Search for Higgs decaying to WW at CMS

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on behalf of the CMS Collaboration

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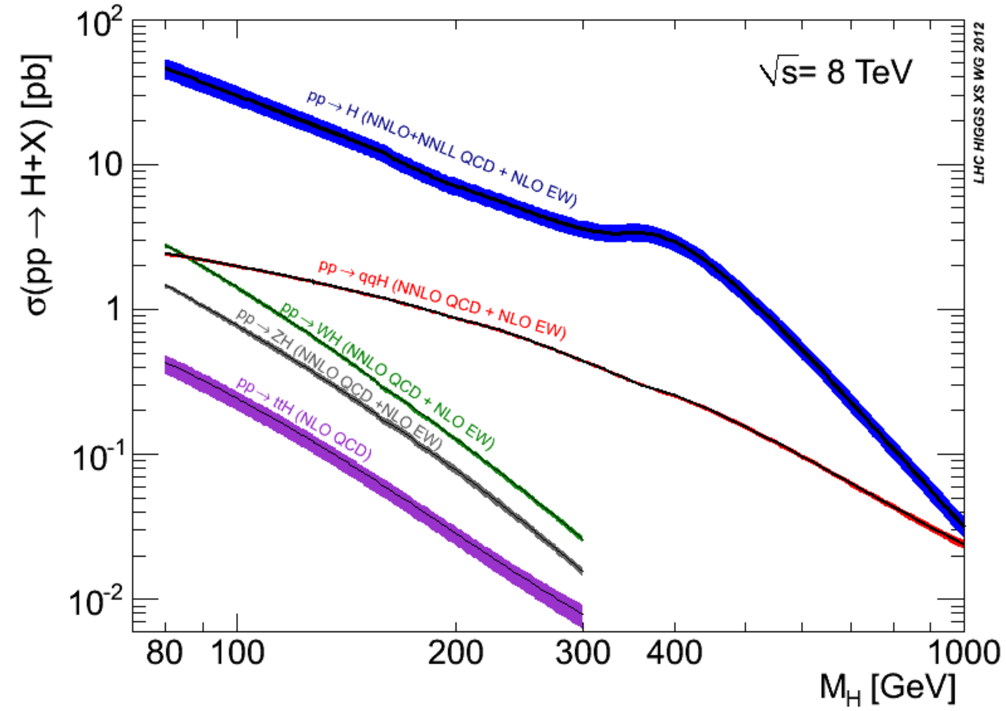
Talk overview

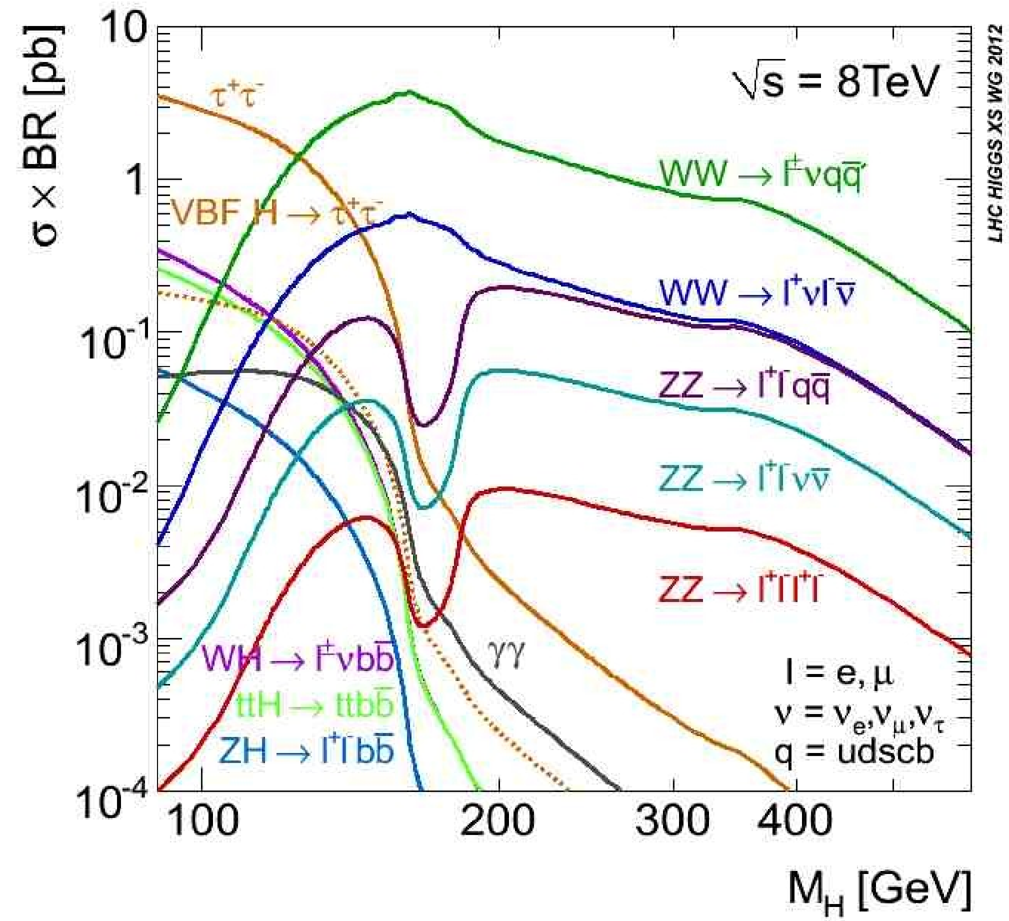
- In this talk I will present the main CMS Higgs searches with the WW decay mode
- In general **H → WW** most relevant decay in the allowed Higgs mass range
  - **H → WW → lνqq**
    - Exploits **gg-fusion** production mode
    - Coverage in the **mid-high mass** region
    - **Highest branching ratio**

FRESH NEWS!

  - **H → WW → lνlν**
    - Exploits **gg-fusion, VBF and VH** production modes
    - **Full mass** range coverage
    - **Best S/B**

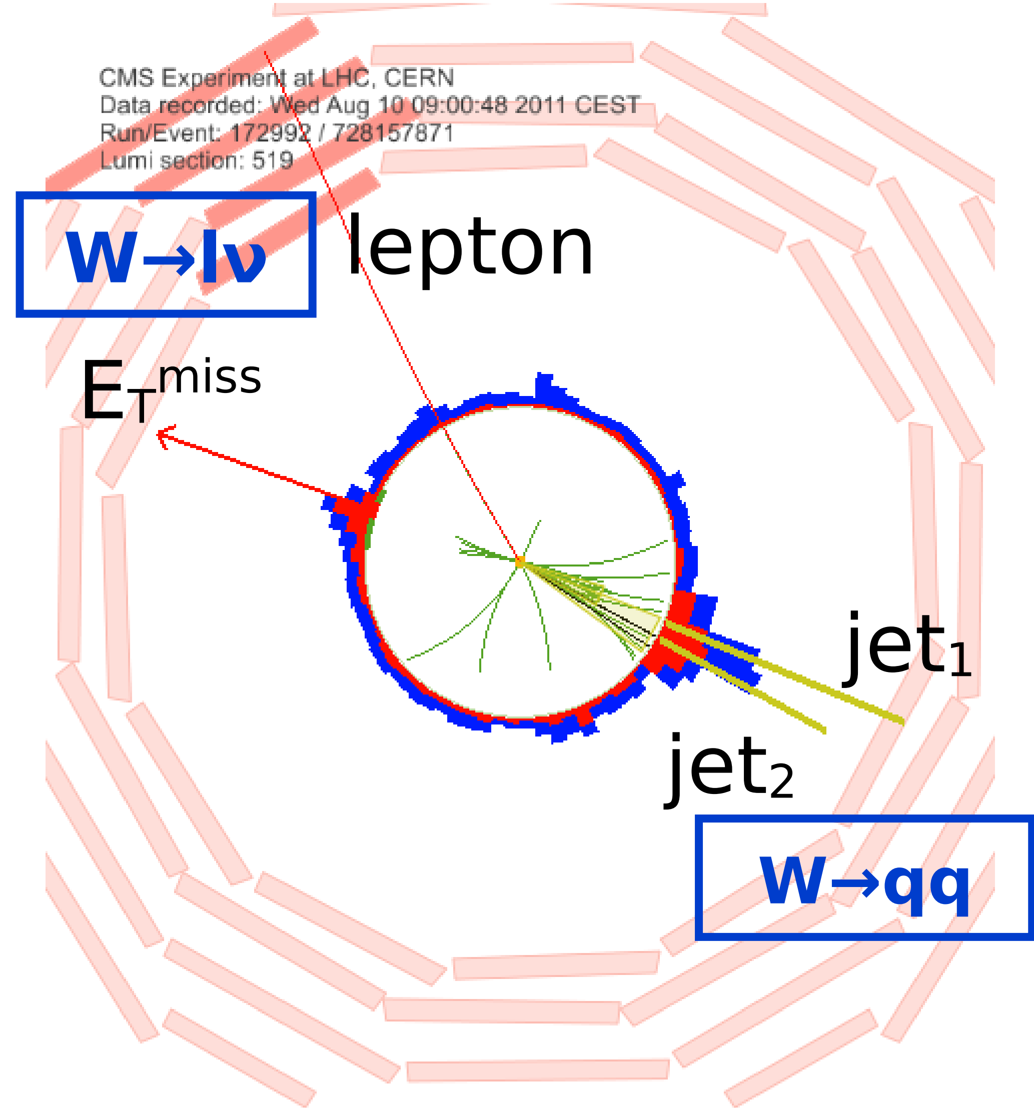
FRESH NEWS!





H → WW → lνqq

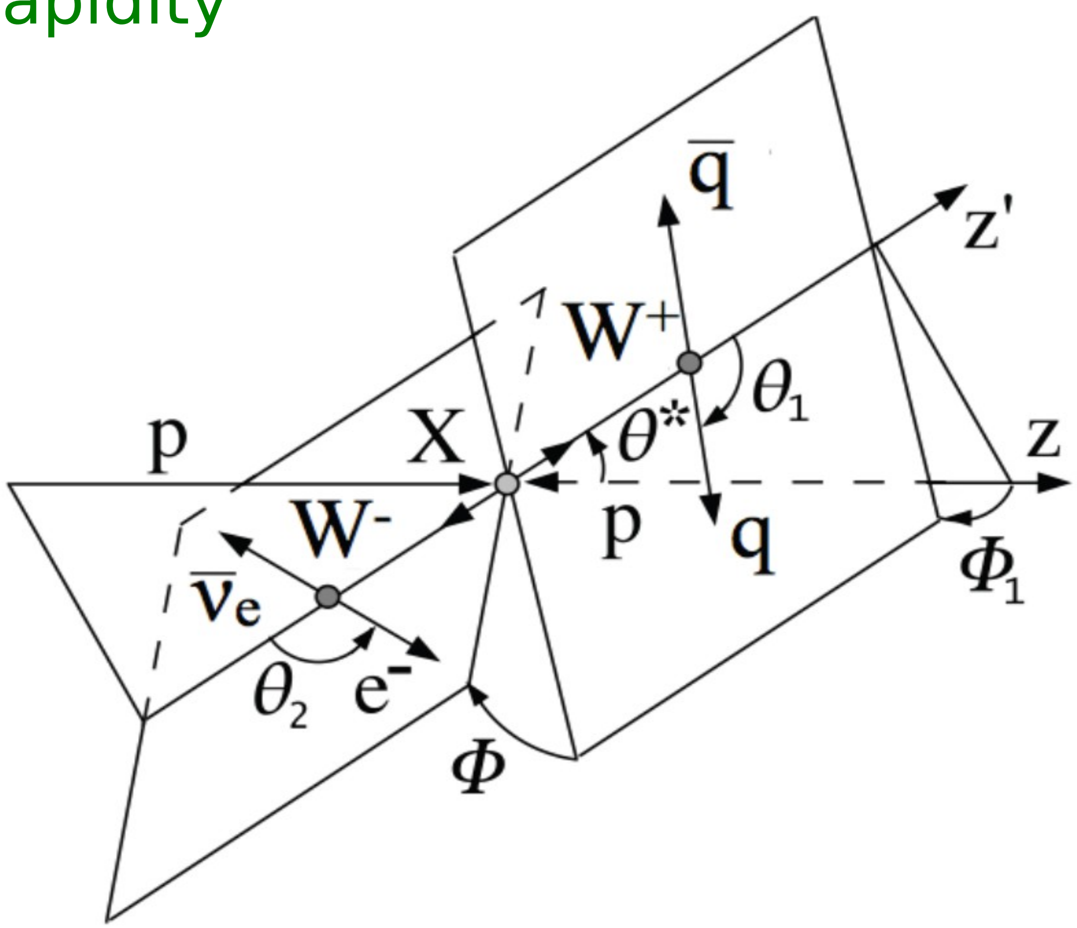
- Pros/Cons
  - Very high cross-section x branching ratio
  - Event is kinematically closed
    → can recontruct a mass peak
  - Only one final state lepton → huge W+jets background, QCD contamination, tight trigger
  - Final state E_T^{miss} → worsening in the mass resolution



- Analysis optimized for gluon fusion production & for real Ws
  - **1! lepton, E_t^{miss}, 2/3 jets** in the central part of the detector
  - **di-jet mass** constrained around **m_W**
  - **4** total **categories** (e/μ) x (2j/3j)

