CMS
H→WW→lνlν

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on behalf of the CMS collaboration

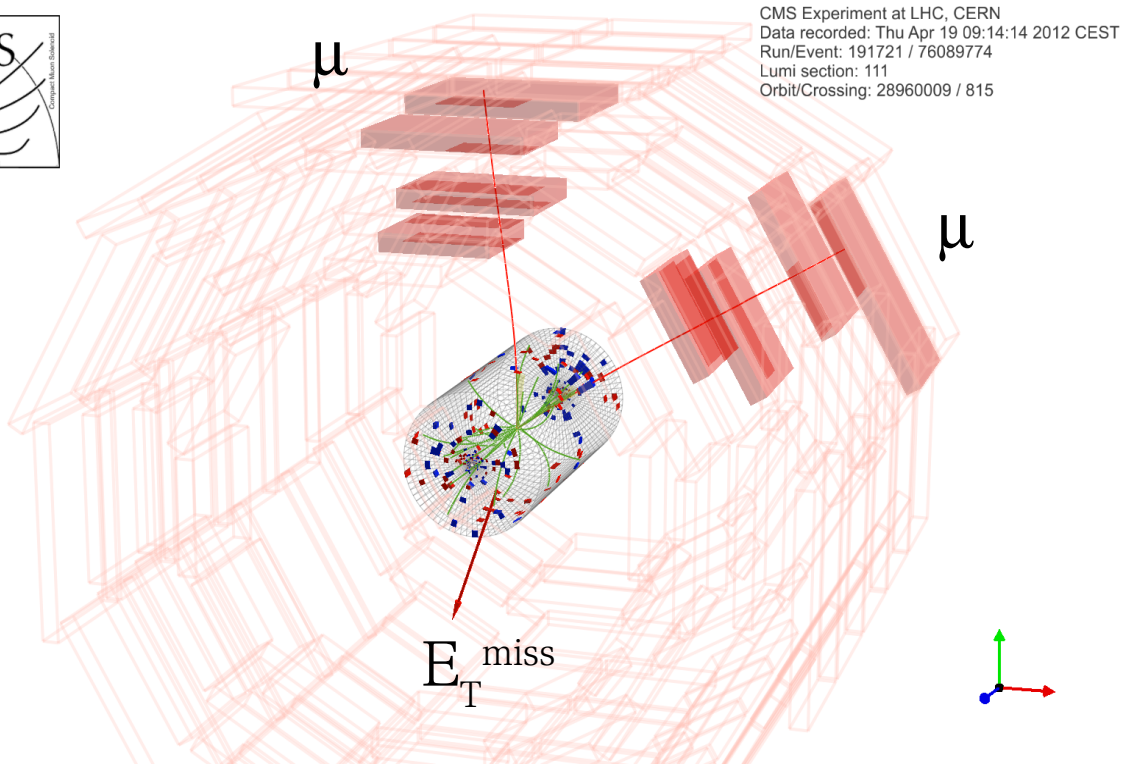
(Northeastern University)

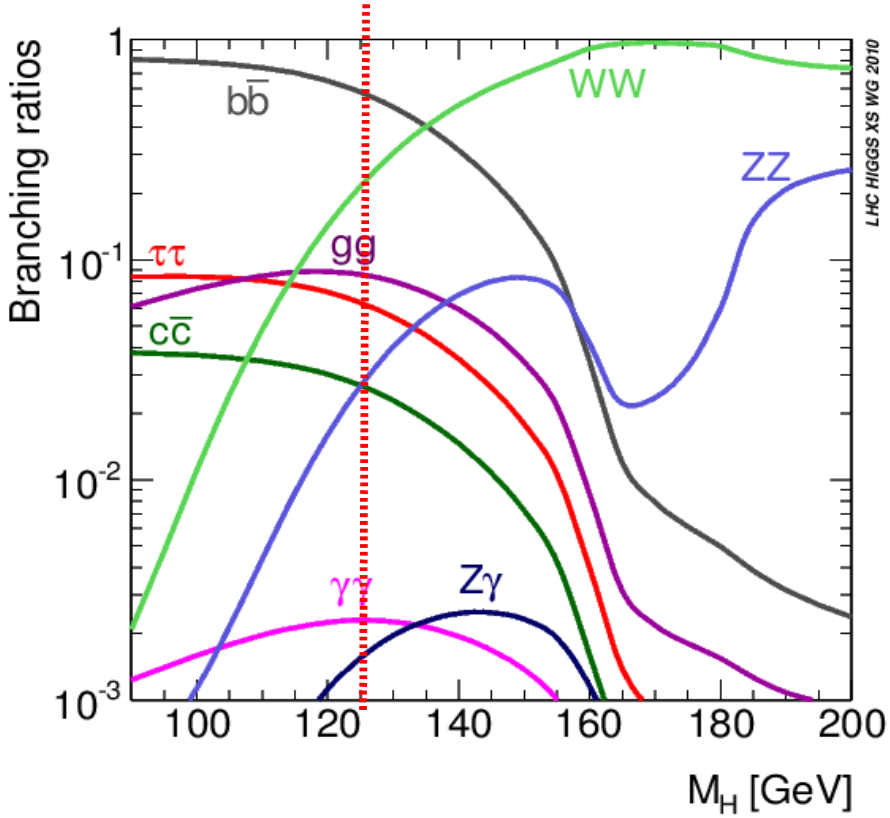
Higgs Hunting 2013

Orsay - France

Outline

- HWW 2l2ν searches
  - Event kinematics
  - Production modes
    - Different analyses
  - Limits and discovery





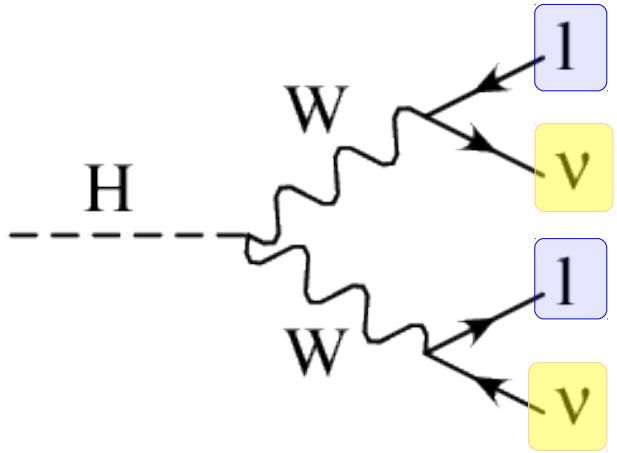
H → WW → lνlν at m_H= 125 GeV
one of the most luminous channels for Higgs searches

Different production modes

ggH	VBF	WH	ZH
436 fb	36 fb	16 fb	9 fb

H → WW → lνlν

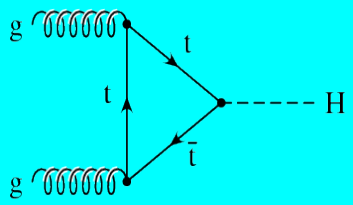
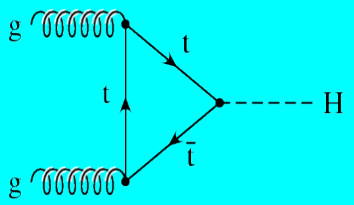
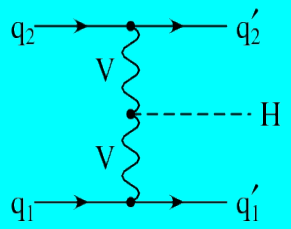
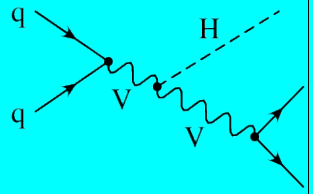
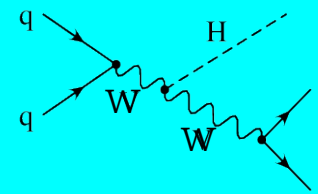
- Final state
  - 2 leptons (e/μ)
  - 2 neutrinos
- Clean signature:
  - 2 high p_T isolated leptons
  - Missing transverse energy E_T^{miss}



- Several production modes have been analyzed:
  - Gluon fusion (**ggH**)
  - Vector Boson Fusion (**VBF**)
  - Associated production (**W/Z H**)

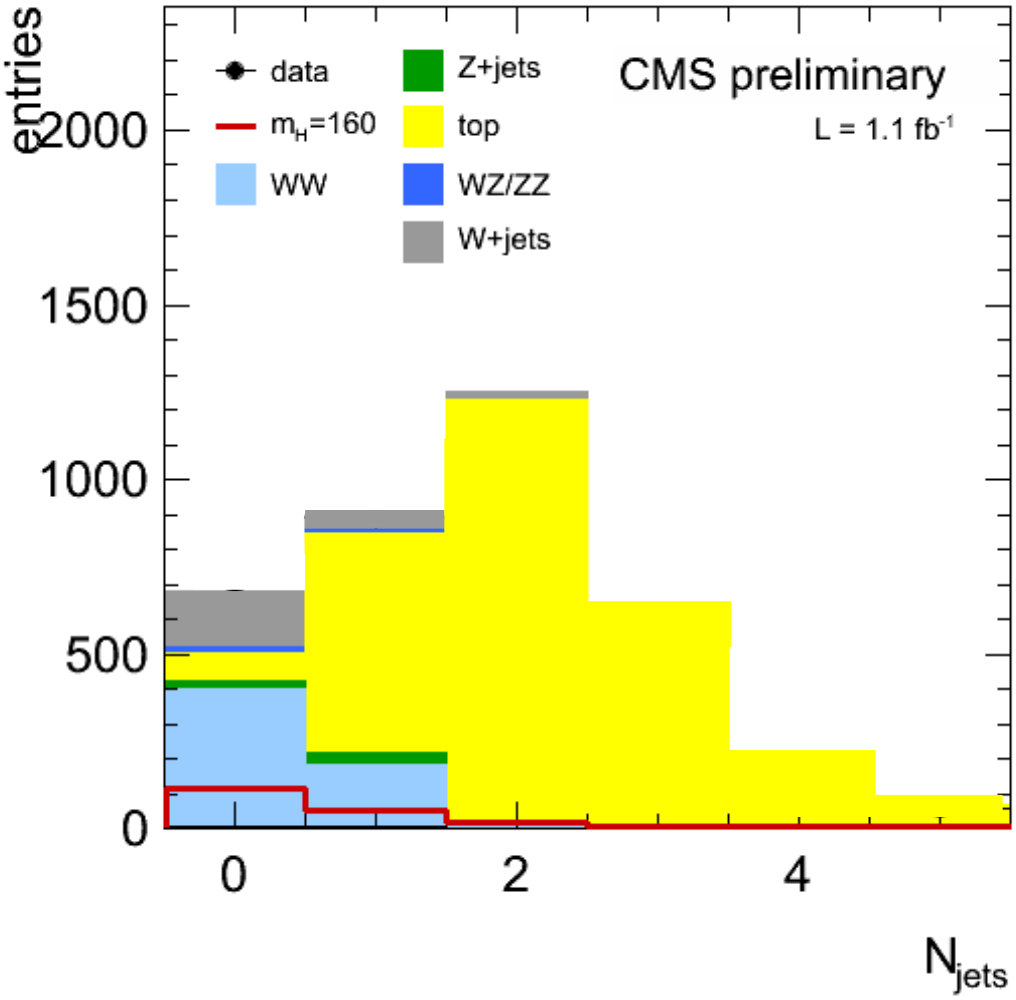
} Measurement of resonance couplings

- Different final states with different background contamination

signature	0 jet	1 jet	2 jet		3 leptons
	ggH	mainly ggH	ggH and VBF	ggH and VH	WH
					
bkg	WW & Wjets	WW and Top	Top	Top	WZ

Backgrounds

- Since there is no mass peak it's important to control the background contamination
- Strategies to suppress all the backgrounds have been developed
- The main backgrounds after requiring 2 leptons and E_T^{miss} are:



- **WW → lνlν** → kinematic cuts
- **W + jets** → lepton id and isolation requirements
- **Z/γ + jets** → E_T^{miss} cut and Z invariant mass veto for ee/μμ
- **Top: $t\bar{t}$ and tW** → b-veto for jets
- **WZ** → kinematic cuts and number of leptons

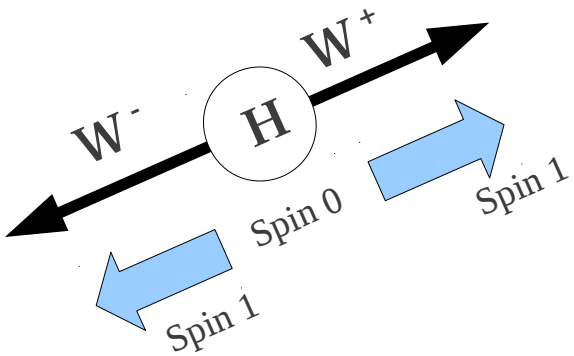
- Data driven estimation for each background has been developed
- Important kinematic distributions checked in phase spaces dominated by a single background
- Relative background importance depends on the actual final state analyzed

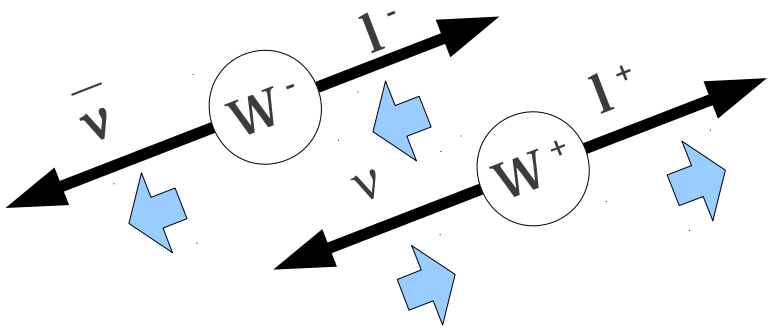
Selections for H → WW → lνlν

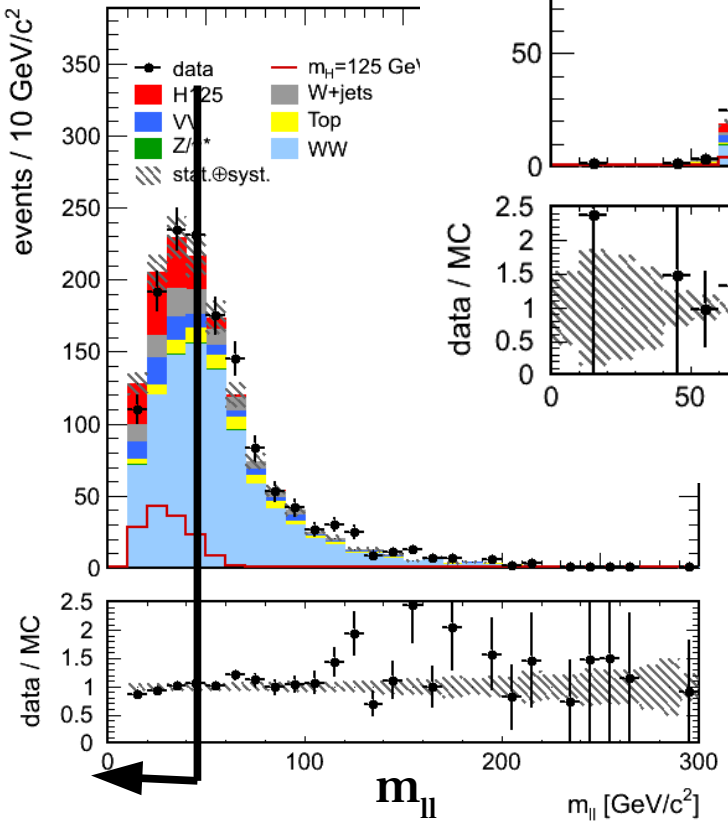
- No mass peak → transverse mass (m_T)

