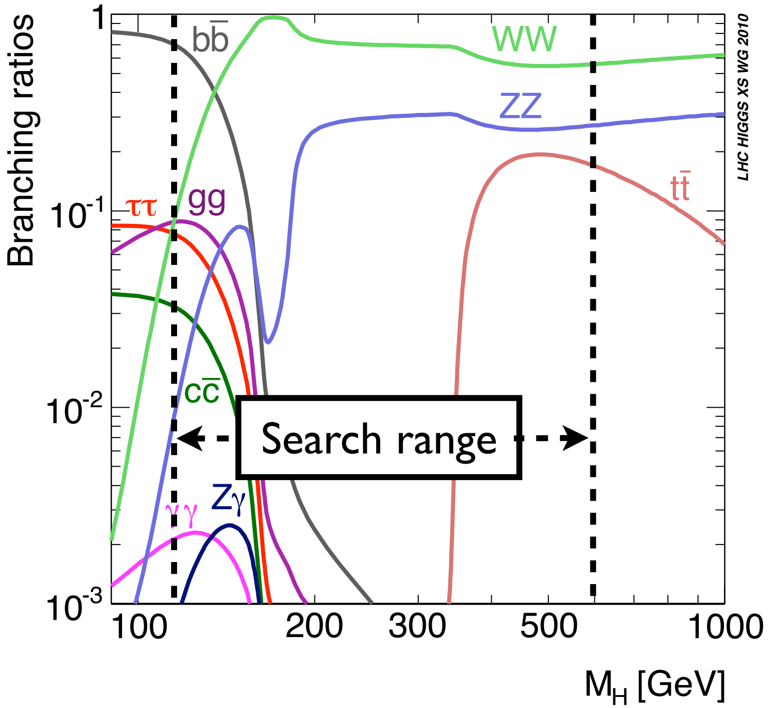
Searches for the SM Higgs boson in the WW decay channel with the CMS experiment

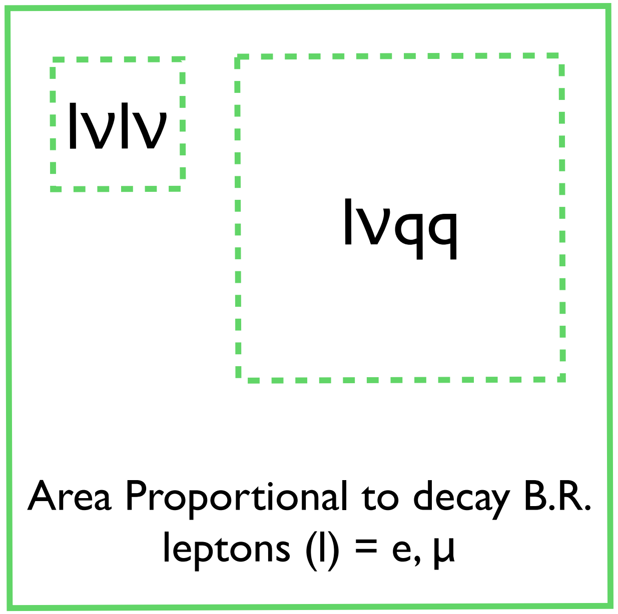
Dave Evans on behalf of the CMS collaboration

Higgs Hunting 2012, July 18, Orsay - France

H→WW Decay Channel

H→WW has the highest production rate in most of the search range

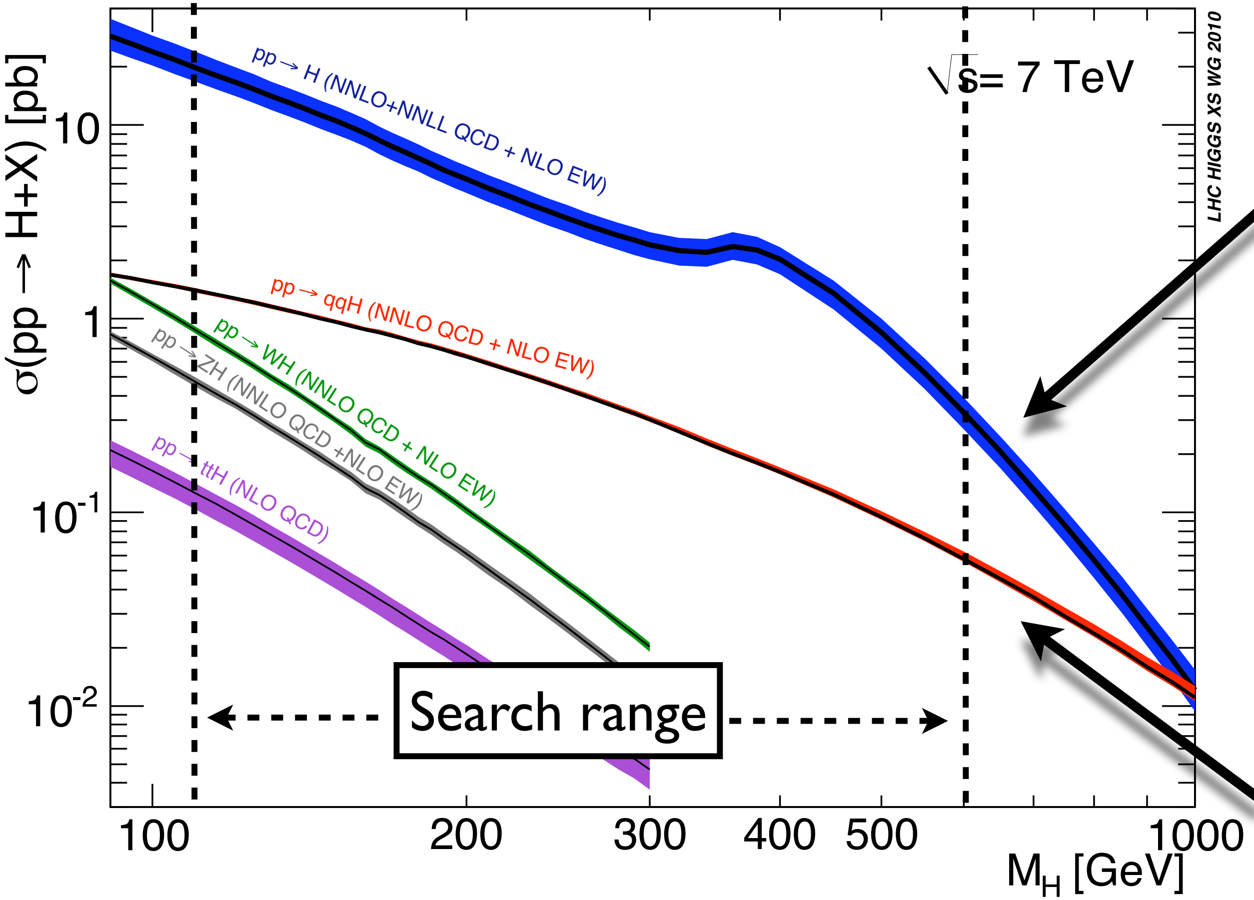




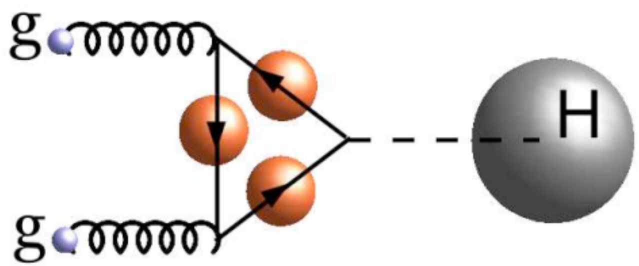
- H→WW→lνqq: Highest rate, but large W+jets background
  - Reconstruct the Higgs boson mass (broad resolution) - exclusion* ~ [250 - 500] GeV
- H→WW→lνlν: Smaller rate, but smaller backgrounds
  - Fundamentally a counting experiment (no mass peak) - exclusion* ~ [122 - 450] GeV

* Expected in 2011 + 2012 datasets - See slide 33

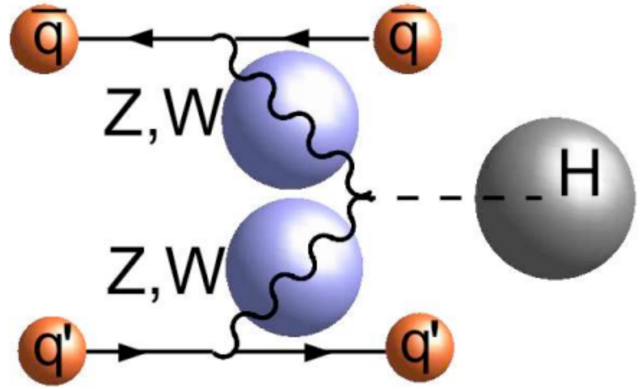
Higgs Boson Production



Gluon-gluon fusion

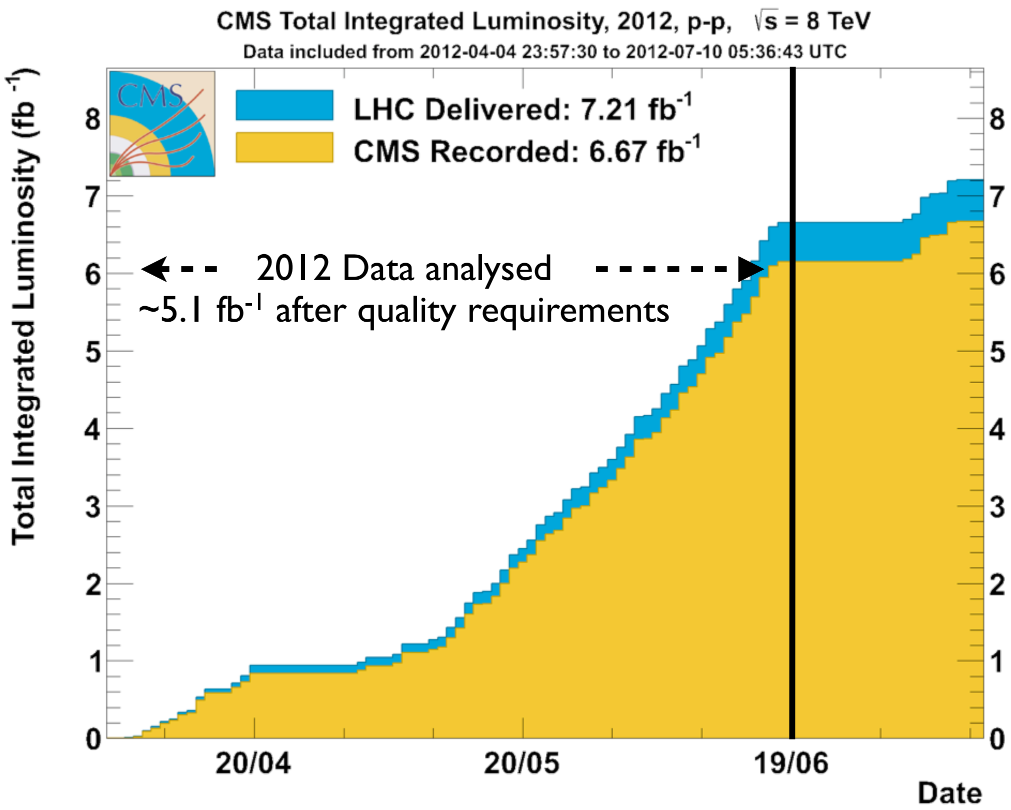


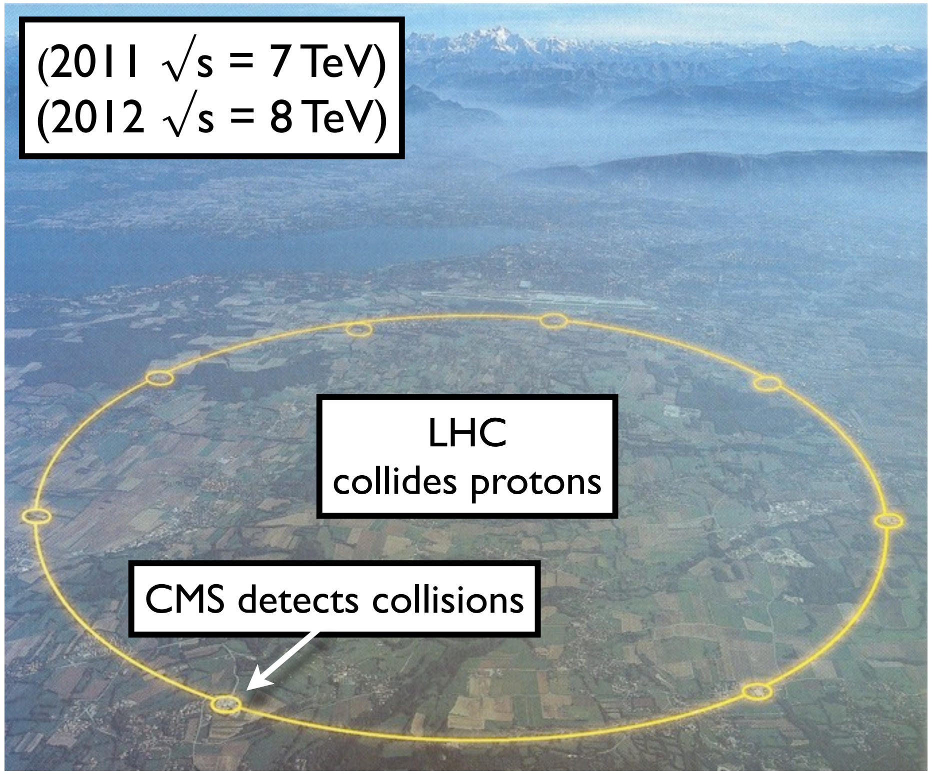
Vector Boson Fusion



- gg-fusion: dominant production mode
- VBF: lower rate but distinctive signature
  - Two forward jets and Higgs decay products central