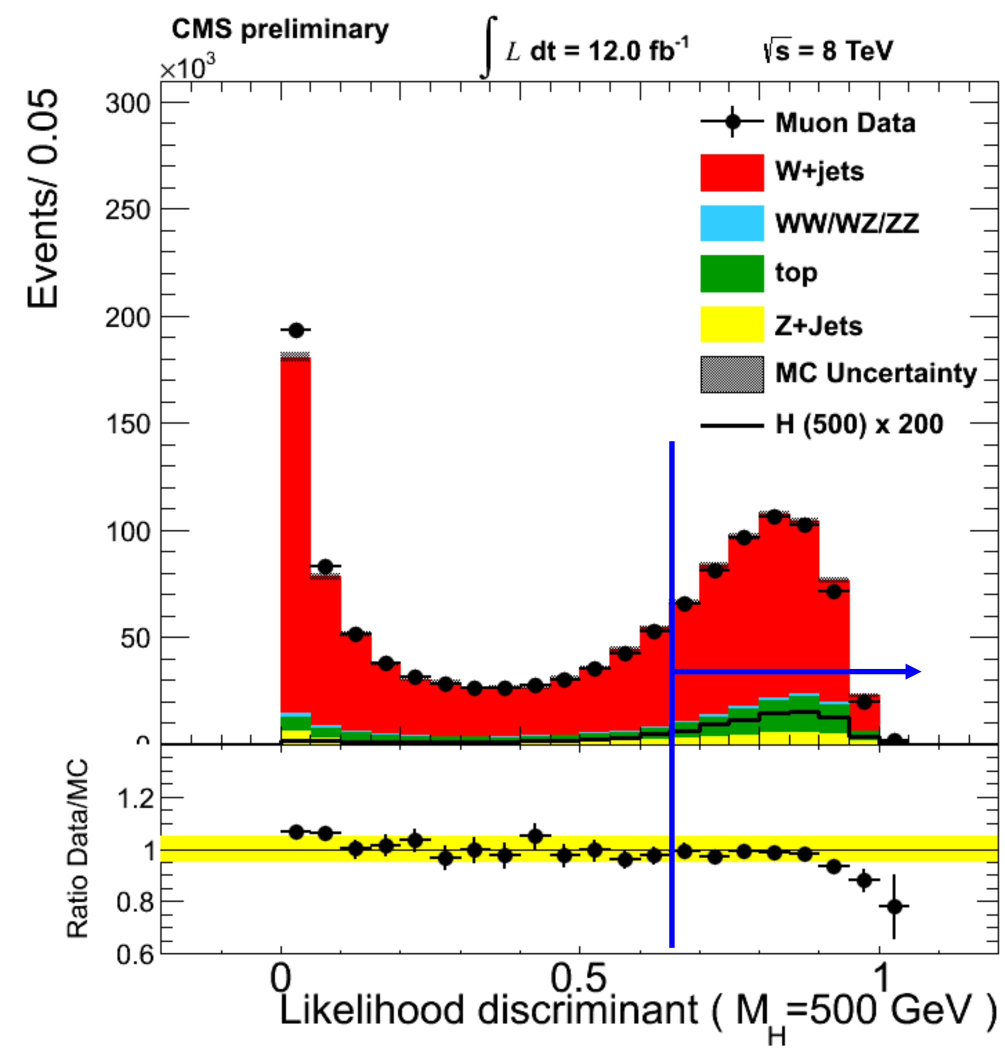
Optimized selection

- Train MVA likelihood discriminators, one for **each mass hypothesis and category** (e|2j, e|3j, μ|2j, μ|3j)
- Include 5 Higgs decay angles, lepton charge, WW p_T and rapidity



- Optimize **cut** to **maximize** the **performance** on the **expected limit**

Muons + 2j

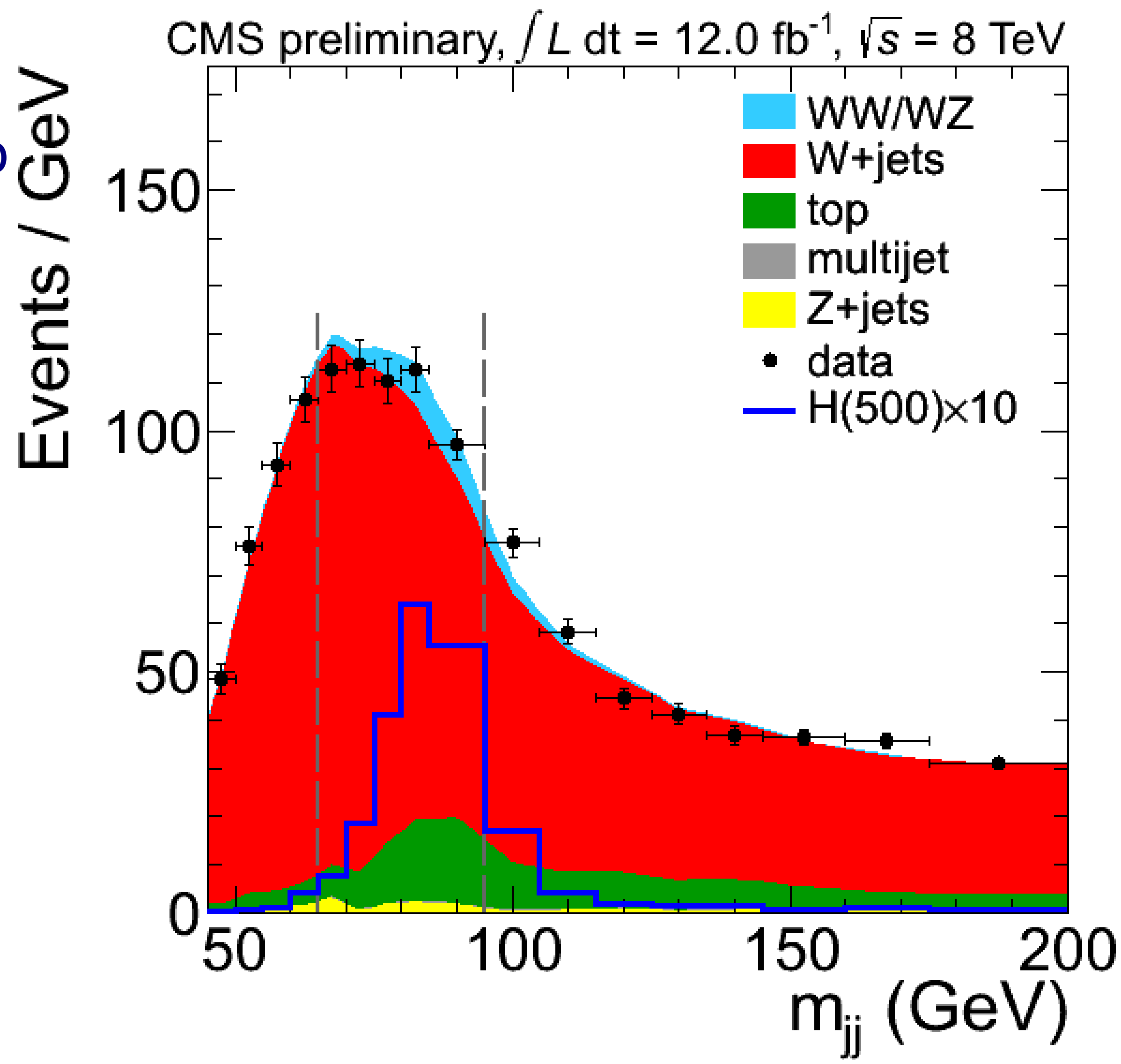


Background normalization

lνqq

- Stack backgrounds, perform unbinned maximum likelihood fit to m_{jj} data
  - **Exclude 65-95 GeV signal region from the fit**, retain signal sensitivity
  - **W+Jets is unconstrained**, let data best determine its normalization
  - **QCD multijet** normalization **contrained** to estimation from **fit to data lep-MET m_T**
  - Apply **gaussian constraints for other backgrounds** to NLO/NNLO predictions + uncertainties
- Extract relative **background normalizations in m_{jj} signal** window for the **next step**
- **diboson contribution visible**
  http://arxiv.org/abs/1210.7544

Muons + 2j



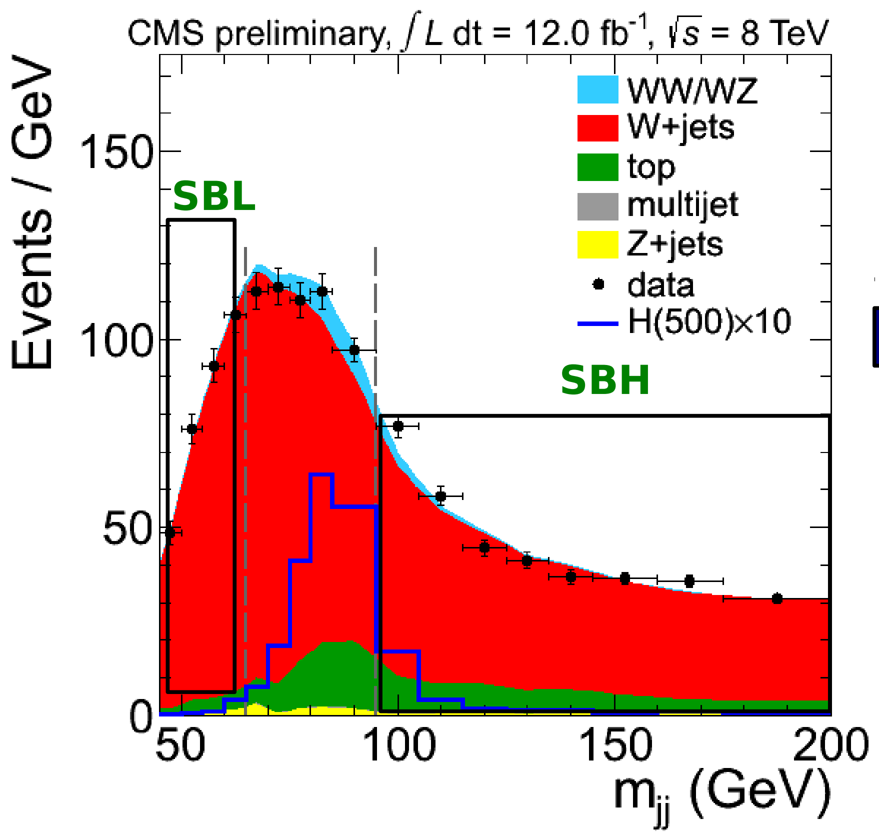
Background m_{WW} Shapes

lνqq

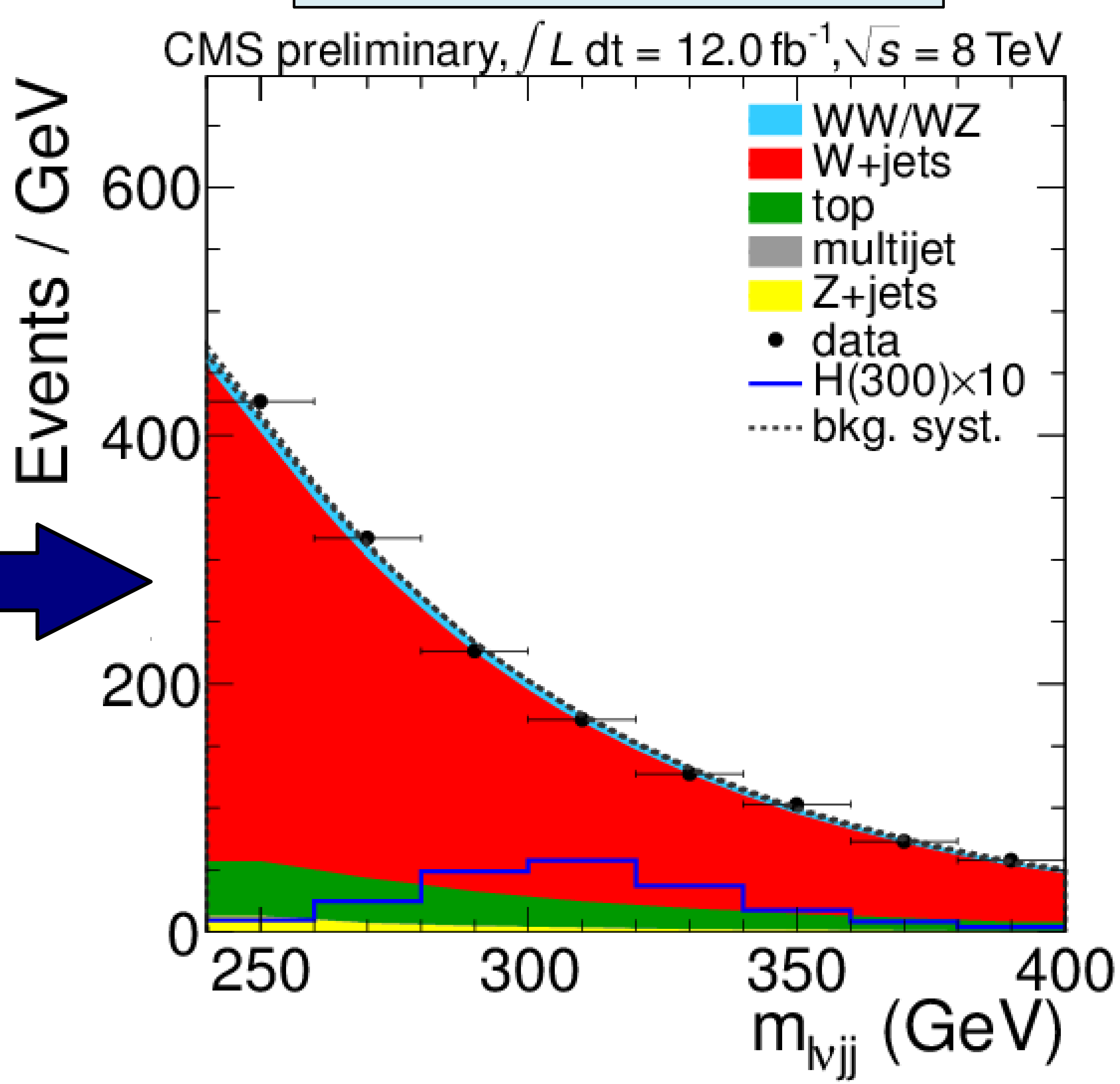
- **m_{WW} shapes used for limit setting**
  - **Signal** and **minor backgrounds** taken from **simulation**
  - **QCD multijet** from **data** in a non-isolated **control region**
  - **W+jets** m_{WW} shape as a linear combination of the shapes from high and low m_{jj} **data sidebands** (SBH, SBL)