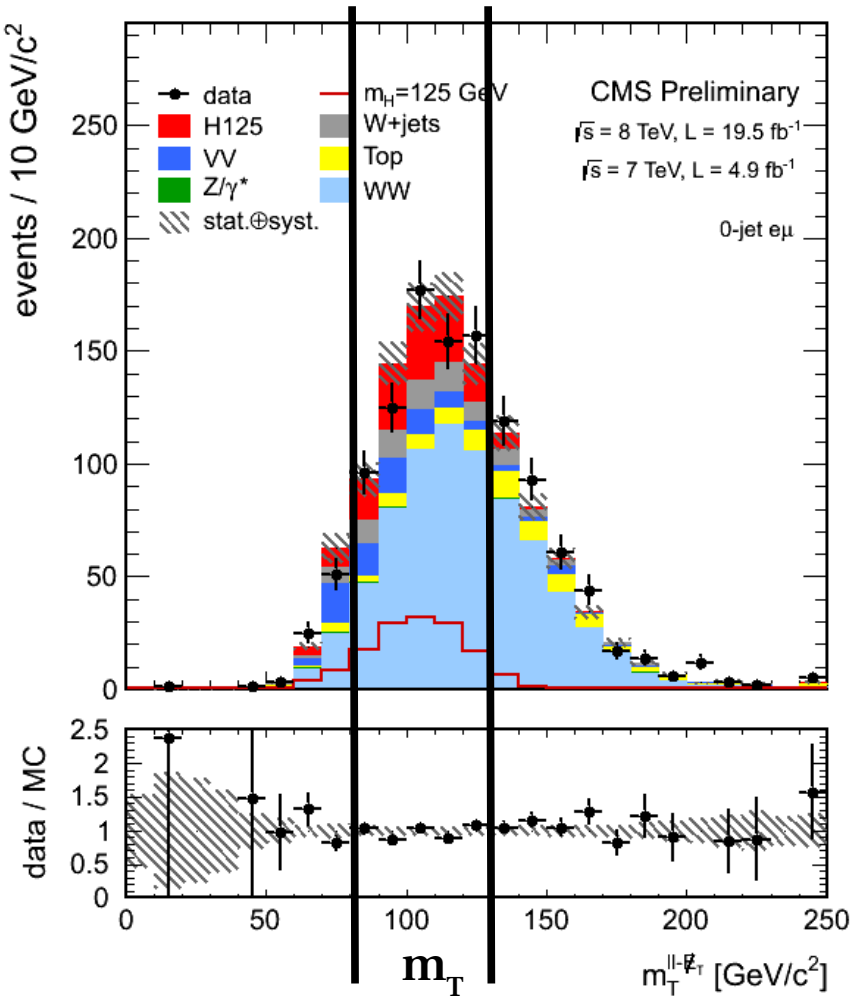
$$m_T = \sqrt{2 \cdot p_T^{\ell\ell} \cdot E_T^{miss} \left(1 - cos\Delta\phi_{\ell\ell, E_T^{miss}}\right)}$$

- Exploiting kinematics of Higgs decay products
  - Low invariant mass of di-lepton system (m_{ll})
  - Low azimuthal angular distance ($\Delta\phi_{ll}$)







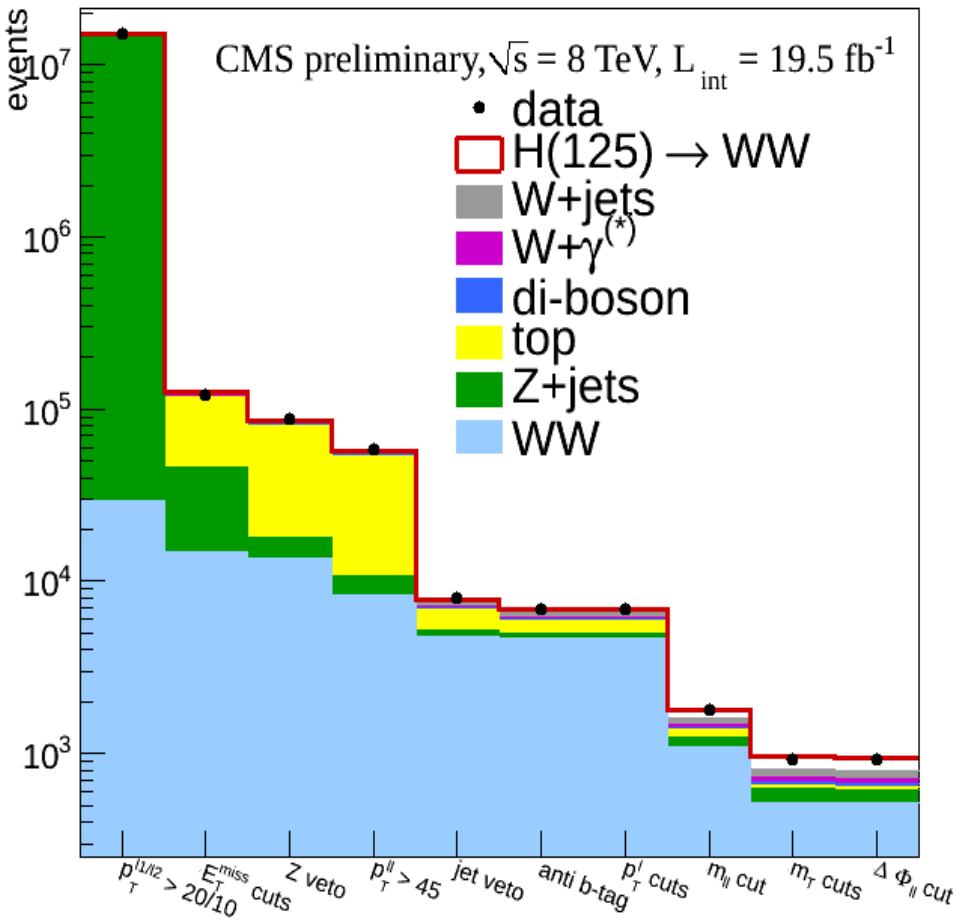


N-1 plot

ggH H → WW → lνlν

CMS-PAS-HIG-13-003

- Gluon fusion (ggH)
  - Basic preselections to suppress background
  - **0 jet** and **1 jet** in the event and **ee/μμ** and **eμ** final states treated separately
    - Different backgrounds → divide et impera
  - Analysis approach:
    - Shape analysis in eμ final state on kinematics variables: $\mathbf{m_{ll}}$ **:** $\mathbf{m_T}$
    - Cut based analysis as a cross check

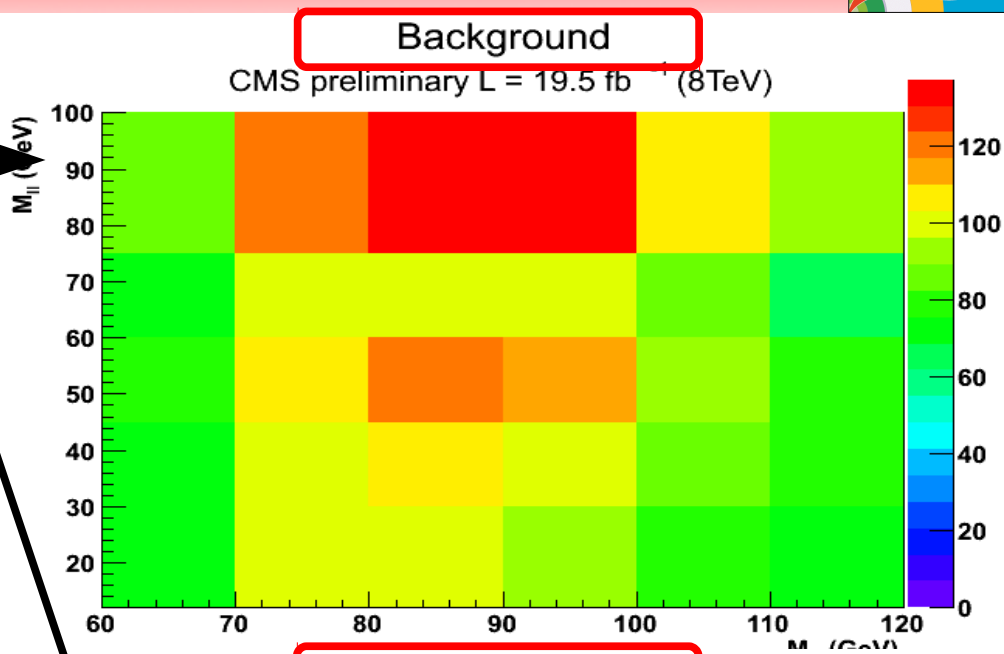


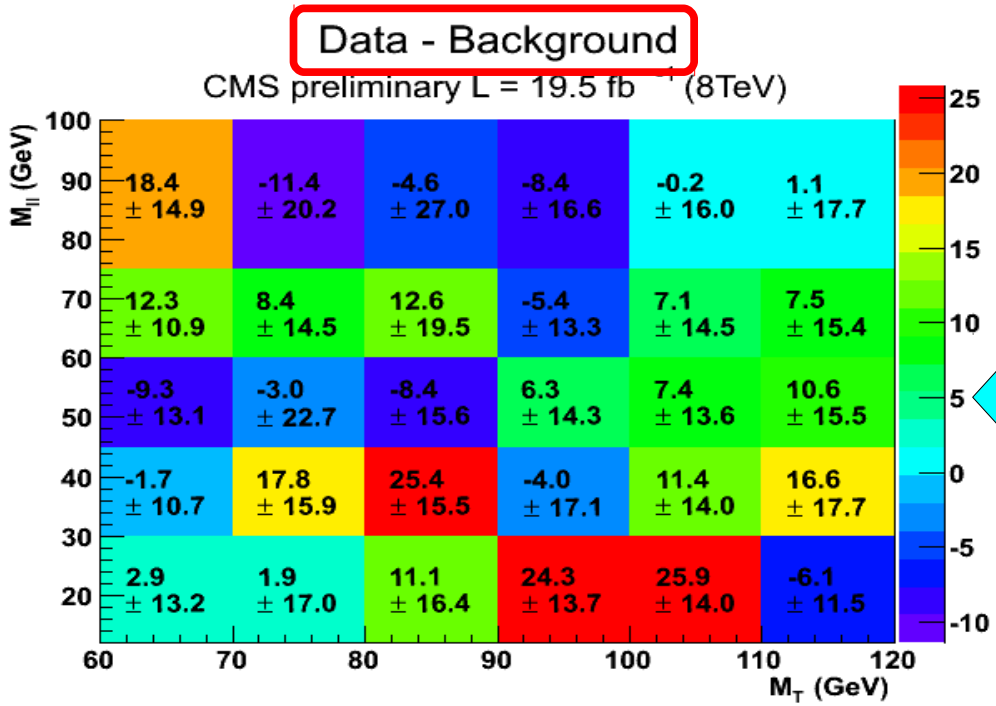
19.5 fb^{-1} at 8 TeV

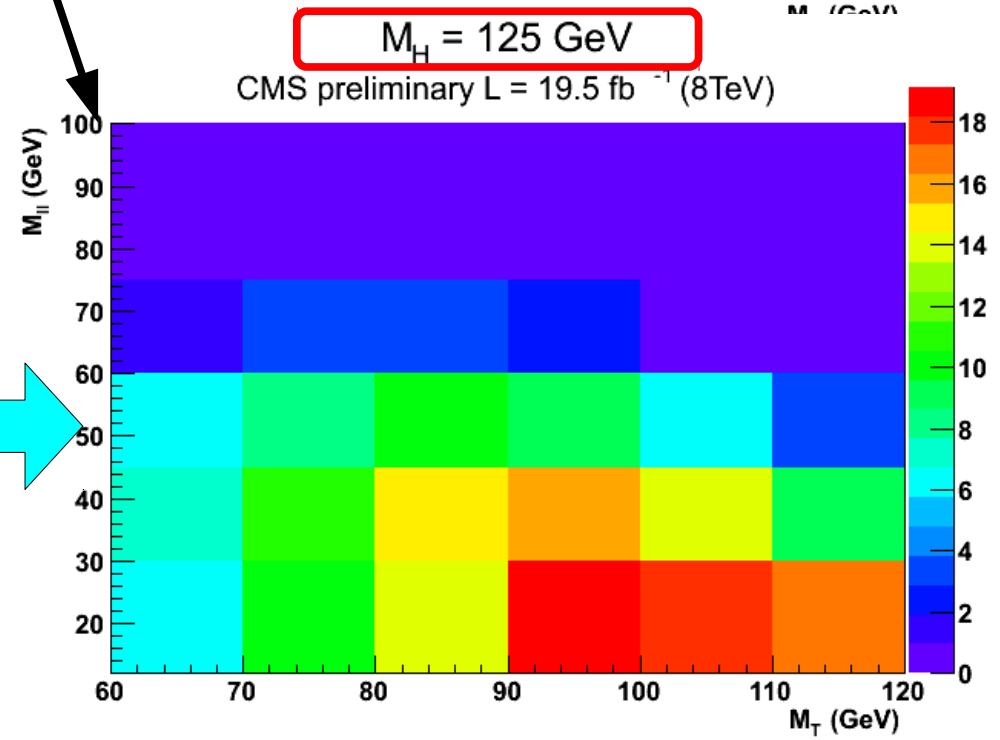
channel		Data	Signal	Background
0 jet	eμ	505	90 ± 19	429 ± 34
	ee/μμ	421	56 ± 12	360 ± 38
1 jet	eμ	228	42 ± 12	209 ± 14
	ee/μμ	140	18 ± 5	111 ± 9

ggH shape analysis

- Shape analysis on 2D distribution: $m_{ll} : m_T$
  - Different shape for signal and background
  - Different shapes for different backgrounds
- Excess compatible with a SM Higgs boson