Experimental Apparatus - Large Hadron Collider



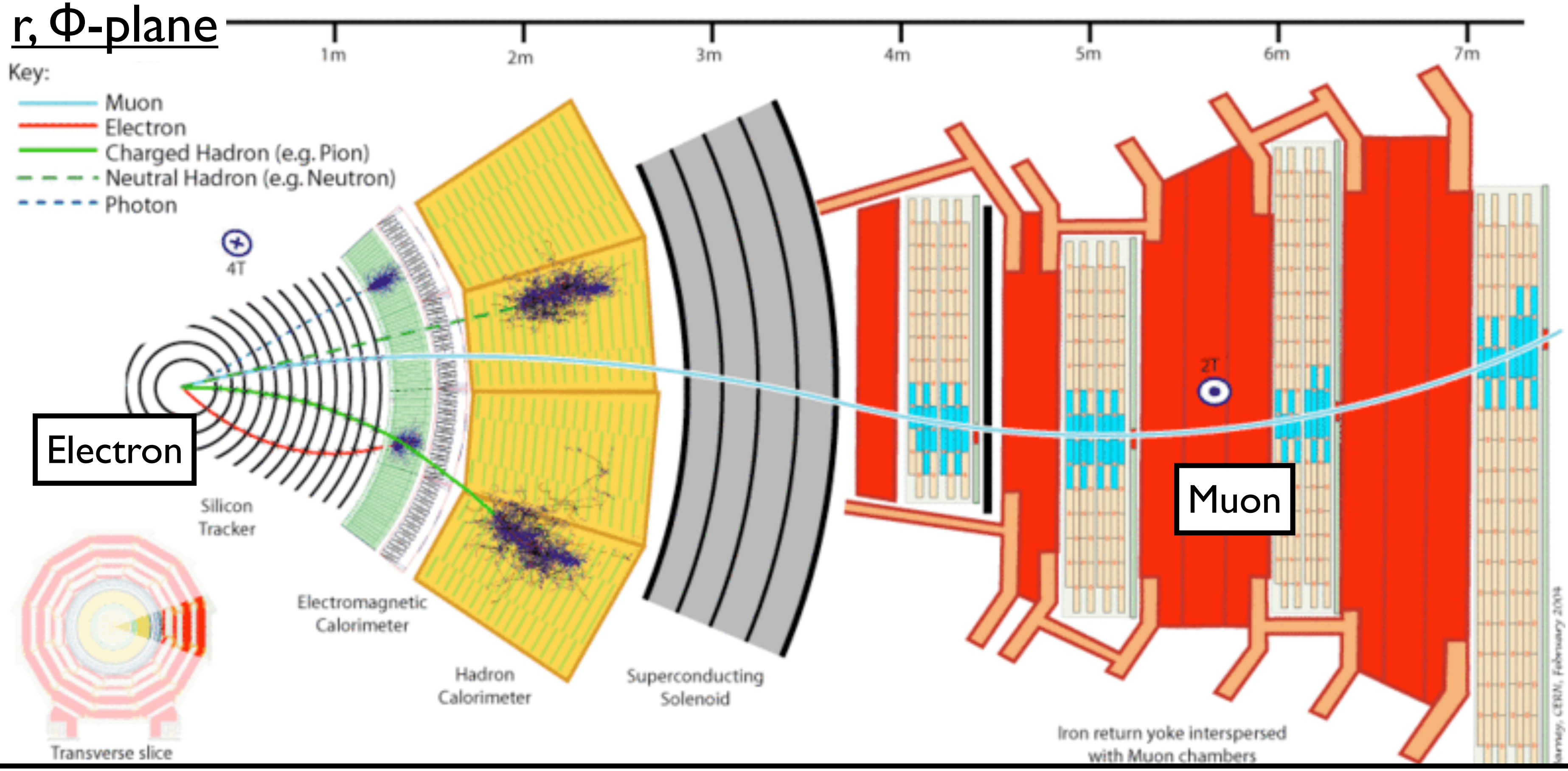


- Analysed datasets of ~ 4.9 fb^{-1} (5.1 fb^{-1}) in 2011 (2012)
  - Peak luminosity above 5×10^{33} s^{-1}cm^{2}
  - Average between 10-30 interactions per bunch crossing in Run2012

Experimental Apparatus - CMS Detector

Select events consistent with the decay of WW
→ Two opposite sign leptons (e or μ) and large MET (lνlν channel)

r, Φ-plane



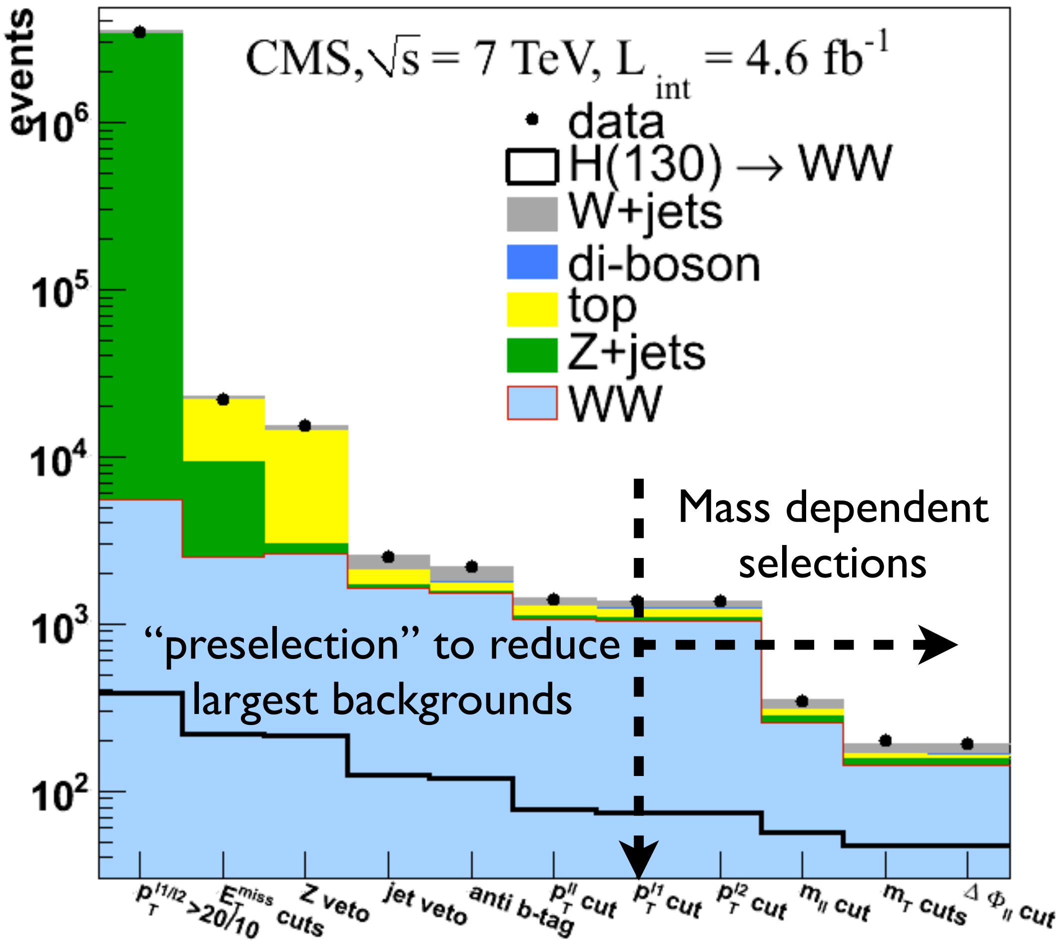
Jets clustered by using the anti-k_T algorithm with distance parameter 0.5

Neutrinos are observed as "MET":
Negative vector sum of the transverse momentum of reconstructed particle candidates

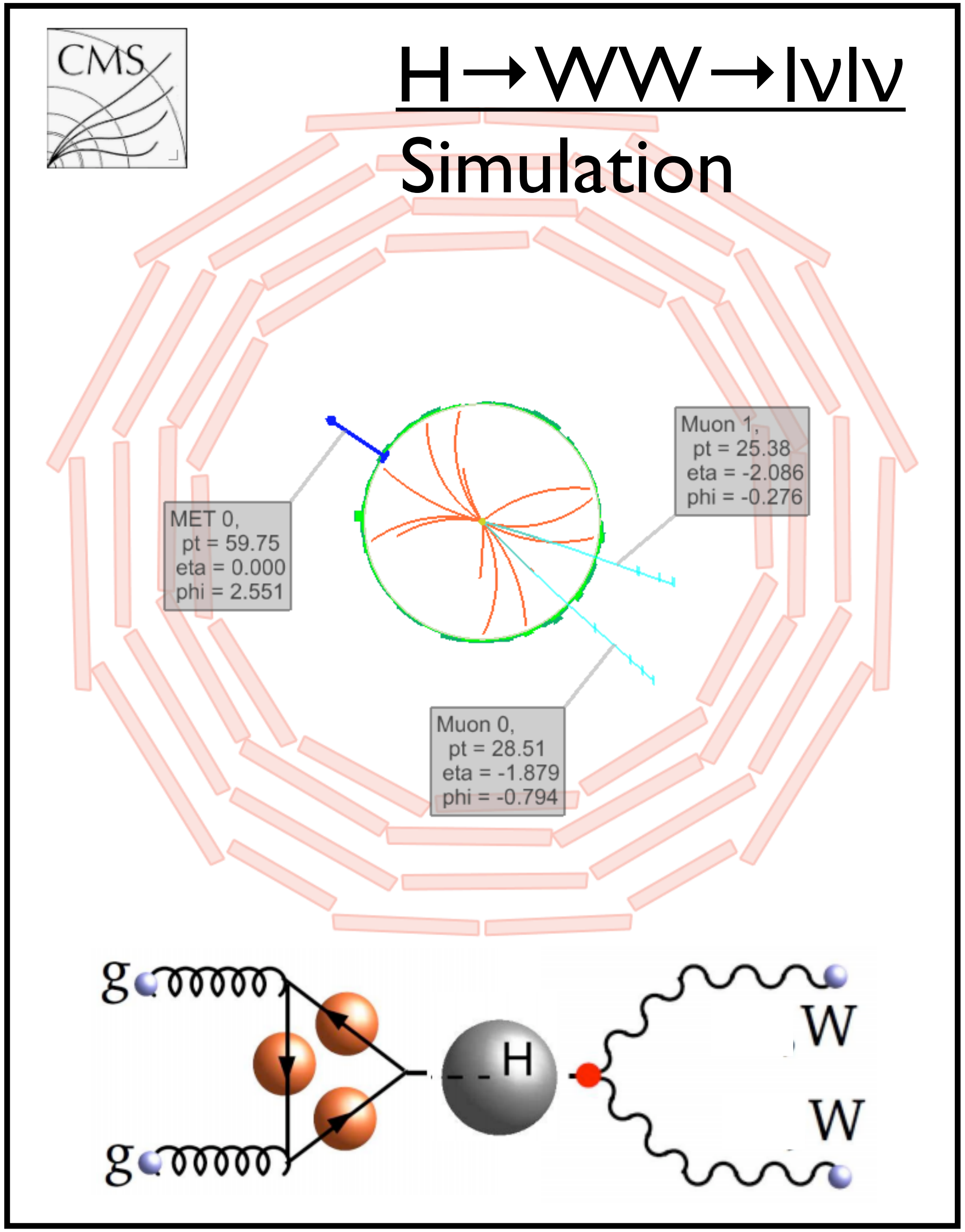
H→WW→lνlν Analysis

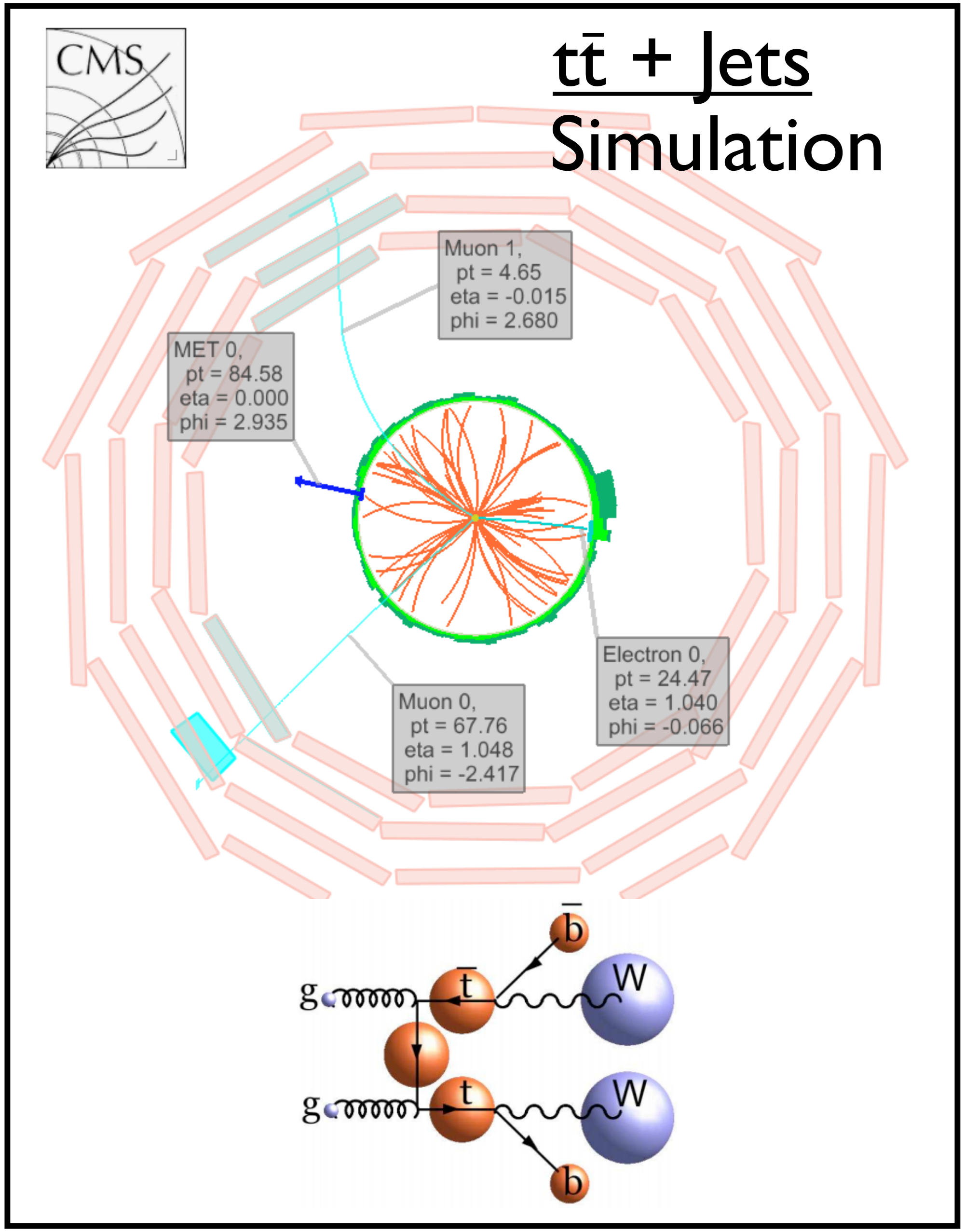
- Higgs boson signal
  - Two isolated leptons (e or μ) and MET
- Main reducible backgrounds
  - Z→ll+(jets→fake MET)
  - W→lν+(jets→fake lepton)
  - tW and ttbar production
- Main irreducible backgrounds
  - Standard model diboson decays to two leptons and MET

Events passing selection cuts (2011 dataset)



H→WW→lνlν: Separating Reducible Backgrounds





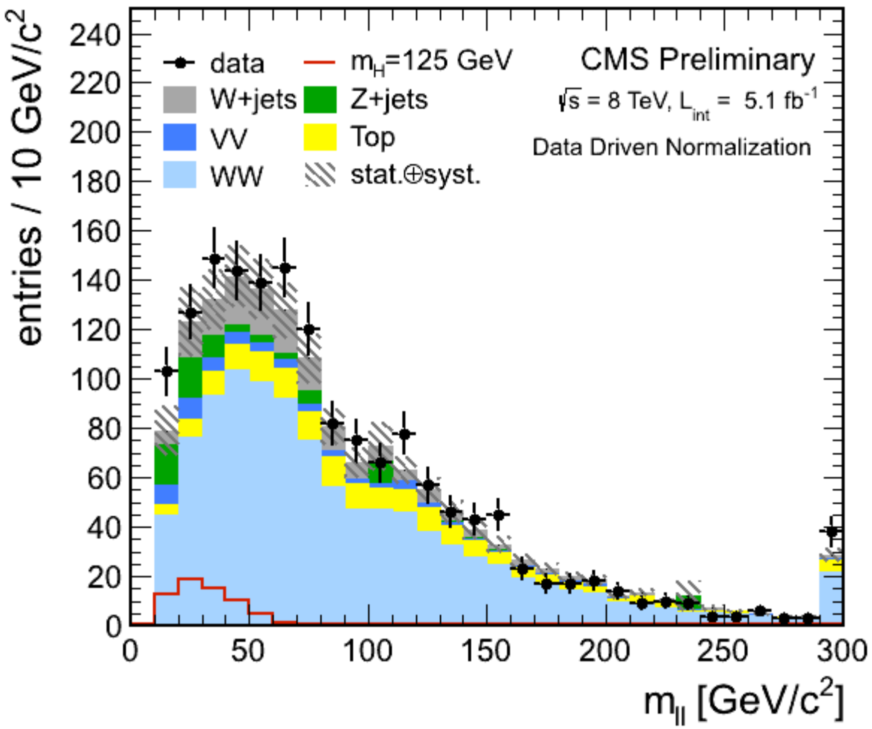
$H \to WW \to l\nu l\nu$ Analysis

- Initial preselection common to all Higgs boson mass hypotheses
  - Signal is expected to be small at preselection level
  - Can use preselection to validate analysis procedures
- Reduce top-quark decay background
  - Apply top-veto based on jet b-tagging and soft muon tagging
- Reduce WZ background
  - Reject events with a third lepton passing identification requirements
- Require lepton identification and isolation to reject mis-identified jets