$$m_{l\nu jj}(SIG) = \alpha\, m_{l\nu jj}(SBL) + (1-\alpha)\, m_{l\nu jj}(SBH)$$

- α determined from W+jets MC, χ^2 fit to m_{WW} shape in the signal region

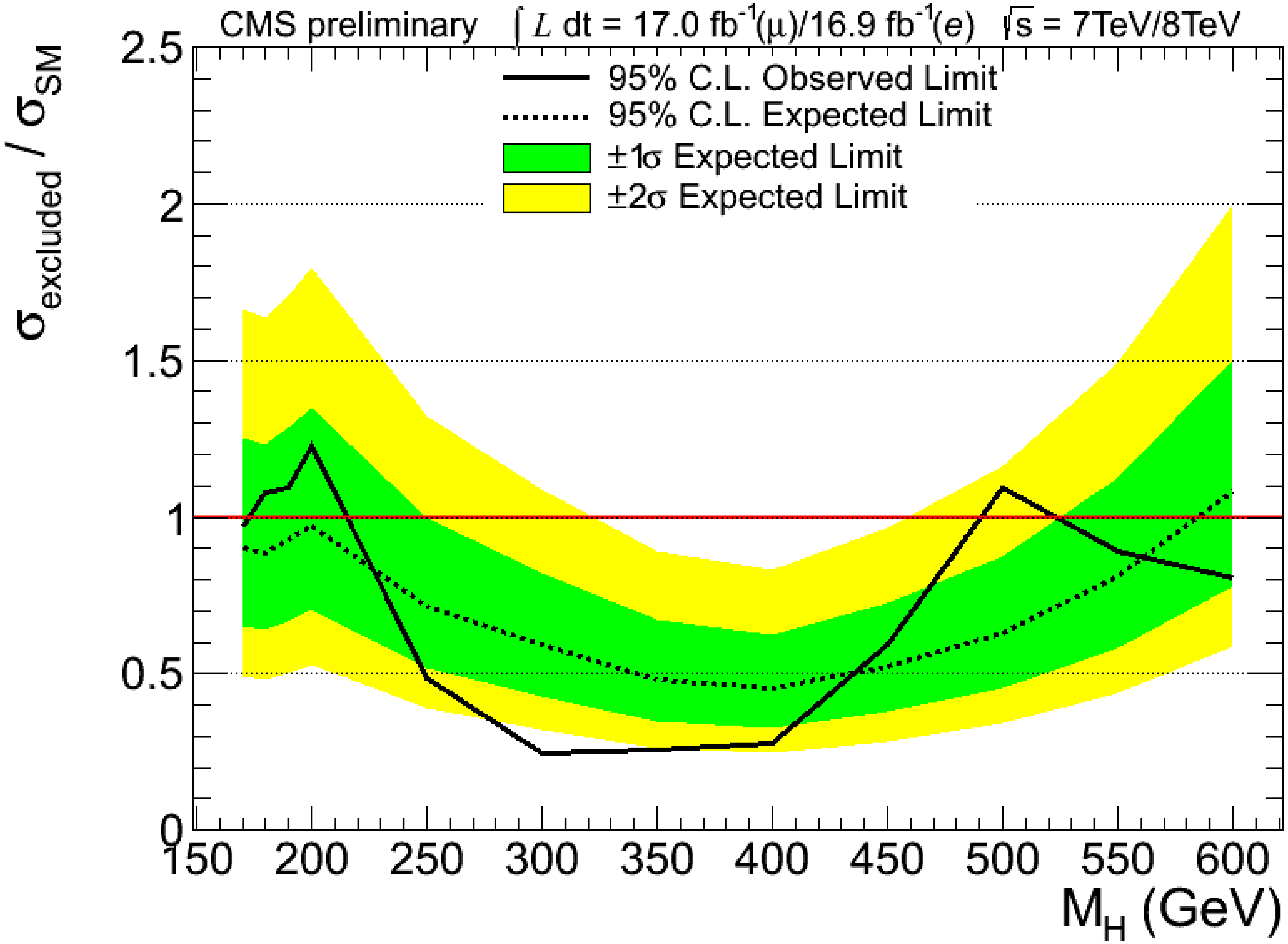


Muons + 2j



Results with 7 + 8 TeV data lνqq

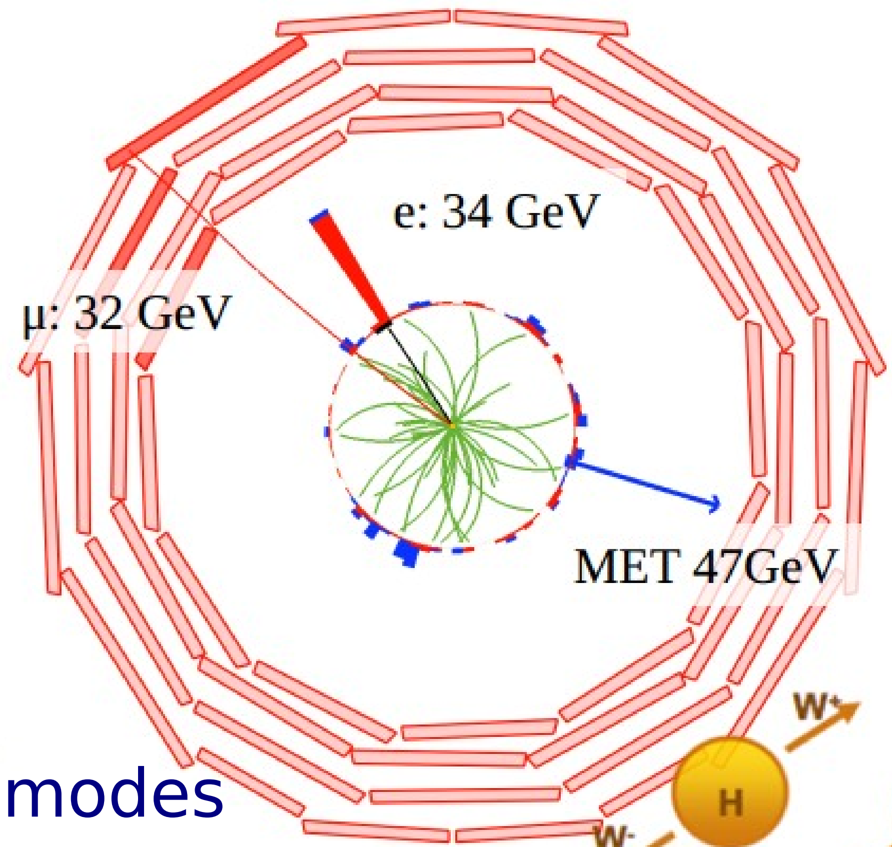
- Results obtained with **7 TeV (5 fb^{-1})** and **8 TeV (12 fb^{-1})** data

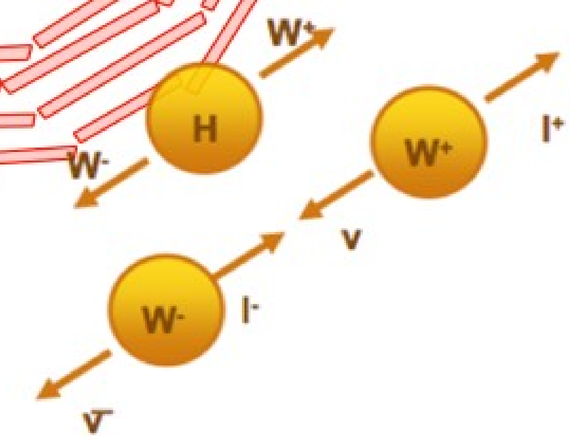


Expected **170 – 585** GeV
Observed **215-490, 525-600** GeV

$H \to WW^{(*)} \to l\nu l\nu$

- Pros/Cons
  - High cross-section x branching ratio
  - Two final state leptons → high S/B, high signal acceptance
  - No mass peak → need precise background estimation → heavily data driven





- Analysis optimized for different production modes
  - **2! leptons opposite charge, large E_t^{miss}, 0/1/2 jets**
  - **0/1** jet → **ggH**   **2** jet → **VBF**
  - Additional **flavour** based **categorization**: different flavour (DF) and same flavour (SF) → **6** total **categories** (ee-μμ/eμ) x (0j/1j/2j)
- **Two** different **approaches** for signal extraction
  - **Cut&Count**
  - **2-D shape** [m_{ll} | m_T] fit

	0 jet	1 jet	2 jet
SF	**cut**	**cut**	**cut**
DF	**2D shape**	**2D shape**	**cut**

Handling backgrounds

lνlν

Two levels of selection

- **WW level** → reduce non-WW backgrounds
- **Higgs level** → reduce non resonant WW

decreasing cross-section (8 TeV)

process	characteristic	selection
W+jets (~36000 pb)	Lepton + fake lepton	2 well identified & isolated leptons
Z+jets (~5700 pb)	Z peak, no real E_T^{miss}	• MVA (0-jet/1-jet) • E_t^{miss} > 45/20 GeV (SF/DF 2-j) • $\lvert m_{ll} - m_Z \rvert$ > 15 GeV (SF)
$t\bar{t}$ (~225 pb), tW (~22 pb)	Additional b-jets	Jet anti b-tagging
W,Z+photon (~250 pb)	Electron from γ conversions	Conversion veto
WW (~47 pb)	Non resonant	m_{ll}, m_T (m_H dependent selection)
WZ (~18 pb), ZZ (~6 pb)	Z peak	• 3^{Rd} lepton veto • $\lvert m_{ll} - m_Z \rvert$ > 15 GeV (SF)

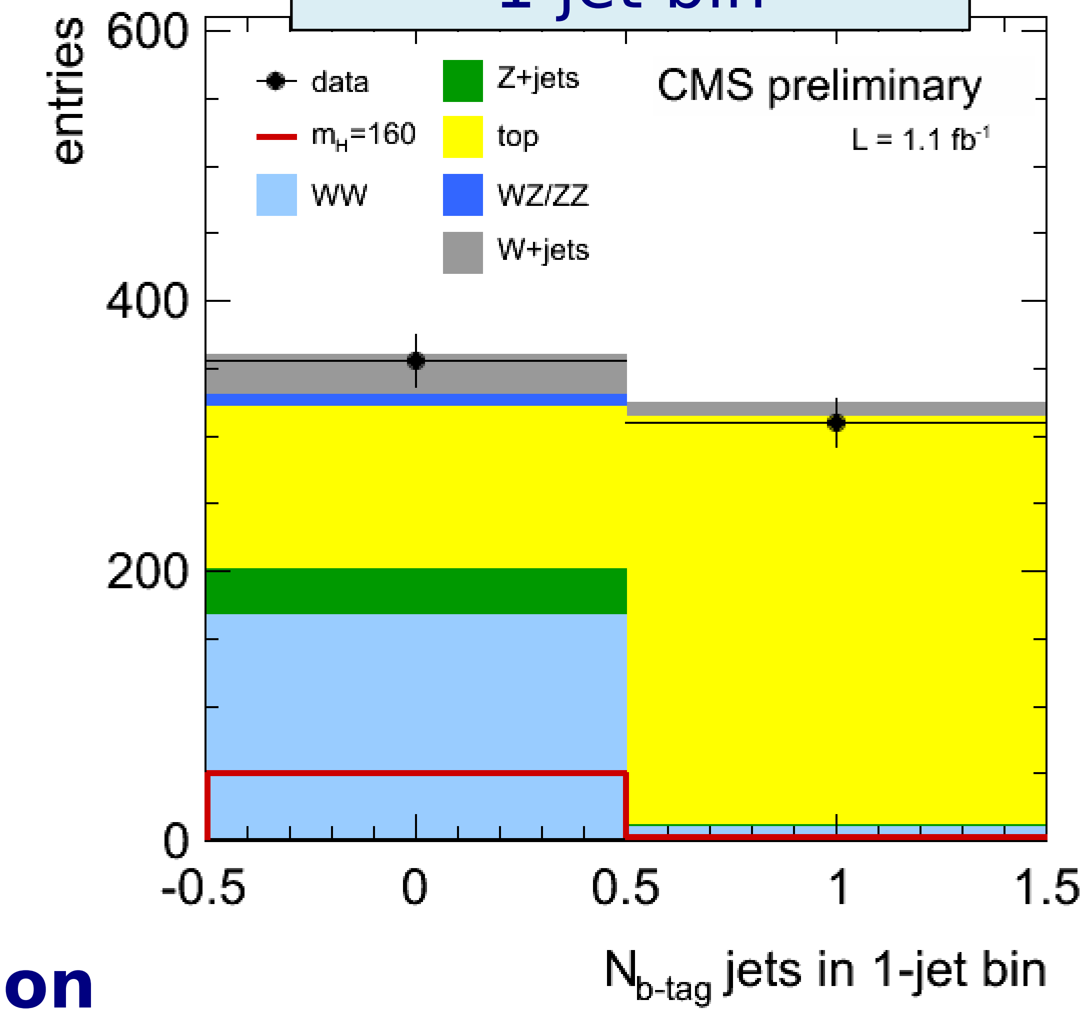
relative importance after selection depends on m_H and jet bin

Measuring backgrounds

lνlν

- Measure all backgrounds from data control samples
  - **WW** from signal free region ($\mathbf{m_{ll} > 100}$ GeV)
    - For $m_H > 200$ GeV use only simulation
  - **Top** from **b-tagged events**
  - **DY** from **Z in-peak data** events
  - **W+jets** from **fake-enriched sample**, weighted with fake→lepton probability

Top control sample
1 jet bin



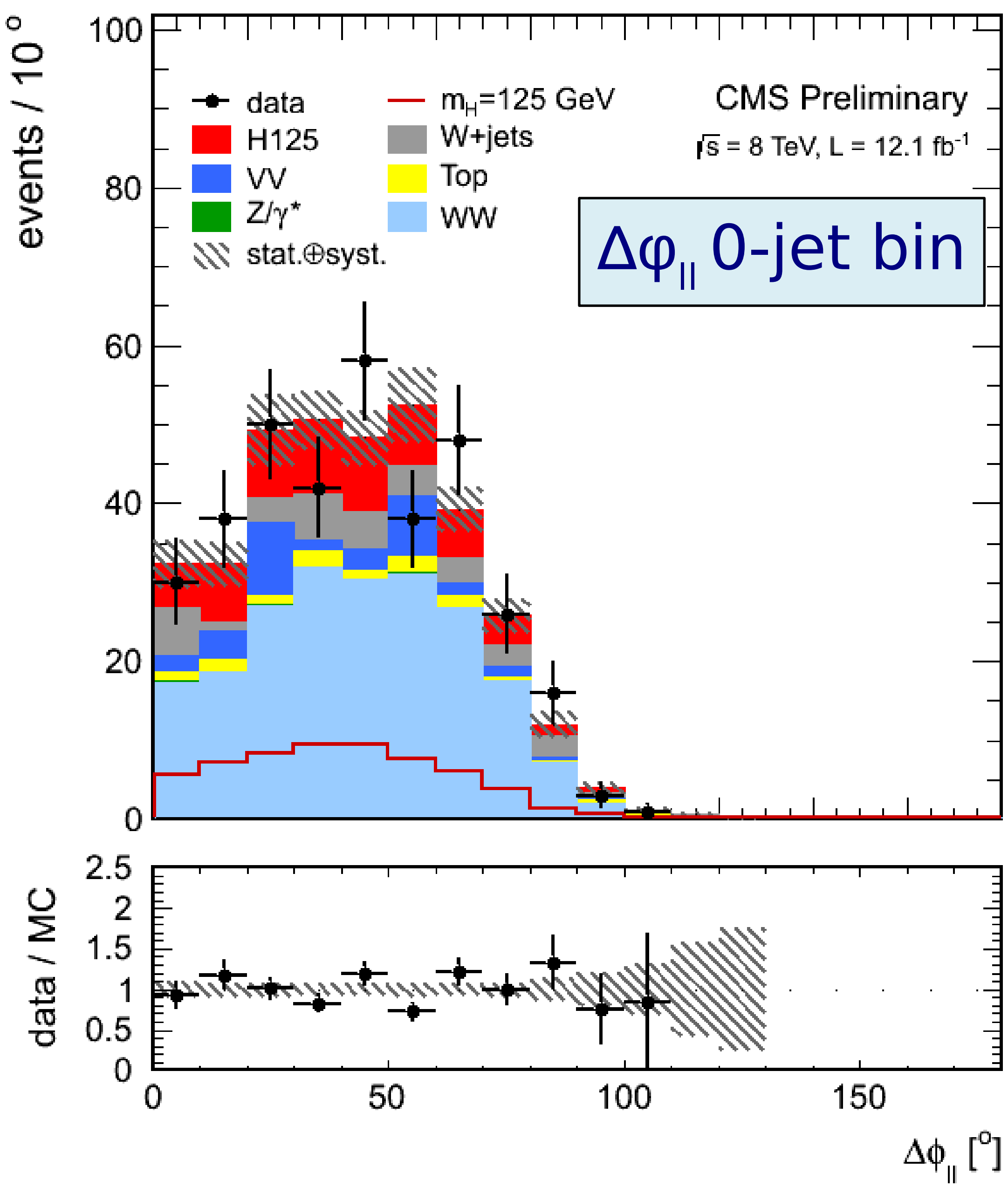
- **Cut&Count** analysis **dominated** by **systematics** on background **normalization**
  - **WW** : 5-10%
  - **Top** : 5-20 %
  - **Drell-Yan** : 30 %
  - **W+jets :** 30-40 %

