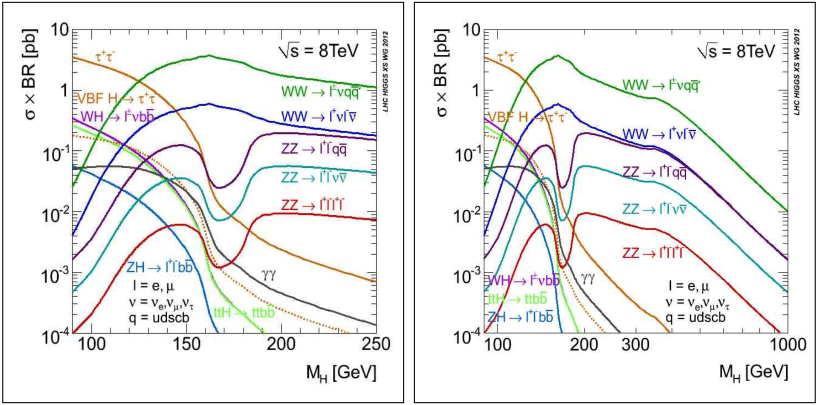
[1] For spin separation hypothesis analyses, both $\mathrm{H} \to \mathrm{ZZ}$ and $\mathrm{H} \to \mathrm{WW}$, see Mingshui's talk

Back-Up

Production Mechanics



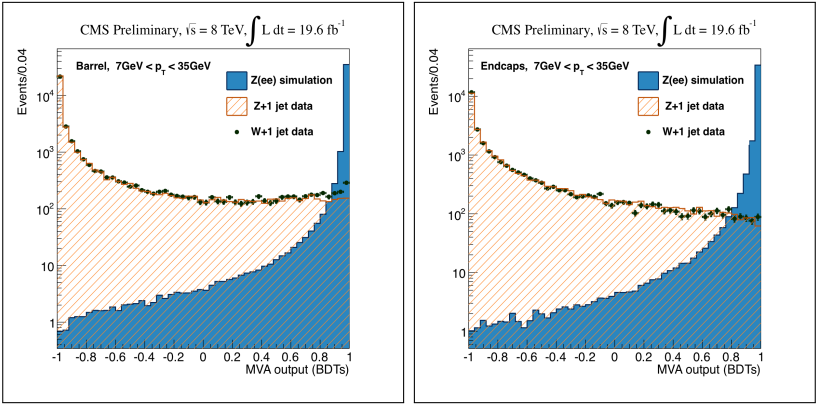
$\sigma \times BR$ at $\sqrt{s} = 8\ TeV$



- Large number of available channels at $m_H \sim 125\ GeV$

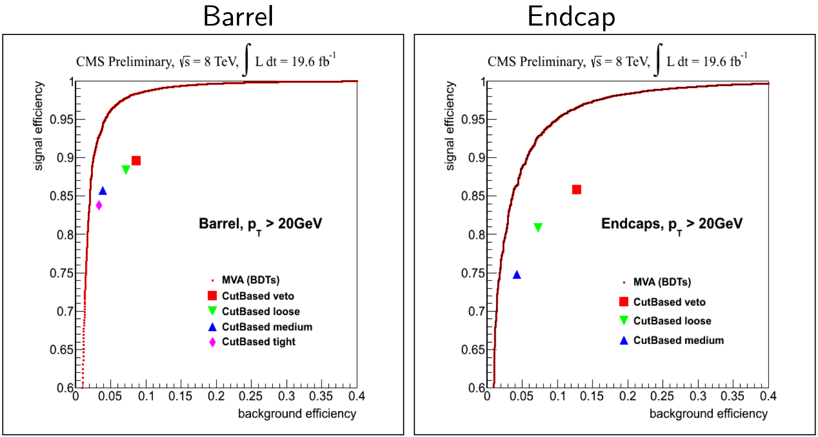
Electron Identification (I)

Barrel Endcap



- BDT analysis
- Trained using fake electrons from $\mathrm{W} + 1$ *jet* events

Electron Identification (II)

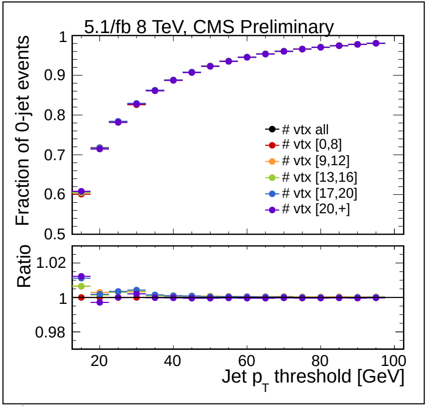


- Great improvement w.r.t cut-based approaches

Jet Identification

Pile-up jets structure differs wrt regular jets:

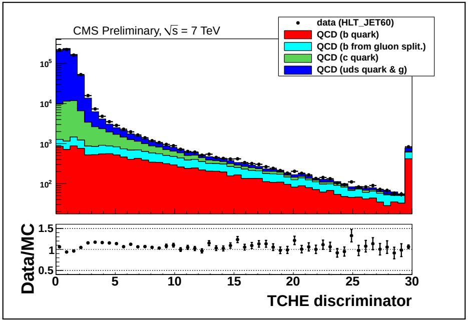
- pile-up jets originate from several overlapping jets which merge together
- likelihood grows rapidly with high pileup
- discriminant exploits shape and tracking variables
- discrimination both inside and outside tracker acceptance