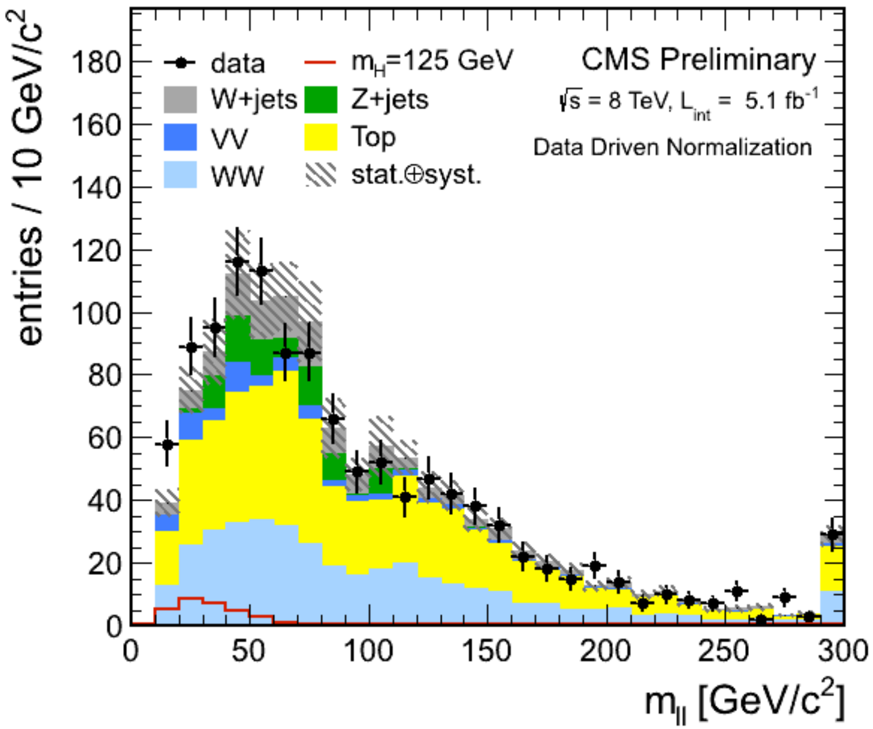
- Final analysis optimised for each Higgs boson mass hypothesis
  - 8 TeV analysis (2012): Cut based 0, 1-jet and VBF analyses
  - 7 TeV analysis (2011): Multivariate analysis for 0, 1-jet events and cut based VBF analysis

H→WW→lνlν Preselection and Jet Categorisation

0-jet ee/μe/eμ/μμ



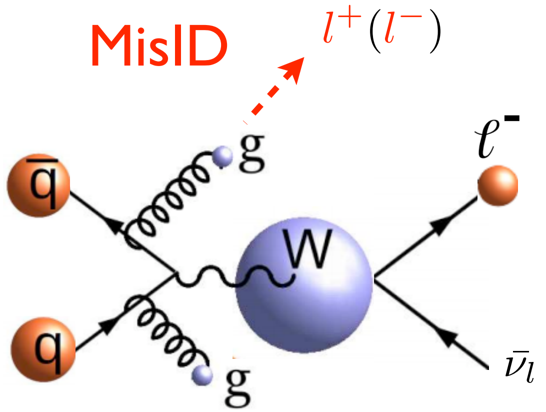
1-jet ee/μe/eμ/μμ



- After preselection, categorise events by number of jets with p_T > 30 GeV
- Improve sensitivity by separating top quark background from signal
  - Zero jet category (most sensitive) dominated by irreducible background
  - Largest backgrounds in one and two-jet categories are top and non-resonant WW

H→WW→lνlν: W+Jets and Top Backgrounds

W+Jets

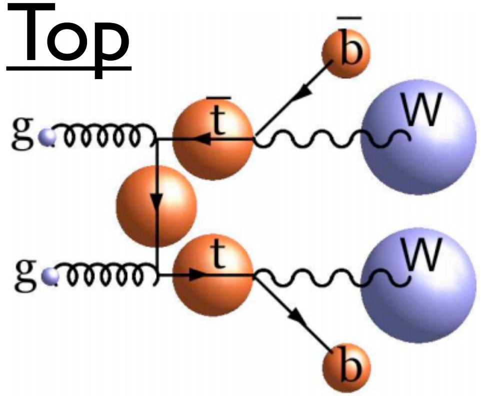


Systematic Uncertainty ~ 36%

- W+jets estimated from dilepton control region enriched in misidentified leptons
  - Require one lepton to pass the analysis selection, and the other to fail it but pass a loose selection
  - Weight these events by the probability (FR) for a misidentified jet that passes the loose selection to also pass the analysis selection
  - FR is measured in a dijet enriched control sample recorded using loose single lepton triggers

- Top background estimated from control region with inverted top veto
  - Background surviving the veto estimated by weighting events by the per event tagging efficiency
  - The per jet tagging efficiency for high and low p_T jets is measured in a separate control sample

Top



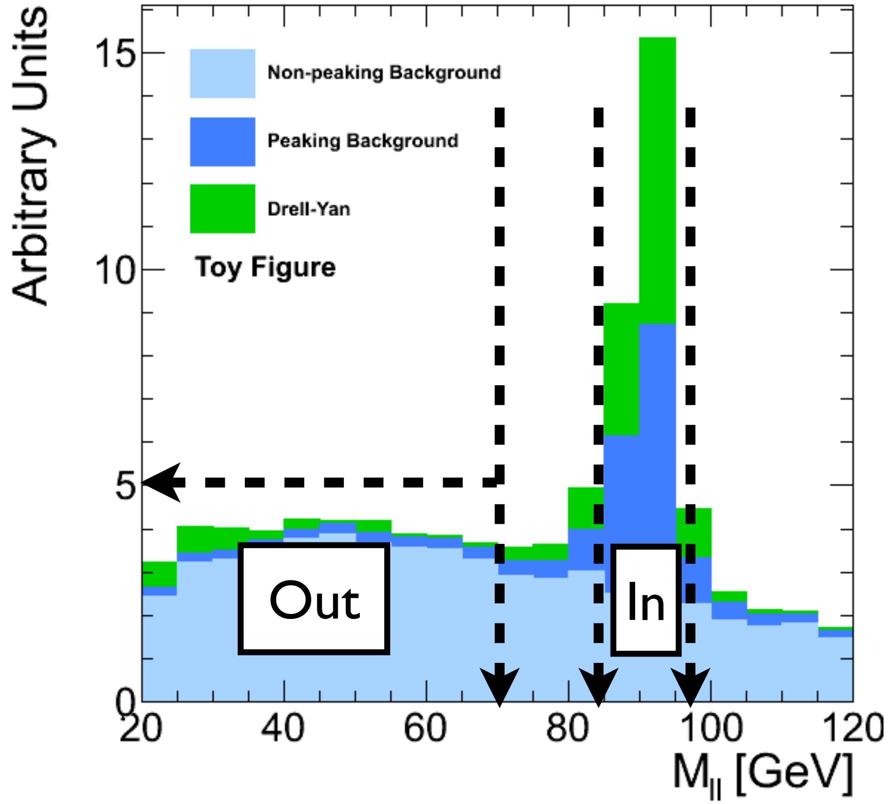
Systematic Uncertainty ~ 20%*

* For the zero jet category

H→WW→lνlν: Drell-Yan Background

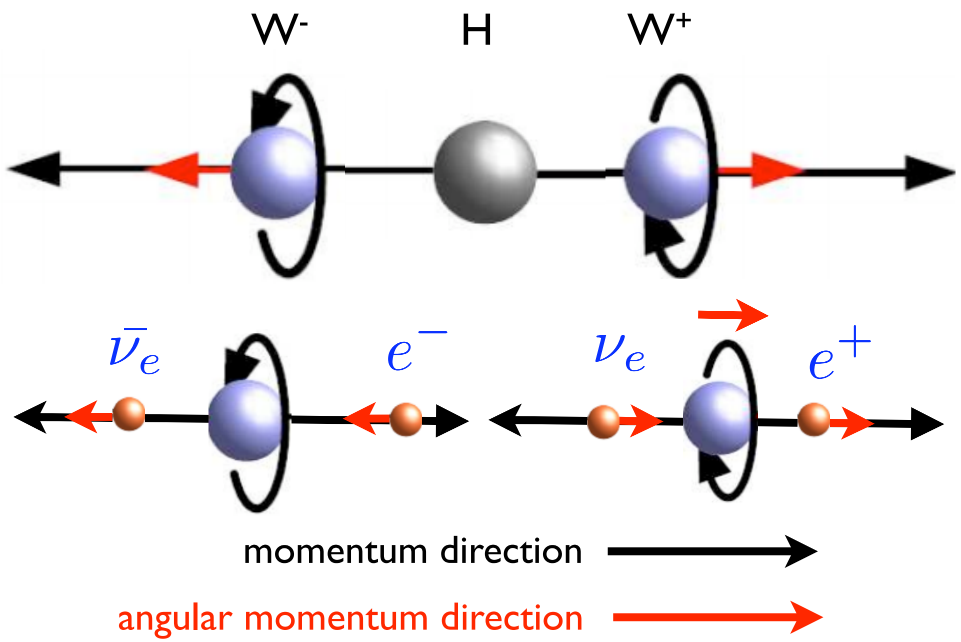
- Reduce Drell-Yan background by applying a MET selection and Z mass veto

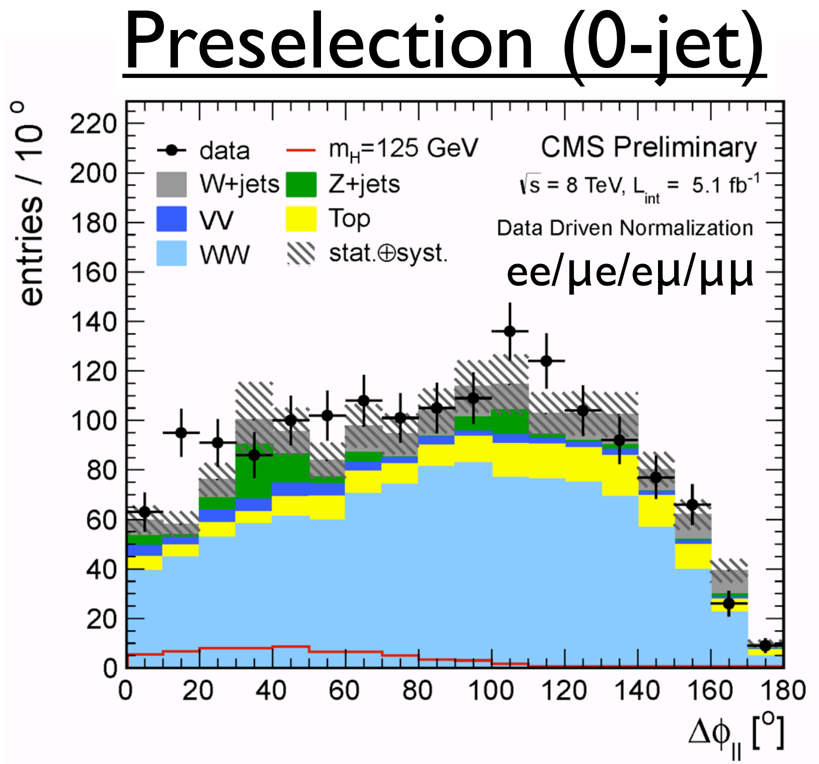
- Measure Drell-Yan yield within the Z mass window
  - Subtract WW and Top decays by using eμ/μe events (non-peaking background)
  - Subtract resonant WZ and ZZ by using simulation (peaking background)
- Extrapolate to get the residual yield in the signal region using the expected ratio "$R_{out/in}$"



Systematic Uncertainty
~ 30-60% depending on jet category and final analysis selection

H→WW→lνlν: Separating Irreducible Background



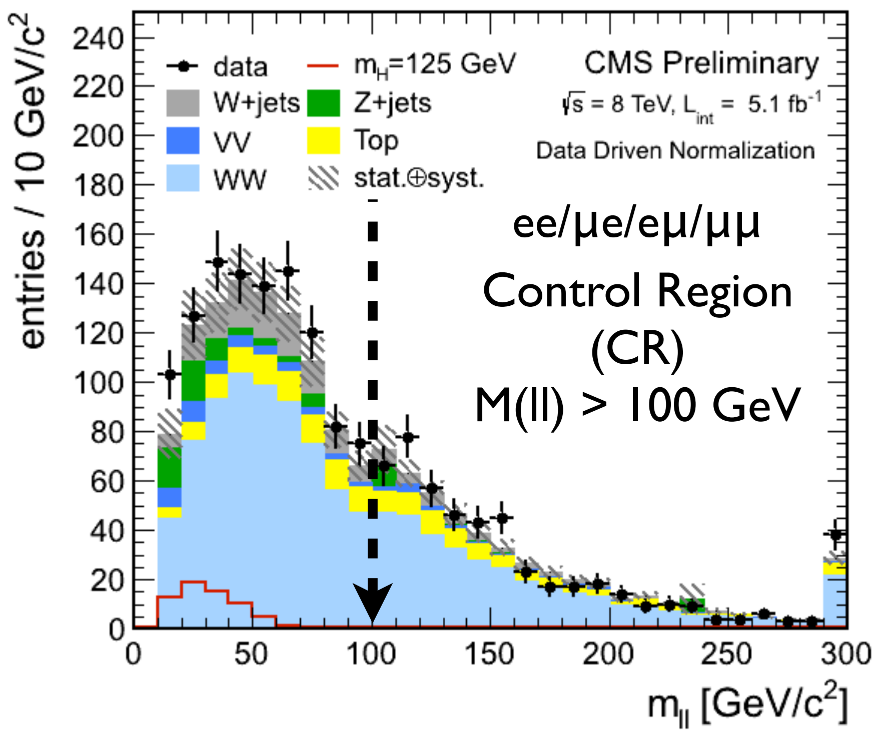


- Dominant irreducible background is non-resonant WW decay
- Conservation of spin angular momentum and the weak interaction on left (right) handed particles (anti-particles) leads to a correlation between the directions of the observable leptons
  - Expect small dilepton Δφ and invariant mass if standard model Higgs boson

H→WW→lνlν: Estimating WW Background

Preselection (0-jet)