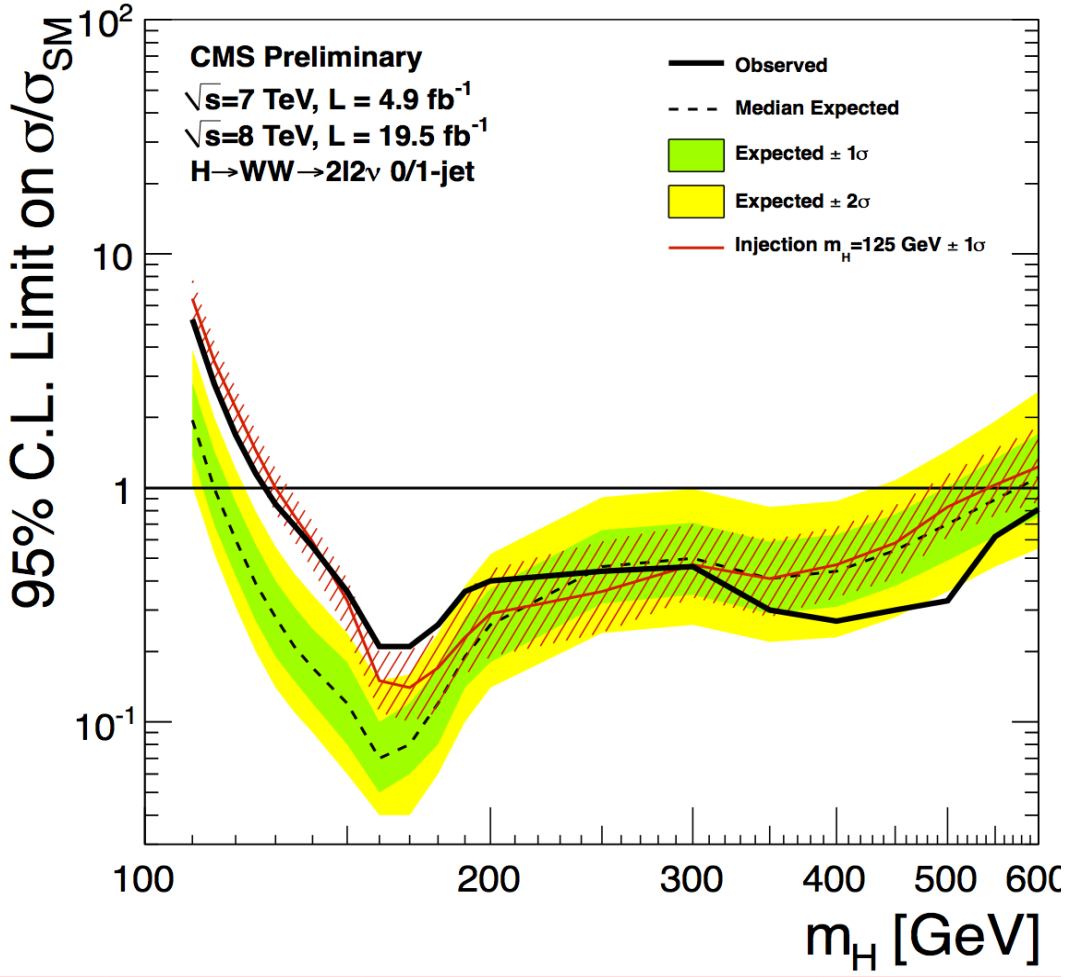


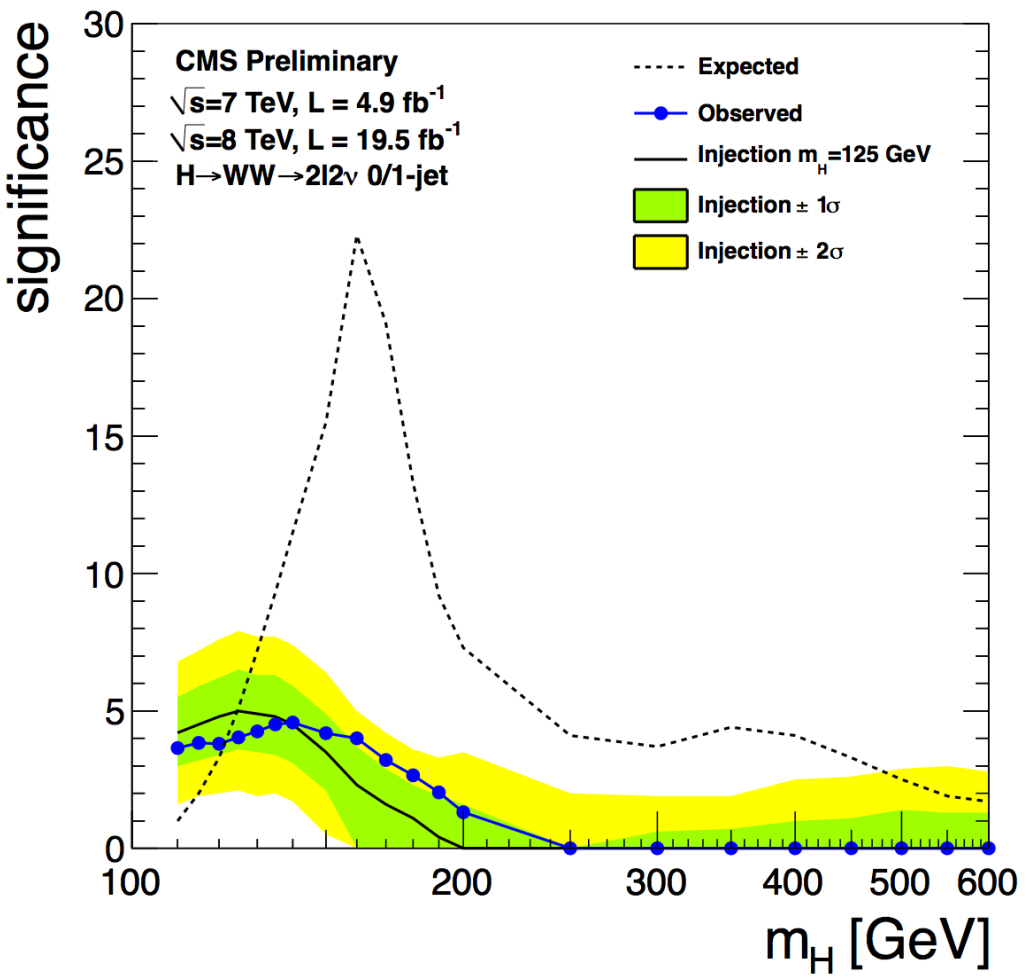




Limits and discovery significance

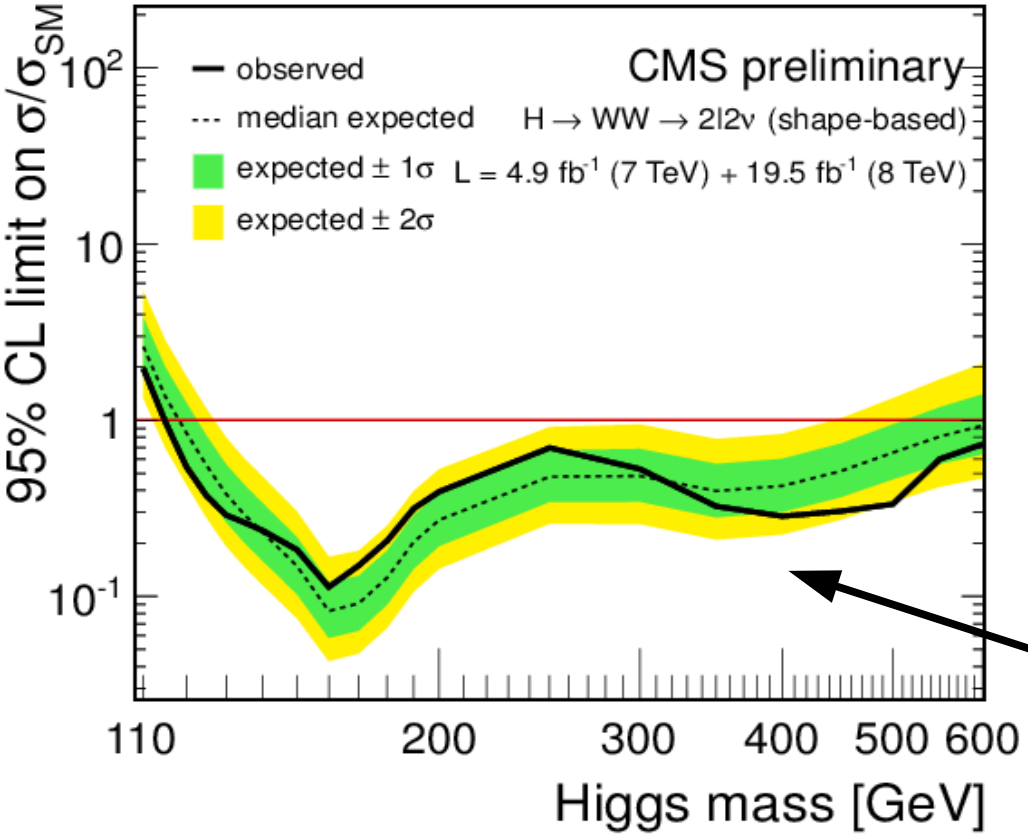
- Limit plot: 95% CL σ/σ_{SM}
  - Injection of a SM Higgs boson (m_H125 GeV)
    - Observed limit compatible with it
  - Excess smaller than expected
- Discovery significance:
  - Injection of a SM Higgs boson (m_H125 GeV)
  - Observed (expected) = **4.0 (5.1) σ**
  - Mass resolution ~ 20%: broad excess

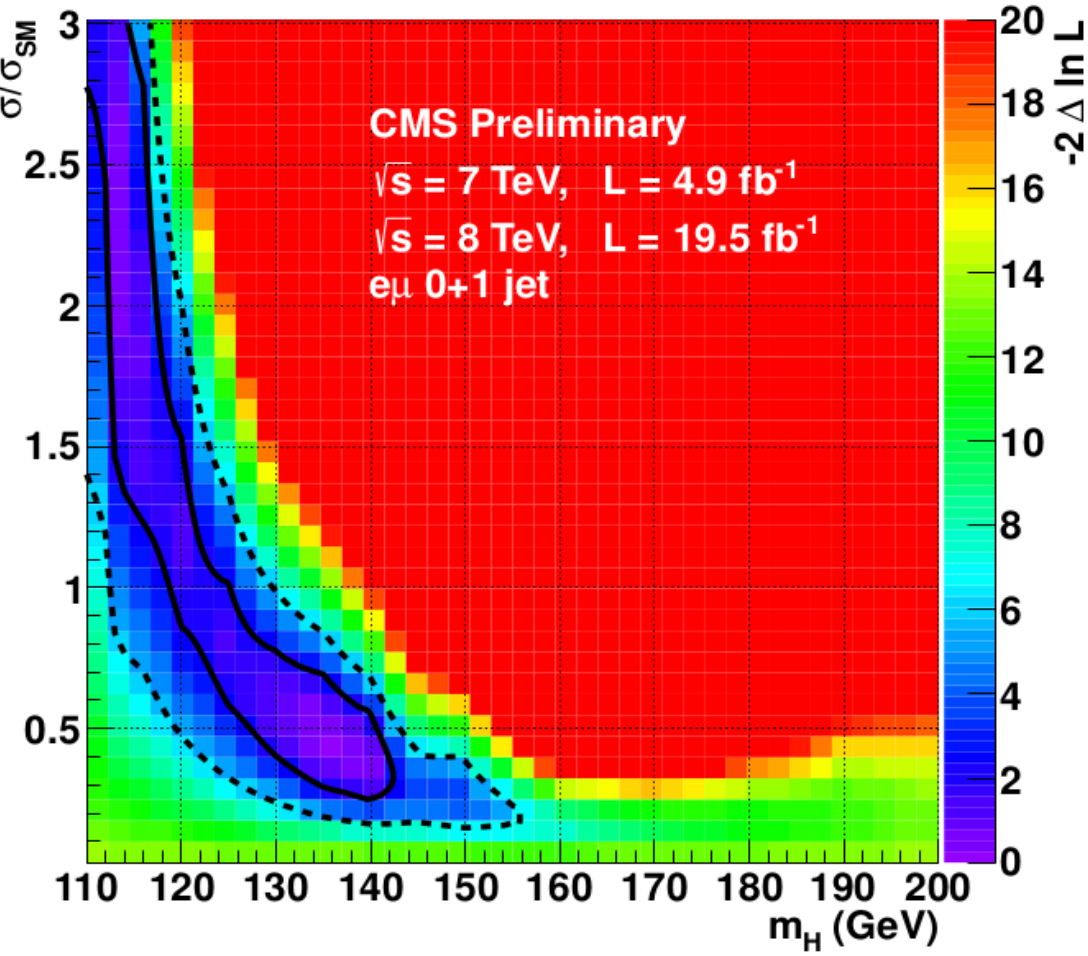




Properties of the resonance

- σ/σ_{SM} scan vs m_H
  - Sensitivity to the mass mainly through σ*BR mass dependence
  - **σ/σ_{SM} = 0.76 ± 0.13 (stat) ± 0.16 (syst)**
    - One of the most accurate channels to measure it!



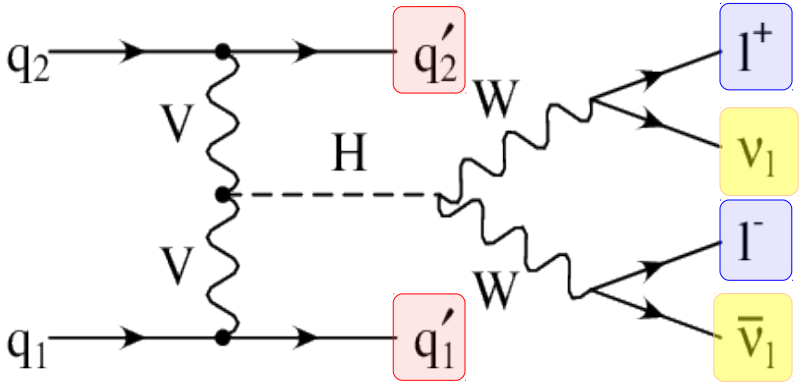


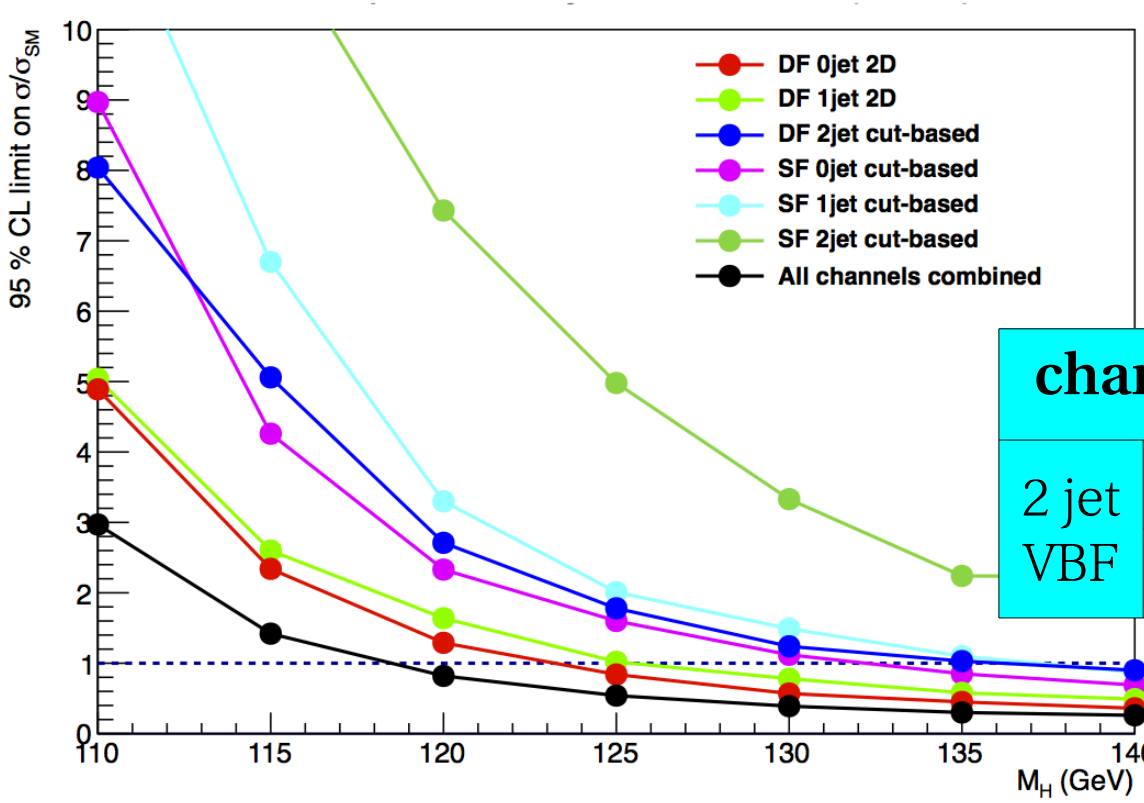
- Are there additional Higgs bosons?
  - Limit plot with the Higgs as a background:
    - No significant excess seen

VBF $H \rightarrow WW \rightarrow l\nu l\nu$

CMS-PAS-HIG-12-042

- Vector Boson Fusion
  - 4.9 fb^{-1} at 7 TeV + 12.1 fb^{-1} at 8 TeV
    - $\Delta\eta_{jj} > 3.5$, $m_{jj} > 500$ GeV and no jet ($p_T > 30$ GeV) between tag jets
    - 80% VBF, 20% ggH
    - High S/B ~ 0.5
  - Stay tuned for fresh new updates in the next weeks