$p_T^{jet} > 30\ \mathrm{GeV}$ is a usual requirement

b-Jet Tagging

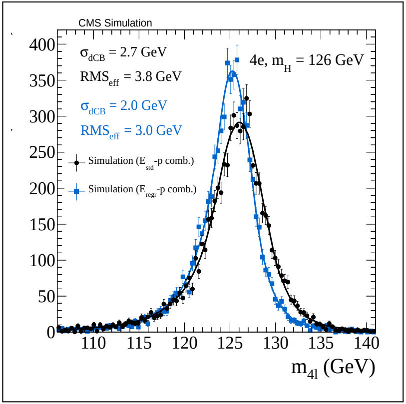
- Mostly used either to select $H \to b\bar{b}$ events or reject $t\bar{t}/Wt$ events
- Techniques:
  - find tracks with large impact parameter
  - find set of tracks not coming from the interaction point
  - find leptons within jets
  - combine all together



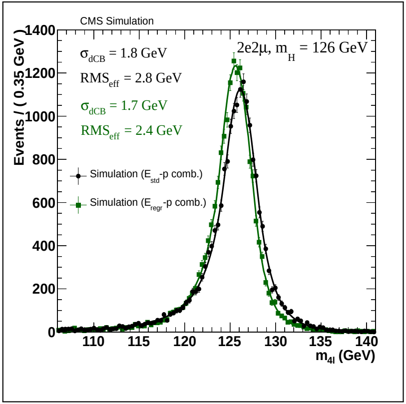
Track Counting High Efficiency (TCHE): impact parameter significance of the second most displaced track in the jet

$H \rightarrow ZZ \rightarrow 4\ell$ Electron Energy Regression

$4e$

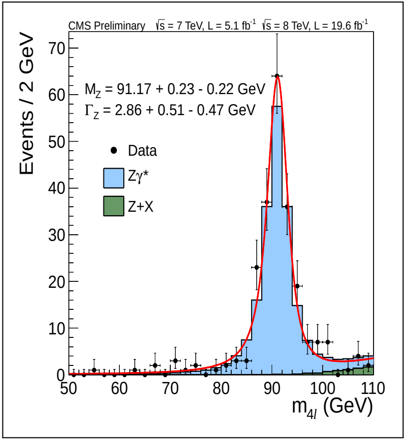


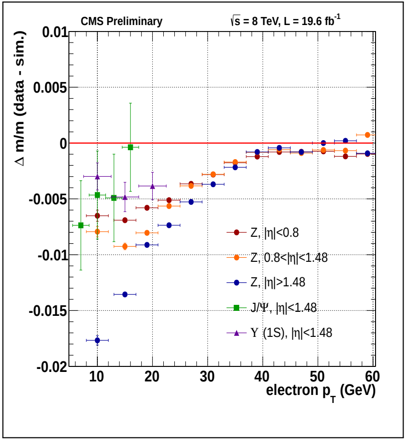
$2e2\mu$



- Great improvement in the energy resolution by applying an electron regression

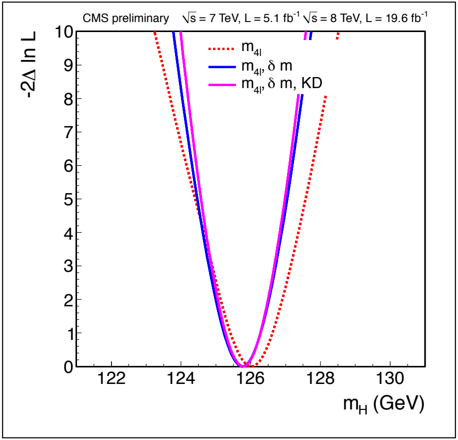
$H \to ZZ \to 4\ell$ Mass Study





- Mass distribution in the mass range $50 < m_{4\ell} < 110$ GeV
- $Z \to 4\ell$ used to validate mass measurement technique
- Good agreement between the measured and PDG values

$H \to ZZ \to 4\ell$ Mass Measurement



- $\sigma_{m_{\mathrm{H}}}(1D - m_{4\ell})$: 0.60 GeV
- $\sigma_{m_{\mathrm{H}}}(2D - m_{4\ell}/\delta m_{4\ell})$: 0.53 GeV
- $\sigma_{m_{\mathrm{H}}}(3D - m_{4\ell}/\delta m_{4\ell}/K_D)$: 0.48 GeV

$X \to ZZ \to 4\ell$ Angles

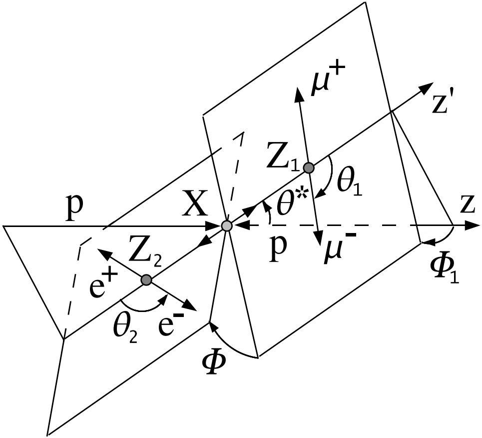


Illustration of a particle X production and decay $ab \to X \to Z_1 Z_2 \to 4\ell$ with the two production angles θ^* and Φ_1 shown in the X rest frame and three decay angles θ_1, θ_2, and Φ shown in the Z_i rest frames

$\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ Yields

Number of event candidates observed, compared to the mean expected background and signal rates for each final state. For the $\mathrm{Z} + X$ background, the estimates are based on data. The results are given integrated over the full mass measurement range for the SM-like Higgs boson search from 100 to 1000 GeV