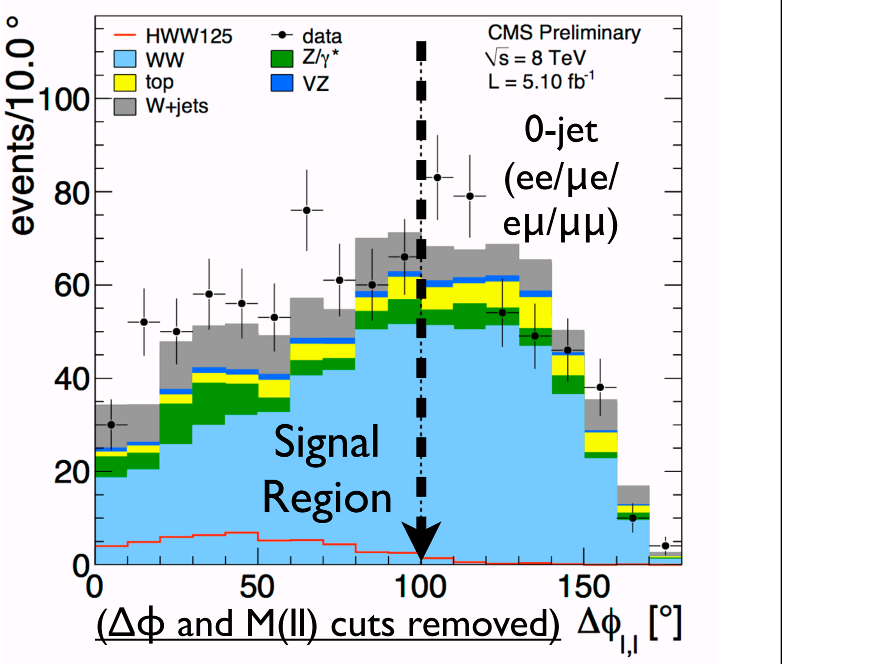
- Measure a simulation-to-data scale factor for the WW background in a high mass control region
  - Method applied for Higgs boson mass hypotheses up to 200 GeV
  - For larger mass hypotheses, control region has large signal contamination so use simulation predictions directly

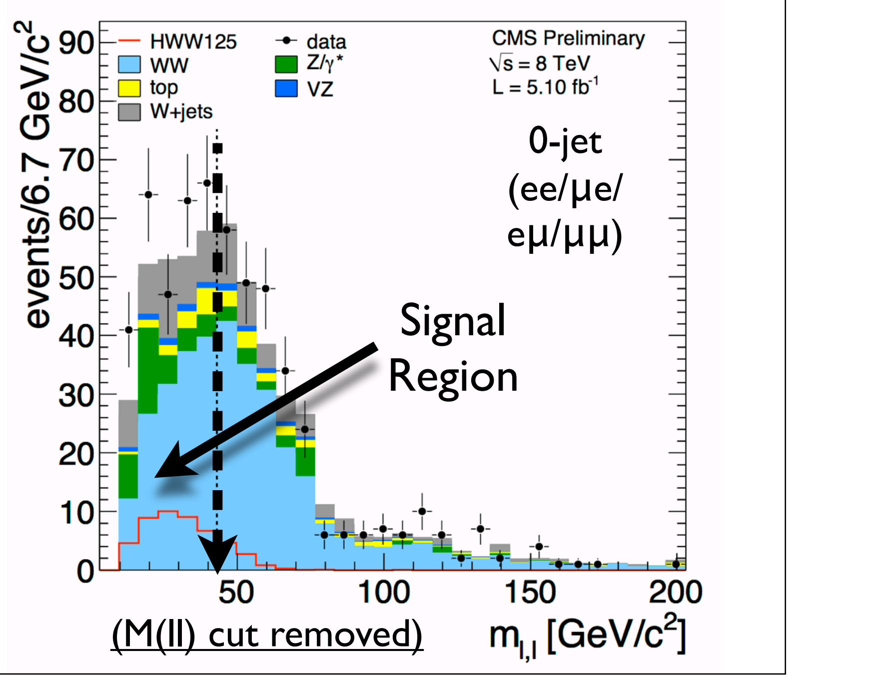


- Extrapolate to find the yield in the signal region using simulation
  - Scale factor measured before applying m_T and ΔΦ(ll) cuts
  - Scale factor is applied to simulation prediction in signal region after all cuts
  - Systematic uncertainty including CR statistics ~ 10-20% depending on jet category

$H \rightarrow WW \rightarrow l\nu l\nu$: Signal Selection

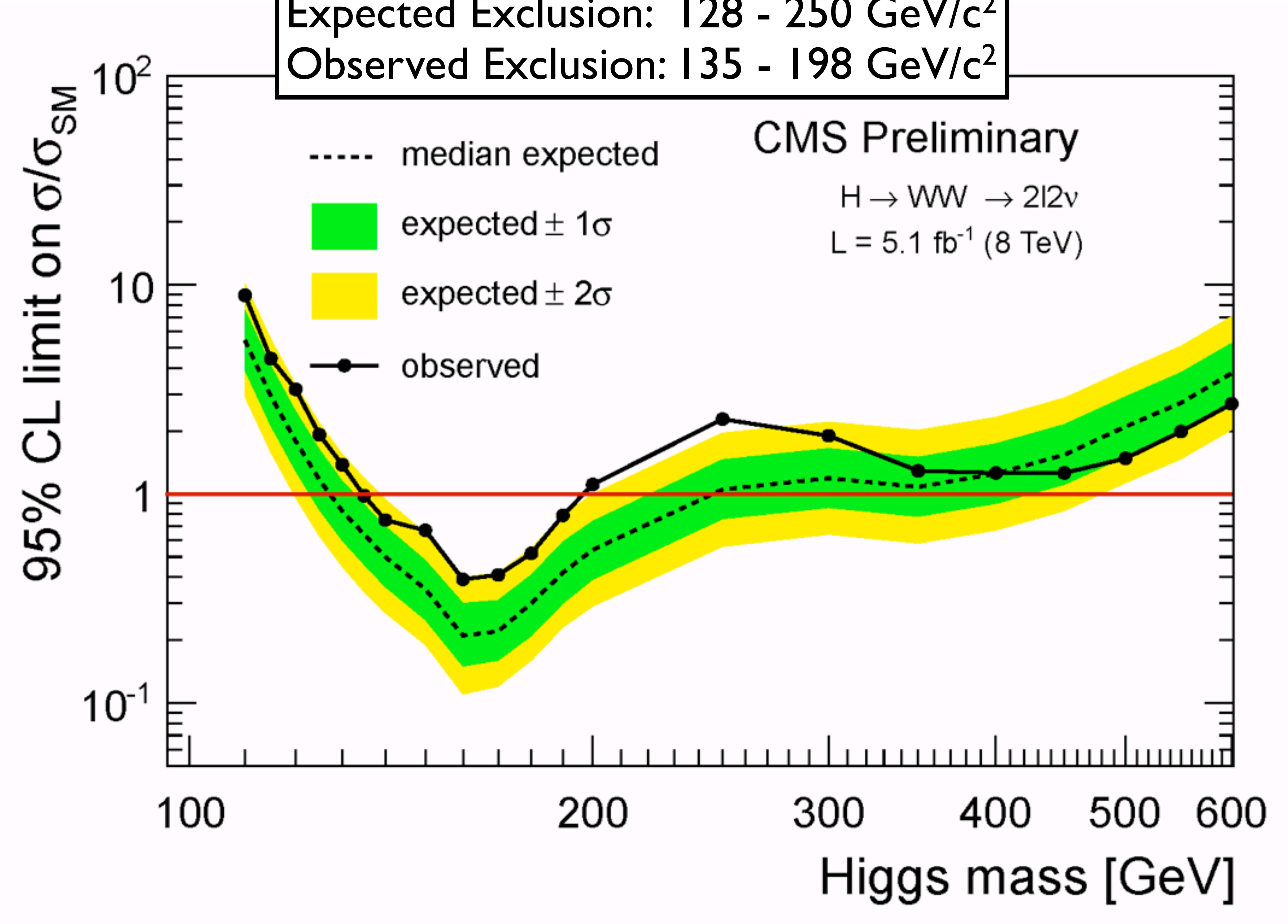
- Analysis for 0, 1-jet events
  - 8 TeV (2012) analysis:
    - $p_T^{max}(l)$, $p_T^{min}(l)$, $M(ll)$, $\Delta\phi(ll)$, $p_T(ll)$, m_T
  - 7 TeV (2011) analysis:
    - Train a boosted decision tree (BDT) for each Higgs boson mass hypothesis against non-resonant WW background
    - To train BDT, use cut based analysis variables plus $\Delta R(ll)$, and $\Delta\phi(ll, MET)$ and $\Delta\phi(ll, jet)$ in 1-jet events
- VBF analysis for 2-jet events
  - M(jet, jet) > 450 GeV
  - $\Delta\eta$(jet, jet) > 3.5 for p_T > 30 GeV tagged jets
  - No p_T > 30 GeV jet between the tagged jets





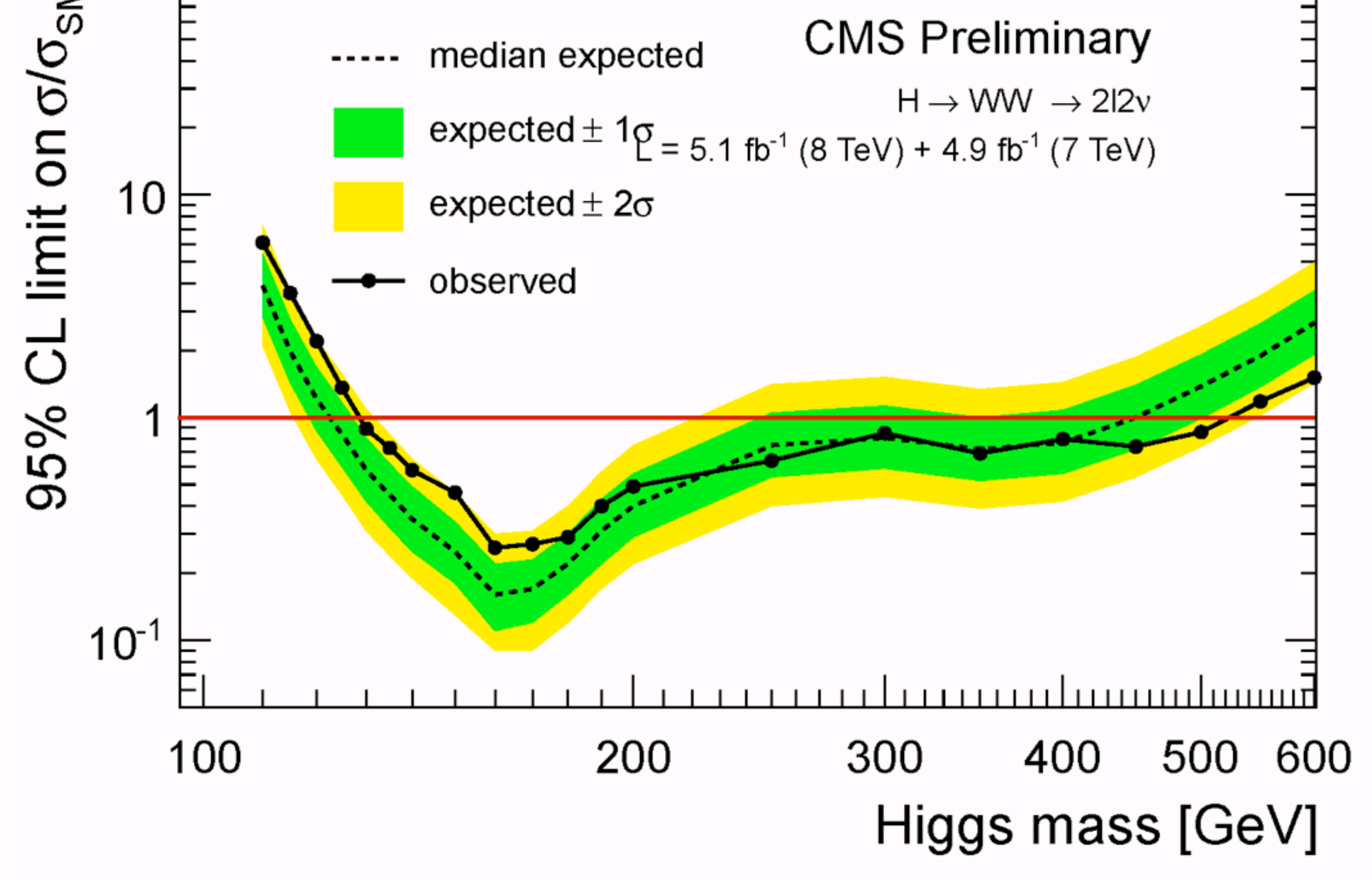
$H \to WW \to l\nu l\nu$: Results in 8 TeV Dataset

