



# Search for the Standard Model Higgs boson in $H \rightarrow WW \rightarrow \ell \nu q \bar{q}$

Kalanand Mishra

*Fermilab*

*CMS Collaboration*

Public note: <http://cdsweb.cern.ch/record/1449158?ln=en>

Public twiki: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12003TWiki>

DOE visit, FNAL, June 8, 2012

# The team (in alphabetical order)



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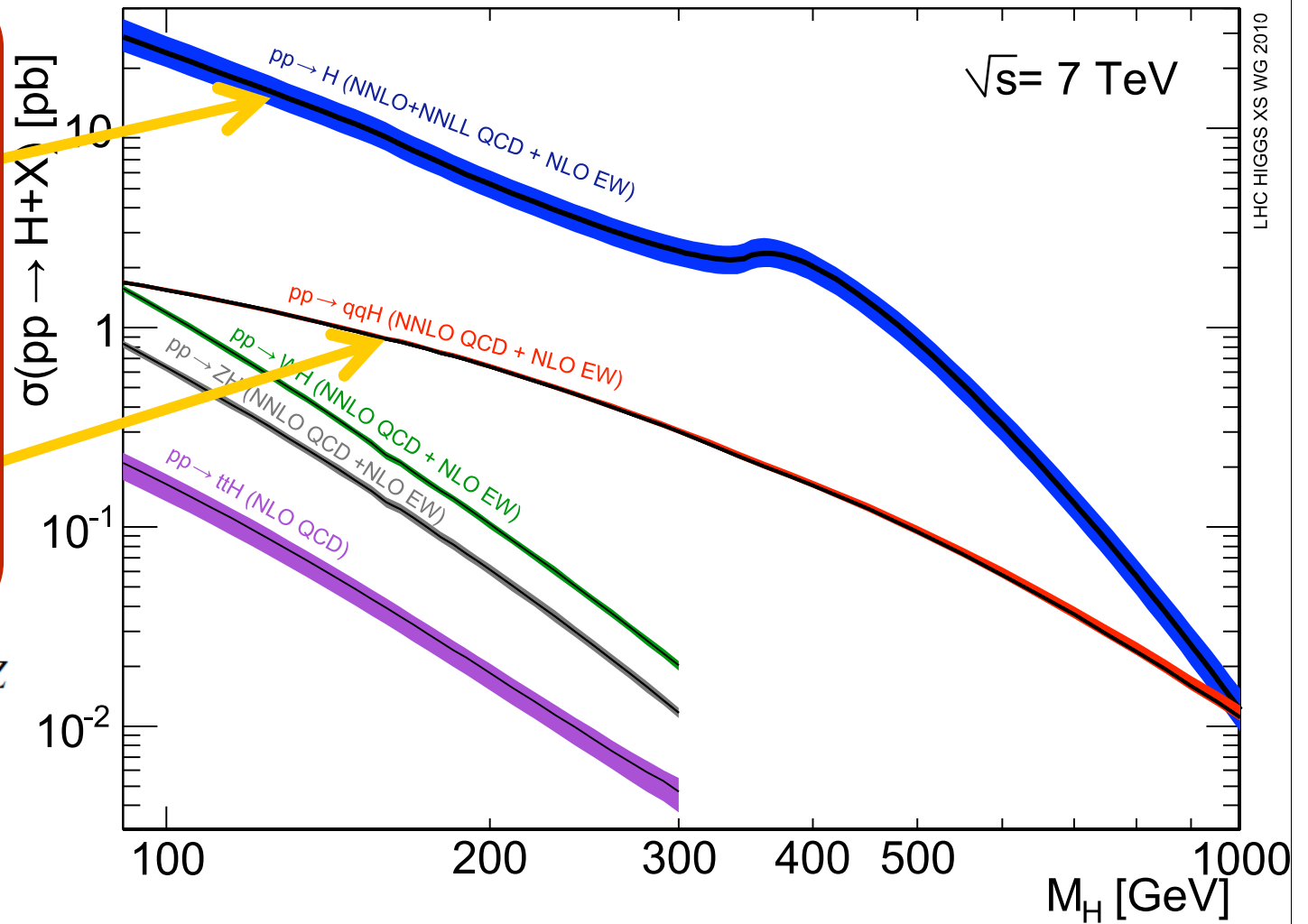
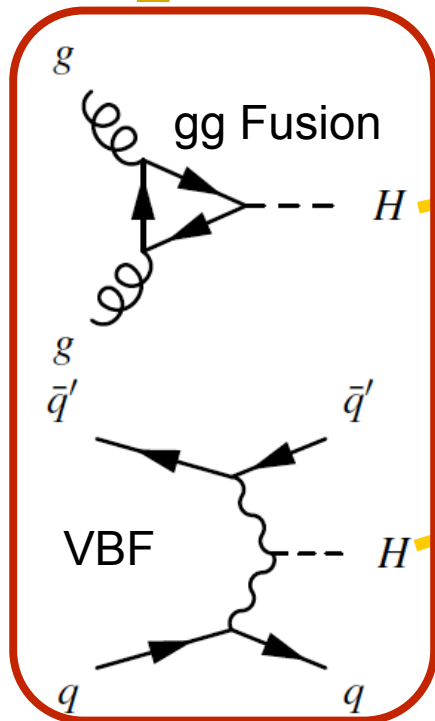
<sup>13</sup> CERN