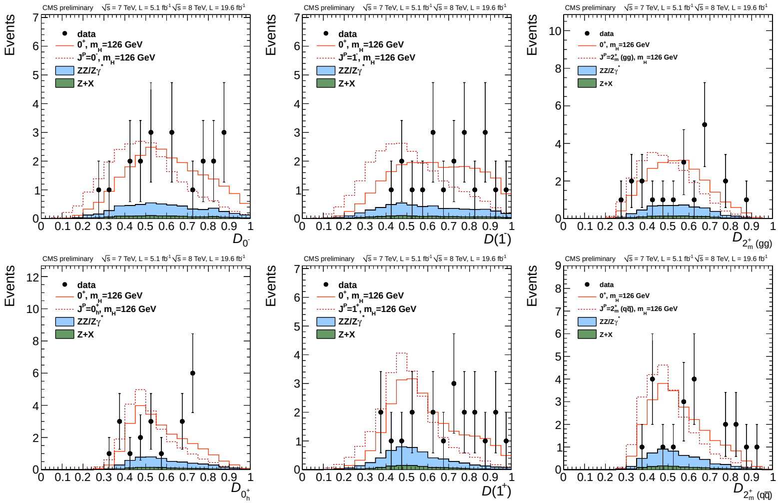
Channel	$4e$	4μ	$2e2\mu$	$2\ell 2\tau$
ZZ background	78.9 ± 10.9	118.9 ± 15.5	192.8 ± 24.8	27.4 ± 3.6
$\mathrm{Z} + X$	6.5 ± 2.6	3.8 ± 1.5	9.9 ± 4.0	22.9 ± 7.8
All background expected	85.5 ± 11.2	122.6 ± 15.5	202.7 ± 25.2	50.3 ± 8.6
$m_{\mathrm{H}} = 125$ GeV	3.5 ± 0.5	6.8 ± 0.8	8.9 ± 1.0	–
$m_{\mathrm{H}} = 126$ GeV	3.9 ± 0.6	7.4 ± 0.9	9.8 ± 1.1	–
$m_{\mathrm{H}} = 500$ GeV	5.1 ± 0.6	6.8 ± 0.8	12.0 ± 1.3	3.7 ± 0.4
$m_{\mathrm{H}} = 800$ GeV	0.7 ± 0.1	0.9 ± 0.1	1.6 ± 0.2	0.4 ± 0.1
Observed	86	125	240	57

$H \to ZZ \to 4\ell$ Spin Separation Analysis

J^P	production	comment	expect	obs. J^P	obs. 0^+	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ	3.3σ	0.5σ	0.16%
0^+_h	$gg \to X$	higher dim operators	1.7σ	1.7σ	0.0σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ	2.7σ	0.8σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ	4.0σ	1.8σ	$<$0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ	$>4.0\sigma$	1.4σ	$<$0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ	$>4.0\sigma$	1.7σ	$<$0.1%

- Aim to separate 0^+ w.r.t. several other models
- All studied alternative models disfavor by CMS data
- More details given in Mingshui's talk

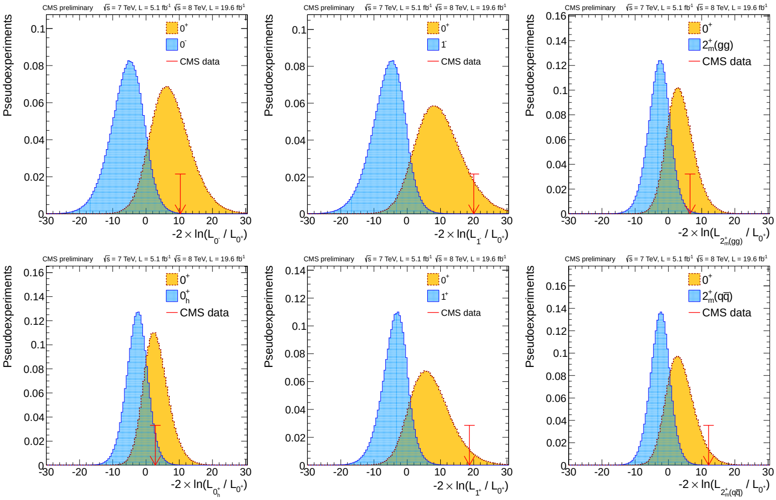
$H \rightarrow ZZ \rightarrow 4\ell$ $\mathcal{D}_{J^P}$ with a requirement $\mathcal{D}_{\mathrm{bkg}} > 0.5$



Six alternative hypotheses from top to bottom and left to right:

$$J^P = 0^-, 0^+_h, 1^-, 1^+, 2^+{}_{mgg}, 2^+{}_{mq\bar{q}}$$

$H \to ZZ \to 4\ell$ $q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{SM})$

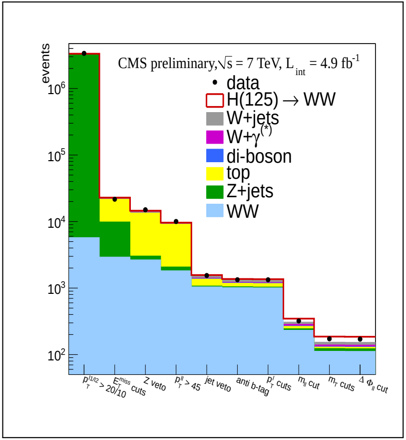


Six alternative hypotheses from top to bottom and left to right:

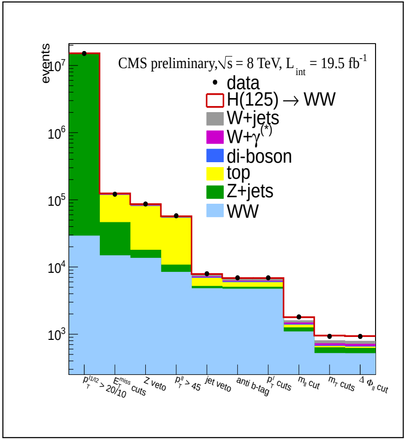
$$J^P = 0^-, 0^+_h, 1^-, 1^+, 2^+{}_{mgg}, 2^+{}_{mq\bar{q}}$$