Expected Exclusion: 128 - 250 GeV/c^2
Observed Exclusion: 135 - 198 GeV/c^2



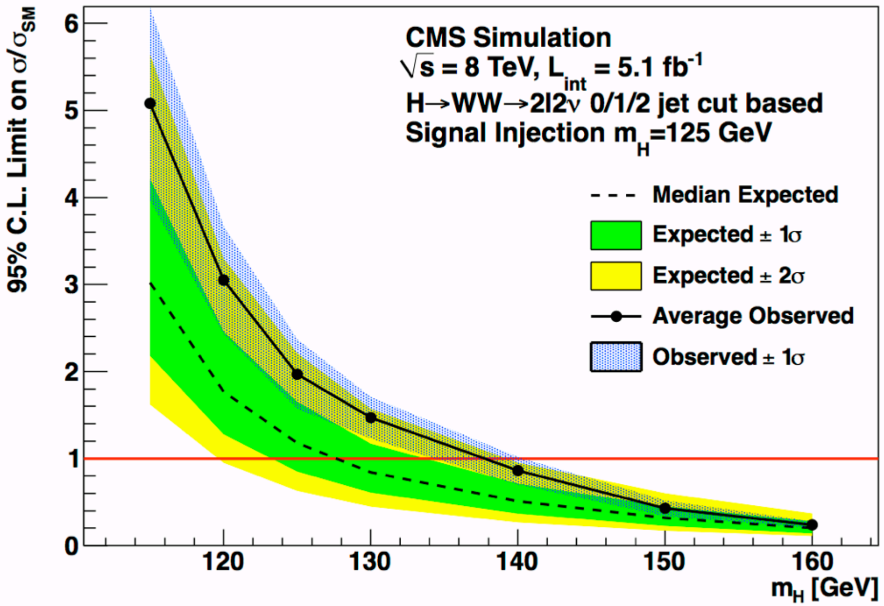
H→WW→lνlν: Results in 7+8 TeV Datasets

Expected Exclusion: 122 - 450 GeV/c^2
Observed Exclusion: 129 - 520 GeV/c^2

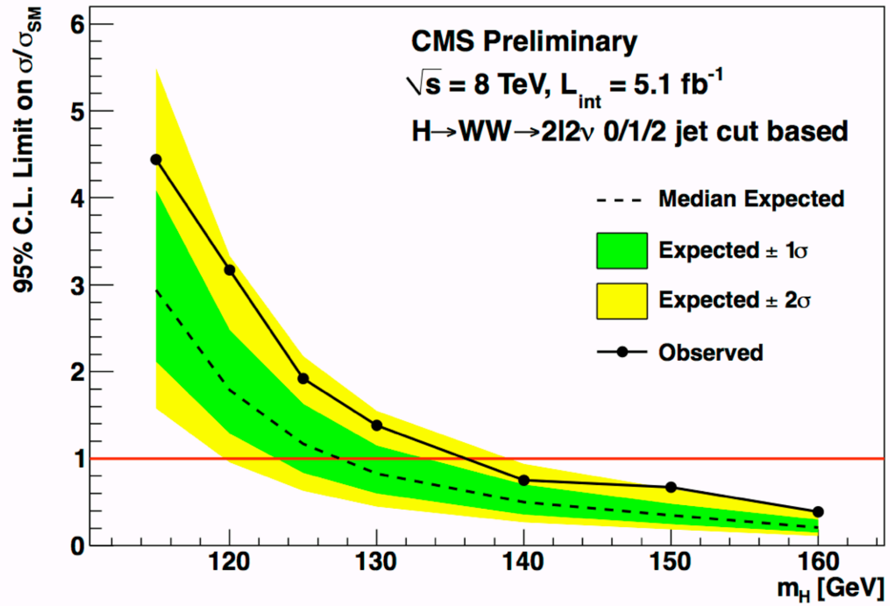


H→WW→lνlν: Low Mass Region Interpretation

Pseudo experiments

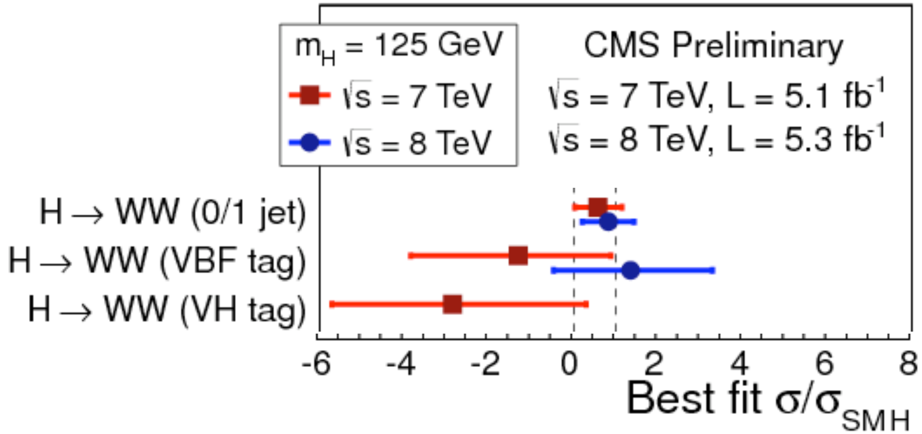


Result in data

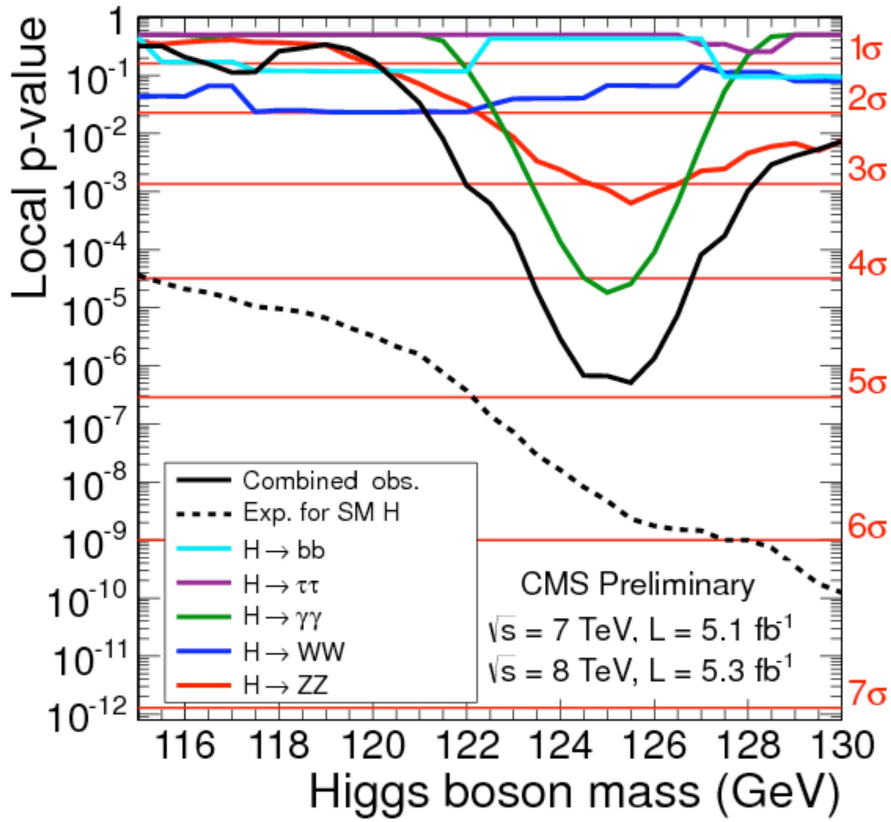


- Perform pseudo-experiments for signal (m_H = 125 GeV) + background
  - Draw a yield for signal and each background from a Poisson distribution
  - Record mean and standard deviation of observed limit for each mass hypothesis
- Expect to observe a broad excess up to around m_H = 160 GeV

H→WW→lνlν: Measured Properties



Observed local p-value



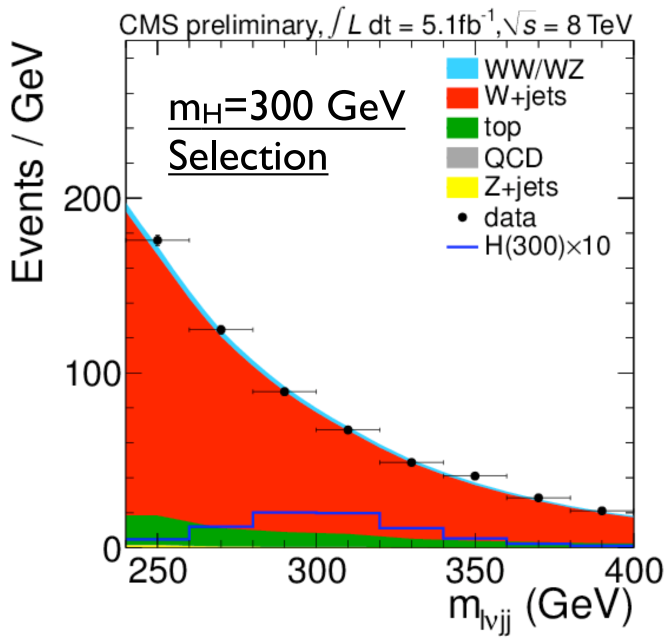
- Results in WW sub channels are compatible within uncertainties
  - See talk on Friday on the combination of CMS results by M. Chen
- The ratio of the signal strength in the WW and ZZ channels is measured to be $R_{WZ} = 0.9^{+1.1}_{-0.6}$
  - See talk by S. Baffioni tomorrow afternoon for more details on ZZ

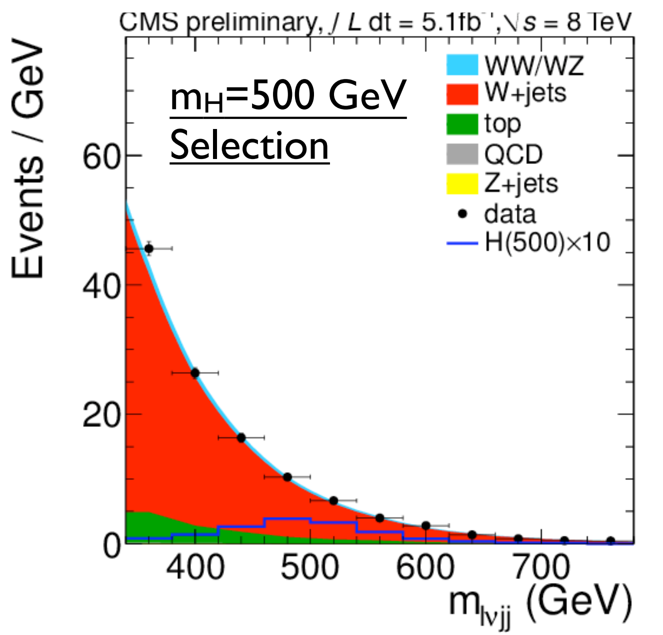
Talks on Thursday:

bb/ττ:	M. De Gruttola
γγ:	Y. Chang
ZZ:	S. Baffioni

H→WW→lνqq Analysis

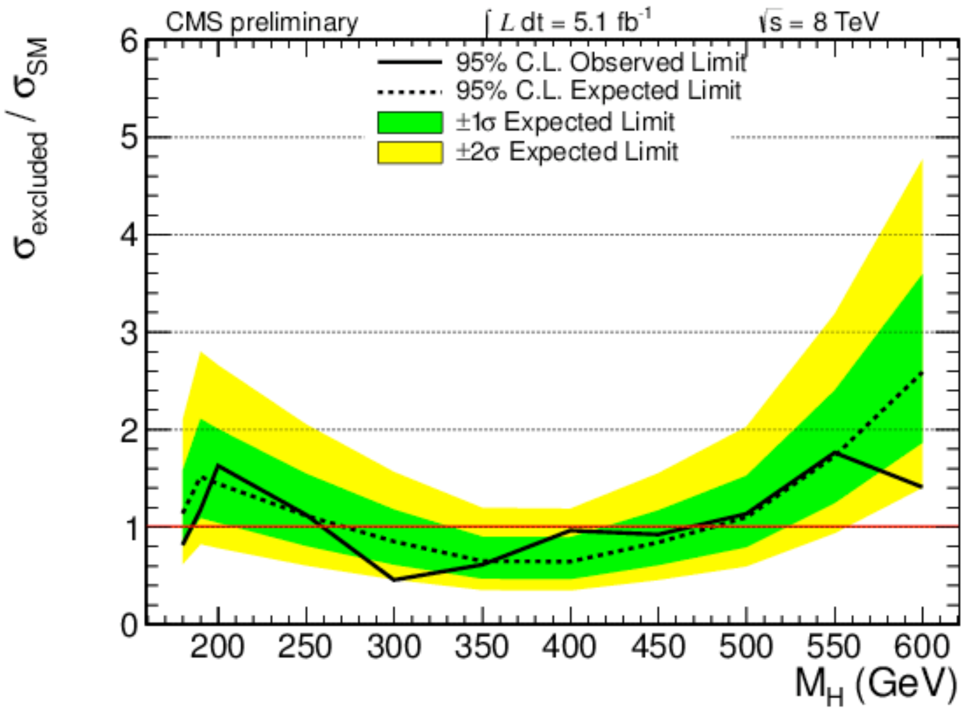
- Selection differences from lνlν analysis
  - One electron (muon) with p_T > 35 (25) GeV and MET > 25 (30) GeV (leptonic W decay - trigger)
  - Two jets with 65 < M(jj) < 95 (hadronic W decay)
- Analysis is sensitive to if both W decays are on shell: best sensitivity ~ 350 GeV
- Main background: W+jets
  - Suppressed using angular likelihood discriminant for each mass hypothesis
- Signal extraction
  - Kinematic fit allows reconstruction of Higgs boson mass
  - Search for mass peak against continuum background from W+jets events



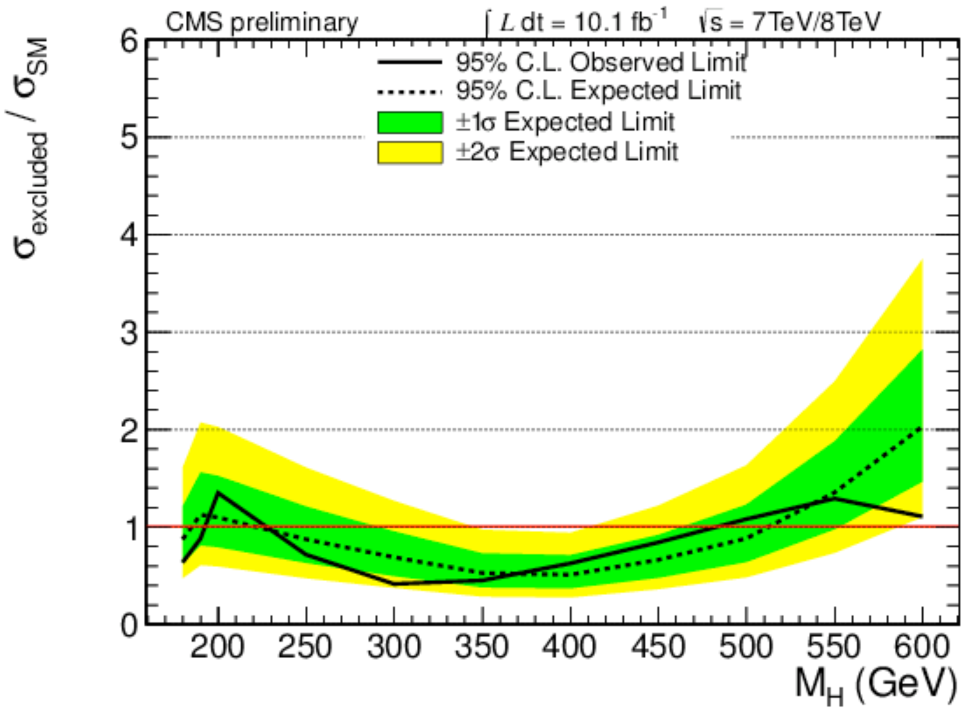


H→WW→lνqq: Results

8 TeV Analysis



Combined 7+8 TeV Result



- The 8 TeV data analysis excludes [260, 390] GeV at 95% CL
- In combination with the 7 TeV data [240, 450] GeV is excluded at 95% CL

H→WW Conclusion

- The standard model Higgs boson is excluded in the mass range [129, 520] by the lνlν channel and [240, 450] GeV by the lνqq channel at 95% CL
  - Thus the range [122, 129] GeV cannot be excluded
  - We observe an excess of events compared to the background in the lνlν channel
- The excess is roughly two sigma above the background predictions
  - The excess is compatible with a Higgs boson of mass 125 GeV
  - The signal strength of the excess is compatible with a standard model Higgs boson
  - The signal strength observed in the WW and ZZ channels are consistent
- Next steps in H→WW→lνlν analysis with full year dataset
  - Test properties of the excess - measure the cross section and spin

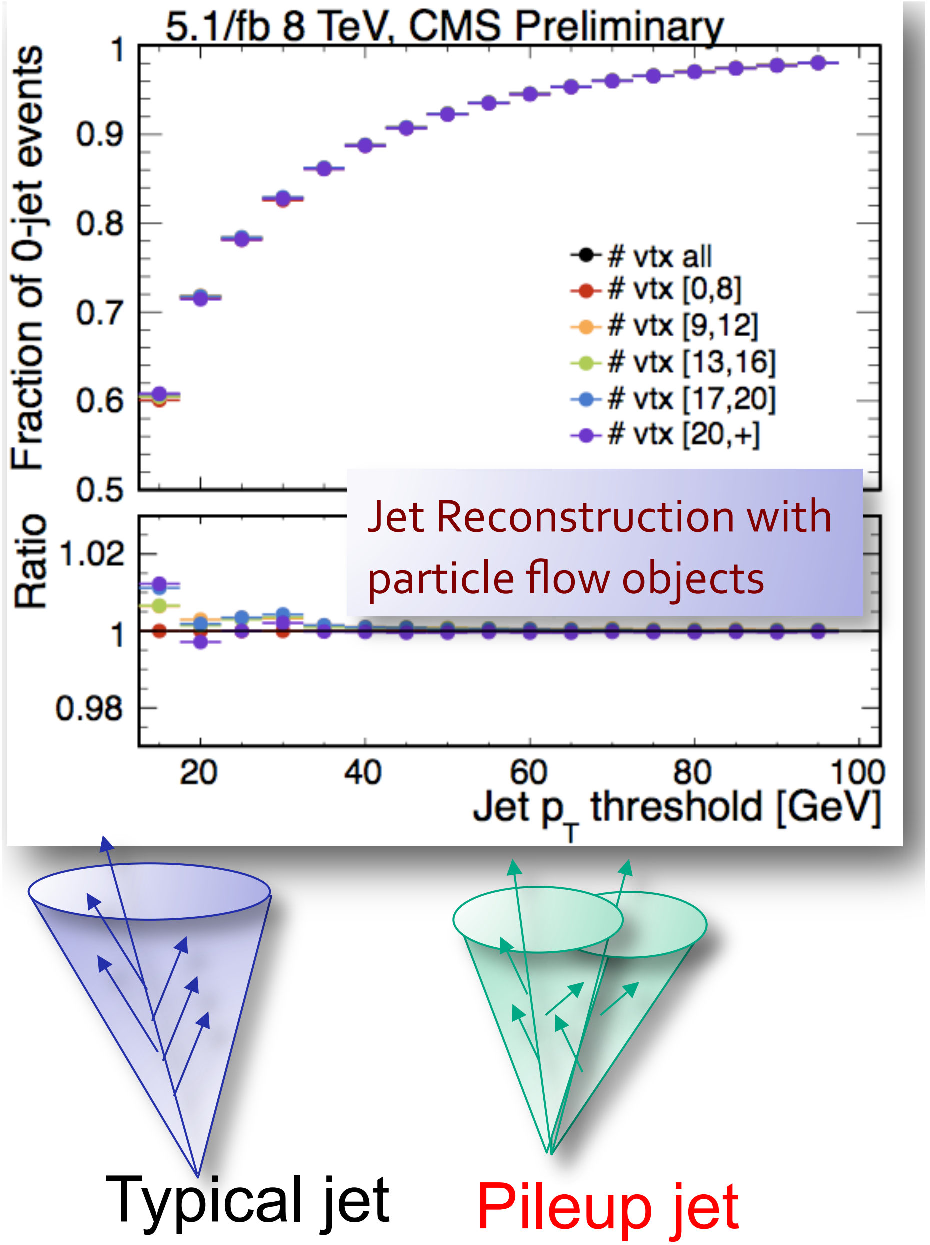
Bibliography

- CMS Public Higgs Results
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- Combined 2011 and 2012 Higgs analysis
  - $H \to WW \to l\nu l\nu$: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12017TWiki
  - $H \to WW \to l\nu qq$: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12021TWiki
  - Combinations: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12020TWiki
- Other measurements
  - WW cross section: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12013
  - $WH \to WW \to l\nu l\nu l\nu$ (7 TeV): https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11034TWiki