•Center-of-gravity at LPC

•Significant contribution from Fermilab CMS Center

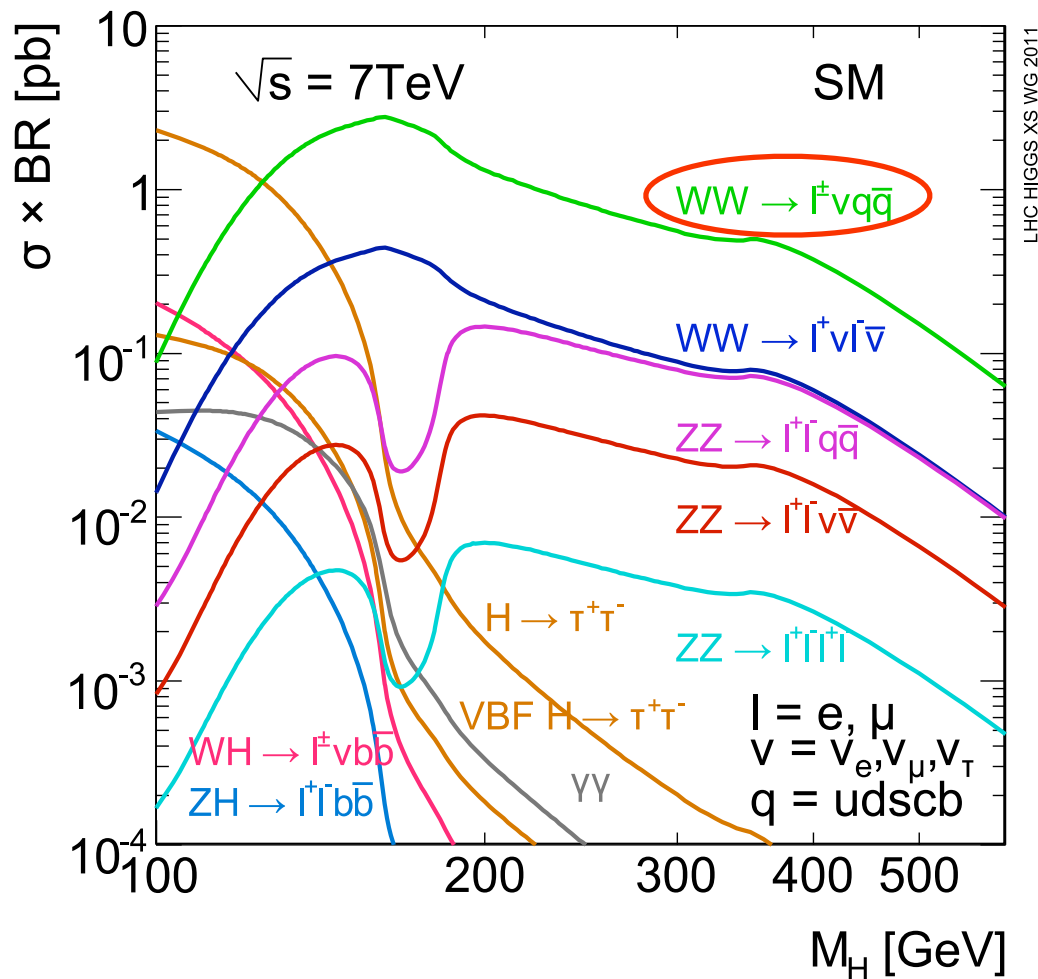
**A truly global collaboration. FNAL also involved heavily in  $H \rightarrow WW \rightarrow \ell\nu\ell\nu$  analysis.**