$H \rightarrow W^+W^- \rightarrow 2\ell 2\nu$ Cut Flow

7 TeV data

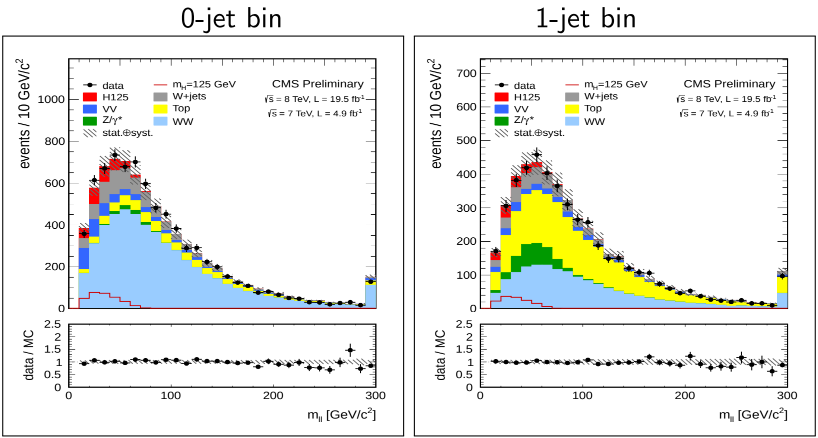


8 TeV data



- Good agreement between data and signal plus background prediction

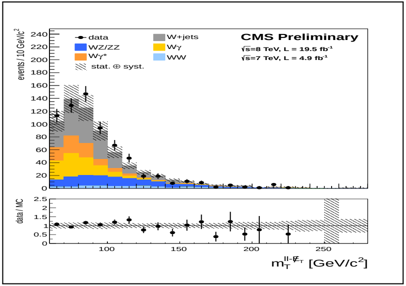
$W^+W^- \to 2\ell 2\nu$ Preselection

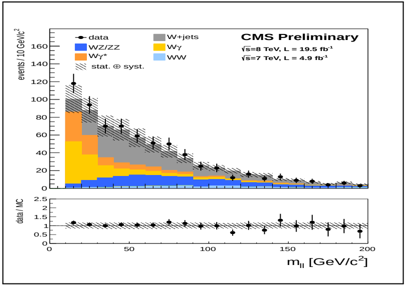


- W^+W^- background dominates in the 0-jet bin
- W^+W^- and top backgrounds dominate in the 1-jet bin

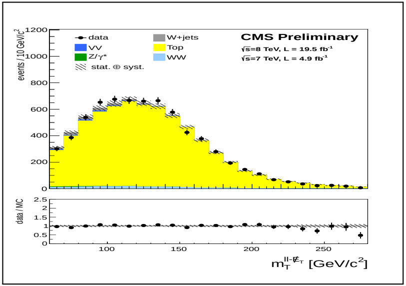
$W^+W^- \to 2\ell 2\nu$ Same-Sign & Top Control Regions

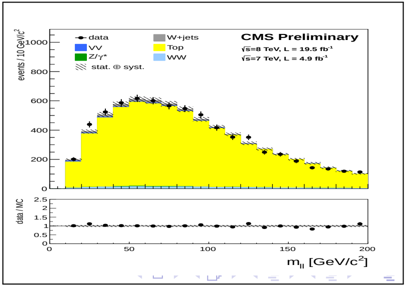
same-sign 0-jet bin





top 1-jet bin





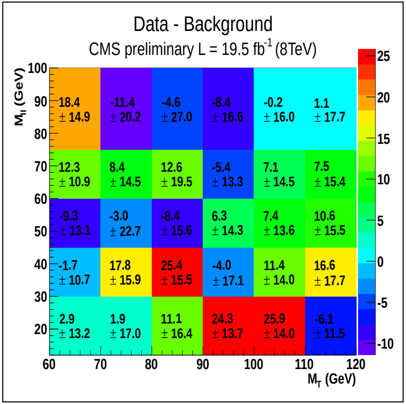
$H \rightarrow W^+W^- \rightarrow 2\ell 2\nu$ vs. $q\bar{q} \rightarrow W^+W^-$ Generators

7+8 TeV data sample expected/observed significance		
MC@NLO	POWHEG	MADGRAPH
5.3/4.2	5.1/3.9	5.1/4.0
best fit value		
MC@NLO	POWHEG	MADGRAPH
0.82 ± 0.24	0.74 ± 0.21	0.76 ± 0.21

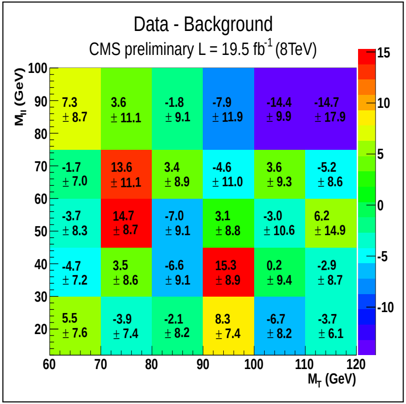
Expected and observed significance and best fit value of σ/σ_{SM} for a SM Higgs with a mass of 125 GeV for the shape-based analysis, where three different generators have been used to model the $q\bar{q} \rightarrow W^+W^-$ background process

$H \rightarrow W^+W^- \rightarrow 2\ell 2\nu$ 2D Analysis

DF 0-jet (8 TeV)



DF 1-jet (8 TeV)



- “Data - background” 2D distributions
- Excess seen over several bins
- Statistical analysis follows