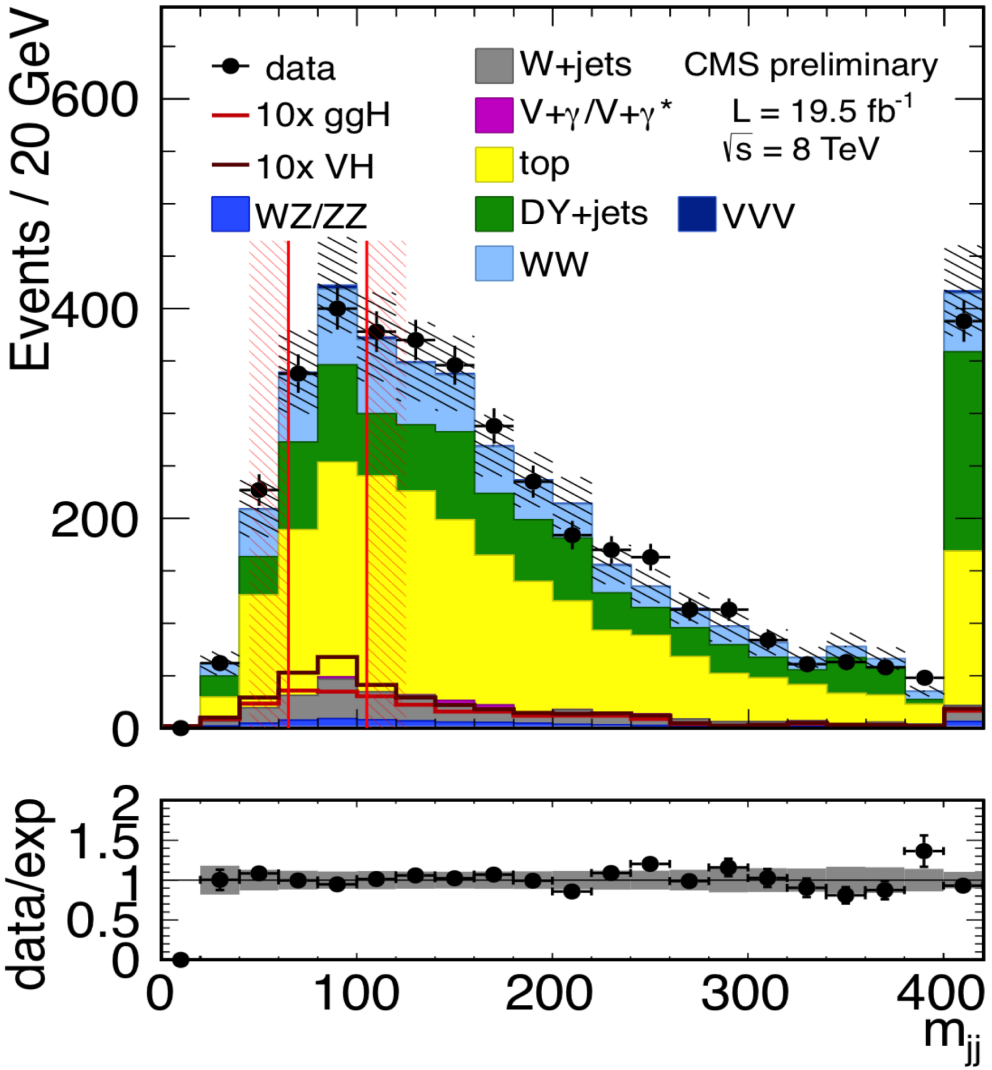
12.1 fb^{-1} at 8 TeV

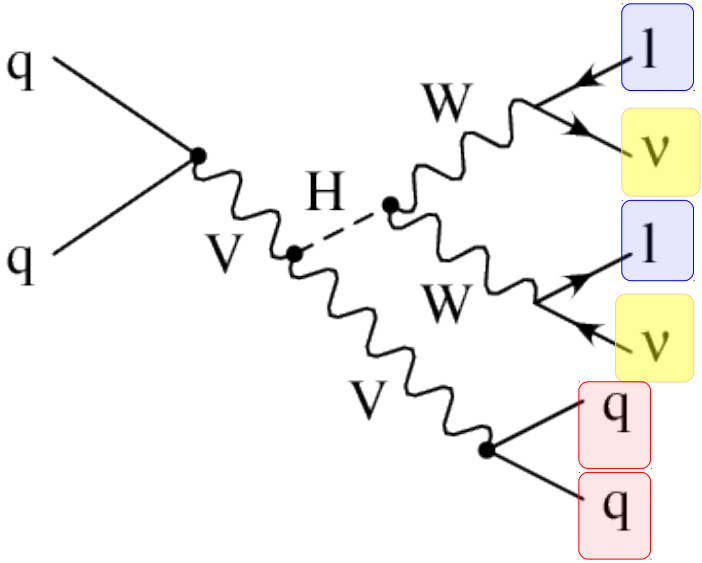
channel		Data	Signal	Background
2 jet VBF	eμ	2	2.8 ± 0.4	2.9 ± 0.8
	ee/μμ	11	1.5 ± 0.2	6.5 ± 1.5

V(jj)H H → WW → lνlν

- Search for Higgs boson in association with a vector boson V (=W/Z)
  - m_{jj} in 65-105 GeV range and $\Delta\eta_{jj} < 1.5$ since V → jj
  - 40% VH, 60% ggH

CMS-PAS-HIG-13-017





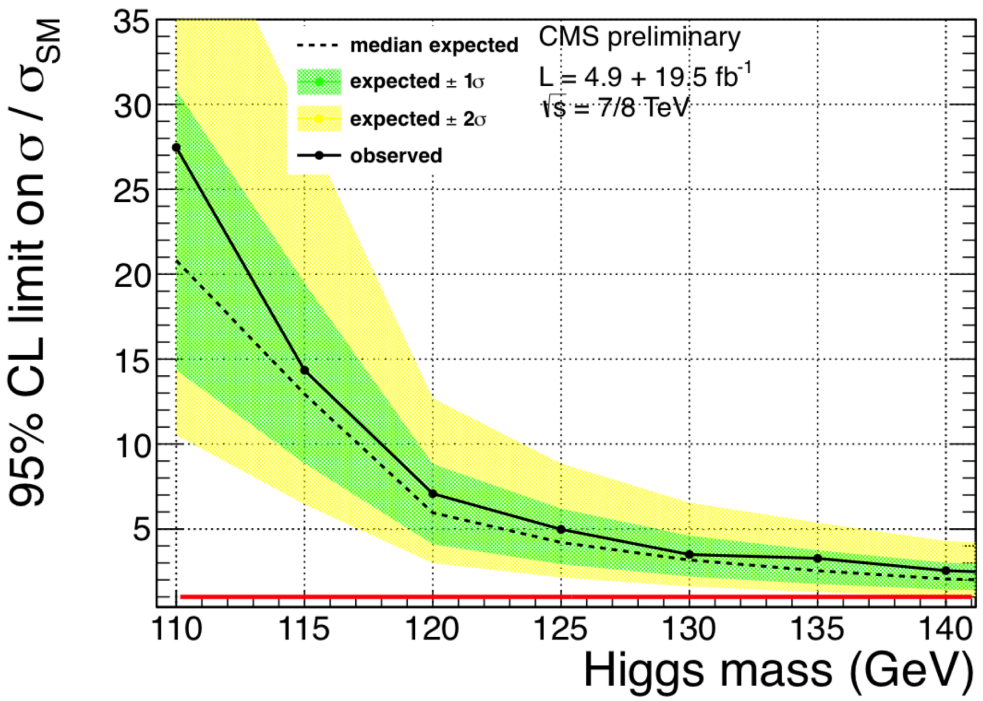
- Analysis approach:
  - **ee/μμ** and **eμ** final states treated separately
  - Cut based analysis (ee/μμ and eμ)
  - Shape analysis on m_{ll} in eμ final state

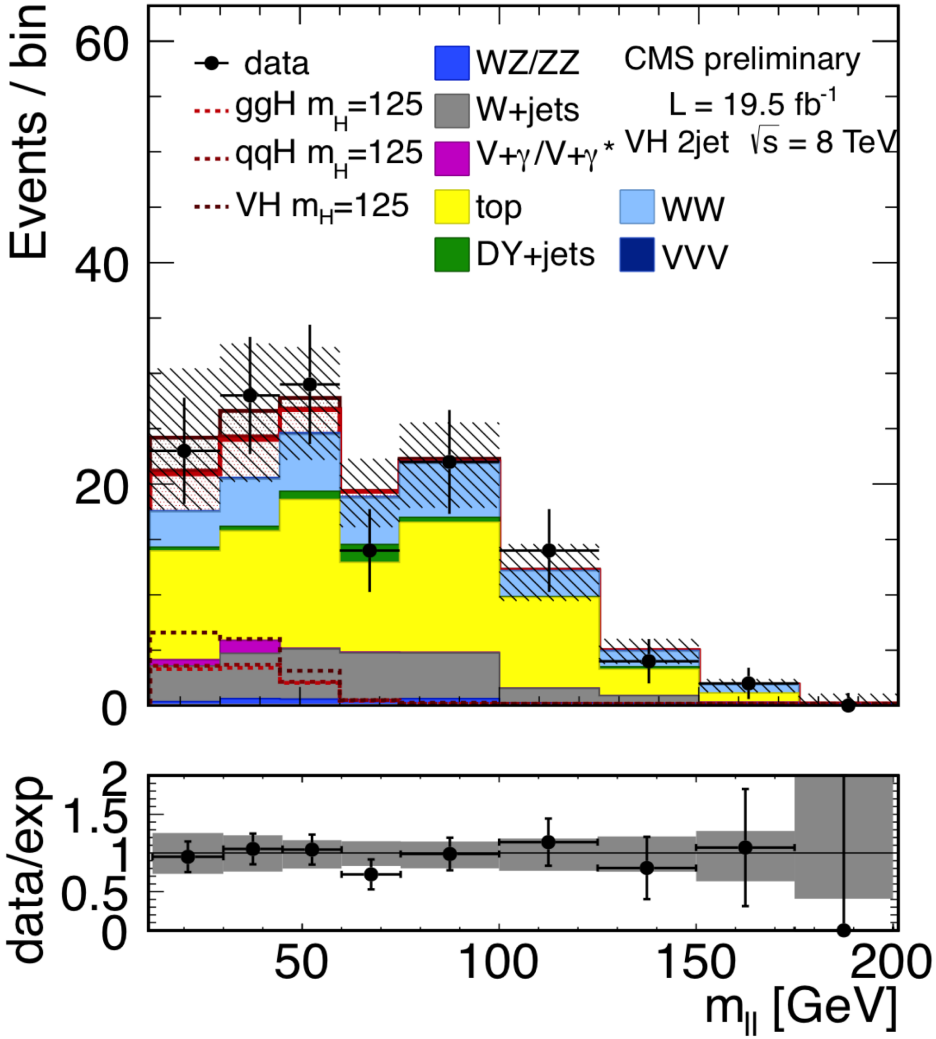
Results V(jj)H H → WW → lνlν

- Observed (expected) limit = 5.0 (4.2)
  - Similar performance for cut based and shape analysis
  - Still statistical dominated

19.5 fb^{-1} at 8 TeV

channel		Data	Signal	Background
2 jet VH	eμ	55	4.2 ± 0.8	43 ± 6
	ee/μμ	79	2.7 ± 0.6	81 ± 8

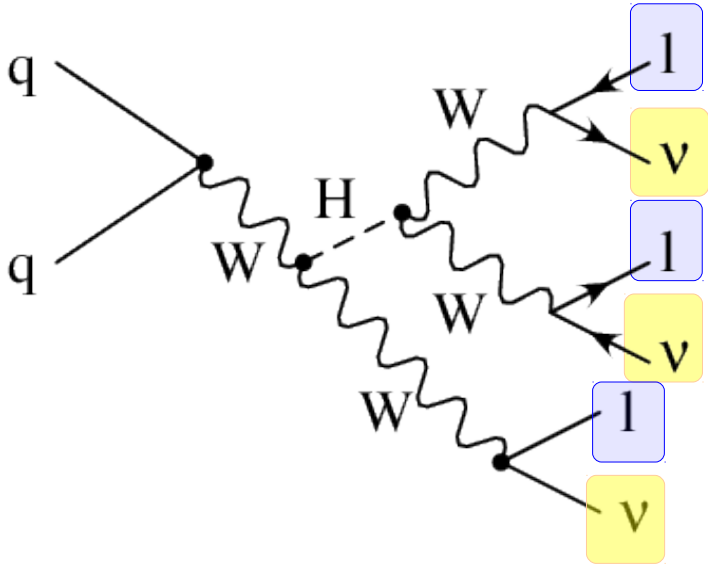


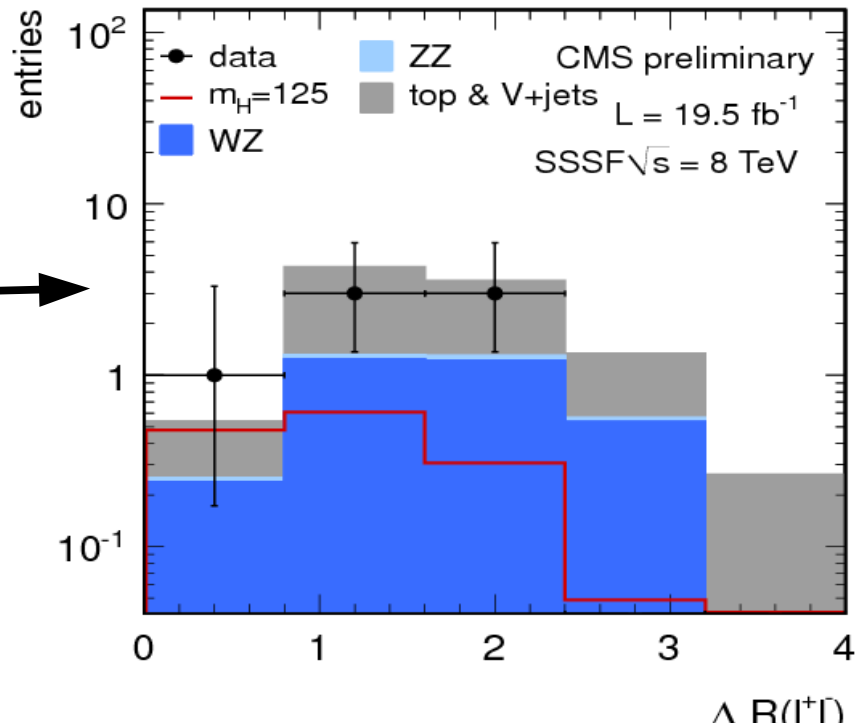


W(lν)H H → WW → lνlν

CMS-PAS-HIG-13-009

- Search for Higgs boson in association with a W
  - **3 leptons** final state:
    - Signature: 3 high p_T leptons and E_T^{miss}
  - Two categories:
    - 2 leptons opposite sign and same flavour (OSSF)
    - otherwise (SSSF)
  - 90% WH → WW, 10% WH → ττ
  - Z veto and b veto to reject WZ and top background
  - Analysis strategy:
    - Cut based
    - Shape analysis on opposite charge leptons $\Delta R_{l^+l^-}$