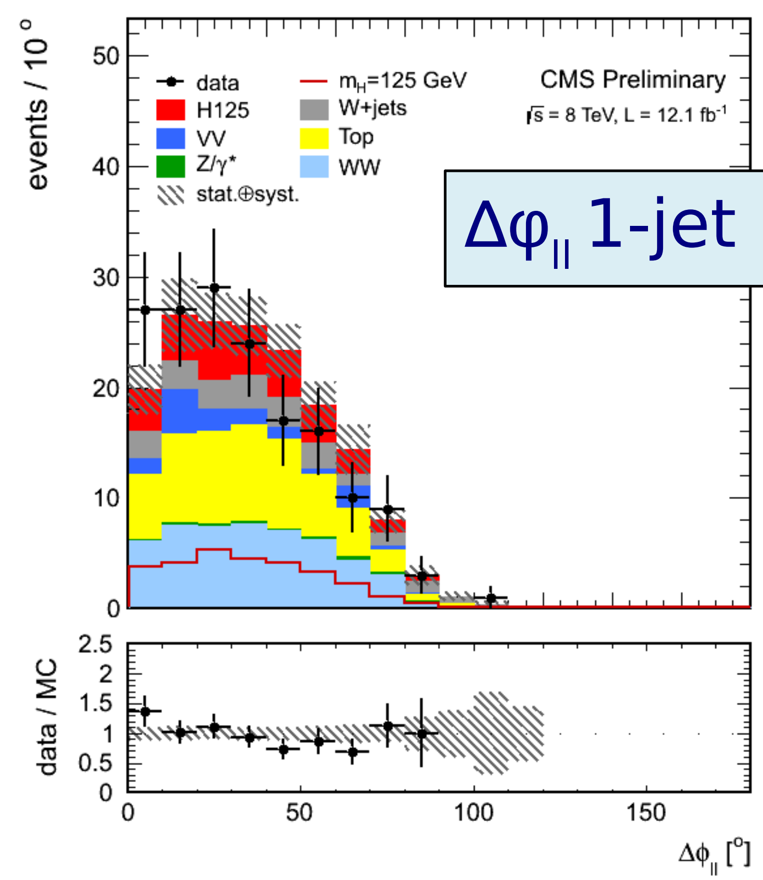
→ Continuous efforts to improve background measurement precision

Cut&Count selections

- To **improve S/B** further **cuts** on kinematic variables: **m_H dependant** optimization
  - For **m_H ~ 125 GeV excess** found in data

m_H [GeV]	$p_T^{\ell,max}$ [GeV]	$p_T^{\ell,min}$ [GeV]	$m_{\ell\ell}$ [GeV]	$\Delta\phi_{\ell\ell}$ [°]	m_T [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]



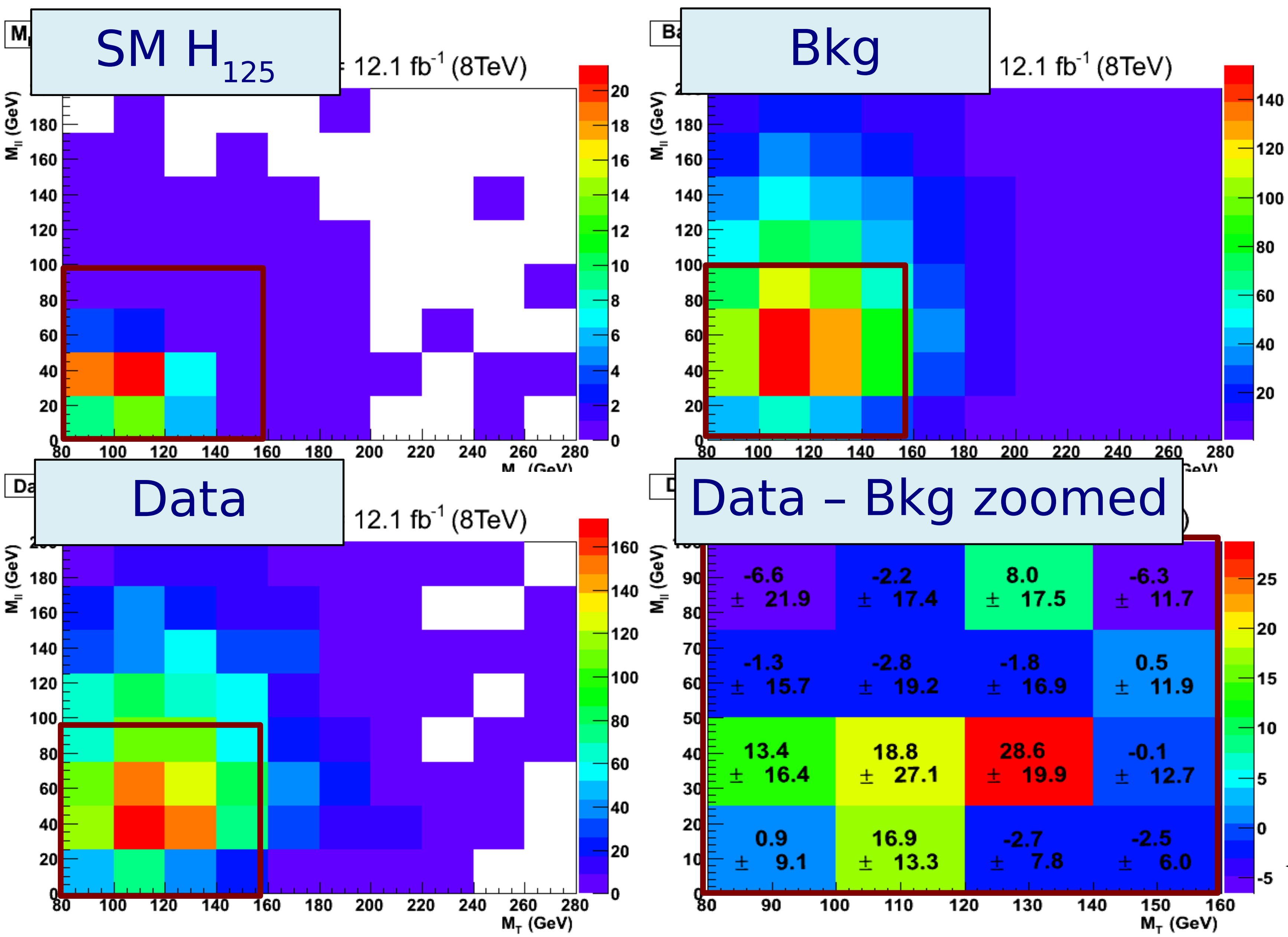


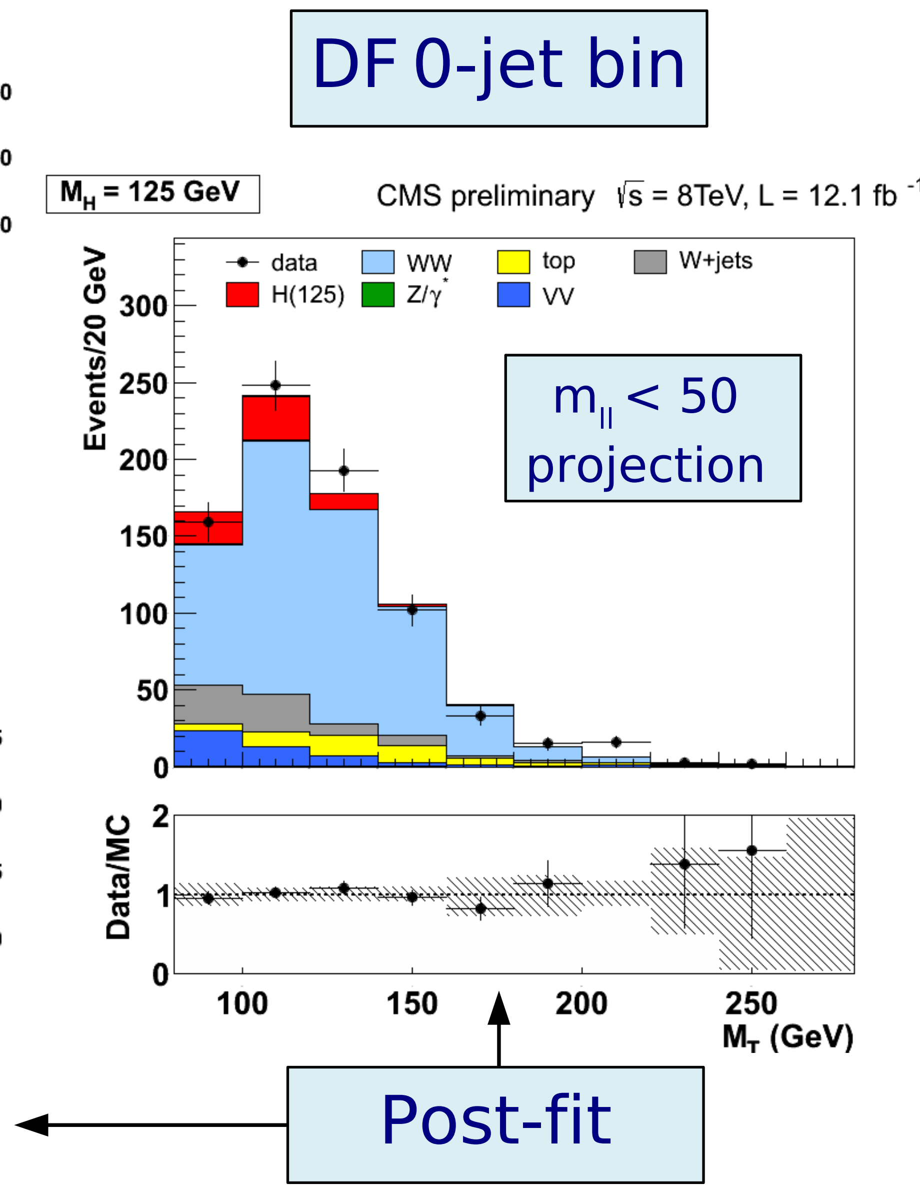
2-D shapes fit

lνlν

- Alternatively: improve discrimination power with 2-d approach (DF 0jet and 1-jet) → simple selections applied and S&B **[m_{ll}, m_T]** distributions are **fitted on data**

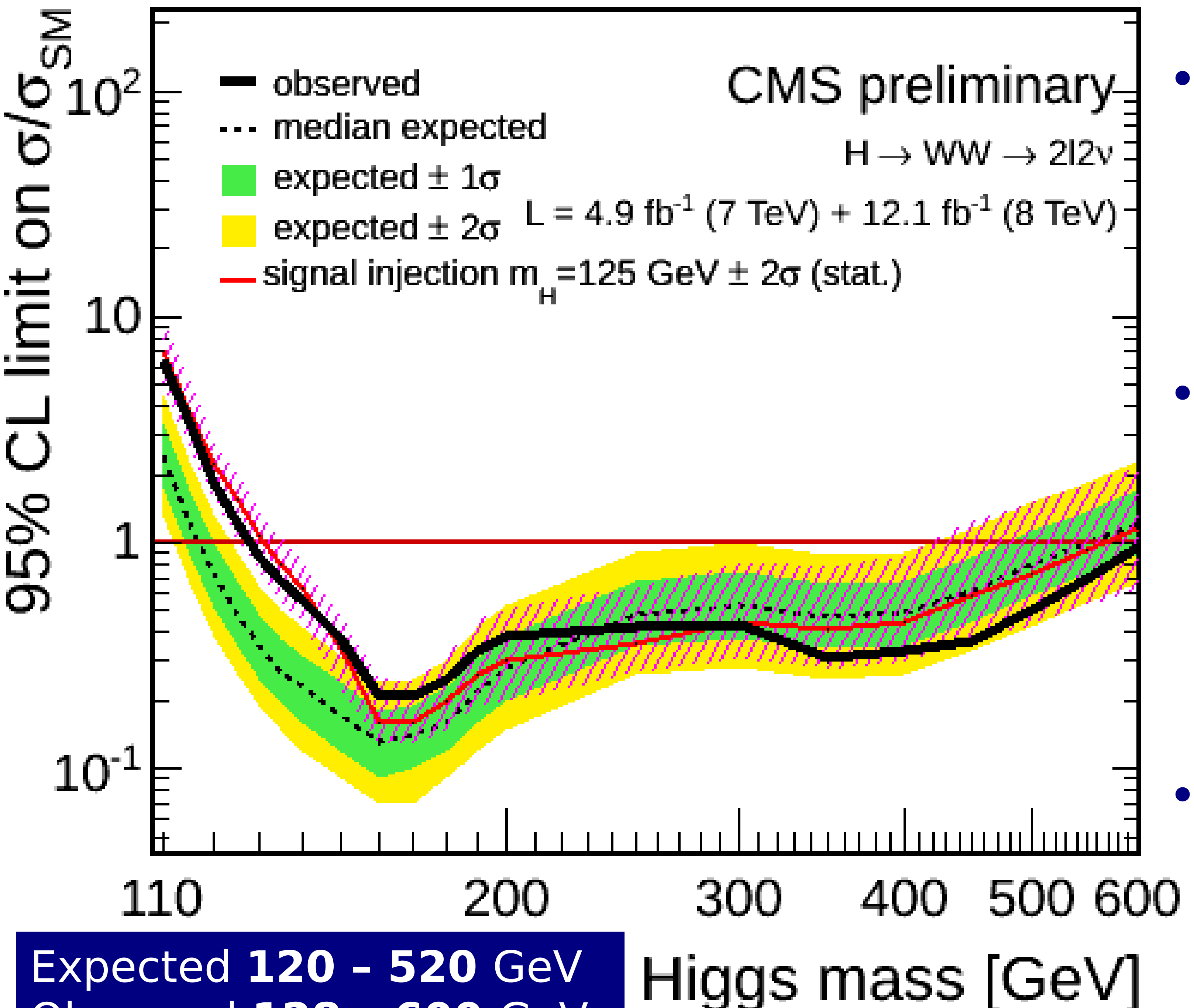
m_H (GeV)	m_T (GeV)	m_{ll} (GeV)	$p_T^{l,max}$
< 250	[80, 280]	< 200	> 20
> 250	[80, 280]	< 600	> 50