BACKUP

Pileup and Jet Veto

- Zero jet bin is most sensitive in lνlν analysis
- Jet veto is stable with pileup
  - Measured using Z+jets events
  - Plot shown at ICHEP http://indico.cern.ch/contributionDisplay.py?contribId=5&sessionId=16&confId=181298 - Joe Incandela



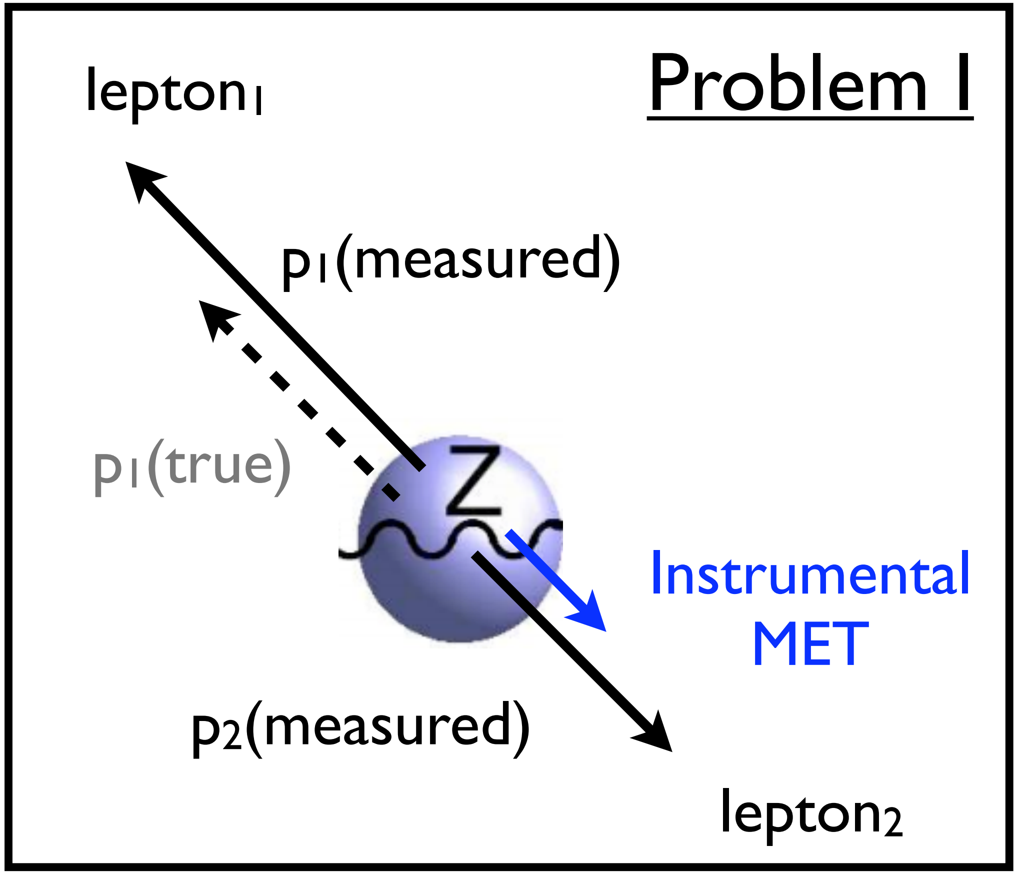
MET Definition for H → WW → lνlν Selection

- If the momentum of a lepton from Z decay is mis-measured
  - Invariant mass is also mis-measured
    - Event passes Z veto
  - Instrumental MET is generated
    - Event passes MET selection
- To reduce instrumental MET
  - Define a "Projected MET"
    - The MET component perpendicular to the lepton with the smallest ΔΦ(MET, l)
  - Projected MET also reduces background from DY→ττ

Projected MET Definition

$$\Delta\phi_{min} = min(\Delta\phi(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}}), \Delta\phi(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}}))$$

$$= \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{min} > \frac{\pi}{2}, \\ E_{\mathrm{T}}^{\mathrm{miss}} \sin(\Delta\phi_{min}) & \text{if } \Delta\phi_{min} < \frac{\pi}{2} \end{cases}$$

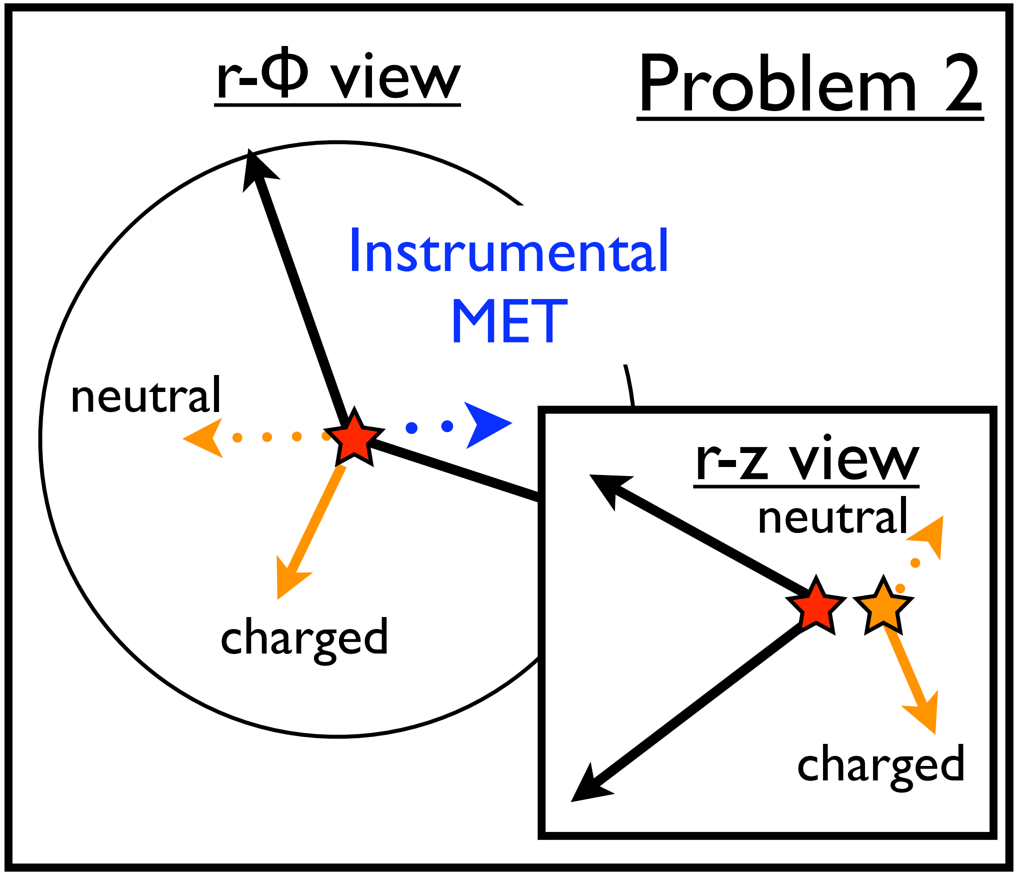


MET Definition for $H \rightarrow WW \rightarrow l\nu l\nu$ Selection

- Multiple proton-proton interactions per bunch crossing can produce instrumental MET
- Select events by taking the minimum of two different estimators of MET
  - Projected MET
  - Projected Track MET
- Track MET definition
  - Negative vector sum of tracks
    - $|Z_{track} - Z_{PV}| < 0.1$ cm
- The two estimators are more correlated for real MET than instrumental MET

Min MET Definition

$$\mathrm{MinMET} \quad = \quad min(\mathrm{pMET}, \mathrm{pTrackMet})$$



$H \to WW \to l\nu l\nu$ Preselection

m_H [GeV]	ee/μμ	eμ
pT (max) [GeV]	20	20
pT (min) [GeV]	10	10
Third lepton veto	Applied	Applied
Opposite-sign	Applied	Applied
Mll [GeV]	> 12 and not [76, 106]	> 12
MET [GeV]	45 (Drell-Yan MVA for Higgs mass < 140 GeV)	20
ΔΦ(ll, jet) [dg.]	< 165	---
Top Veto	Applied	Applied
$p_T(ll)$ [GeV]	> 45	> 45

H→WW→lνlν Preselection Yields

2012 Data

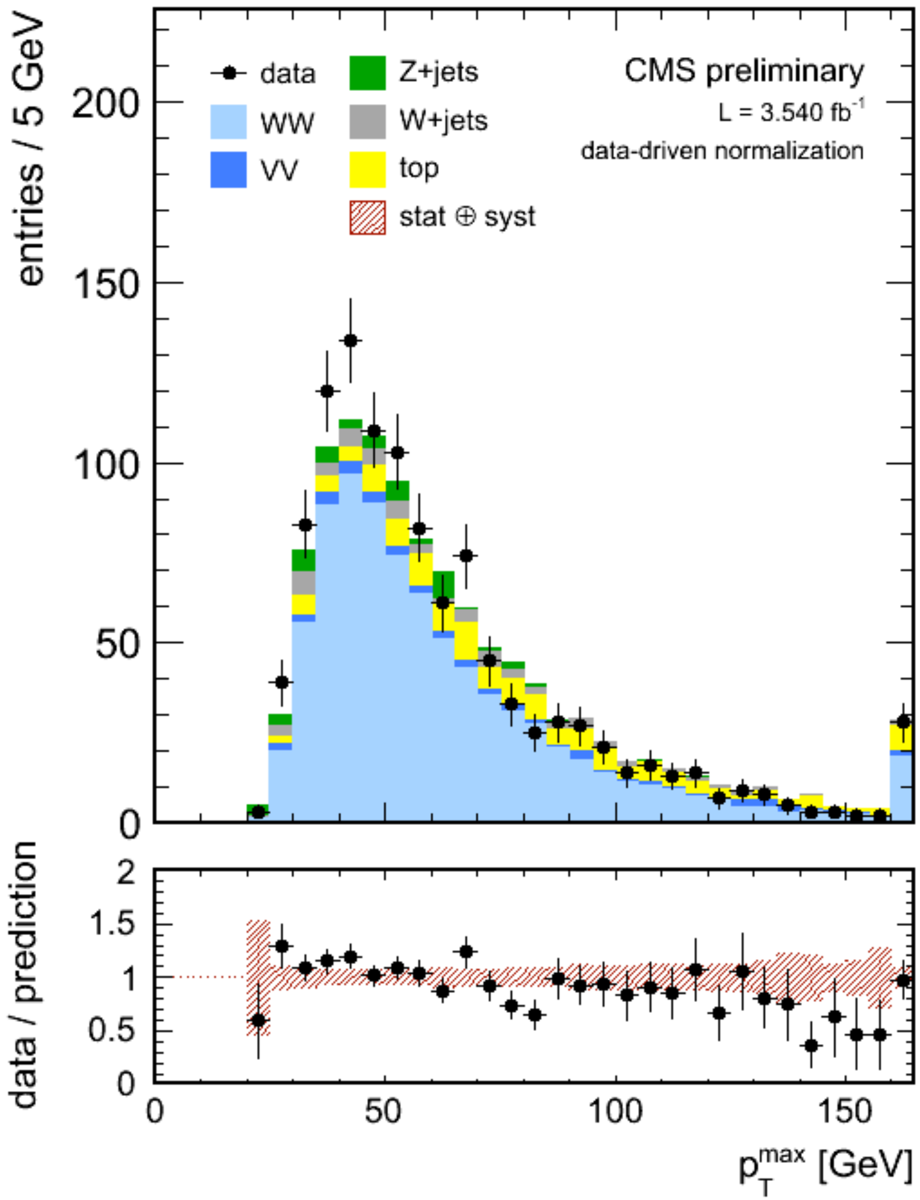
Table 2: Observed number of events and background estimates for an integrated luminosity of 5.1 fb^{-1} after applying the W^+W^- selection requirements. Only statistical uncertainties on each estimate are reported.

	data	tot bkg.	WW	$t\bar{t}$ +tW
0-jet bin	1594	1501 ± 21	1046.1 ± 7.2	164.2 ± 5.4
1-jet bin	1186	1162 ± 27	381.0 ± 4.0	527.3 ± 8.4
2-jet bin	1295	1412 ± 24	177.0 ± 2.8	886.5 ± 11.1
	W+jets	WZ+ZZ	Z/γ^*	$W+\gamma^{(*)}$
0-jet bin	158.2 ± 7.1	32.6 ± 0.6	73 ± 17	27.1 ± 3.9
1-jet bin	122.6 ± 6.7	30.3 ± 0.6	77 ± 24	23.7 ± 5.2
2-jet bin	94.9 ± 6.4	20.8 ± 0.5	227 ± 20	5.6 ± 2.1

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12017TWiki

WW Cross Section Measurement

- Measure WW cross section in H→WW→lνlν preselection
  - Increase trailing lepton pT cut to 20 GeV to reduce W+jets background and potential Higgs boson signal contamination
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12013
- Results
  - σ_{WW} = 69.9 ± 2.8 (stat.) ± 5.6 (syst.) ± 3.1 (lumi.) pb.
  - σ_{WW} (Theory) = 57.3 $^{+2.4}_{-1.6}$ pb



$H \to WW \to l\nu l\nu$ Cut Based Analysis (8 TeV)

- Select signal like events by exploiting kinematic correlations
  - Low dilepton invariant mass and delta phi
  - Transverse mass endpoint at Higgs boson mass

m_H [GeV]	p_T(max) [GeV] >	p_T(min) [GeV] >	M(ll) [GeV] <	$\Delta\phi$(ll) [dg.] <	m_T [GeV] [,]	p_T(ll) [GeV] >
120	20	10	40	115	[80, 120]	45
130	25	10	45	90	[80, 125]	“
160	30	25	50	60	[90, 160]	“
200	40	25	90	100	[120, 200]	“

H→WW→lνlν Selection Yields (0-Jet)