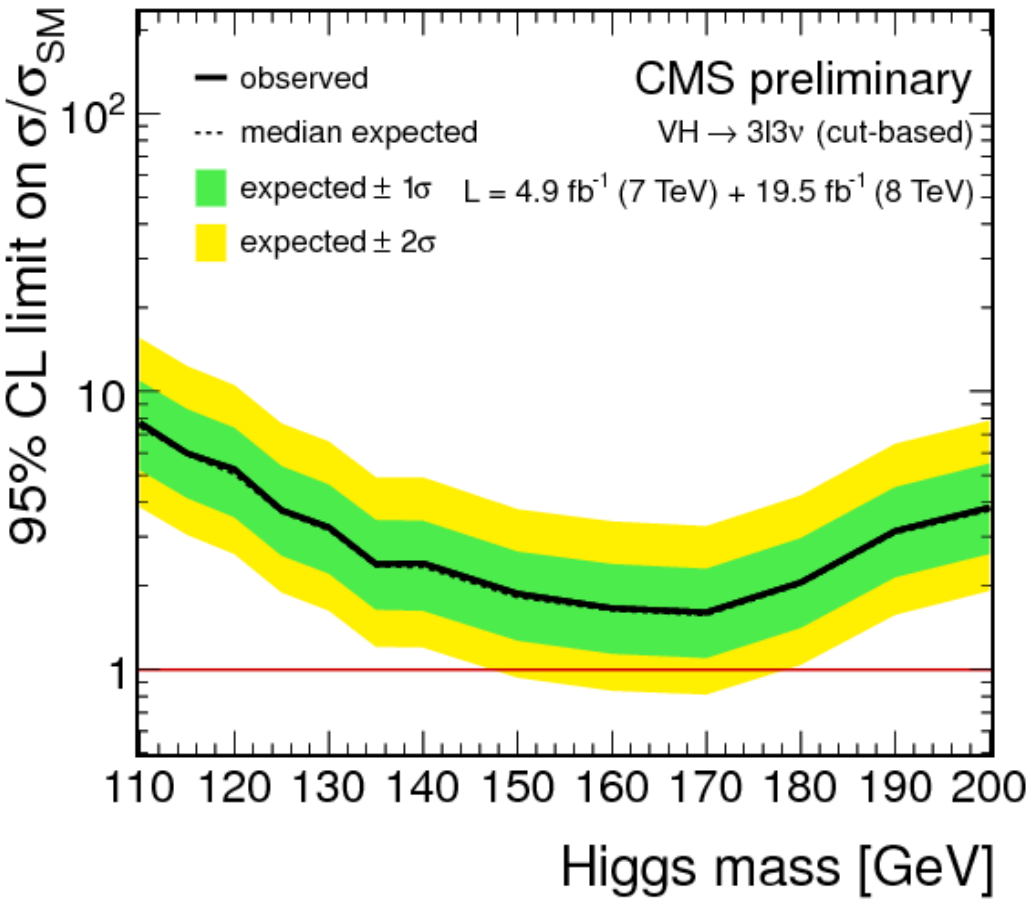




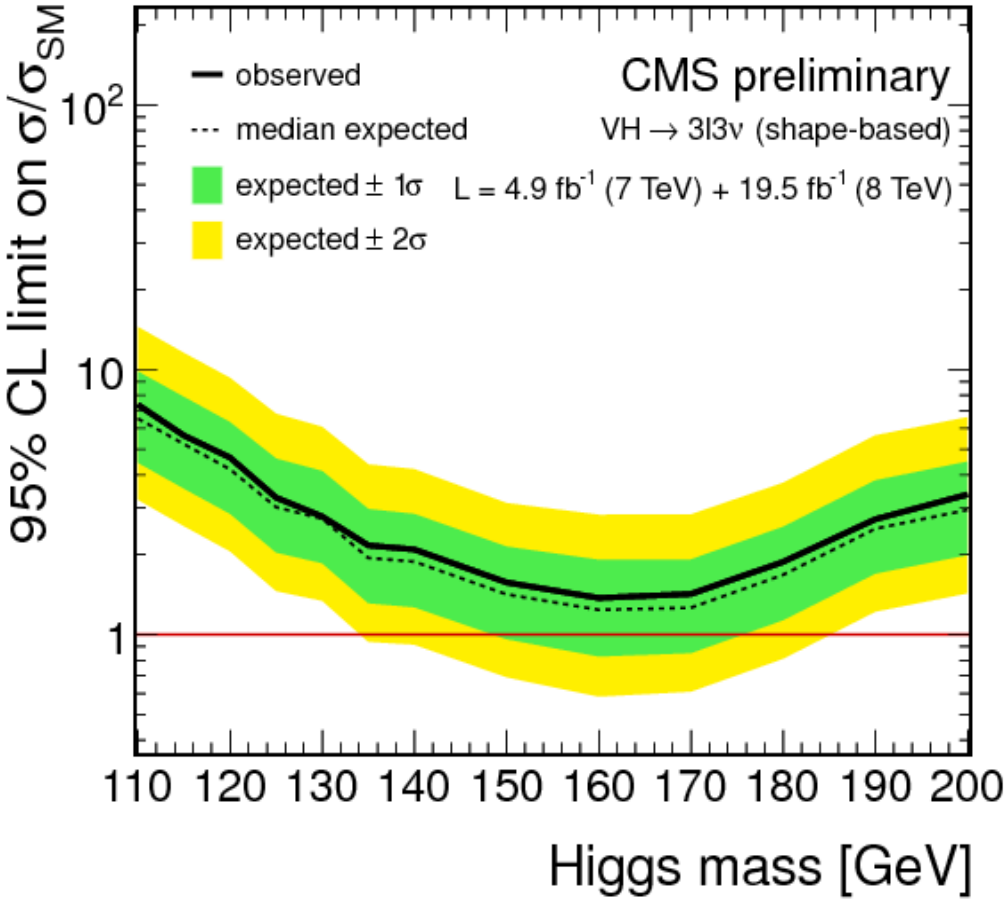
Results W(lν)H H → WW → lνlν

- shape analysis ~ 20% improvement w.r.t. cut based
- Observed (expected) limit = 3.3 (3.0)

cut based



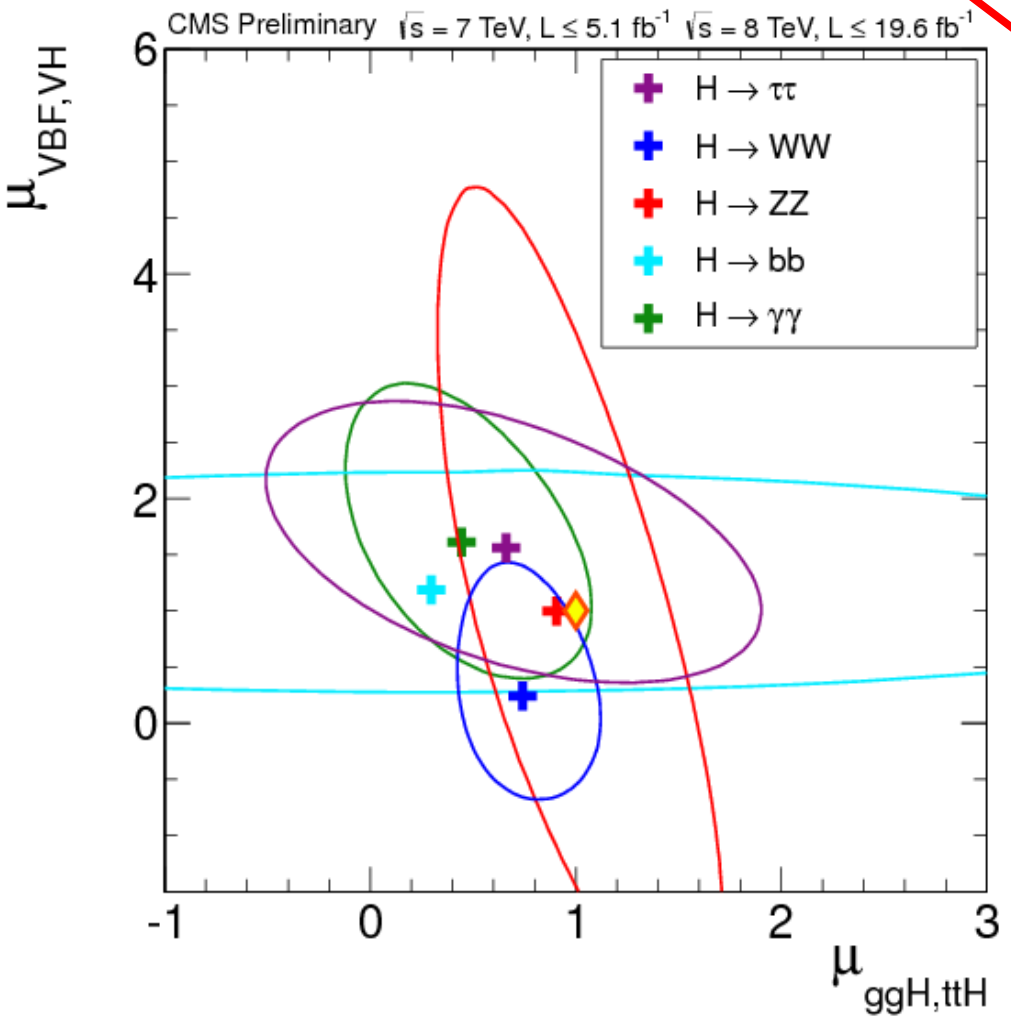
shape based

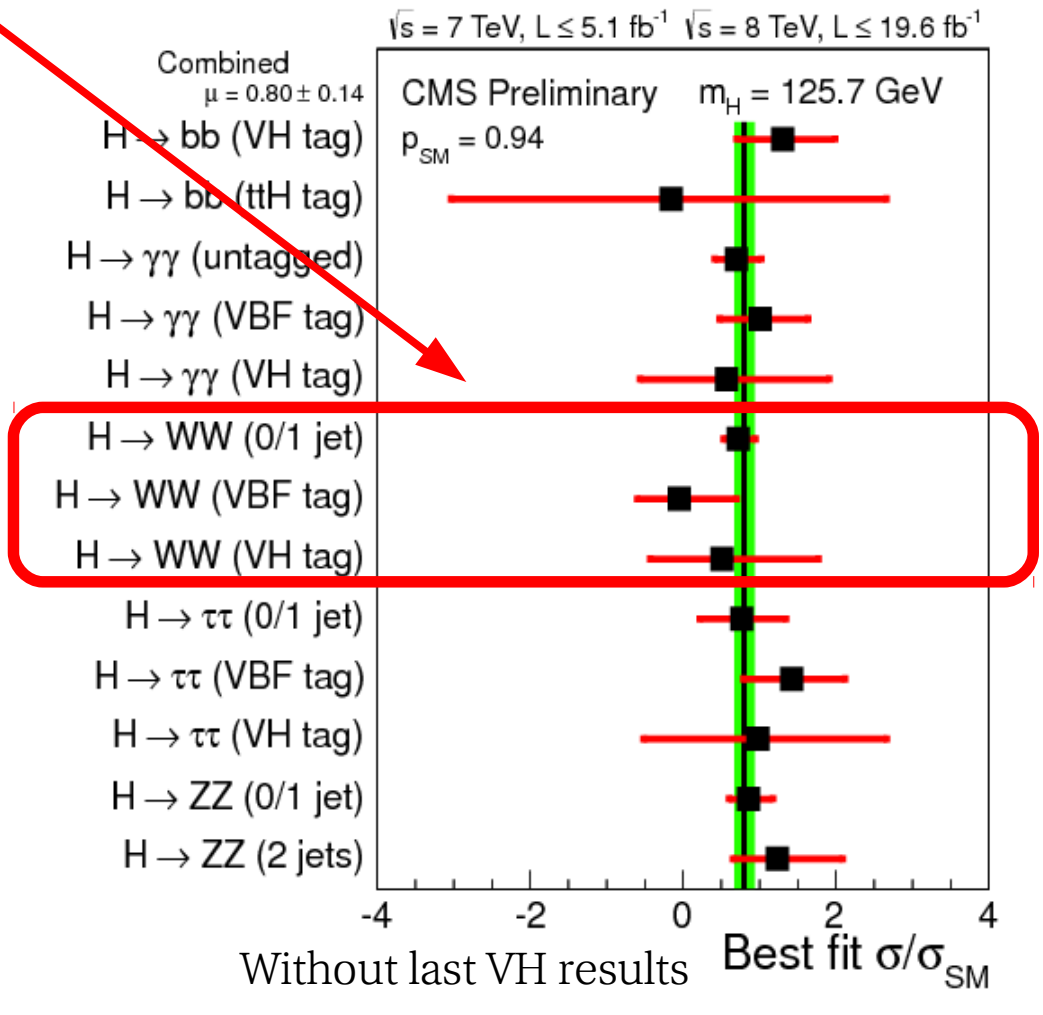


Combining H→WW→lνlν searches

- Sensitivity to the production modes:
  - σ/σ_{SM} **VBF** vs σ/σ_{SM} **ggH**
  - Smaller ellipse!
- Compatibility between different channels

CMS-PAS-HIG-13-005





Without last VH results

Conclusions

- Higgs boson searches at CMS in the **H → WW → lνlν** decay channel

  - The boson has been seen: hundreds of events
    - significance discovery **4.0 σ**
    - the “hunt” is a **success**!

  - Different production modes studied
    - **Gluon fusion**, **Vector Boson Fusion** and **Associate production**
    - Measurement of resonance couplings

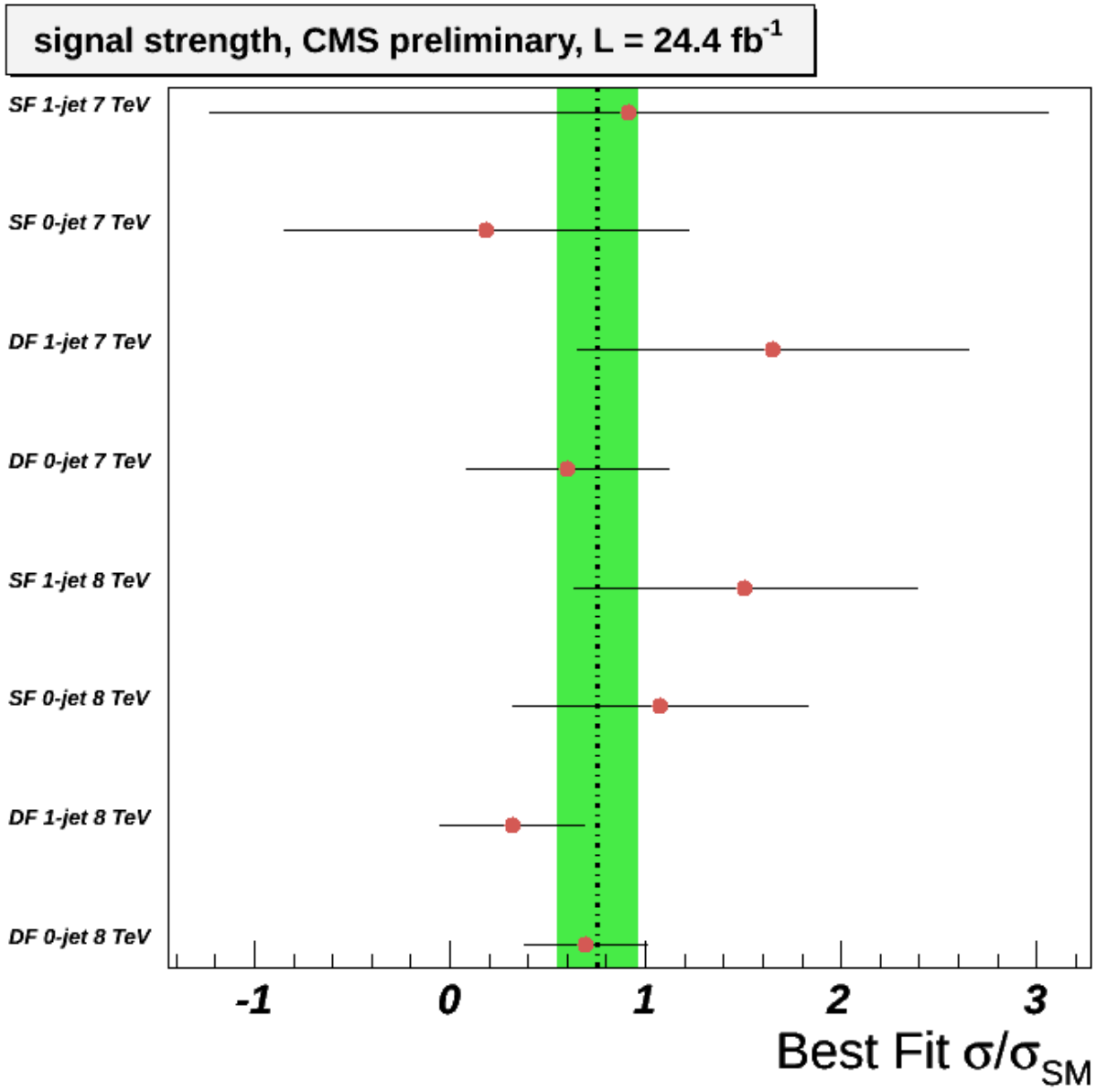
  - Signal strength σ/σ_{SM} **= 0.76 ± 0.13 (stat) ± 0.16 (syst)**

  - Now it's time to measure the Higgs boson properties: spin (see talk by Sten Luyckx and Sara Bolognesi)
  - And prepare for the next run at 13 TeV!