Results: exclusion

lνlν



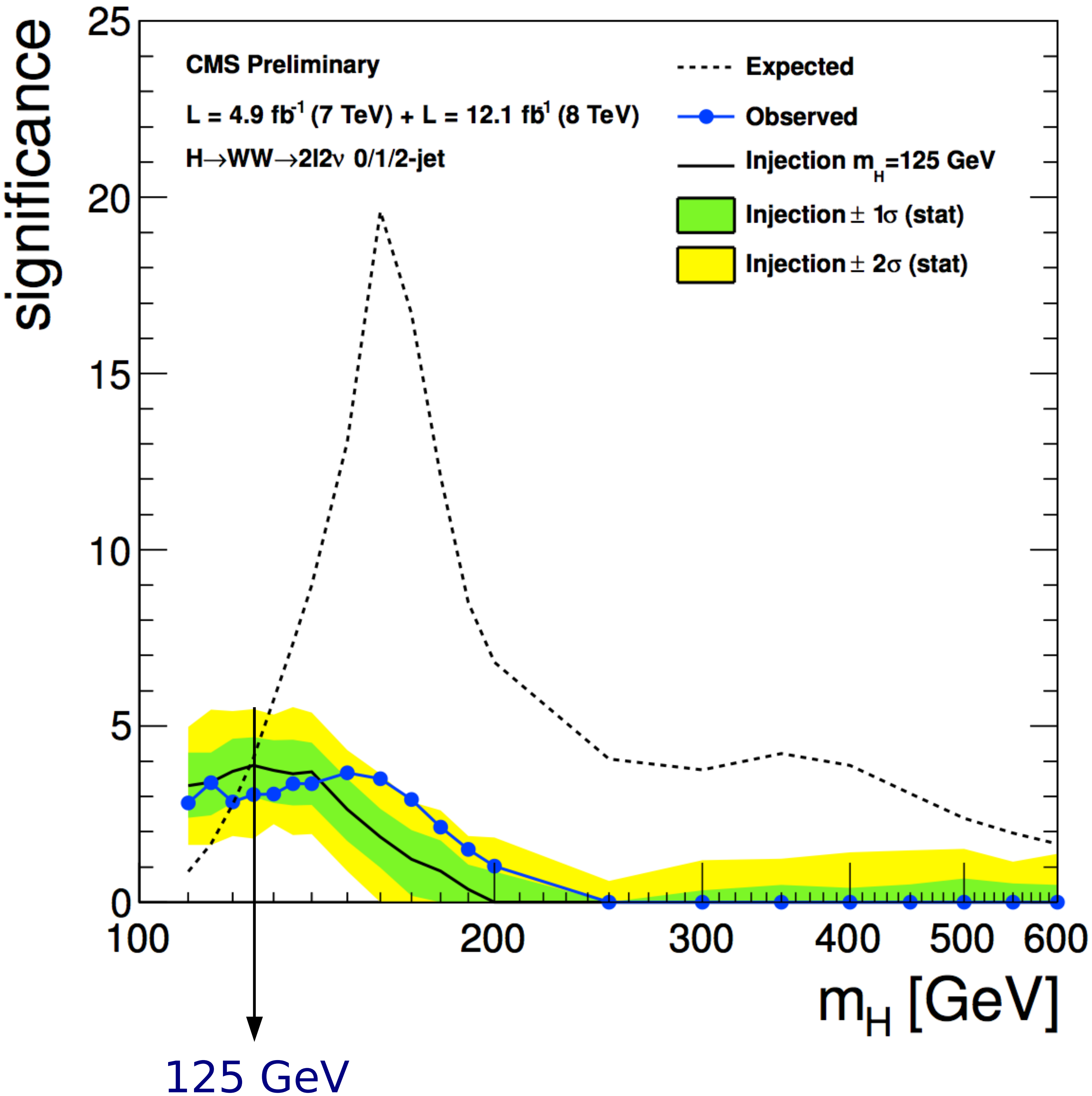
Expected **120 – 520** GeV
Observed **128 – 600** GeV

- **Higgs excluded** @ 95% CL **above 128 GeV**

- Low mass excess
  - Compatible with H^{125}?
  - Injection test → check red line

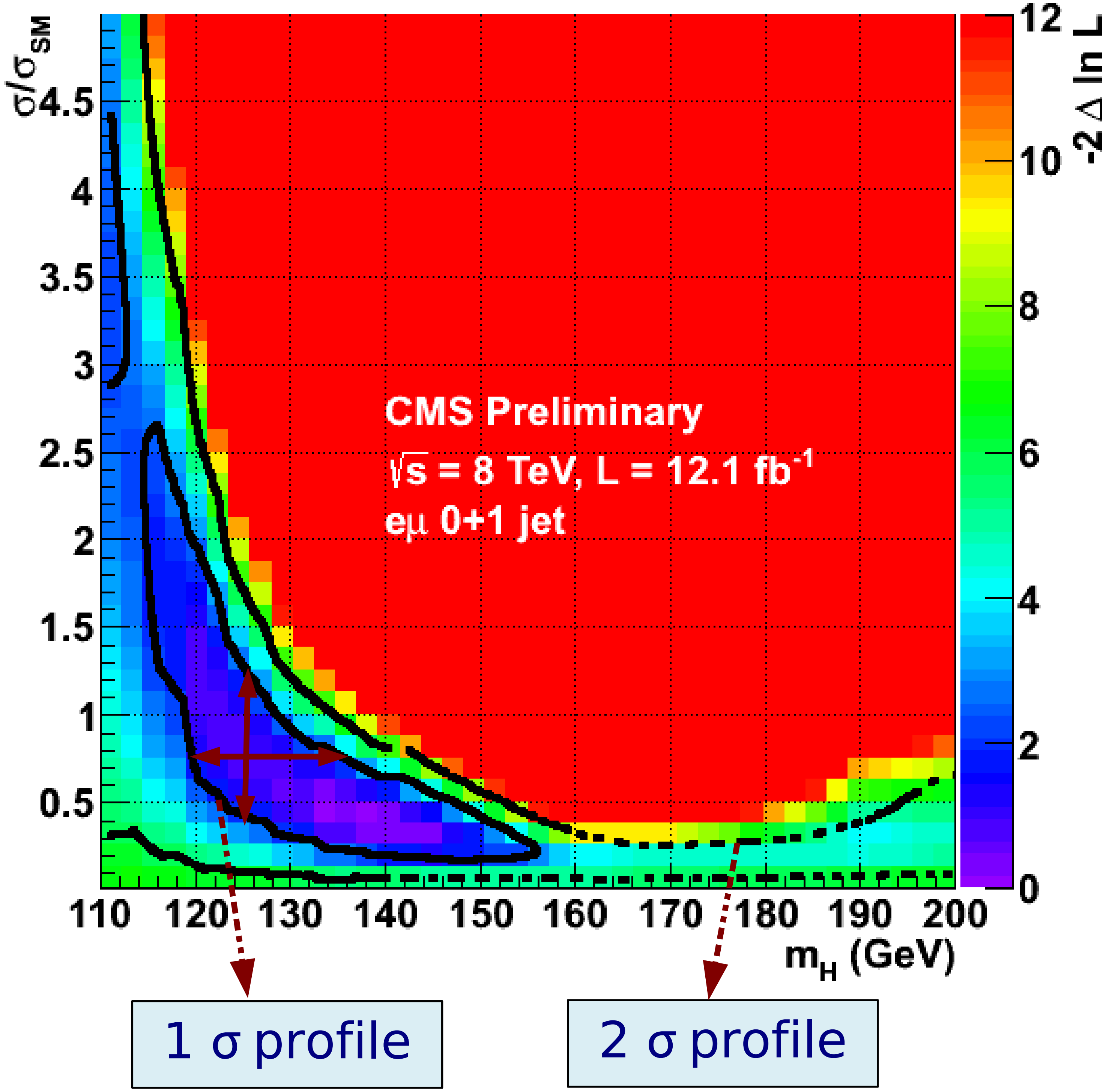
- Low mass **excess compatible** with a Standard Model **Higgs** with **mass = 125 GeV**

Results: signal significance $l\nu l\nu$

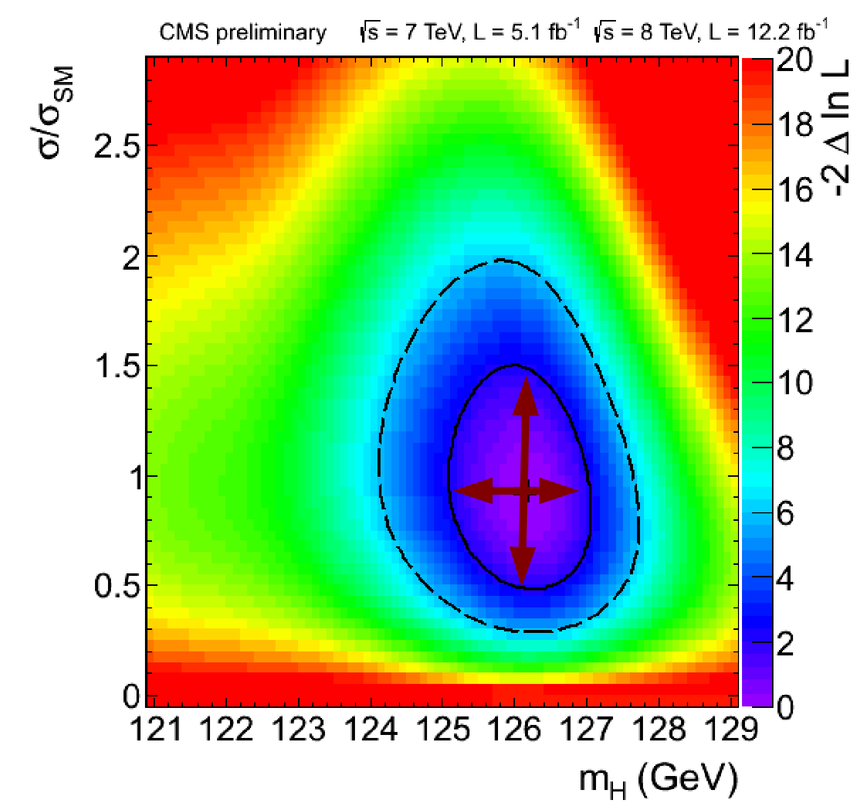


- Significant excess for a low m_H hypothesis
- For m_H = 125 GeV
  - **Expected 4.1 σ**
  - **Observed 3.1 σ**
- **Evidence of a new boson with mass around 125 GeV!**
- Best signal strenght fit **0.74 ± 0.25 $\sigma^{SM}(H_{125})$**

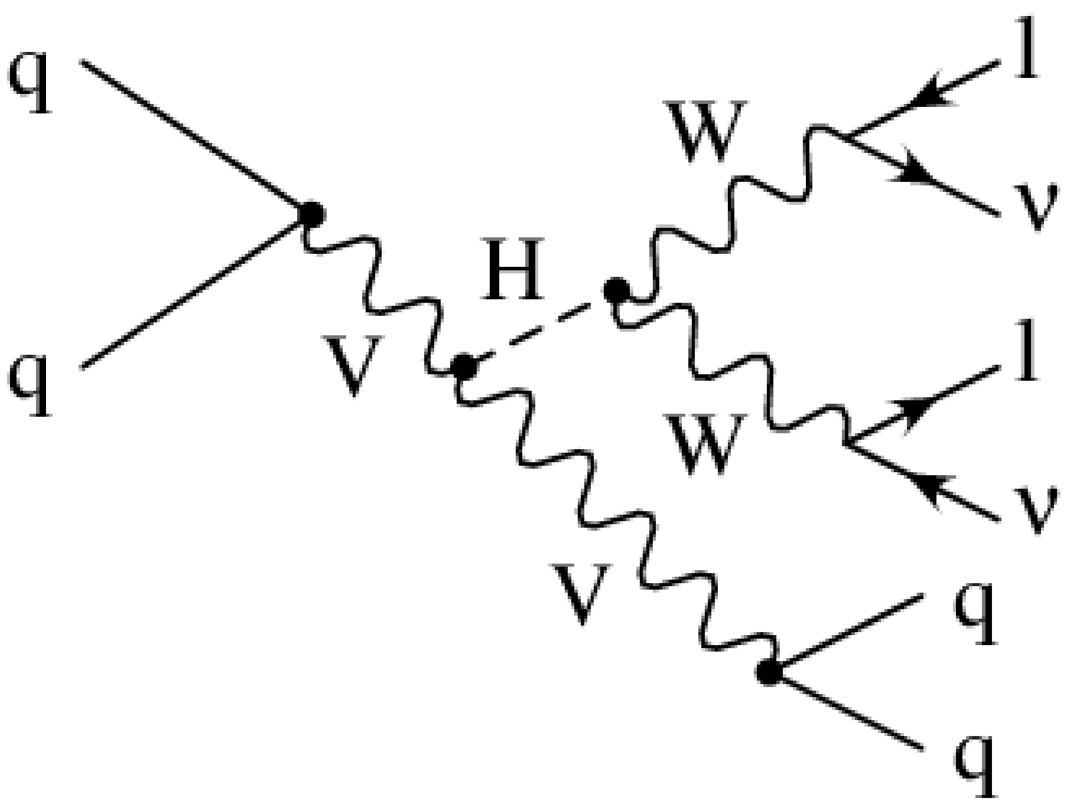
Results: anatomy of the excess



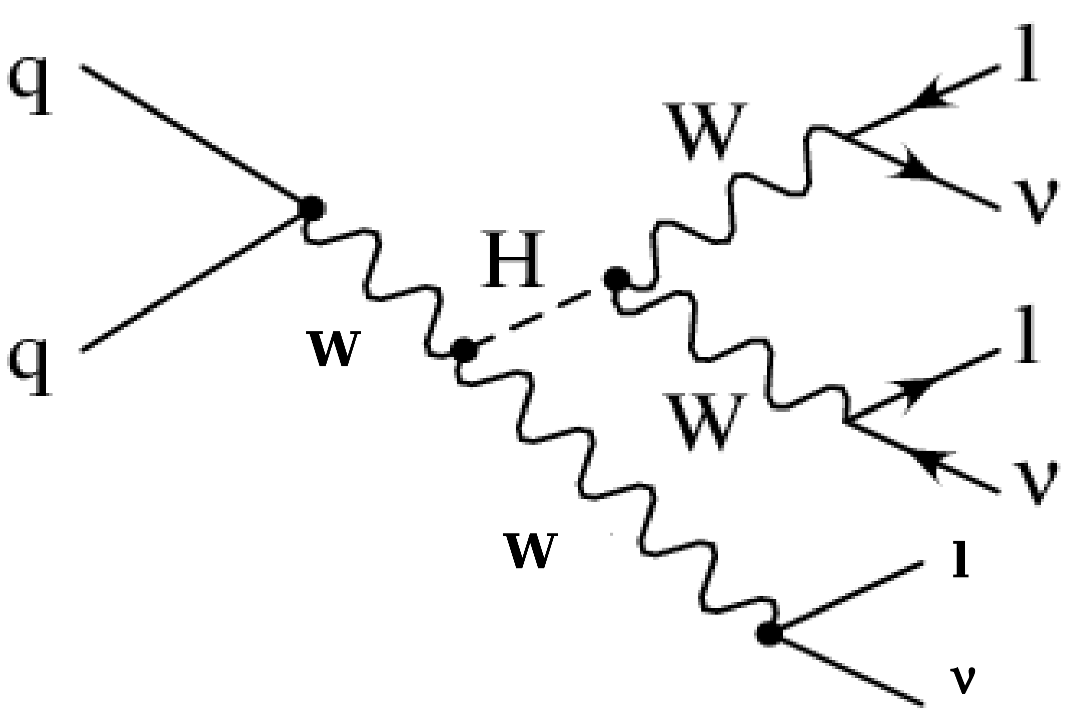
- H → WW deals a poor mass resolution in the excess characterization
  - eg. 125 Higgs lies in [120,135]
- H → WW provides the **best** handle in the signal **cross-section measurement**
  - See eg. comparison with H → ZZ