2012 Data

Table 3: Observed number of events, background estimates and signal predictions for an integrated luminosity of 5.1 fb^{-1} after applying the $\mathrm{H} \rightarrow \mathrm{W}^{+}\mathrm{W}^{-}$ cut-based selection requirements. The combined statistical, experimental, and theoretical systematic uncertainties are reported. The $\mathrm{Z}/\gamma^{*} \rightarrow \ell^{+}\ell^{-}$ process includes the dimuon, dielectron and ditau final state.

m_{H}	$\mathrm{H} \rightarrow \mathrm{W}^{+}\mathrm{W}^{-}$	$\mathrm{pp} \rightarrow \mathrm{W}^{+}\mathrm{W}^{-}$	$\mathrm{WZ}+\mathrm{ZZ}$ $+\mathrm{Z}/\gamma^{*} \rightarrow \ell^{+}\ell^{-}$	Top	$\mathrm{W}+\mathrm{jets}$	$\mathrm{W}\gamma^{(*)}$	all bkg.	data
0-jet category $e\mu$ final state								
125	23.9 ± 5.2	87.6 ± 9.5	2.2 ± 0.2	9.3 ± 2.7	19.1 ± 7.2	6.0 ± 2.3	124.2 ± 12.4	158
130	35.3 ± 7.6	96.8 ± 10.5	2.5 ± 0.3	10.1 ± 2.8	20.7 ± 7.8	6.3 ± 2.4	136.3 ± 13.6	169
160	98.3 ± 21.2	53.6 ± 5.9	1.2 ± 0.1	6.3 ± 1.7	2.5 ± 1.3	0.2 ± 0.1	63.9 ± 6.3	79
400	16.6 ± 4.8	50.5 ± 5.8	1.5 ± 0.2	26.1 ± 5.7	4.5 ± 2.0	0.7 ± 0.5	83.3 ± 8.4	92
0-jet category $ee/\mu\mu$ final state								
125	14.9 ± 3.3	60.4 ± 6.7	37.7 ± 12.5	1.9 ± 0.5	10.8 ± 4.3	4.6 ± 2.5	115.5 ± 15.0	123
130	23.5 ± 5.1	67.4 ± 7.5	41.3 ± 15.9	2.3 ± 0.6	11.0 ± 4.3	4.8 ± 2.5	126.8 ± 18.3	134
160	86.0 ± 18.7	44.5 ± 4.9	11.3 ± 13.4	3.8 ± 0.9	1.3 ± 1.1	0.4 ± 0.3	61.4 ± 14.4	92
400	12.3 ± 3.6	37.1 ± 4.3	5.7 ± 1.3	20.0 ± 4.7	3.4 ± 1.9	13.6 ± 4.8	79.9 ± 8.3	55

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12017TWiki

H→WW→lνlν Selection Yields (1-Jet)

2012 Data

Table 3: Observed number of events, background estimates and signal predictions for an integrated luminosity of 5.1 fb^{-1} after applying the $\mathrm{H} \rightarrow \mathrm{W}^{+}\mathrm{W}^{-}$ cut-based selection requirements. The combined statistical, experimental, and theoretical systematic uncertainties are reported. The $\mathrm{Z}/\gamma^{*} \rightarrow \ell^{+}\ell^{-}$ process includes the dimuon, dielectron and ditau final state.

m_{H}	H $\rightarrow \mathrm{W}^{+}\mathrm{W}^{-}$	pp $\rightarrow \mathrm{W}^{+}\mathrm{W}^{-}$	WZ + ZZ $+\mathrm{Z}/\gamma^{*} \rightarrow \ell^{+}\ell^{-}$	Top	W + jets	$\mathrm{W}\gamma^{(*)}$	all bkg.	data
1-jet category $e\mu$ final state								
125	10.3 ± 3.0	19.5 ± 3.7	2.4 ± 0.3	22.3 ± 2.0	11.7 ± 4.6	5.9 ± 3.2	61.7 ± 7.0	54
130	15.7 ± 4.7	22.0 ± 4.1	2.6 ± 0.3	25.1 ± 2.2	12.8 ± 5.1	6.0 ± 3.2	68.5 ± 7.6	64
160	52.6 ± 14.9	20.1 ± 4.0	1.6 ± 0.2	21.5 ± 1.8	5.0 ± 2.3	0.9 ± 0.5	49.2 ± 5.0	62
400	11.4 ± 3.3	39.1 ± 6.3	2.1 ± 0.3	56.6 ± 3.7	7.1 ± 3.1	0.6 ± 0.6	105.5 ± 8.0	96
1-jet category $ee/\mu\mu$ final state								
125	4.4 ± 1.3	9.7 ± 1.9	8.7 ± 4.9	9.5 ± 1.1	3.9 ± 1.7	1.3 ± 1.2	33.1 ± 5.7	43
130	7.1 ± 2.2	11.2 ± 2.2	9.1 ± 5.4	10.7 ± 1.2	3.7 ± 1.7	1.3 ± 1.2	36.0 ± 6.3	53
160	37.9 ± 10.9	13.8 ± 2.8	28.4 ± 10.7	16.2 ± 1.6	3.8 ± 2.1	0.0 ± 0.0	62.3 ± 11.4	65
400	7.4 ± 2.2	19.6 ± 3.2	7.9 ± 2.4	33.4 ± 2.4	1.6 ± 1.3	4.4 ± 1.8	66.8 ± 5.1	67

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12017TWiki

H→WW→lνlν Selection Yields (VBF)

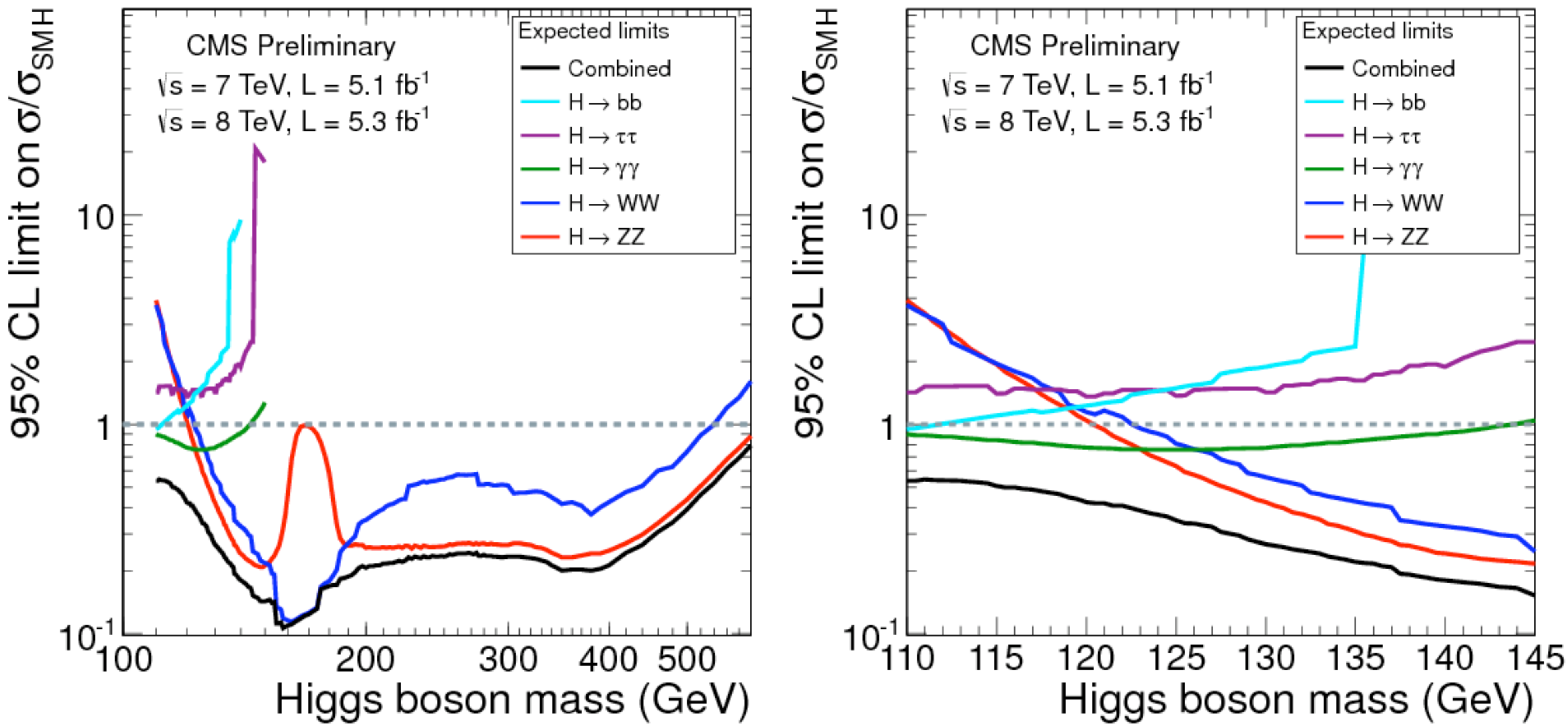
2012 Data

Table 3: Observed number of events, background estimates and signal predictions for an integrated luminosity of 5.1 fb^{-1} after applying the $\mathrm{H} \to \mathrm{W^+W^-}$ cut-based selection requirements. The combined statistical, experimental, and theoretical systematic uncertainties are reported. The $\mathrm{Z}/\gamma^* \to \ell^+\ell^-$ process includes the dimuon, dielectron and ditau final state.

m_H	$\mathrm{H} \to \mathrm{W^+W^-}$	$\mathrm{pp} \to \mathrm{W^+W^-}$	$\mathrm{WZ+ZZ} + \mathrm{Z}/\gamma^* \to \ell^+\ell^-$	Top	W + jets	$\mathrm{W}\gamma^{(*)}$	all bkg.	data
			2-jet category $e\mu$ final state					
125	1.5 ± 0.2	0.4 ± 0.1	0.1 ± 0.0	3.4 ± 1.9	0.3 ± 0.3	0.0 ± 0.0	4.1 ± 1.9	6
130	2.5 ± 0.4	0.5 ± 0.2	0.1 ± 0.0	3.0 ± 1.8	0.3 ± 0.3	0.0 ± 0.0	3.9 ± 1.9	6
160	9.9 ± 1.3	0.8 ± 0.2	0.1 ± 0.0	4.2 ± 2.2	0.6 ± 0.4	0.0 ± 0.0	5.6 ± 2.2	11
400	2.3 ± 0.4	1.9 ± 0.8	0.2 ± 0.0	9.1 ± 2.7	0.5 ± 0.4	0.0 ± 0.0	11.7 ± 2.9	22
			2-jet category $ee/\mu\mu$ final state					
125	0.8 ± 0.1	0.3 ± 0.1	3.1 ± 1.8	2.0 ± 1.2	0.0 ± 0.0	0.0 ± 0.0	5.4 ± 2.2	7
130	1.3 ± 0.2	0.4 ± 0.2	3.8 ± 2.2	2.0 ± 1.2	0.0 ± 0.0	0.0 ± 0.0	6.2 ± 2.5	7
160	6.0 ± 0.8	0.7 ± 0.3	4.7 ± 2.7	2.4 ± 1.2	0.2 ± 0.4	0.0 ± 0.0	8.0 ± 3.0	9
400	1.6 ± 0.2	1.5 ± 0.7	6.6 ± 2.8	4.9 ± 1.9	0.7 ± 0.7	0.0 ± 0.0	13.8 ± 3.5	15

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12017TWiki

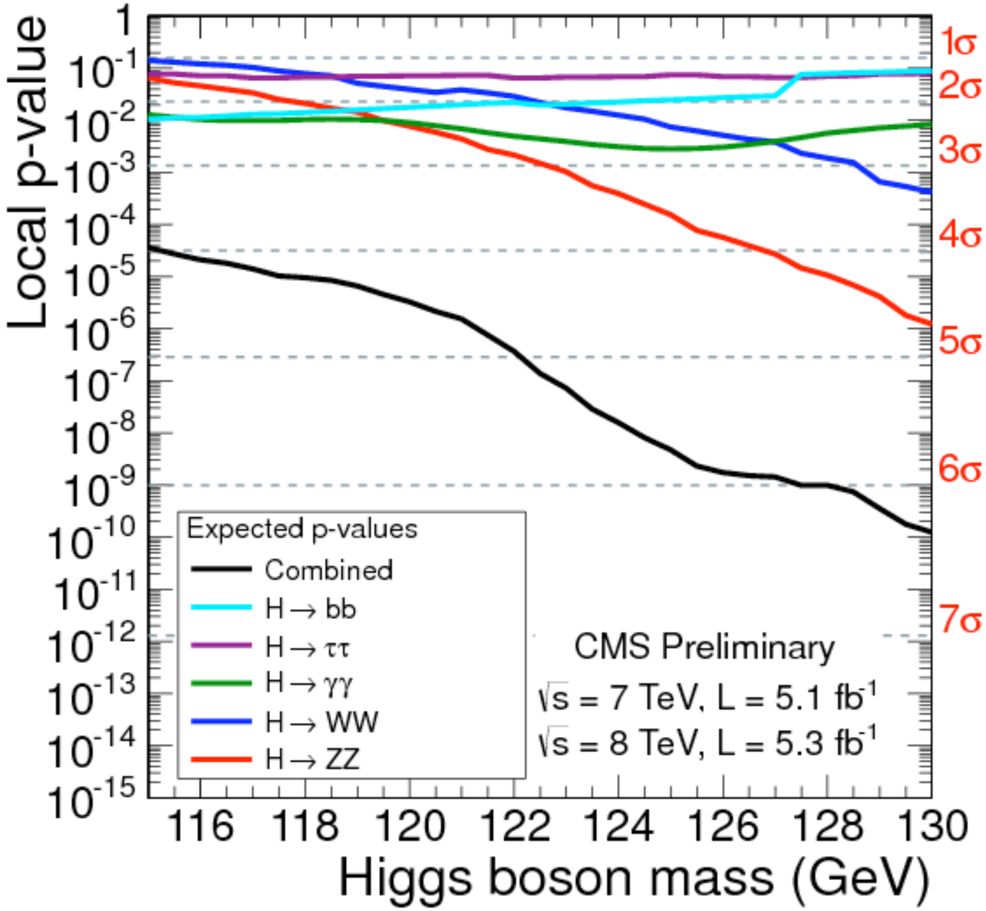
Expected Exclusion in 2011 + 2012 Datasets