Backup

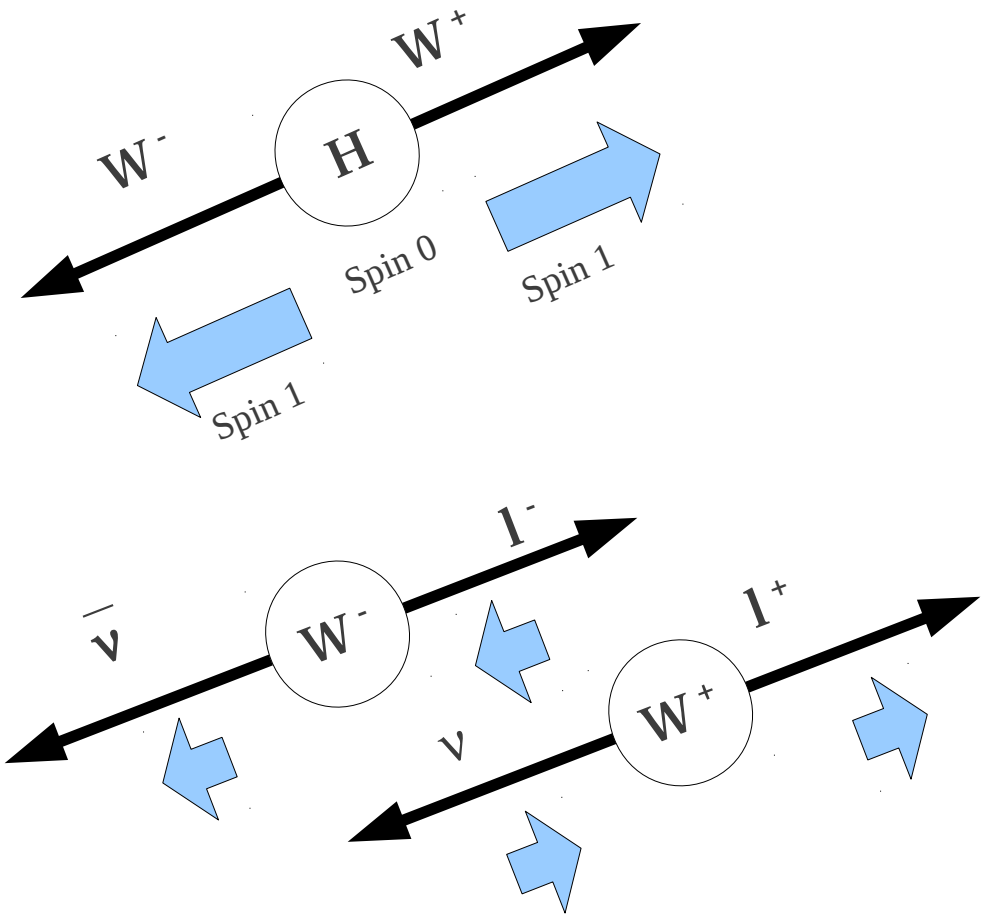
HWW sub-channels

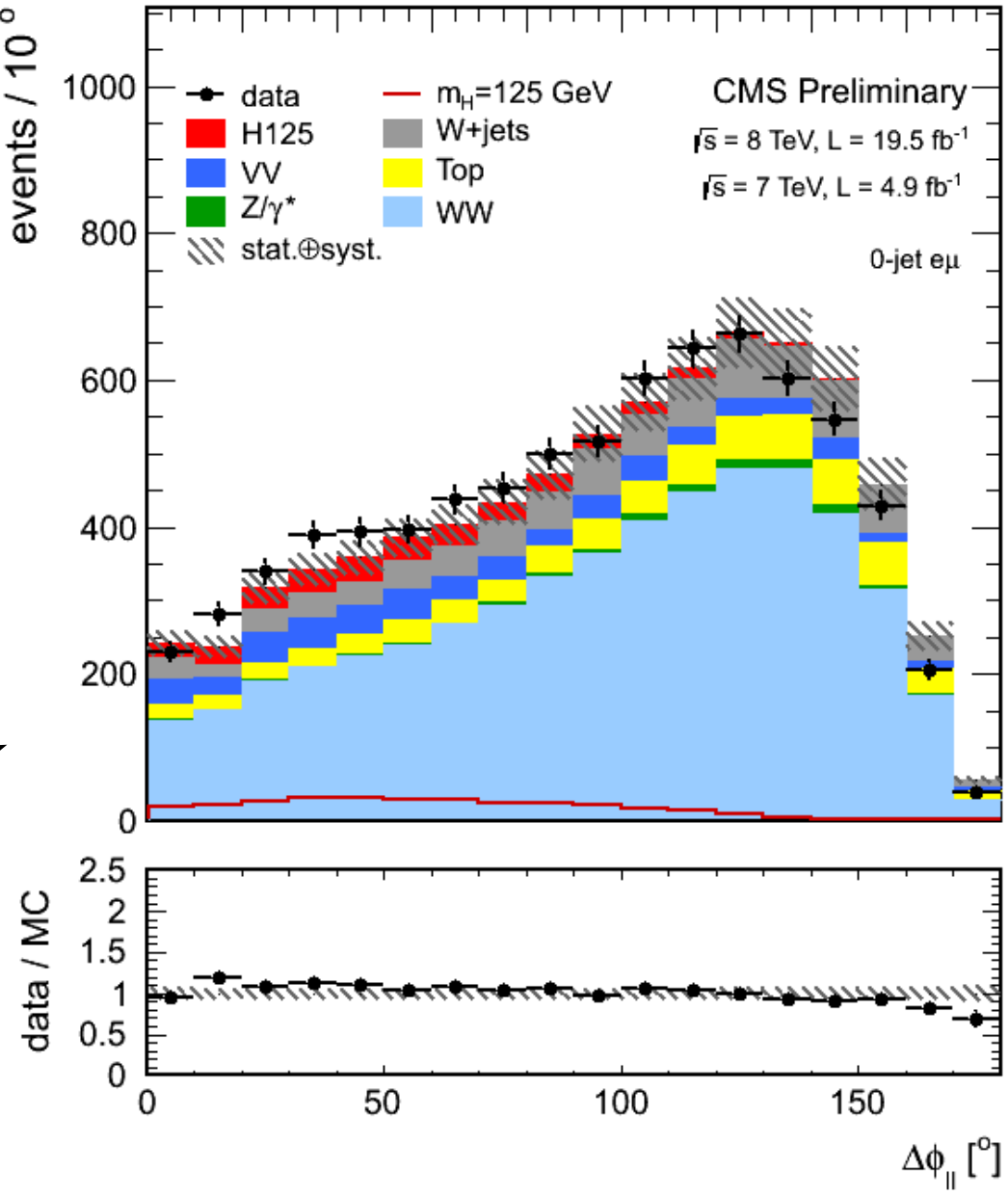
- Main analyses: 0 jet and 1 jet
- Compatibility between different channels



Azimuthal angular distance $\Delta\phi_{ll}$

- Azimuthal distance ($\Delta\phi_{ll}$) between the two leptons





Results cut based W(lν)H H → WW → lνlν

- Event yields for cut based analysis

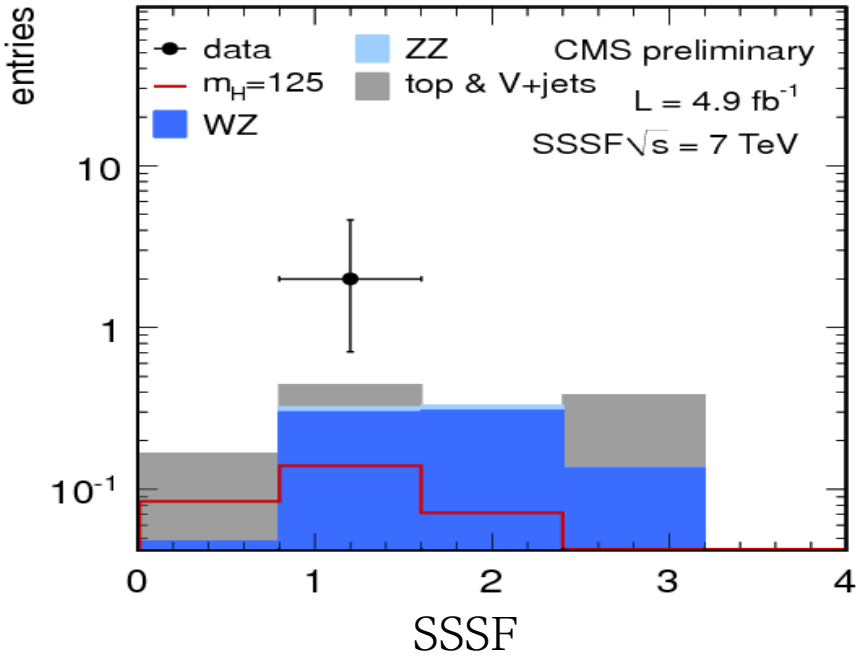
4.9 fb^{-1} at 7 TeV

channel		Data	Signal	Background
3 lep WH	SSSF	2	0.26± 0.01	0.8 ± 0.2
	OSSF	5	0.52± 0.01	6.7 ± 0.5

19.5 fb^{-1} at 8 TeV

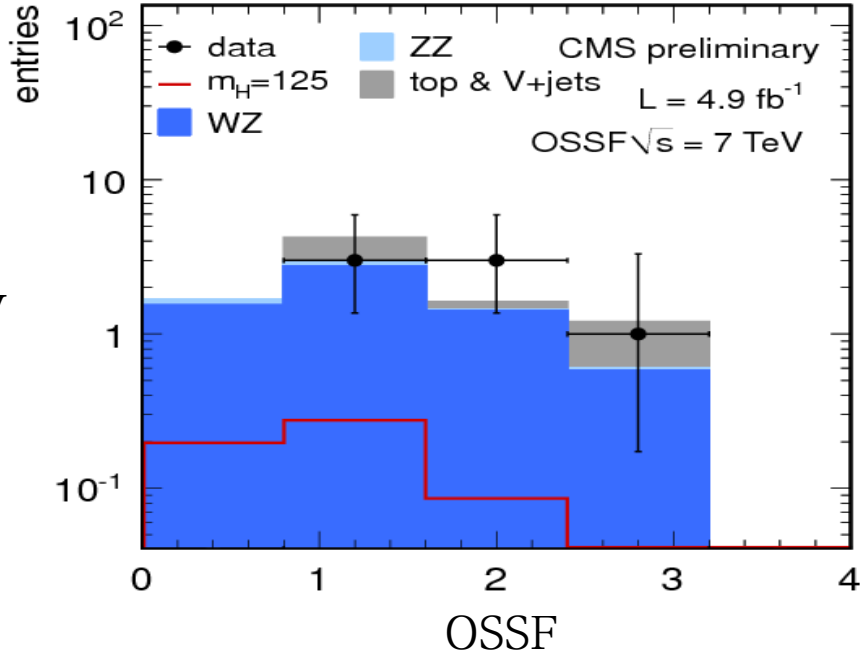
channel		Data	Signal	Background
3 lep WH	SSSF	6	1.1 ± 0.2	6.9 ± 0.9
	OSSF	33	2.2 ± 0.2	33 ± 1

Shape distributions W(lν)H H → WW → lνlν

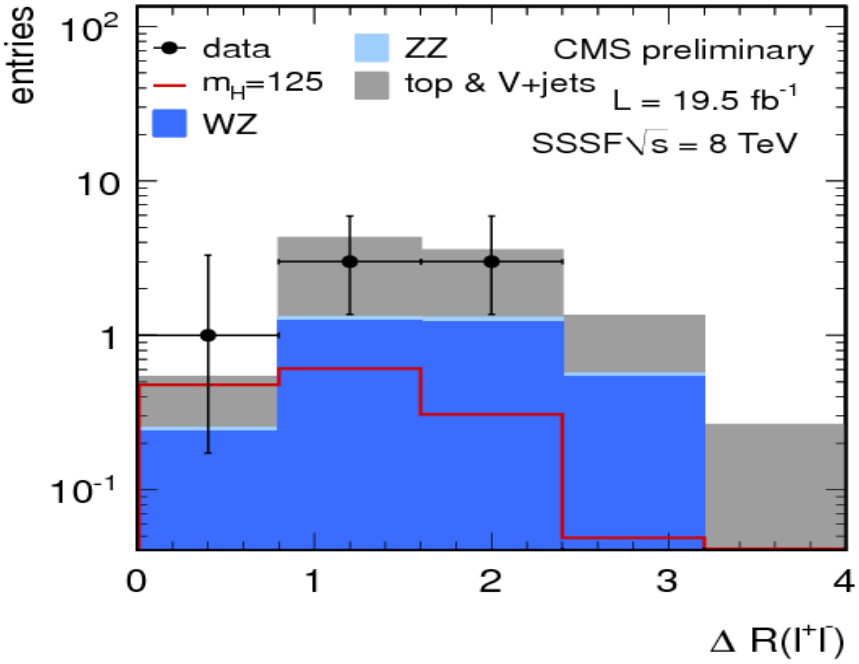


SSSF

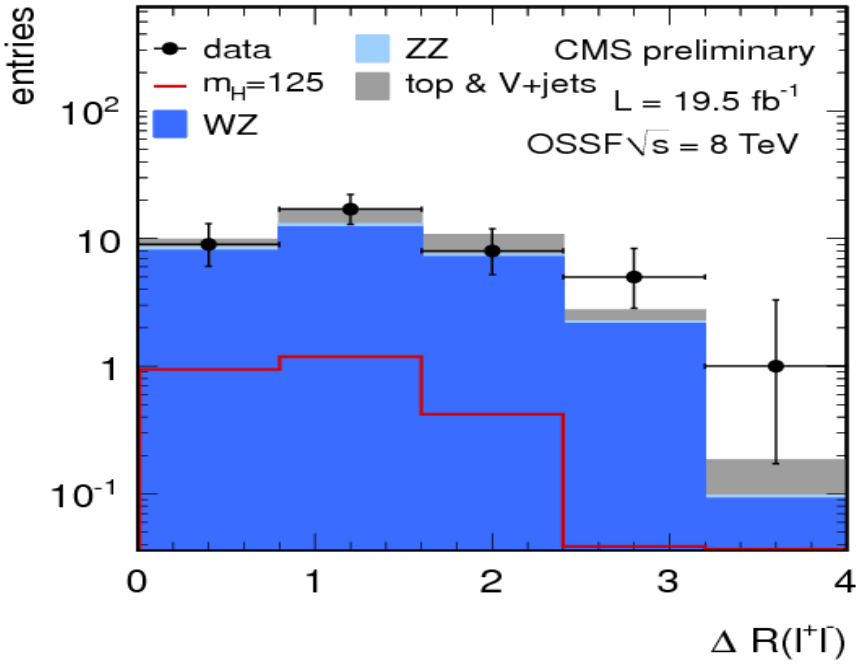
7 TeV



OSSF



8 TeV



Detailed cuts for each channel

0/1/2 jet + 2 leptons + E_T^{miss}

- **Lepton selections:**
  - 2 opposite charge leptons ($|\eta|<2.5$ for e, $|\eta|<2.4$ for μ)
  - $p_T^{lepton} > 20$ (10) GeV
  - WW selections
    - Low mass resonances: $m_{ll} > 12$ GeV
    - Z-peak veto: $|m_{ll} - m_Z| > 15$ GeV for ee/$\mu\mu$ events
    - projected E_t^{miss} selection: min[proj(E_T^{miss} ,ll), proj(charged E_T^{miss} ,ll)] > 20 GeV
    - $E_T^{miss} > 20$ GeV
    - Z/γ rejection: for ee/$\mu\mu$ events cut on DY-mva ($E_T^{miss} > 45$ GeV) for 0/1 (2) jets
    - $\Delta\phi$ (ll, jj/j) < 165°
    - Kinematic cut: $p_T^{ll} > 30$ (45) GeV for 0/1 (2) jets
    - Extra lepton veto: 2 leptons only with $p_T > 10$ GeV
- **Jet selections:**
  - Jet counting for jets with $p_T > 30$ GeV
  - B-veto:
    - b jets identified looking at tracks associated to the jet exploiting lifetime of B mesons
    - No soft muons coming from leptonic b decays

Mass dependent selections 0/1 jet cut based analysis

- Higgs boson mass dependent cuts

m_H	$p_T^{\ell,max}$	$p_T^{\ell,min}$	$m_{\ell\ell}$	$\Delta\phi_{\ell\ell}$	m_T
[GeV]	[GeV]	[GeV]	[GeV]	[°]	[GeV]
	>	>	<	<	[,]
120	20	10	40	115	[80,120]
125	23	10	43	100	[80,123]
130	25	10	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
250	55	25	150	140	[120,250]
300	70	25	200	175	[120,300]
400	90	25	300	175	[120,400]

List of all uncertainties

- List of all uncertainties:

  - Experimental
    - Leptons efficiency, momentum scale and resolution uncertainty
    - Jet scale uncertainty
    - Missing transverse energy modeling
    - B-tag modelling
    - Pile-up simulation
    - Luminosity measurement