VH → WW*



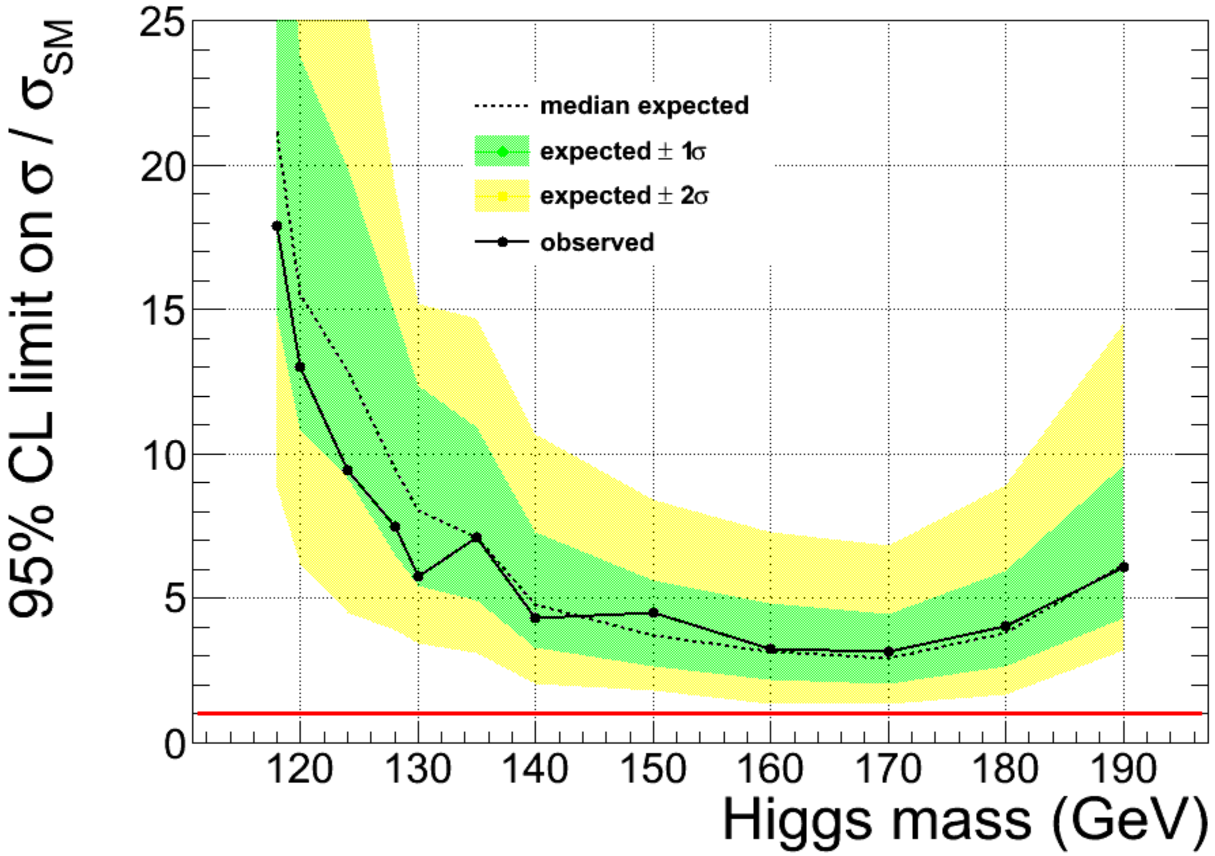
- Exploit the associated Higgs production which is non-negligible @ low mass
  - σ(WH(mH=125)) ~ 0.7 pb
- **lνlνqq** → 2! leptons o.ch. + 2 Jets + MET
  - **Similar to 2-jet bin lνlν analysis**
    - **Require $m_{jj} \sim m_{z}/m_{W}$**
  - Analysis based on 7 TeV dataset



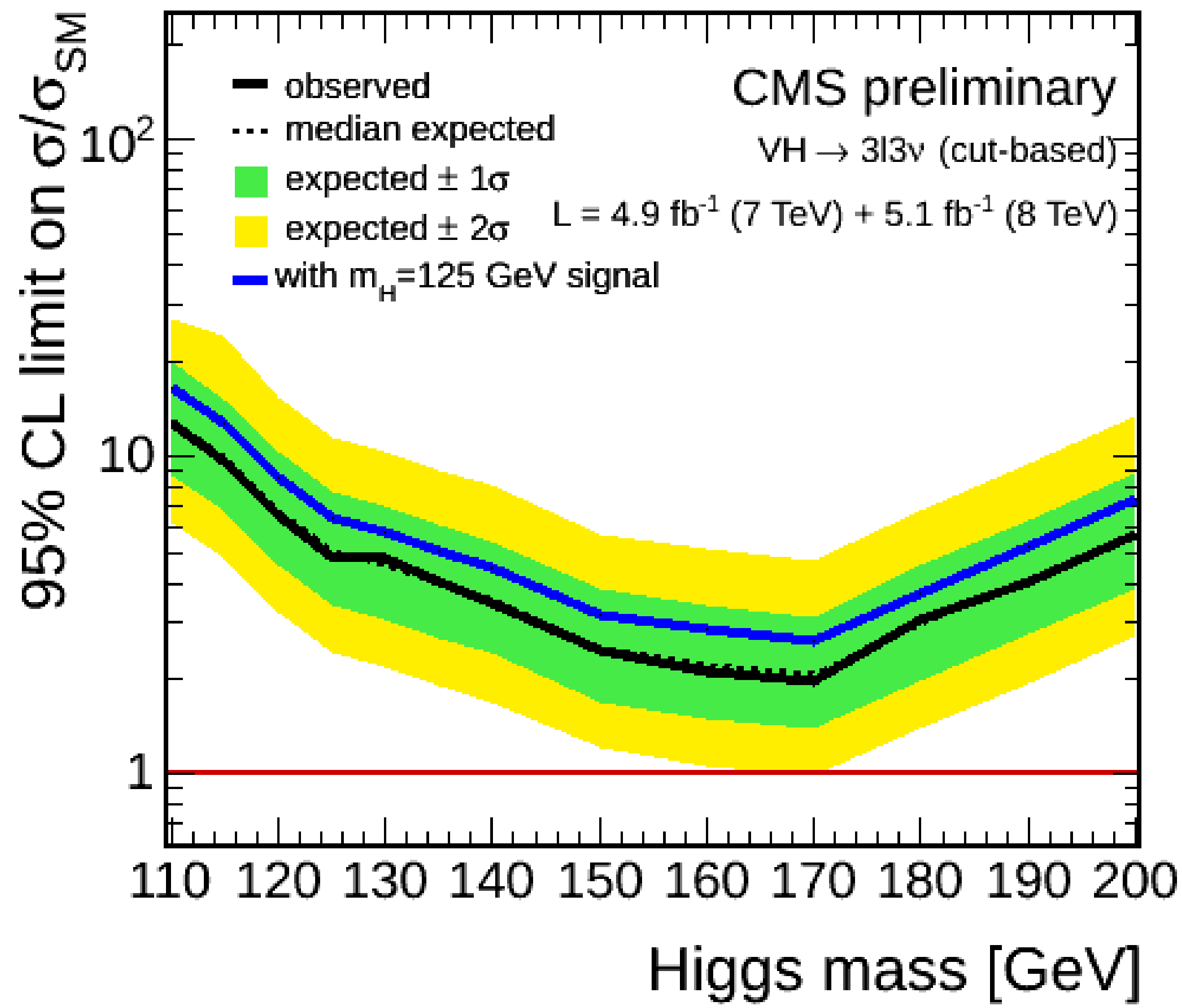
- **lνlνlν** → 3! leptons |tot. ch| = 1 + MET
  - **Similar to 0-jet bin lνlν analysis**
    - **Require additional lepton**
    - **Extend acceptance**
      (looser cuts on MET and leptons)
  - Analysis based on ICHEP dataset
    - 5 fb^{-1}@ 7 TeV + 5 fb^{-1}@ 8 TeV

VH → WW* : Results

Vlνlν



$\sigma^{excl}/\sigma^{SM}(m_H = 125) \sim 10$



$\sigma^{excl}/\sigma^{SM}(m_H = 125) \sim 5$

- Both analyses to be updated with full 2011-2012 dataset
  → expect news for next spring/summer !
  - CMS will be capable of probing H → WW decay also in the VH production mode

Conclusions

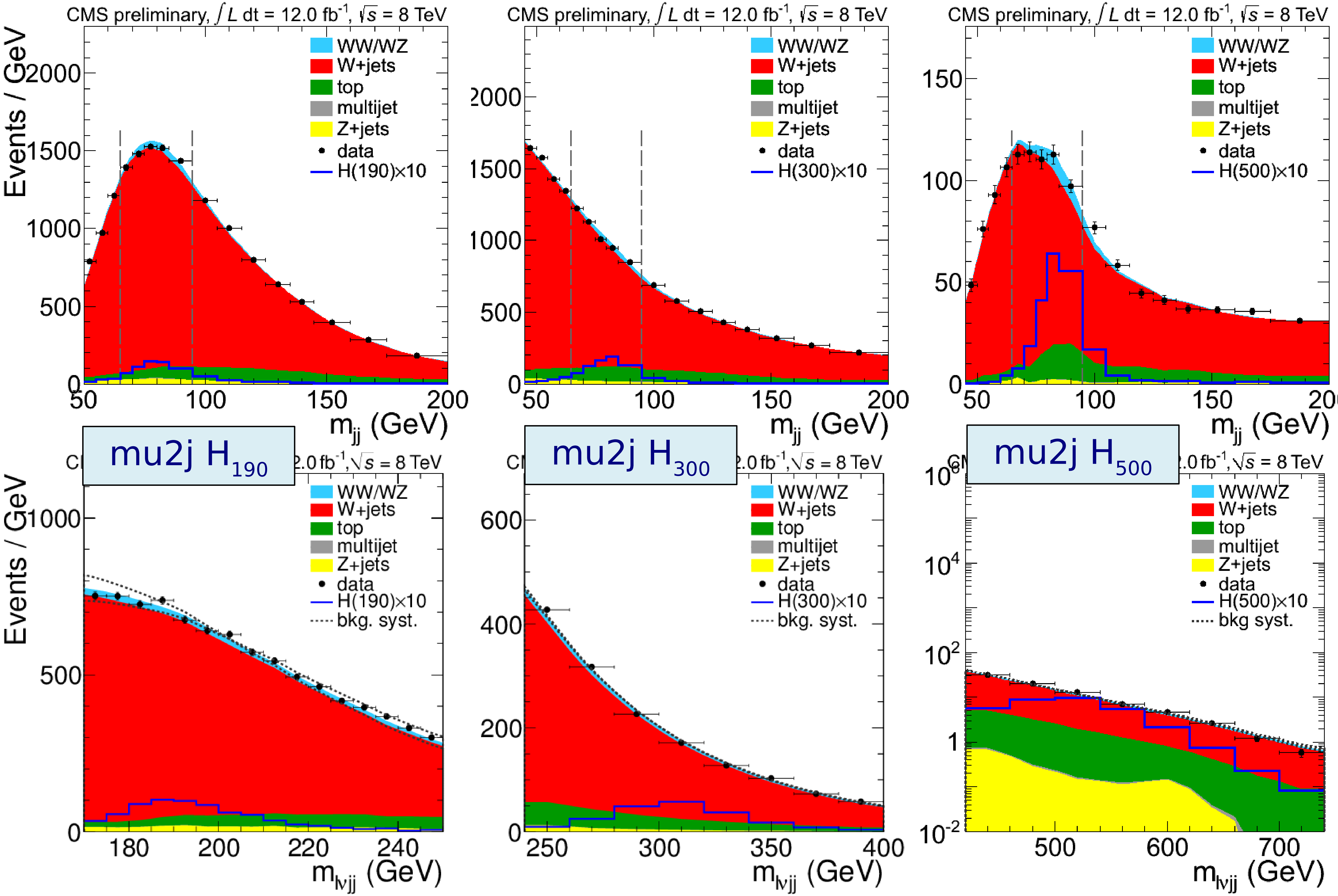
- **CMS** has produced **4 different analysis** exploiting the **H → WW** decay based on ggH, VBF and VH production modes

- The Standard Model Higgs boson is **excluded**, at 95% CL, **above 128 GeV up to 600 GeV**
  - **225-485, 550-600** GeV in the **semileptonic** mode
  - **128-600** GeV in the **fully leptonic** mode