# Higgs production



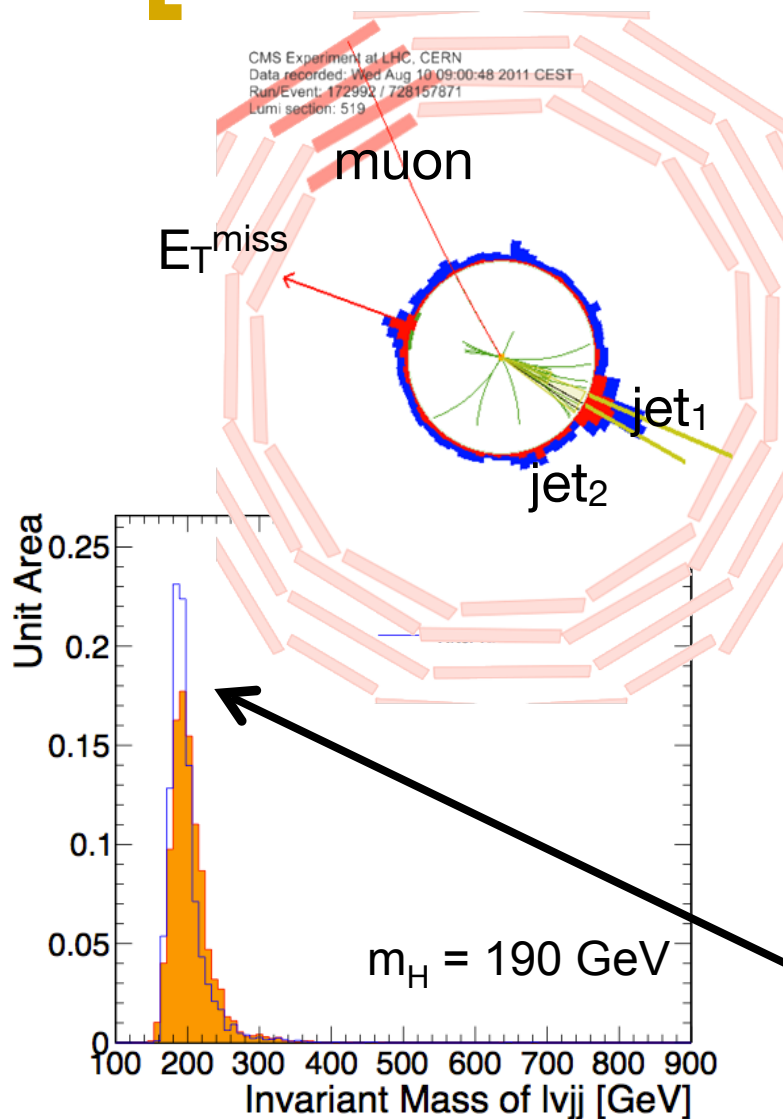
LHC HIGGS XS WG 2010

# Higgs decays



- ◆  $H \rightarrow WW \rightarrow \ell \nu jj$  does a lot of heavy lifting.
  - largest  $\text{BR} \times \sigma$  over most of the mass range.
  - Using a W mass constraint, the decay is sufficiently reconstructed to produce a mass peak.
- ◆ Principal drawback is the large W+jet background
  - We employ data-driven techniques to understand and control this process.