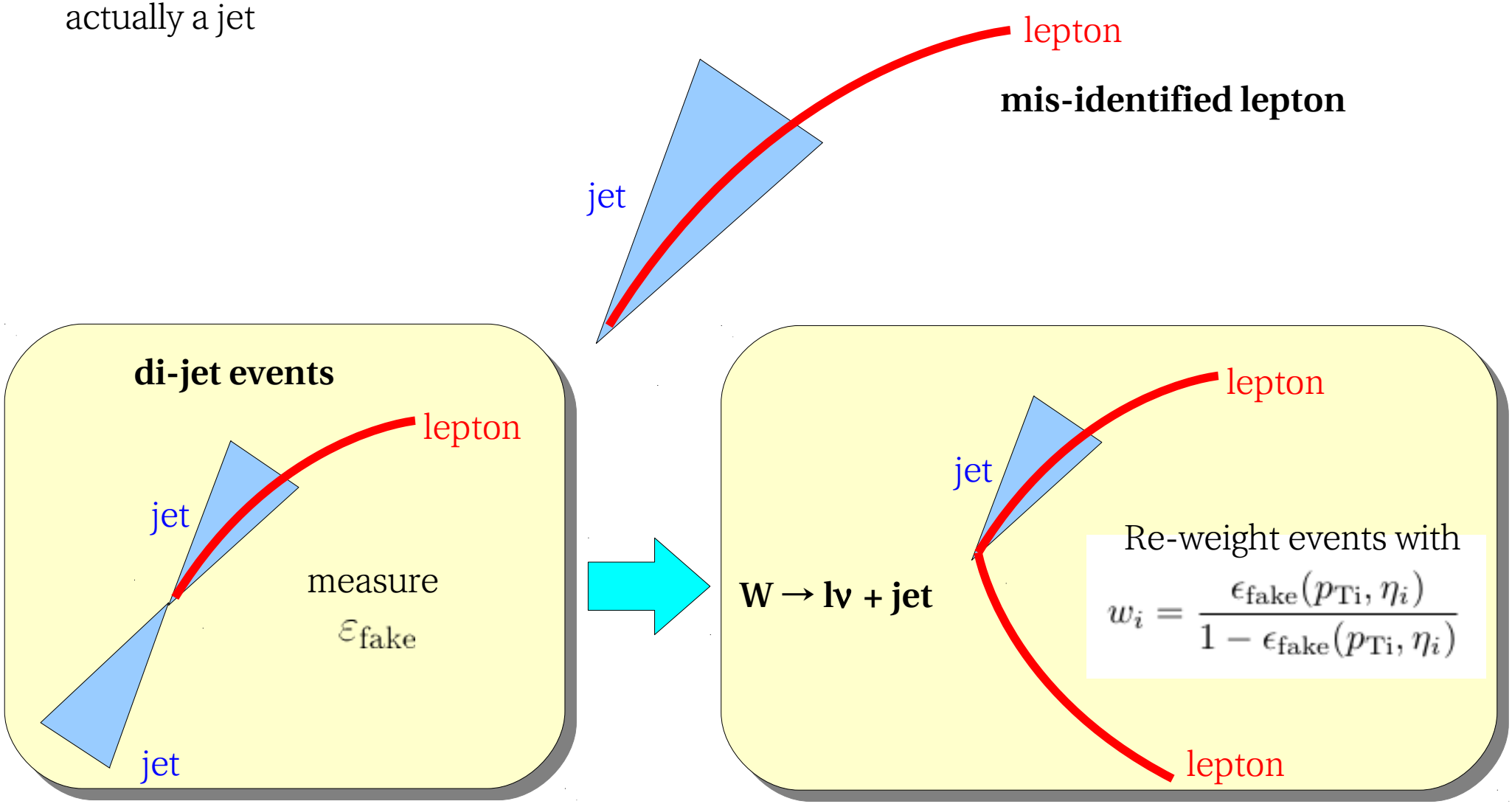
  - Theoretical
    - Error from parton distribution functions
    - Missing higher orders in calculation (scale variation)
    - Parton shower simulation

Details on data-driven

- Details on data-driven estimation of each background:
  - **W + jets** (mis-identified lepton)
    - Measure the probability for a jet to be identified as a good lepton in a di-jet enriched phase space.
    - Use this probability on data to infer how many events have 2/3 good leptons one of which is actually a jet
  - **$Z/\gamma \rightarrow ee/\mu\mu$**
    - Normalize the number Z/γ events measuring the rate in a mass window around the Z one
  - **Top**
    - Measure the b-tag probability in a top enriched phase space
    - Infer the number of b-vetoed events from the number of b-tagged ones
  - **WZ** (for 3 leptons)
    - Normalize the number of WZ events measuring the rate in a 3 leptons final state with a pair of opposite sign same flavour leptons compatible with the Z mass

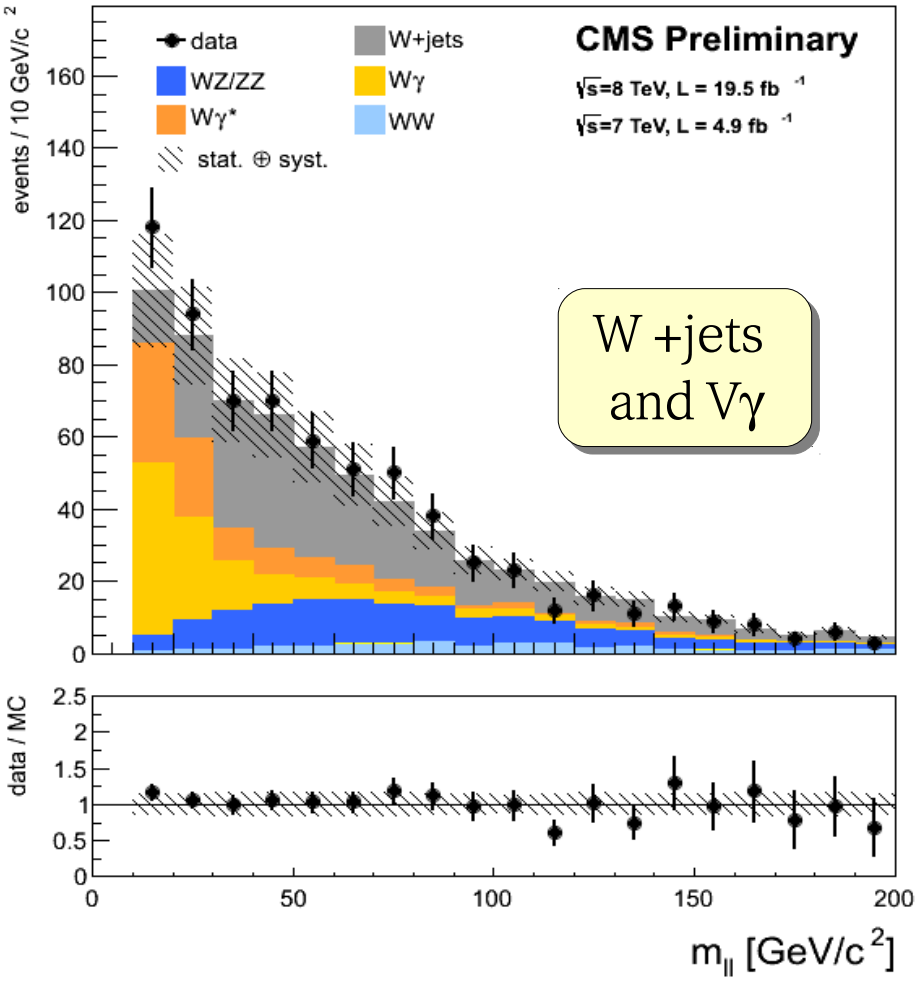
Details on data-driven: W + jets

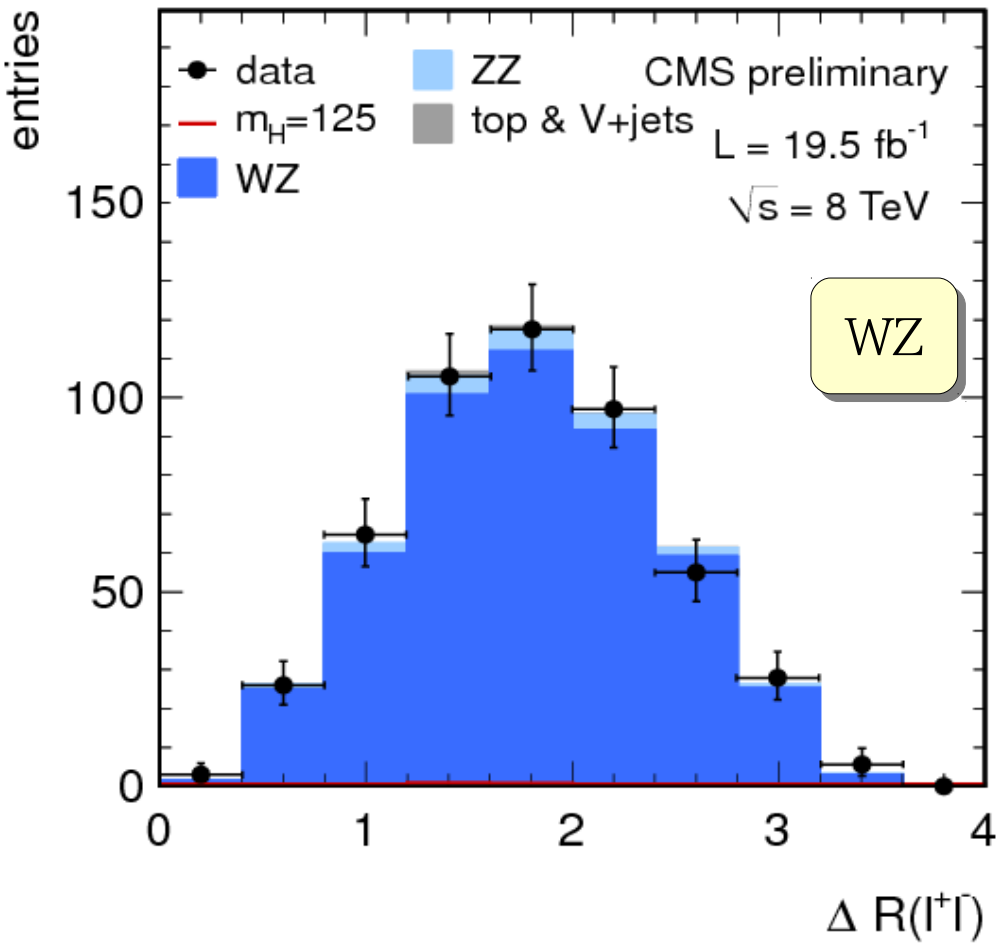
- **W + jets** (mis-identified lepton)
  - Measure the probability for a jet to be identified as a good lepton in a di-jet enriched phase space.
  - Use this probability on data to infer how many events have 2 good leptons one of which is actually a jet



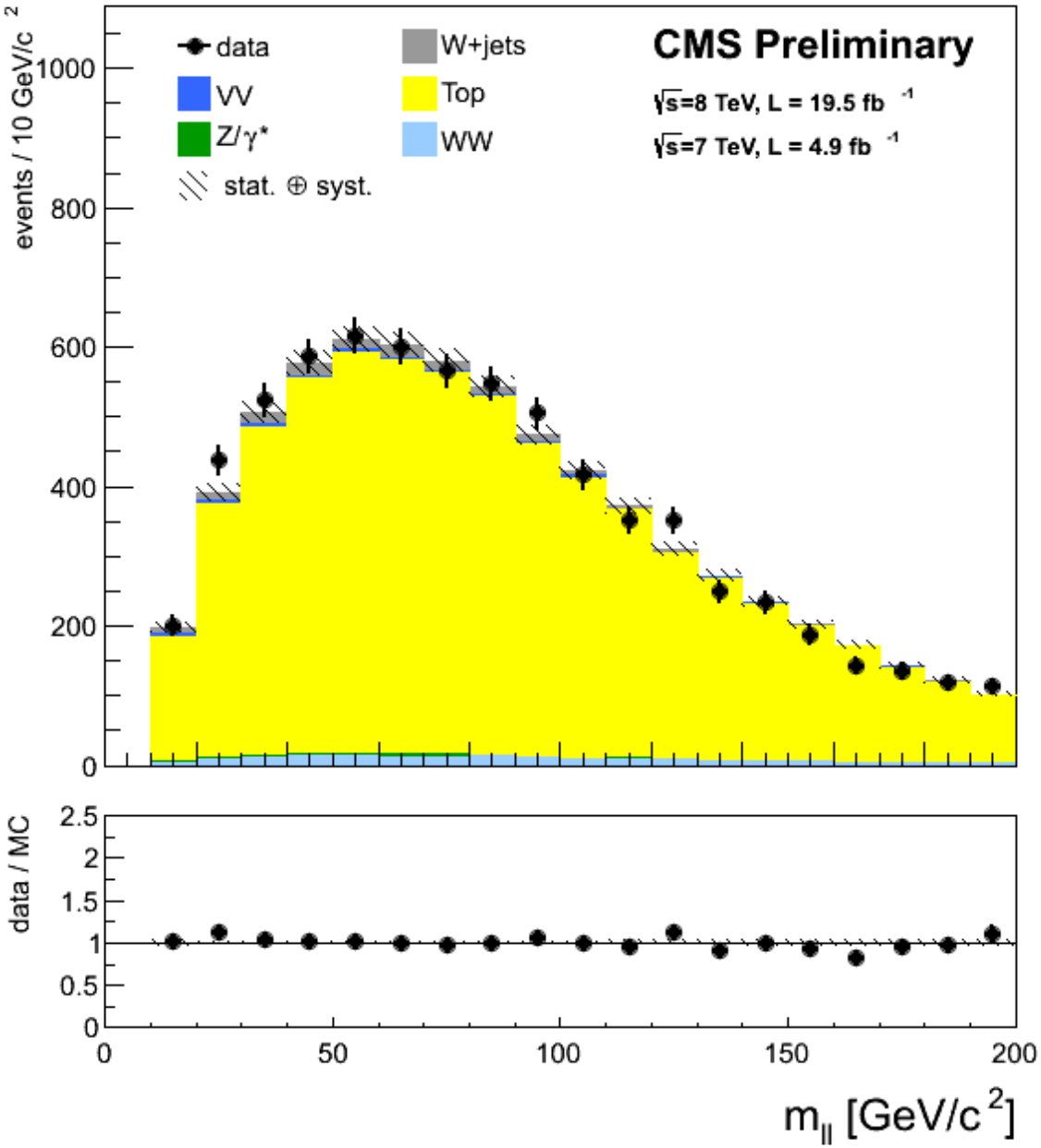
Control regions for each background: W, Vγ and WZ

- Control regions for each background
  - Several kinematic distributions for each background have been checked





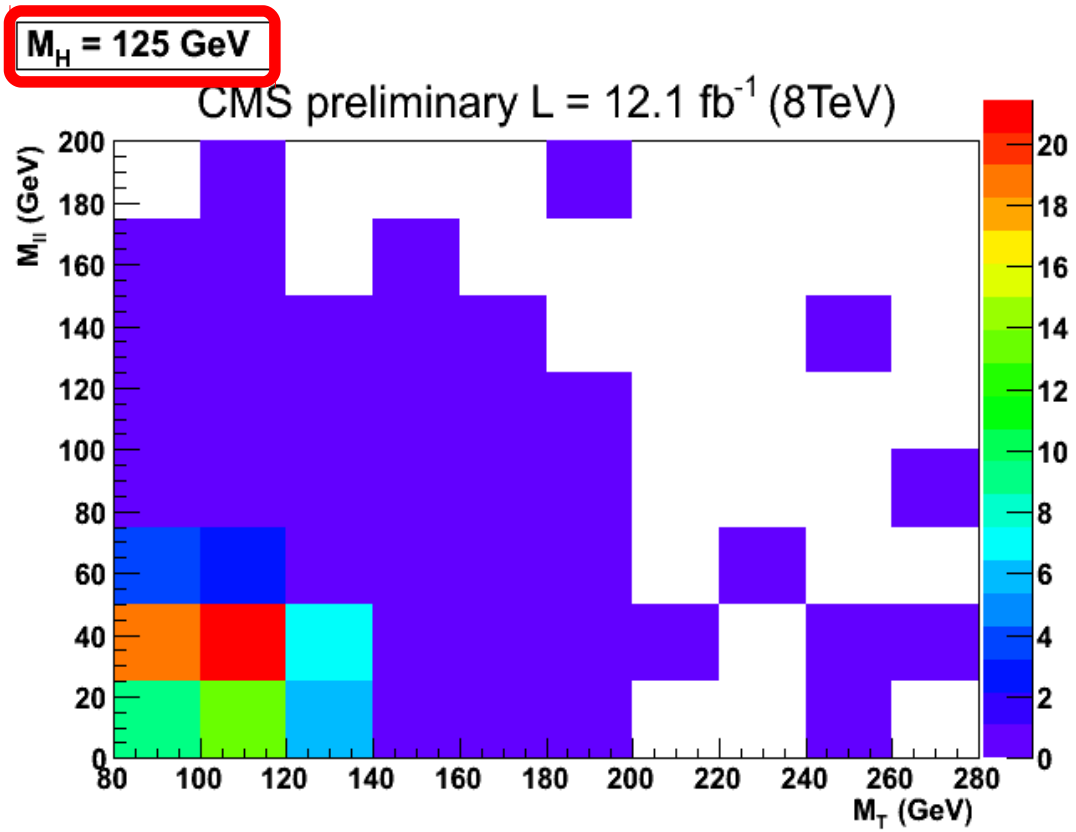
Control regions for each background: Top