- A broad excess is seen in H → WW → lνlν analysis compatible with a low m_H
  - Observed significance of the **excess for m_H = 125 GeV of 3.1 σ** (expected 4.1 σ)
  - Best **signal strenght** fit **0.74 ± 0.25 σ^{SM}** → compatible with SM prediction

Backup

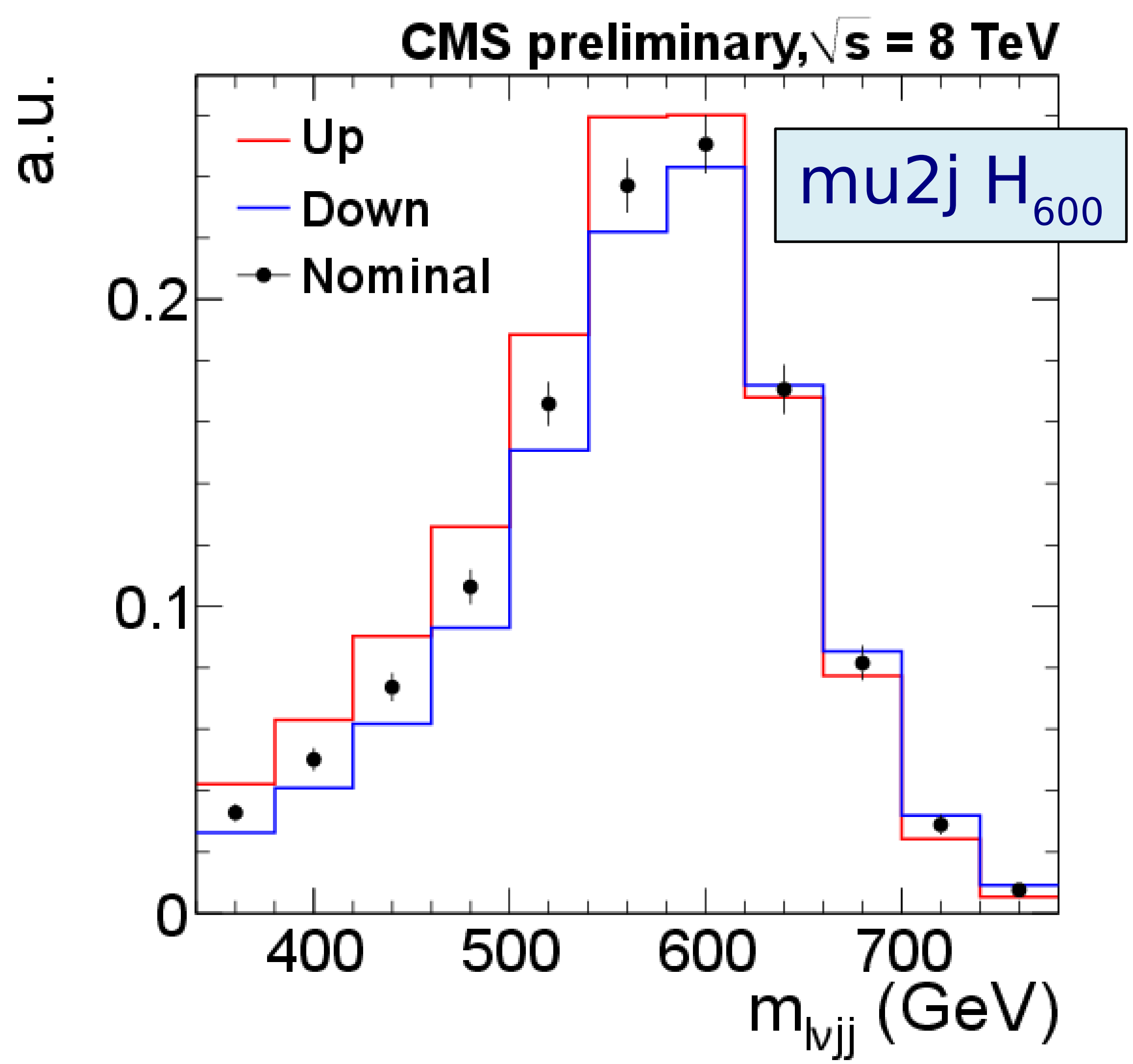
$H \rightarrow WW \rightarrow l\nu jj$ fits



H → WW → lνjj systematics

lνqq

- Dominant systematics are background normalization and shape
- Signal systematics include gg → WW interference correction uncertainty
  - Correction and related uncertainty significant for $m_H > 500$
  - Uncertainty propagated to the lνjj mass spectra



Source of uncertainty	Magnitude
Background $m_{\ell\nu jj}$ shape	See Fig. 5
Background normalization	0-2%
Higgs boson cross-section	13-15%
Theory acceptances (PDF)	1-2%
Scale uncertainties from jet binning	4-28%
Luminosity	4.4%
Lepton selection eff.	1-2%
Lepton trigger eff.	1%
Jet energy scale, resolution, and $E\!\!\!/_T$	<1%
Likelihood selection	10%
Signal shape (interference)	See Fig. 7

$H \to WW \to l\nu l\nu$ 8 TeV yields

lνlν

Cut-based selection DF

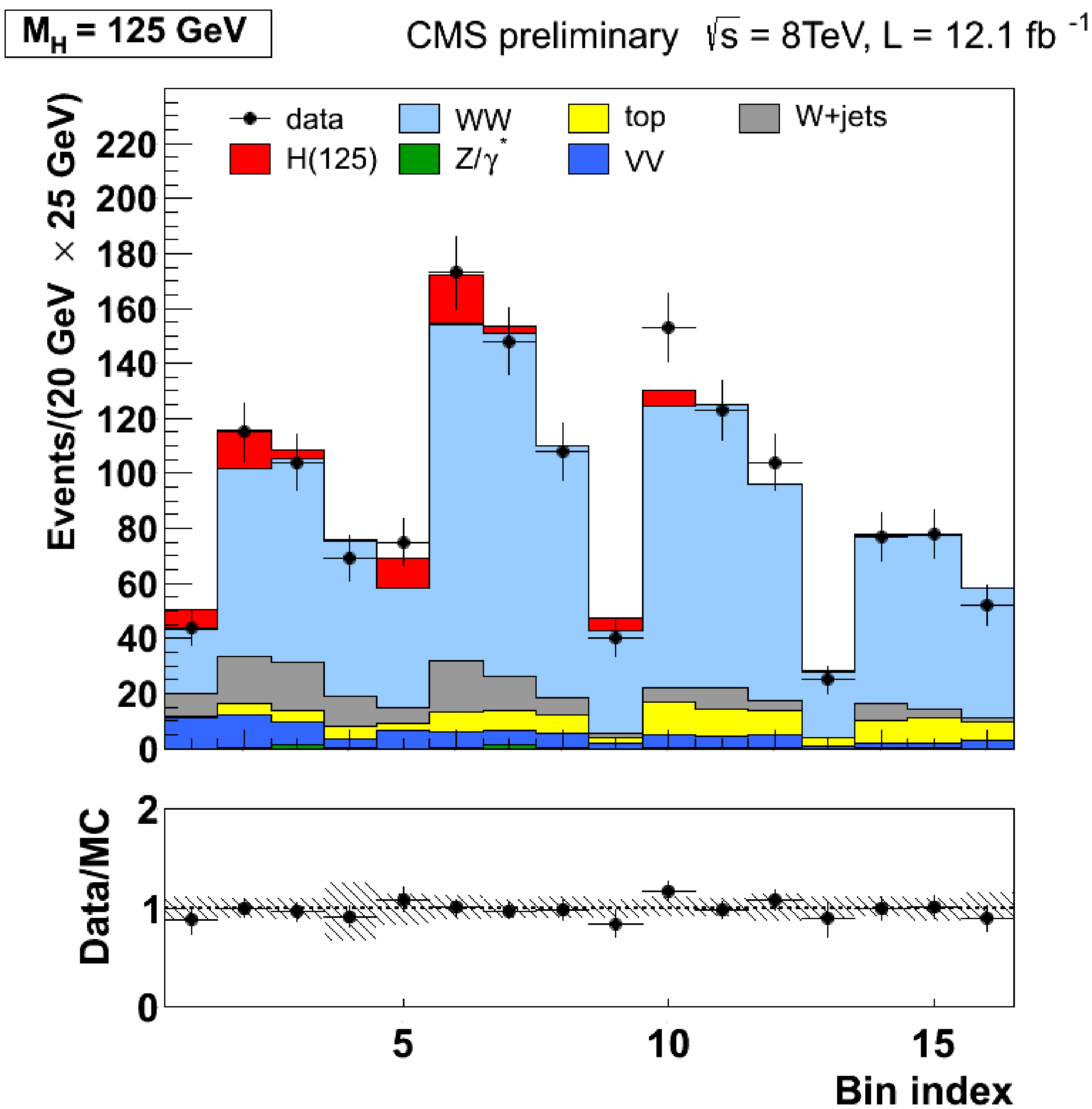
m_H	$H \to W^+W^-$	$pp \to W^+W^-$	$WZ+ZZ$ $+Z/\gamma^* \to \ell^+\ell^-$	Top	W + jets	$W\gamma^{(*)}$	all bkg.	data
0-jet category $e\mu$ final state								
120	34.0 ± 7.3	162 ± 16	5.3 ± 0.5	8.6 ± 2.0	38 ± 14	23.1 ± 8.8	237 ± 23	285
125	58 ± 12	203 ± 19	6.6 ± 0.6	11.0 ± 2.5	44 ± 16	25.6 ± 9.5	291 ± 27	349
130	86 ± 18	226 ± 21	7.1 ± 0.7	12.2 ± 2.8	47 ± 17	27 ± 10	319 ± 29	388
160	238 ± 51	125 ± 12	3.7 ± 0.4	13.1 ± 3.1	5.9 ± 2.7	2.6 ± 1.5	160 ± 13	197
200	95 ± 21	204 ± 19	6.3 ± 0.6	28.9 ± 6.4	7.7 ± 3.5	1.3 ± 0.9	278 ± 21	309
400	40 ± 11	133 ± 15	6.2 ± 0.7	50 ± 11	7.6 ± 3.3	3.5 ± 2.1	200 ± 19	198
600	6.6 ± 2.3	42.2 ± 4.8	2.5 ± 0.3	16.5 ± 3.8	4.4 ± 2.0	2.4 ± 1.8	67.9 ± 6.7	64
1-jet category $e\mu$ final state								
120	14.9 ± 4.3	38.9 ± 6.4	5.3 ± 0.6	40.3 ± 3.0	19.1 ± 7.4	7.1 ± 3.4	111 ± 11	123
125	27.3 ± 8.0	47.9 ± 7.8	6.5 ± 0.7	49.5 ± 3.3	22.4 ± 8.6	7.1 ± 3.4	134 ± 13	160
130	40 ± 12	53.9 ± 8.8	7.3 ± 0.8	55.2 ± 3.6	24.5 ± 9.4	7.1 ± 3.4	148 ± 14	182
160	131 ± 37	44.4 ± 7.0	5.3 ± 0.7	51.8 ± 3.5	9.0 ± 3.9	0.6 ± 0.4	111.1 ± 8.8	145
200	58 ± 15	80 ± 13	6.8 ± 0.8	114.6 ± 6.5	16.1 ± 6.5	0.4 ± 0.3	238 ± 16	276
400	29.4 ± 8.1	81 ± 13	7.9 ± 1.2	129.0 ± 7.1	16.8 ± 6.6	0.6 ± 0.5	235 ± 16	226
600	6.9 ± 1.8	30.0 ± 4.8	3.1 ± 0.4	40.3 ± 3.0	8.4 ± 3.5	0.0 ± 0.0	81.8 ± 6.6	74
2-jet category $e\mu$ final state								
120	1.7 ± 0.2	0.8 ± 0.5	0.1 ± 0.0	0.9 ± 0.3	0.3 ± 0.2	0.1 ± 0.1	2.2 ± 0.6	2
125	2.8 ± 0.4	0.9 ± 0.5	0.1 ± 0.0	1.5 ± 0.5	0.3 ± 0.2	0.1 ± 0.1	2.9 ± 0.8	2
130	4.4 ± 0.6	1.3 ± 0.7	0.1 ± 0.0	1.6 ± 0.5	0.3 ± 0.2	0.1 ± 0.1	3.4 ± 0.9	4
160	11.7 ± 1.5	1.2 ± 0.6	0.0 ± 0.0	1.5 ± 0.5	0.0 ± 0.0	0.1 ± 0.1	2.9 ± 0.8	4
200	9.3 ± 1.2	2.5 ± 1.2	1.7 ± 1.6	4.6 ± 1.3	0.3 ± 0.4	0.0 ± 0.0	9.1 ± 2.4	8
400	3.9 ± 0.5	3.5 ± 2.2	1.7 ± 1.6	4.6 ± 1.3	0.0 ± 0.0	0.0 ± 0.0	9.8 ± 3.0	7
600	1.4 ± 0.2	1.6 ± 1.0	0.0 ± 0.0	1.9 ± 0.8	0.3 ± 0.2	0.0 ± 0.0	3.7 ± 1.3	3