$\mathrm{H} \rightarrow WW \rightarrow 2\ell 2\nu$ - Significance & σ/σ_{SM} $(m_{\mathrm{H}} = 125\ \mathrm{GeV})$

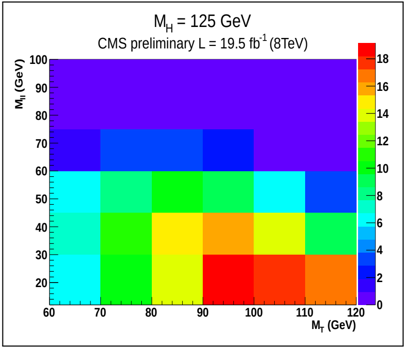
7 TeV exp./obs. significance		8 TeV exp./obs. significance		7+8 TeV exp./obs. significance	
cut-based	shape-based	cut-based	shape-based	cut-based	shape-based
1.7/0.8	2.5/2.2	2.6/2.1	4.7/3.5	2.7/2.0	5.1/4.0
best fit value		best fit value		best fit value	
cut-based	shape-based	cut-based	shape-based	cut-based	shape-based
0.46 ± 0.57	0.91 ± 0.44	0.79 ± 0.38	0.71 ± 0.22	0.71 ± 0.37	0.76 ± 0.21

- Consistent results among the different analyses

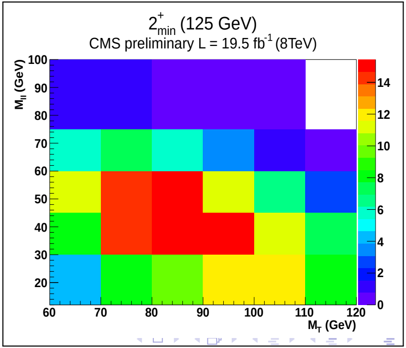
$H \to W^+W^- \to 2\ell 2\nu$ Spin Hypothesis Separation (I)

- Perform hypothesis test to separate 0^+ (SM) and $2^+_{\rm min}$ resonance with minimal couplings
- Include 0/1-jet bins different-flavor channels in 7+8 TeV
- Only $gg \to H$ mode considered for $2^+_{\rm min}$:
  - SM from POWHEG & $2^+_{\rm min}$ from JHU generator
  - same initial normalization for both hypotheses (SM expectation)
  - assuming SM expectations for qqH and VH modes (tiny effect)

0^+ case

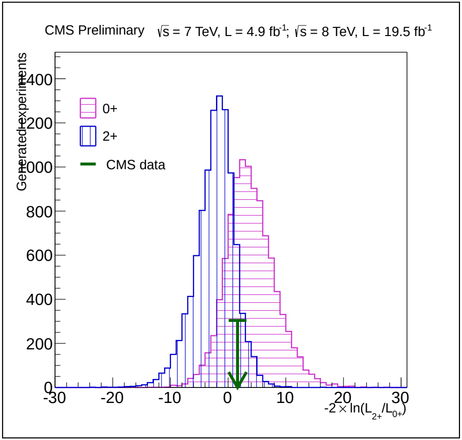


$2^+_{\rm min}$ case



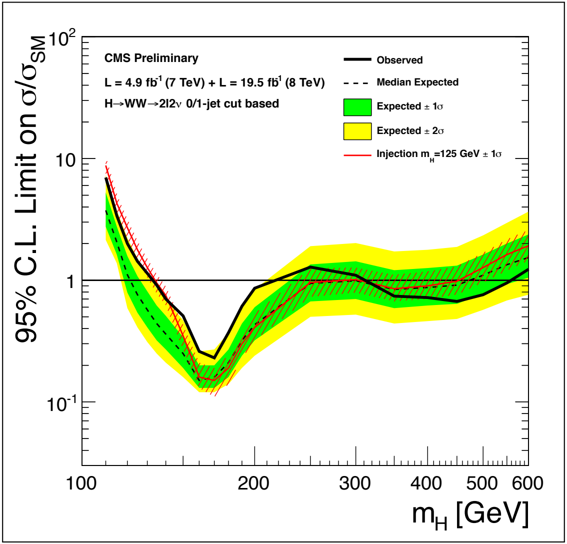
$H \to W^+W^- \to 2\ell 2\nu$ Spin Hypothesis Separation (II)

- Perform a maximum likelihood fit to extract the best fit signal strength for each model
- Compare the best fit likelihoods to determine the consistency of each hypothesis with the data
- Test $q = -2\ \ln(L_{2^+_{\rm min}}/L_{0^+})$
- Expected hypothesis separation at the 2-σ level

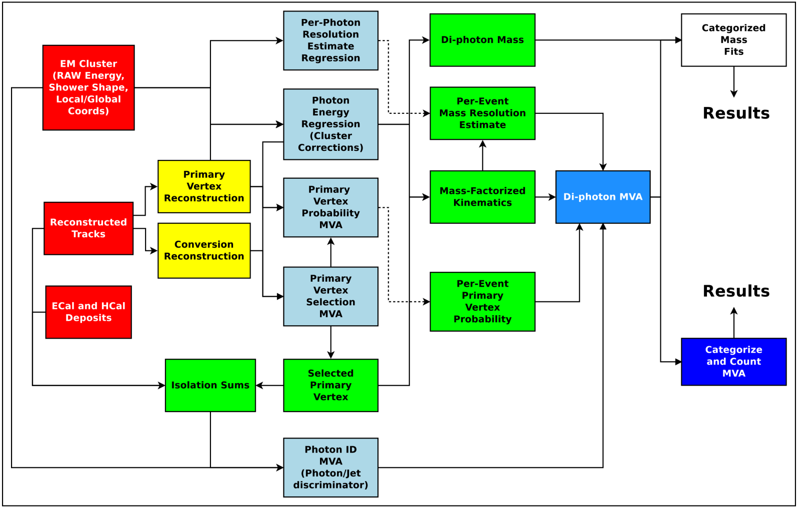


case	expected	observed
assuming $\sigma/\sigma_{SM} \equiv 1$		
0^+	1.9	0.9
$2^+_{\rm min}$	2.4	1.3
assuming $\sigma/\sigma_{SM} \approx 0.8$		
0^+	1.5	0.5
$2^+_{\rm min}$	1.9	1.3