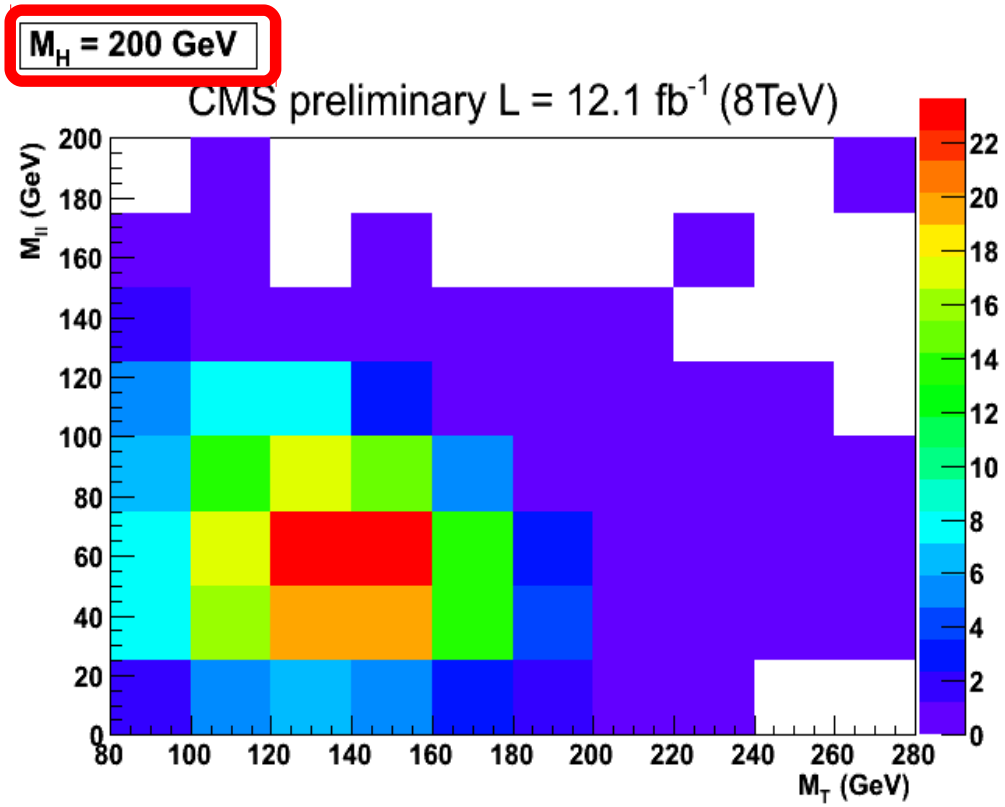


Top

Higgs boson mass dependence for shape analysis

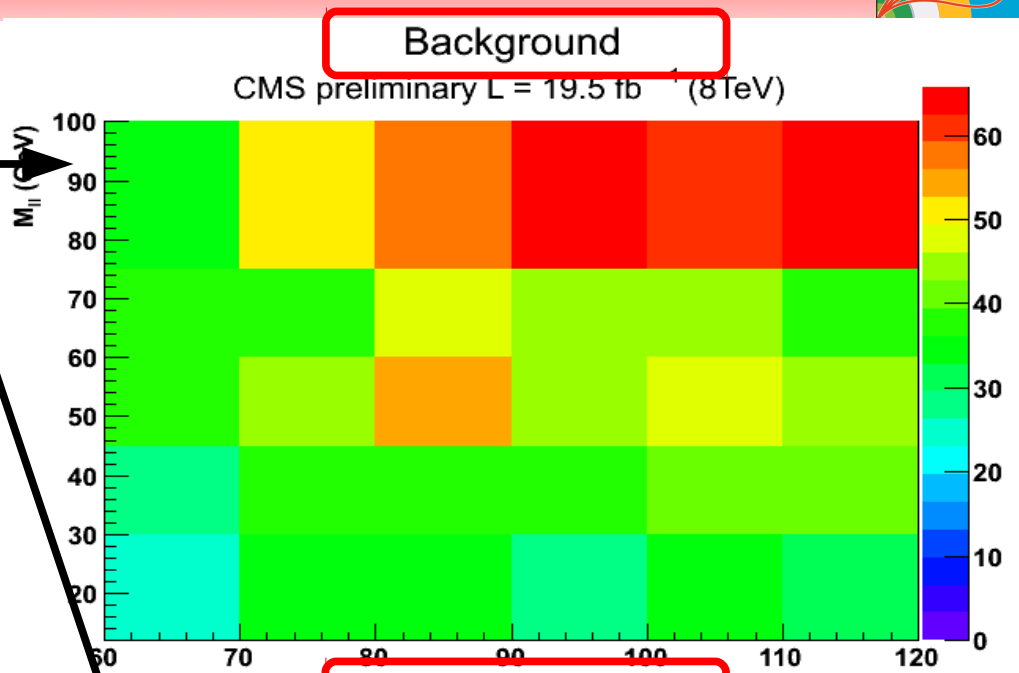
- Mass dependence for shape analysis:
  - M_T and m_{ll} distributions are different for different Higgs boson mass hypotheses

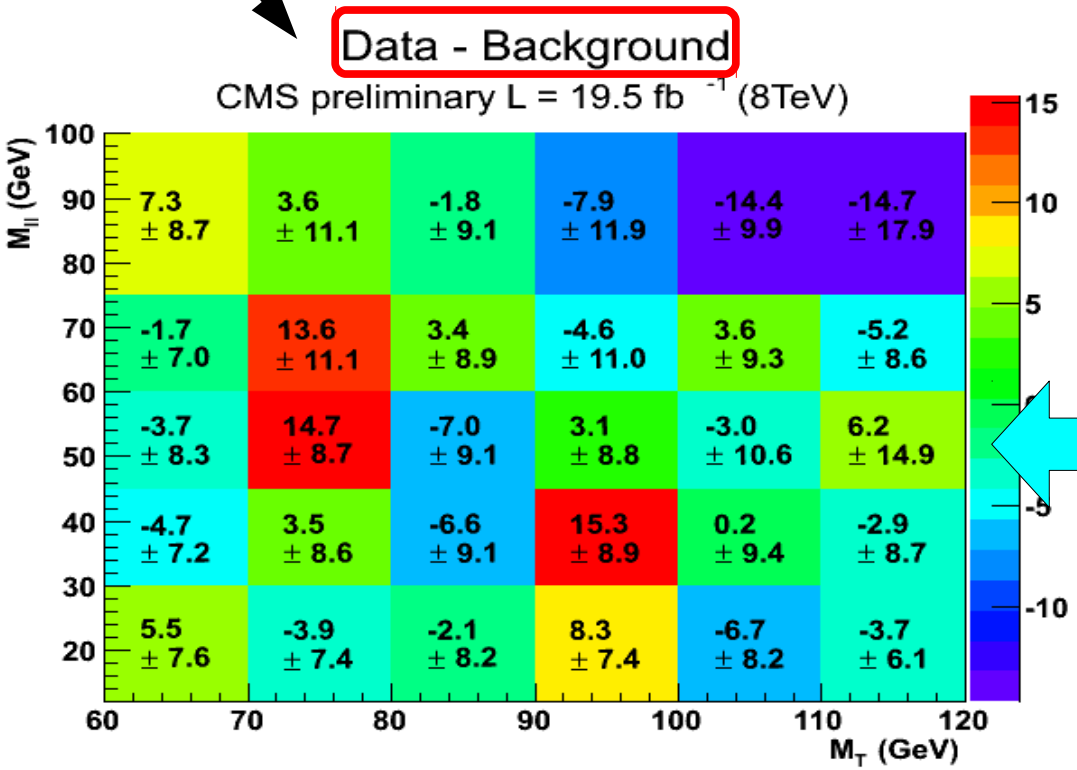


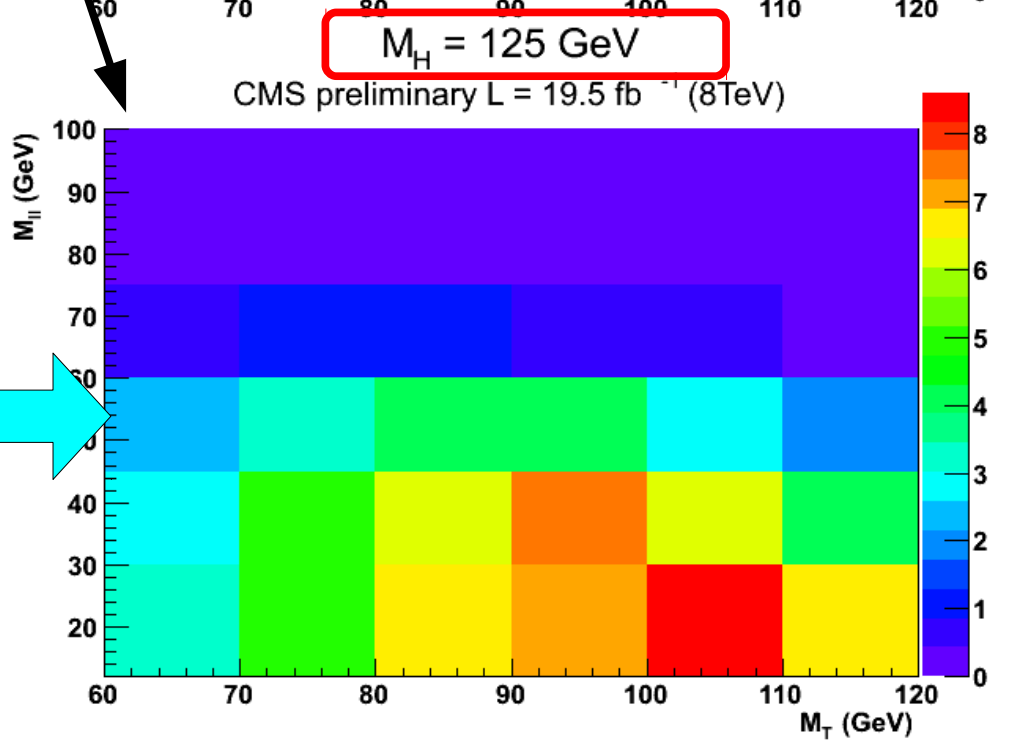


1 jet bin shape analysis

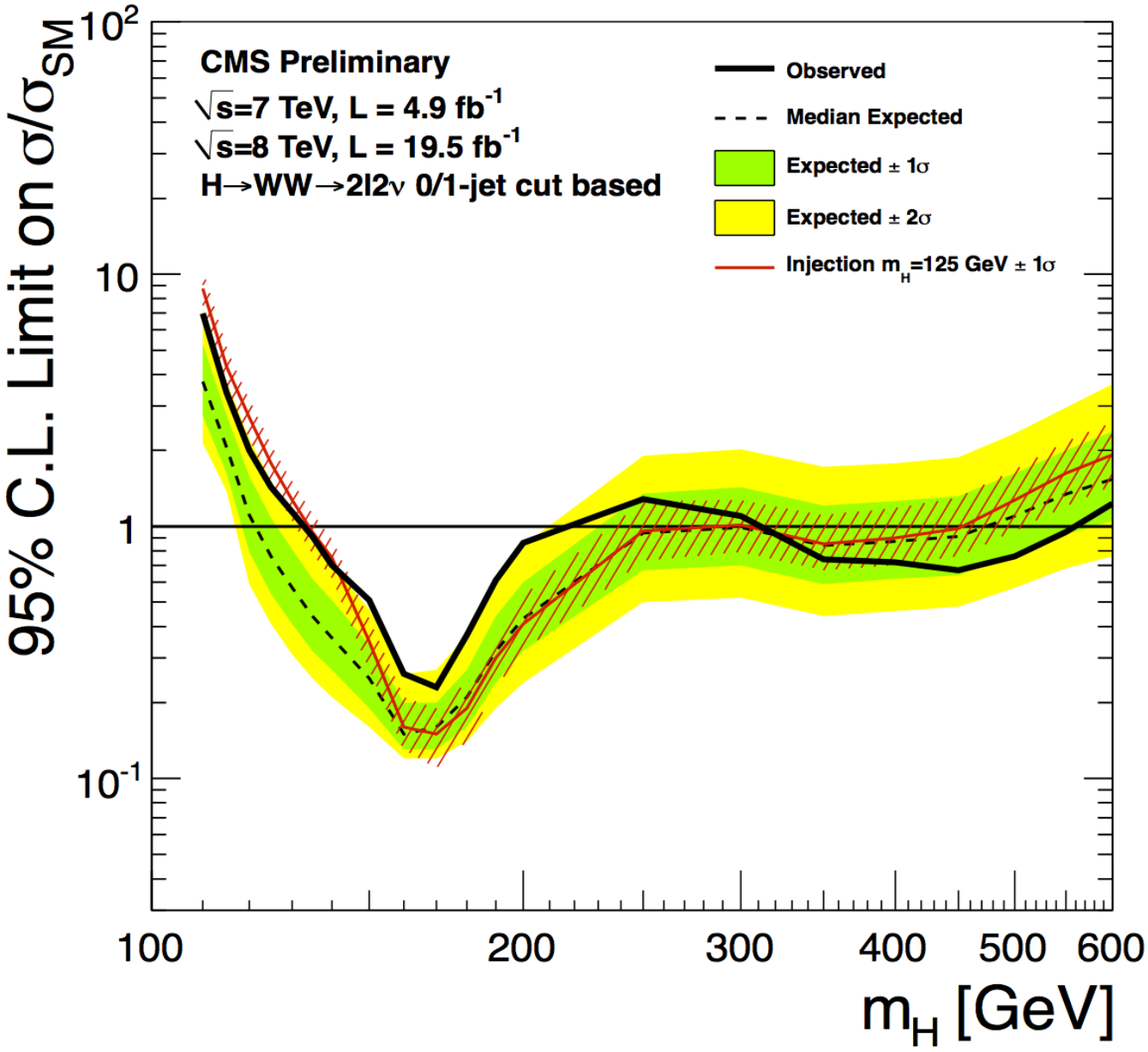
- Shape analysis on 2D distribution: $m_{ll} : m_T$
  - Different shape for signal and background
  - Different shapes for different backgrounds
- Excess compatible with a SM Higgs boson







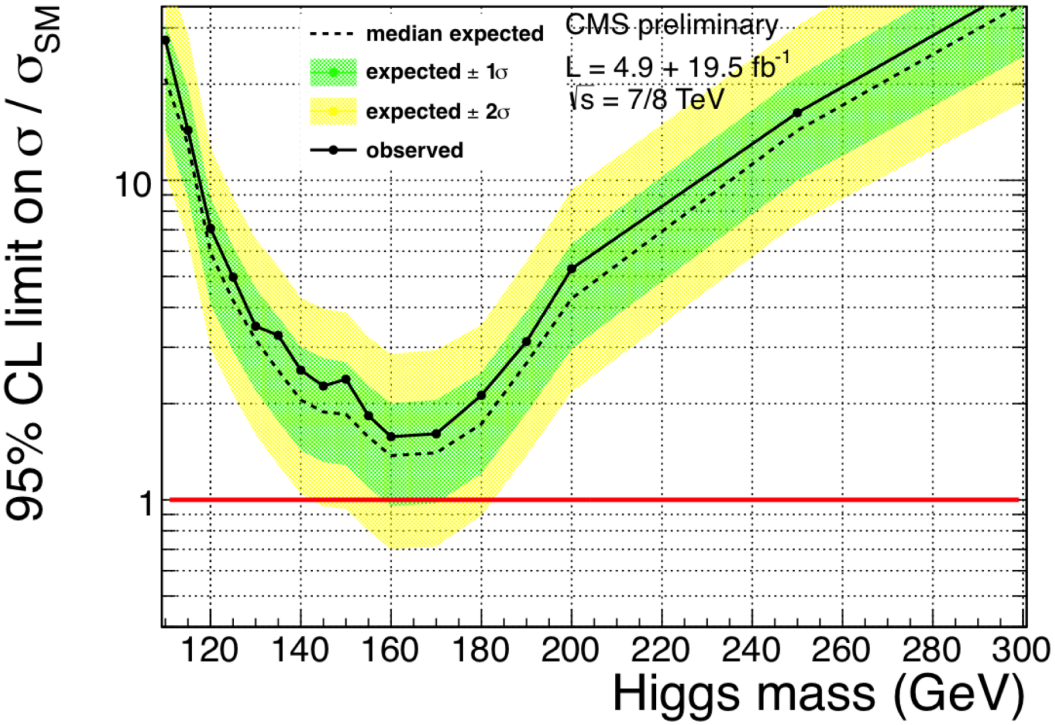
Cut based limits: 0 + 1 jet



Large mass spectrum results V(jj)H H → WW → lνlν

- Results in the whole Higgs mass spectrum

Cut based (7+8 TeV)



Shape (8 TeV)