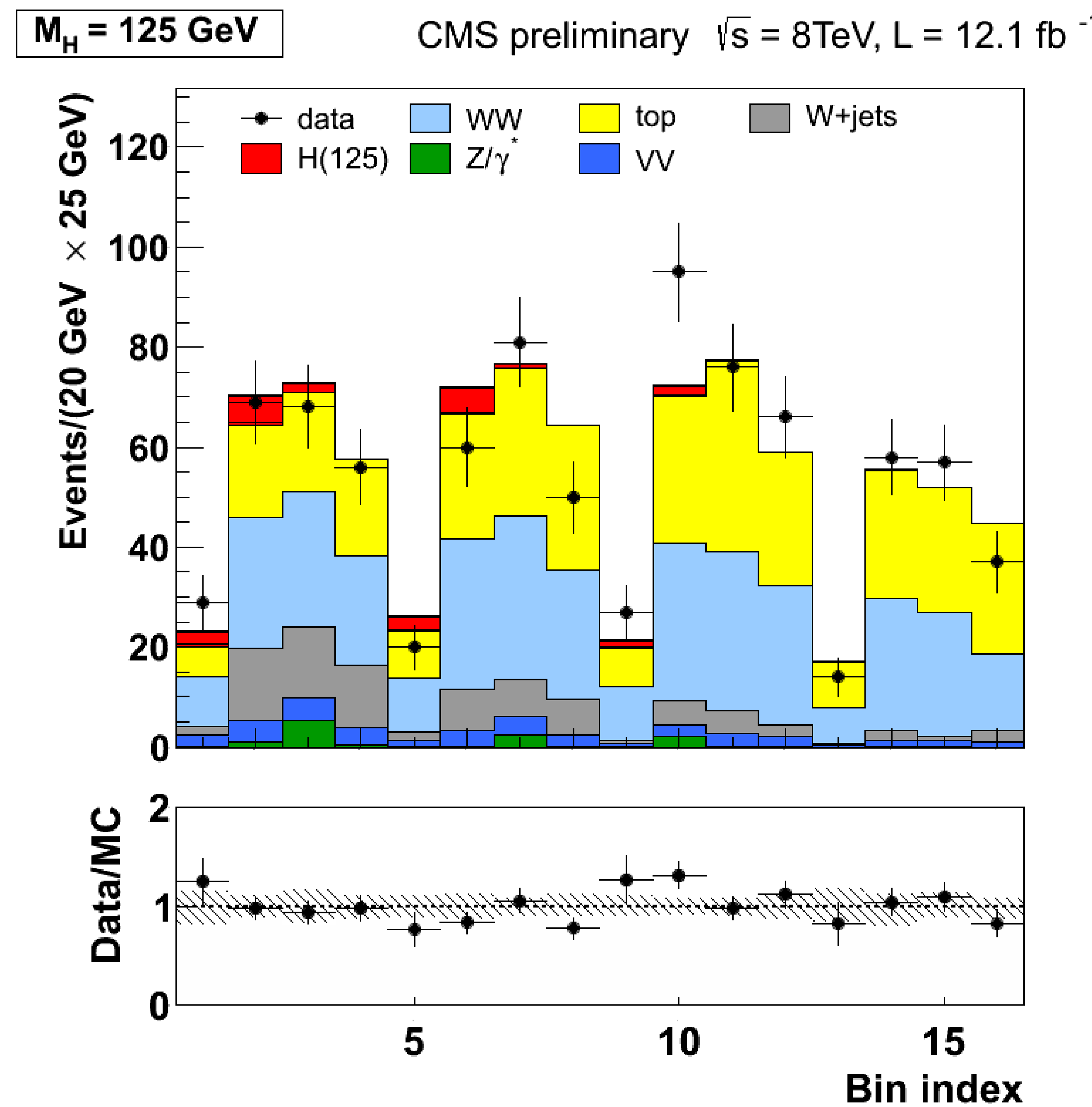
Unrolled 2-d shapes

lνlν

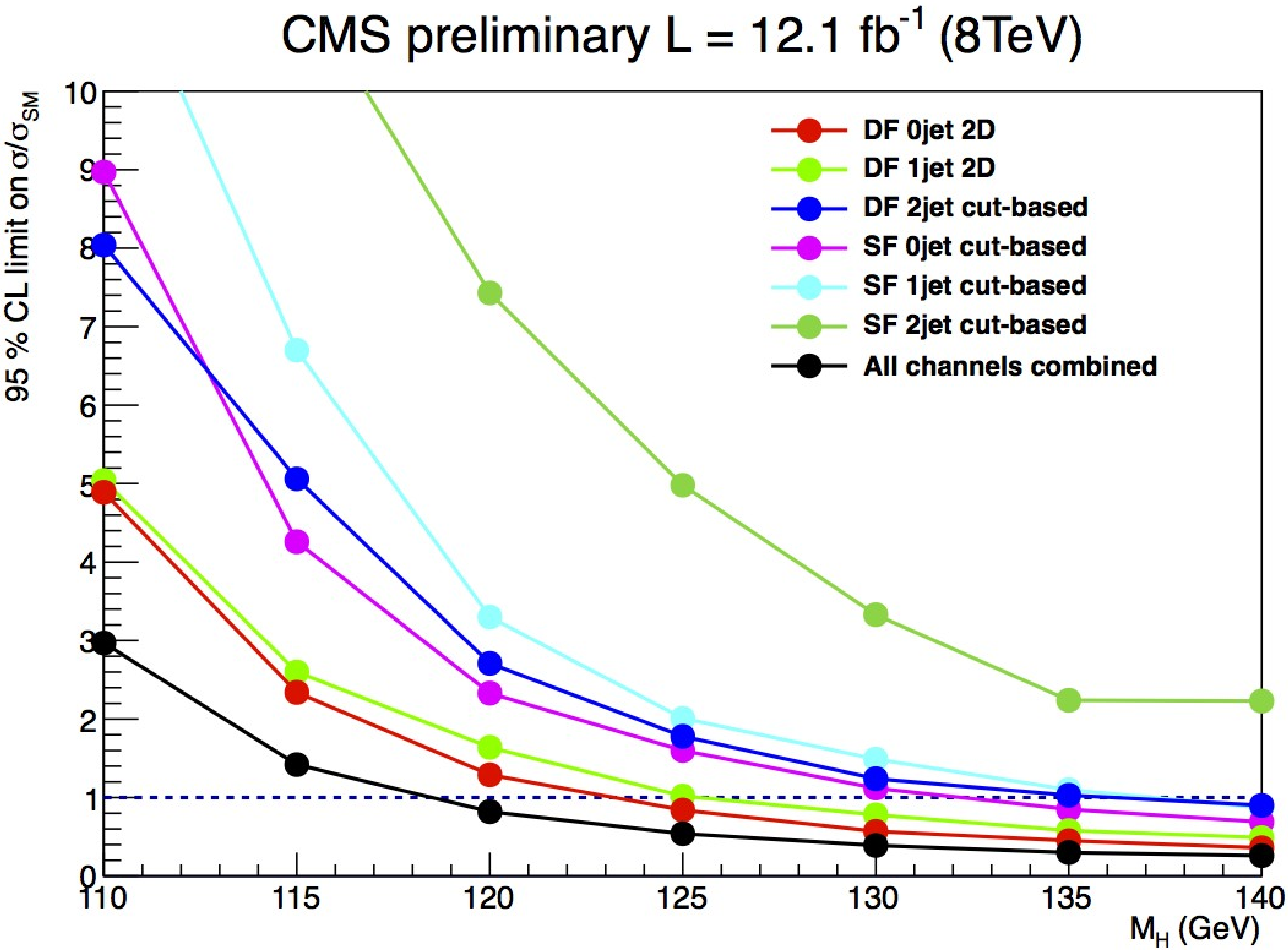
DF 0-jet

DF 1-jet





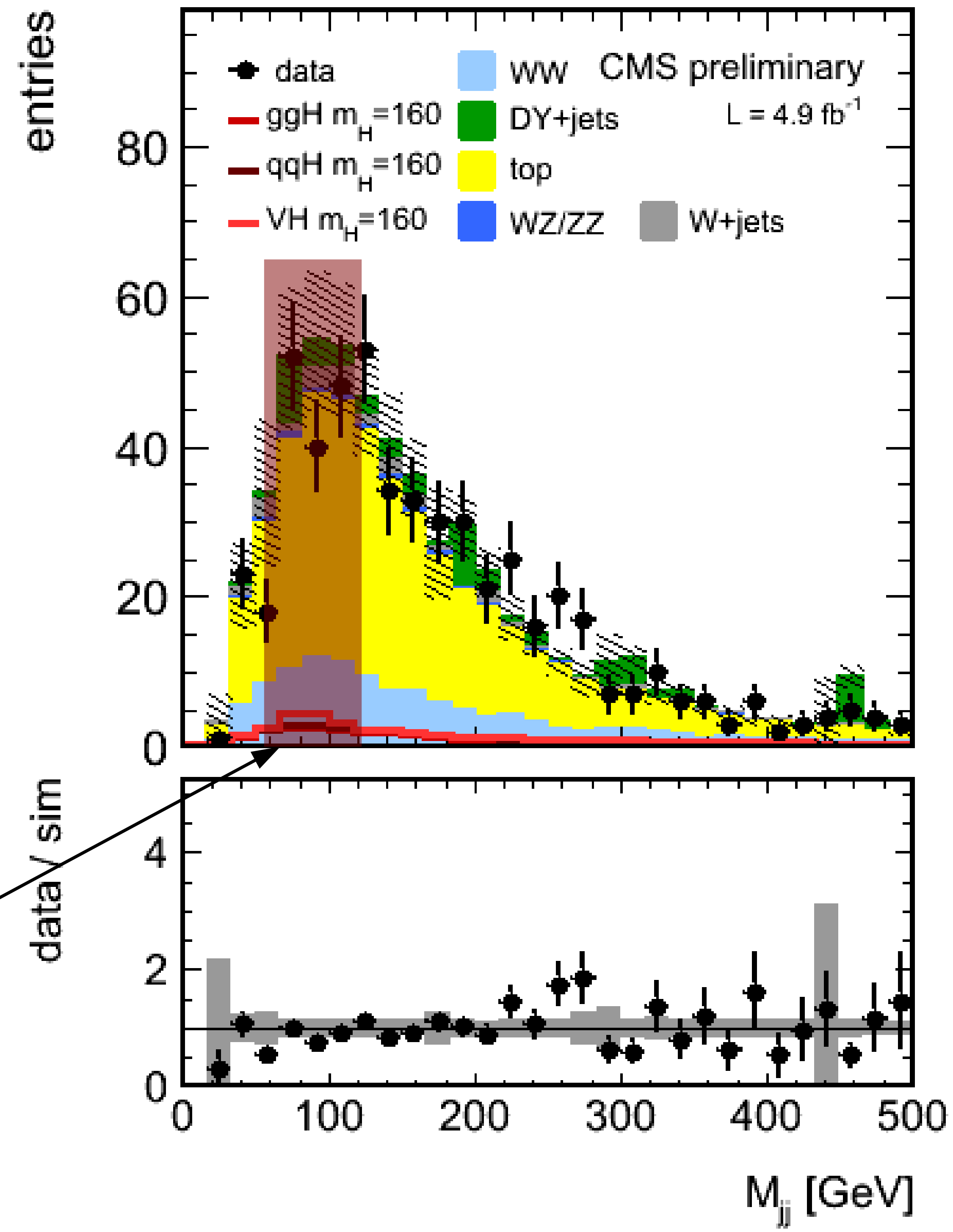
Expected limits by category$_{l\nu l\nu}$



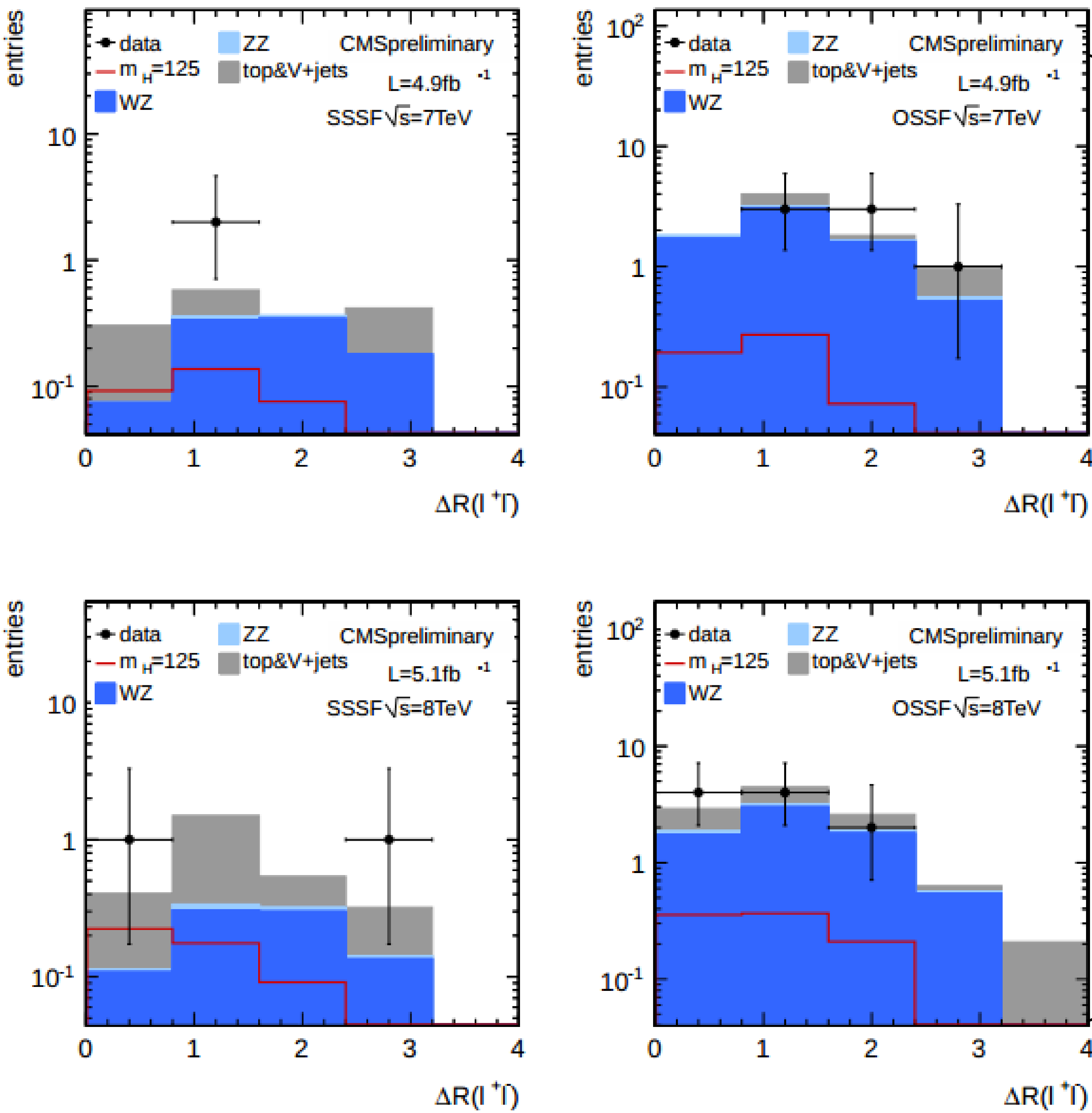
2-jet (VBF/VH) focus

lνlν/Vlνlν

- **Find good jets** (anti-k_T $\Delta R = 0.5$)
  - $E_T > 30$ GeV & $|\eta| < 4.7$
  - Compatibility with primary vertex
- **VBF** candidate if
  - 2 jets
  - $|\Delta\eta(j1,j2)| > 3.5$
  - $M_{j1j2} > 500$
  - Accept additional jet if not between j1,j2
- **VH > lνlνjj** candidate if
  - m_{j1j2} in [60,110] GeV range



WH > lνlνlν focus



- Cut&Count, 2-categories
  - Opposite-sign same-flavour lepton pair (OSSF)
  - Everything else → Same-sign same-flavour (SSSF)

Distributions before last cut ($\Delta R(l^+l^-) < 2$)

Bibliography

- **H → WW → lνqq → CMS-HIG-12-046**
- **H → WW → lνlν → CMS-HIG-12-042**
- **VH → VWW → jjlνlν → CMS-HIG-12-014**
- **WH → WWW → lνlνlν → CMS-HIG-12-039**