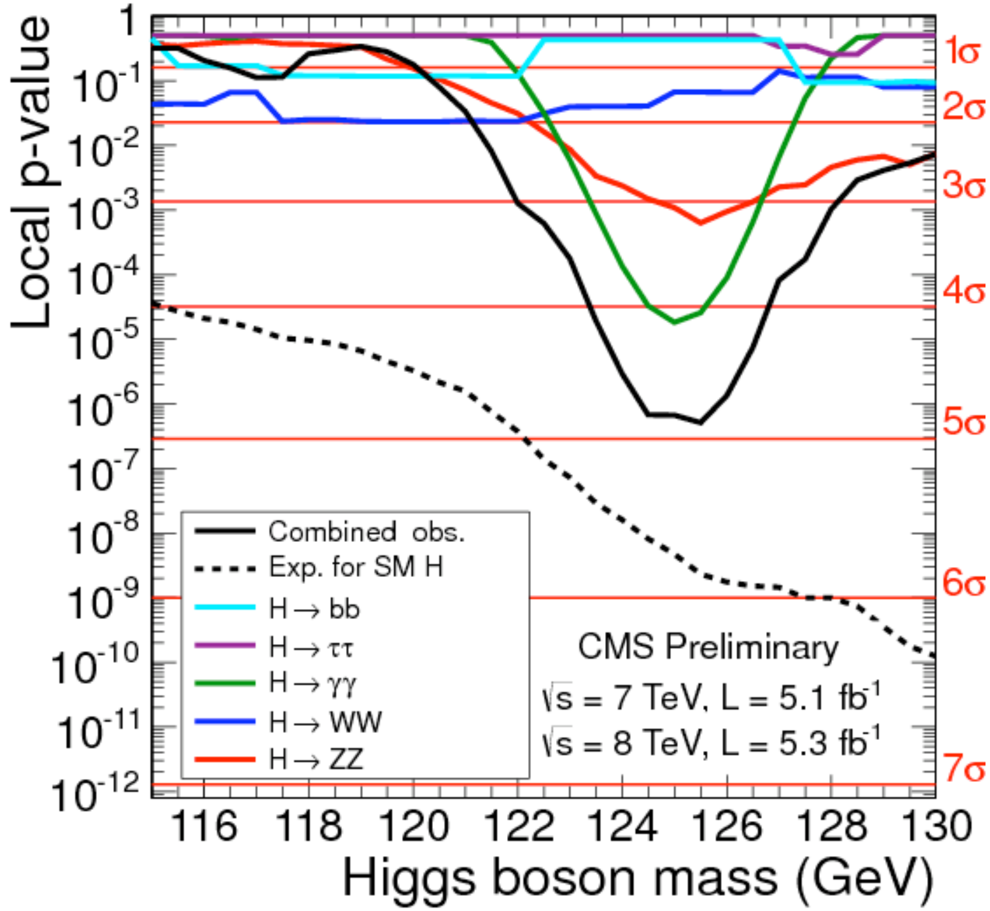
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12020TWiki

Compare Expected and Observed p-Value for Excess

<u>Expected</u>



<u>Observed</u>

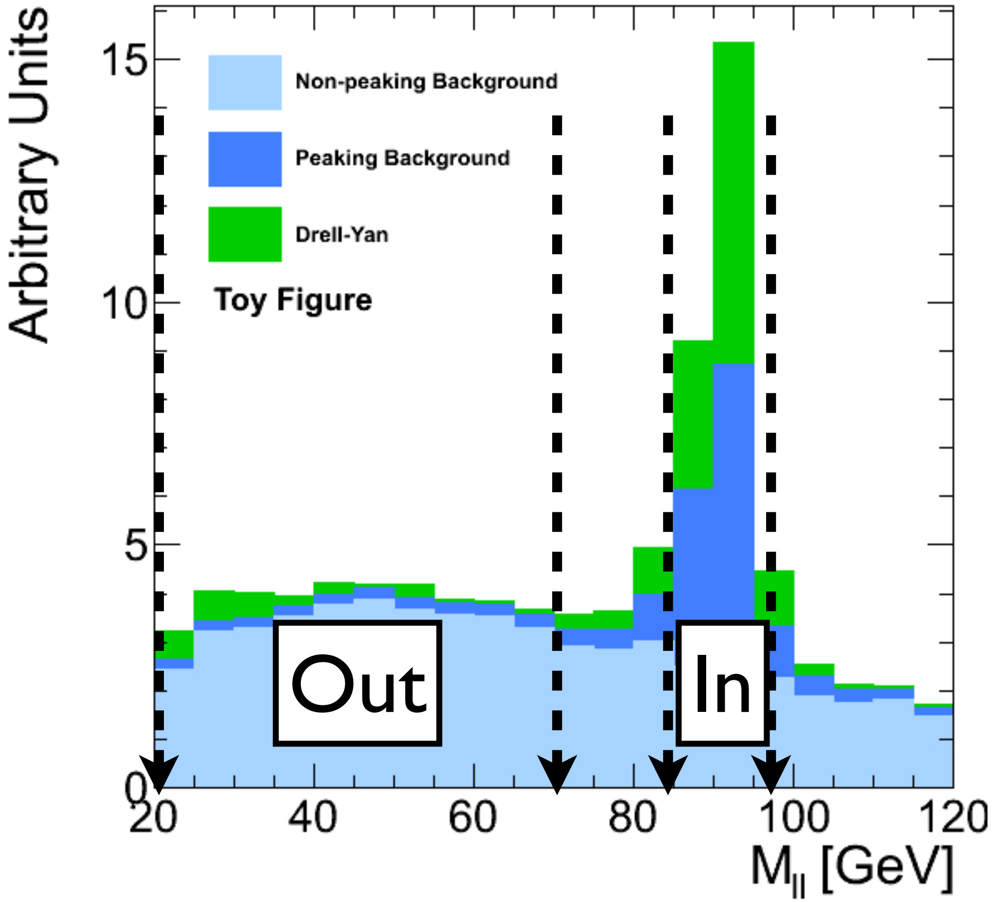


The median expected p-value (left) for observing an excess at mass mH in assumption that the SM Higgs boson with this mass exists and the observed p-value (right)

Drell-Yan Background using "$R_{out/in}$" Method

$$N(\ell\ell)^{DY}_{signal} = N^{DY}_{in} \times R(ll)^{DY}_{out/in}$$

$$N^{DY}_{in} = N(\ell\ell)^{data}_{in} - 0.5 \times N(e\mu)^{data}_{in} \times k_{ll} - N^{ZV,sim}_{in}$$

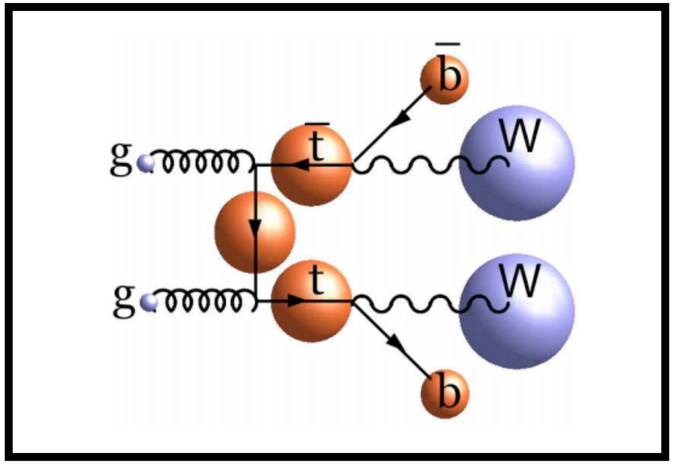


Top Quark Background by Measuring Veto Efficiency

$$N_W^{top} = (N^{d}_{top-Tag} - N^{d}_{-b})\frac{1-\epsilon^{d}_{top}}{\epsilon^{d}_{top}}$$

- General Principle
  - Reduce top quark decay background by rejecting
    - Events with b-tagged jets
    - Events with soft muons from leptonic b-decay
  - Estimate residual background by measuring event tagging efficiency
- Measure per jet tagging efficiency in top decay enriched control sample
  - Require exactly one b-tag with p_T > 30 GeV
  - Exclude this tag and measure the efficiency to find a second b-tag
- Determine event tagging efficiency according to number of jets available

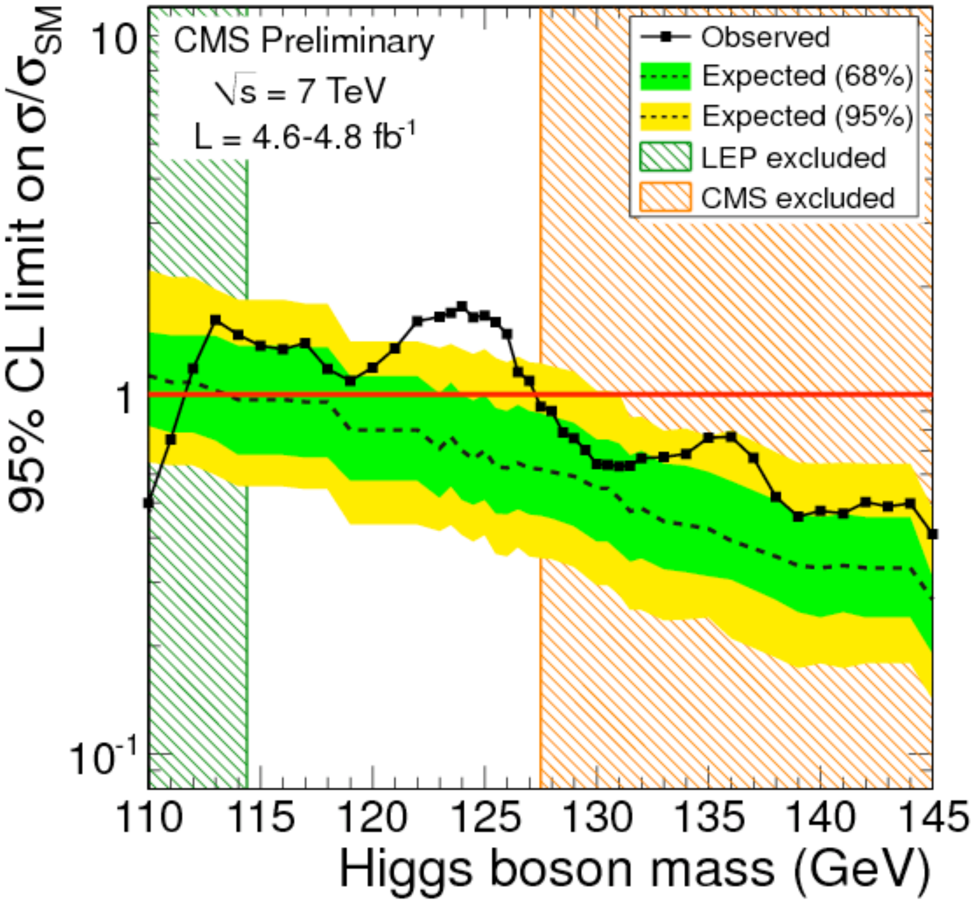
Top decay

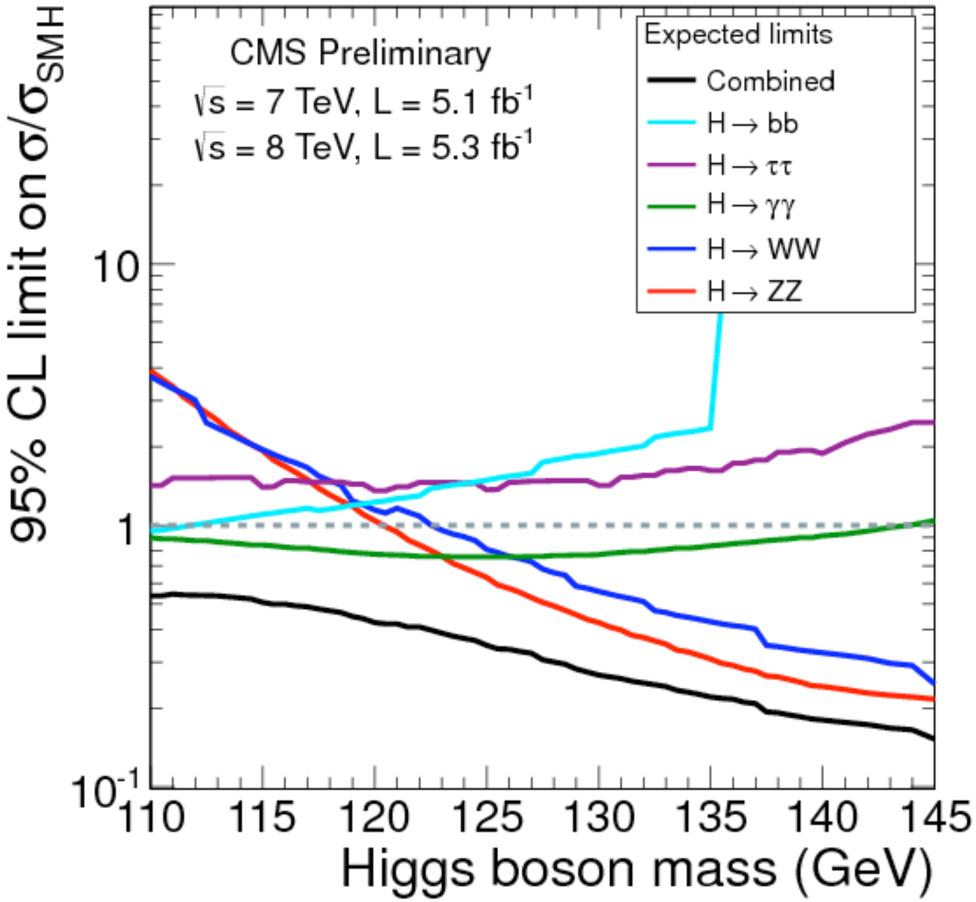


Expected Sensitivities

Moriond 2012

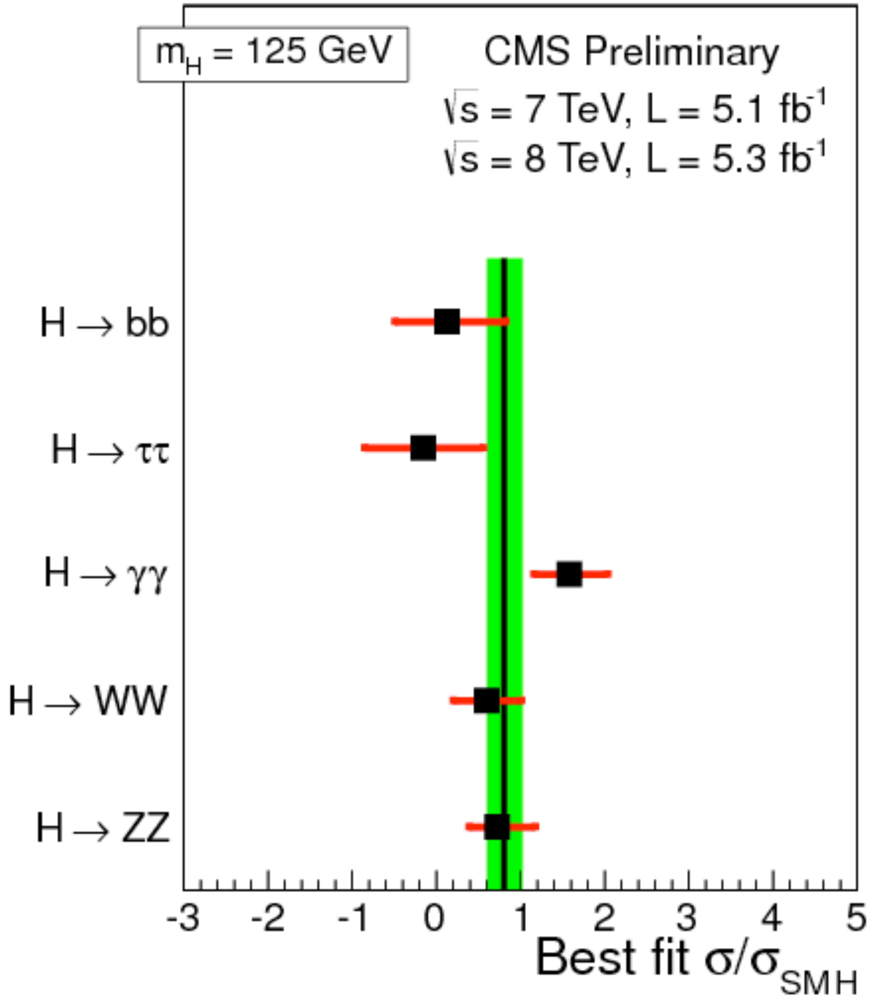
WW still competitive to exclude in this range





Standard Model Signal Strength (7+8 TeV)

- The best fit signal strength is 0.80 ± 0.22 from all channels
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12020TWiki



WH→WW→lνlνlν

- Associated production of WH leading to trilepton final state
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11034TWiki