$H \to W^+W^- \to 2\ell 2\nu$ Upper Limits for Cut-Based Analysis

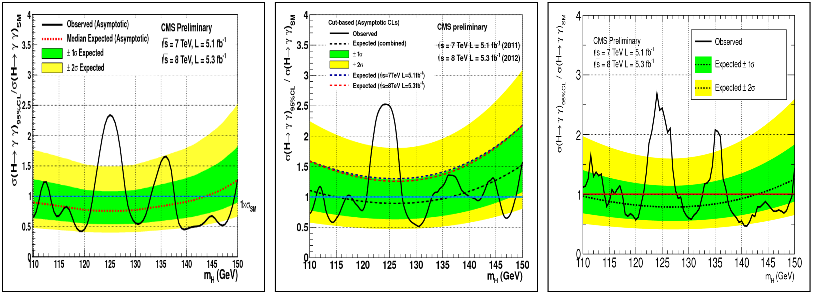


$H \rightarrow \gamma\gamma$ Flow Chart

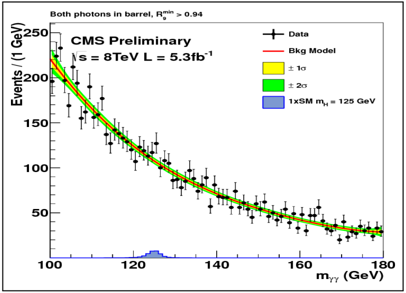


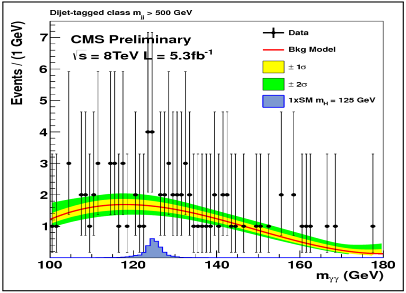
$H \to \gamma\gamma$ Upper Limits

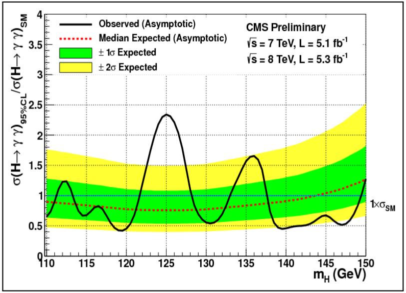
- Three analyses: BDT approach, cut-based approach, mass window approach
- Chosen BDT approach as default analysis due to its superior performance

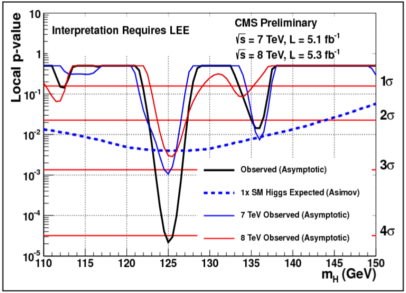


$H \to \gamma\gamma$ Mass/Significance



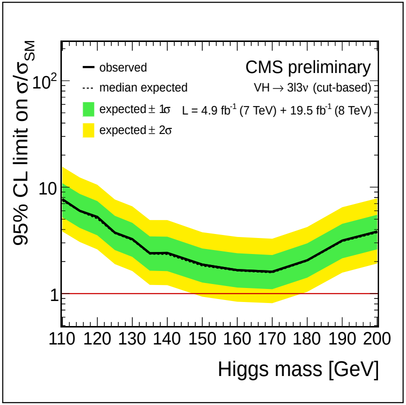




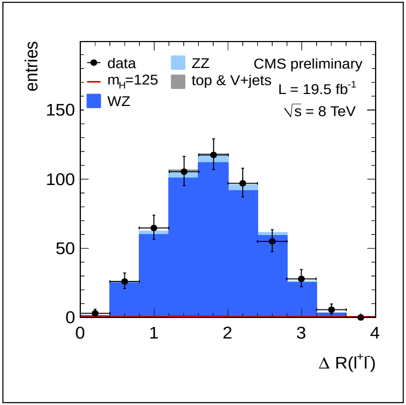


WH → WWW → $3\ell3\nu$ Cut-Based Results

cut-based limits



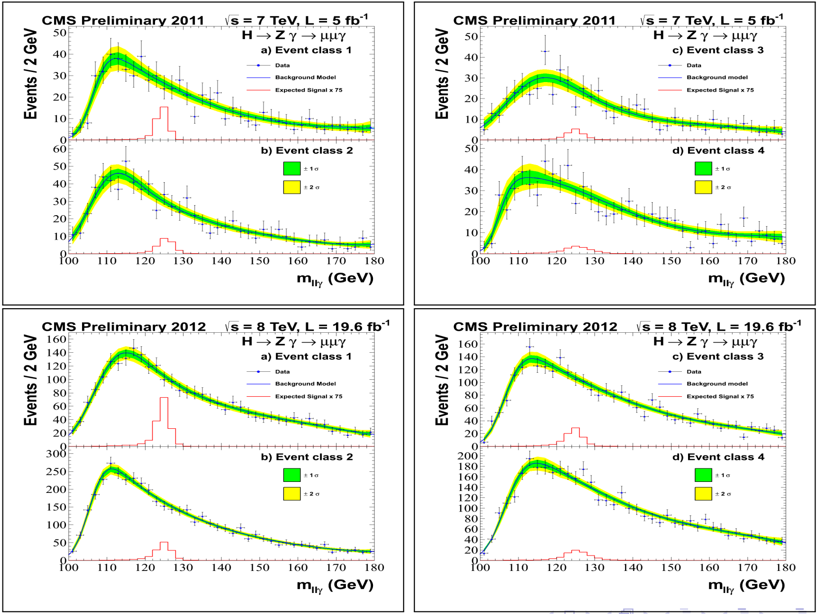
WZ → $3\ell\nu$ enriched sample



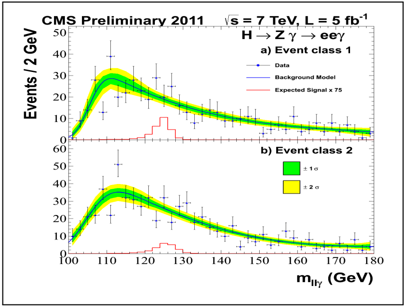
$H \to Z\gamma$ Categories

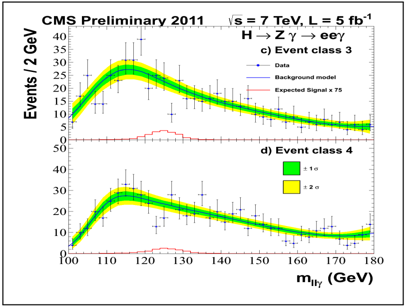
	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
	Event class 1	
	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 1.4442$ $R_9 > 0.94$	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 2.1$ and one lepton $0 < \|\eta\| < 0.9$ $R_9 > 0.94$
Data Signal σ_{eff} FWHM	17% 30% 1.9 GeV 4.5 GeV	20% 34% 1.6 GeV 3.7 GeV
	Event class 2	
	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 1.4442$ $R_9 < 0.94$	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 2.1$ and one lepton $0 < \|\eta\| < 0.9$ $R_9 < 0.94$
Data Signal σ_{eff} FWHM	26% 28% 2.1 GeV 5.0 GeV	31% 31% 1.9 GeV 4.6 GeV
	Event class 3	
	Photon $0 < \|\eta\| < 1.4442$ At least one lepton $1.4442 < \|\eta\| < 2.5$ No requirement on R_9	Photon $0 < \|\eta\| < 1.4442$ Both leptons in $\|\eta\| > 0.9$ or one lepton in $2.1 < \|\eta\| < 2.4$ No requirement on R_9
Data Signal σ_{eff} FWHM	26% 23% 3.1 GeV 7.3 GeV	20% 18% 2.1 GeV 5.0 GeV
	Event class 4	
	Photon $1.566 < \|\eta\| < 2.5$ Both leptons $0 < \|\eta\| < 2.5$ No requirement on R_9	Photon $1.566 < \|\eta\| < 2.5$ Both leptons $0 < \|\eta\| < 2.4$ No requirement on R_9
Data Signal σ_{eff} FWHM	31% 19% 3.3 GeV 7.8 GeV	29% 17% 3.2 GeV 7.5 GeV

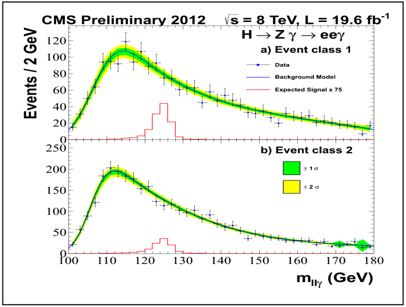
$H \to Z\gamma$ Mass Distributions (I)

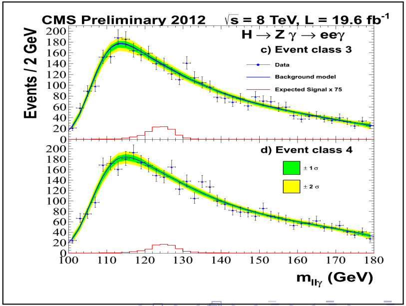


H → Zγ Mass Distributions (II)

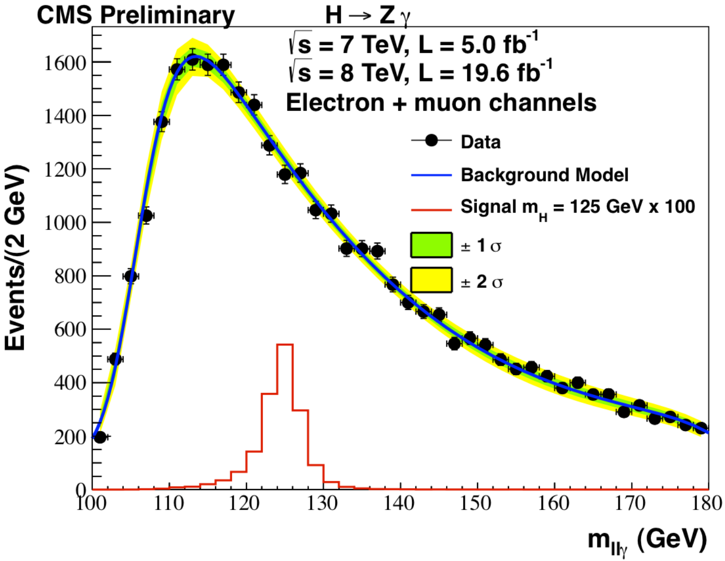




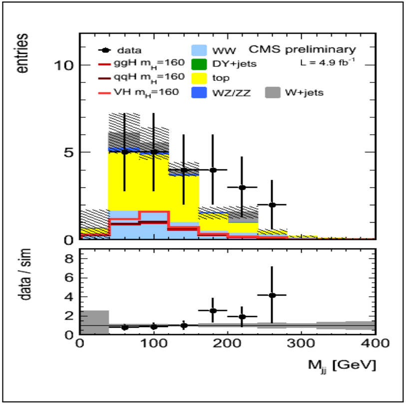


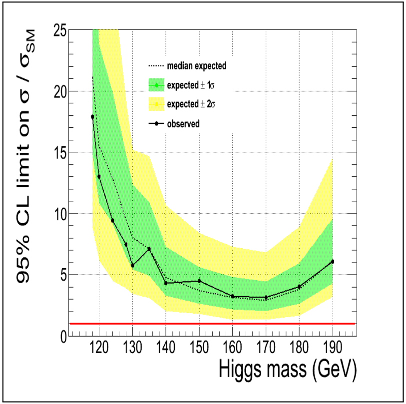


$H \to Z\gamma$ All Channels Together



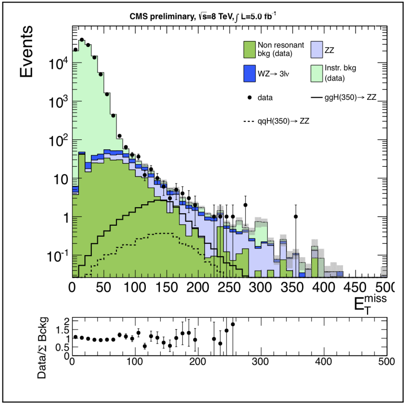
$\mathrm{W/ZH} \rightarrow qq'\mathrm{WW} \rightarrow qq'2\ell 2\nu$

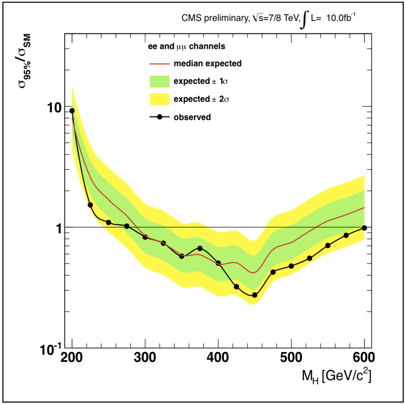




- Two leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$ and two jets in the final state
- Make use techniques from $\mathrm{H} \rightarrow \mathrm{WW} \rightarrow 2\ell 2\nu$ main analysis

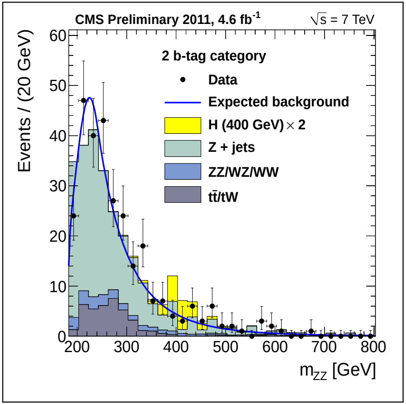
$\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu$

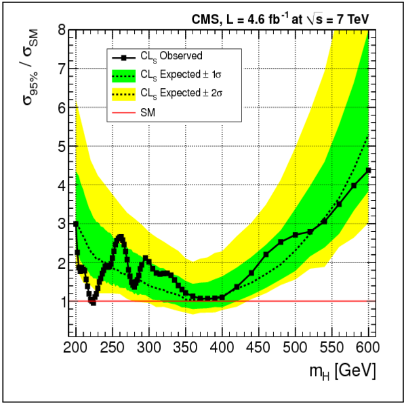




- Two leptons from a Z boson, large $E_{\mathrm{T}}^{\mathrm{miss}}$
- Using m_T as final variable
- Split in several categories: electrons/muons, 0/1/2-jets

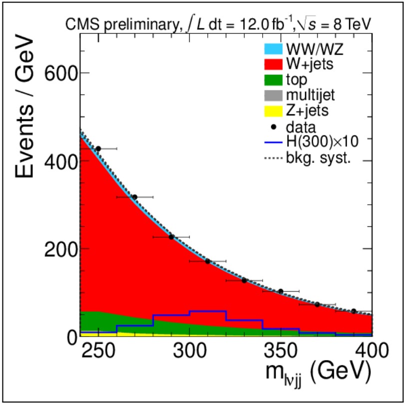
$H \rightarrow ZZ \rightarrow 2q2\ell$

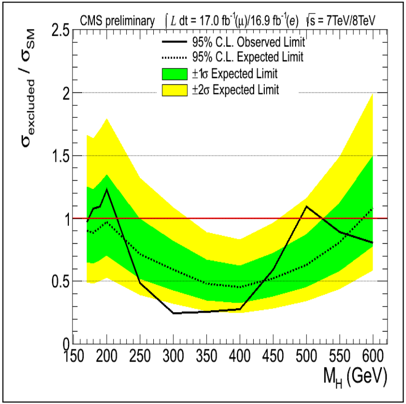




- Two leptons from a Z boson, two jets from another Z boson
- Using $m_{2q2\ell}$ as final variable
- Split in several categories: electrons/muons, 0/1/2 b-jets

$\mathrm{H} \rightarrow \mathrm{W}^+\mathrm{W}^- \rightarrow qq'\ell\nu$





- One high p_{T} isolated lepton, at least 2-jets, and large $E_{\mathrm{T}}^{\mathrm{miss}}$
- Using $m_{qq'\ell\nu}$ as final variable
- No significant excess is seen
- Public document: CMS-PAS-HIG-12-046
- Analysis in progress looking at higher masses