# Pre-selection cuts

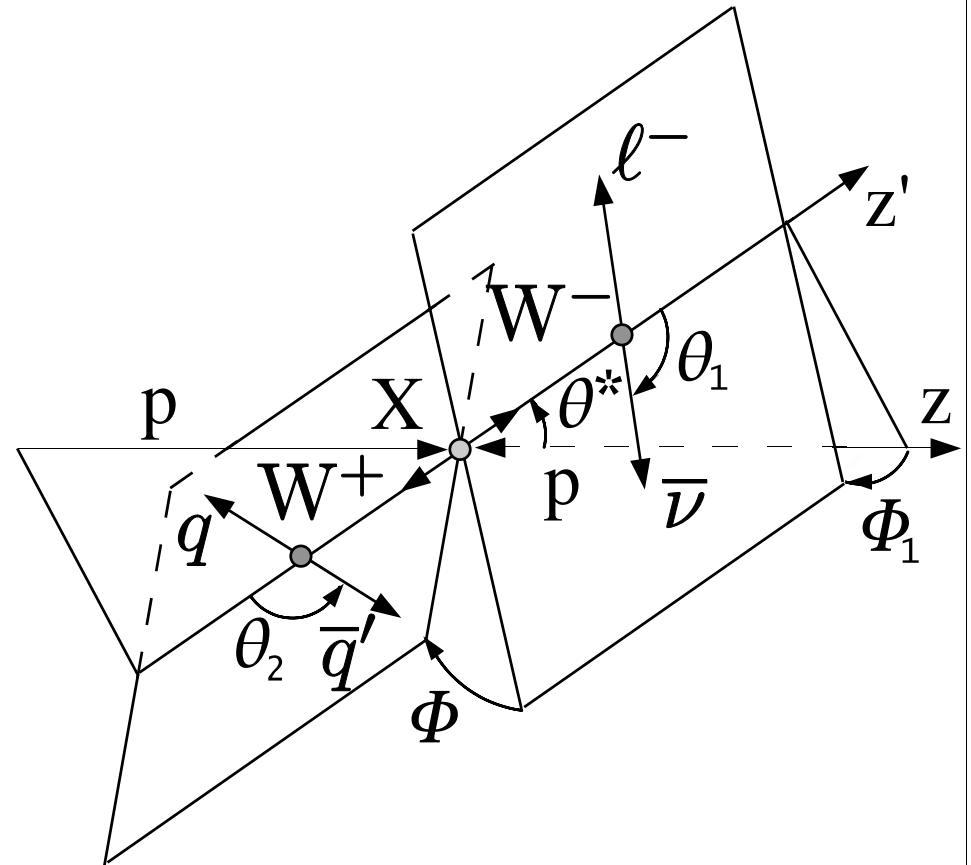


- ◆ One isolated, high- $p_T$  lepton
  - $p_T > 35$  (25) GeV for electrons (muons)
- ◆ High  $E_T^{\text{miss}}$  from 1 neutrino
  - $E_T^{\text{miss}} > 30$  (25) GeV for electrons (muons)
  - $m_T(\text{lepton}+E_T^{\text{miss}}) > 50 \text{ GeV}$
- ◆ Two high  $p_T$  jets with  $m_{jj} \sim 80 \text{ GeV}$ 
  - Anti-Kt 0.5 particle flow jets
  - $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.4$
  - $\Delta R(\text{jet-lepton}) > 0.3$
  - $N_{\text{extra-jets}} = 0, 1$
- ◆ neutrino  $p_z$  from  $m_W$  constraint
- ◆ We do a kinematic fit on lepton,  $E_T^{\text{miss}}$ , hadronic  $W$  to improve Higgs mass resolution and to remove the correlation between  $m_{WW}$  from  $m_{jj}$ .

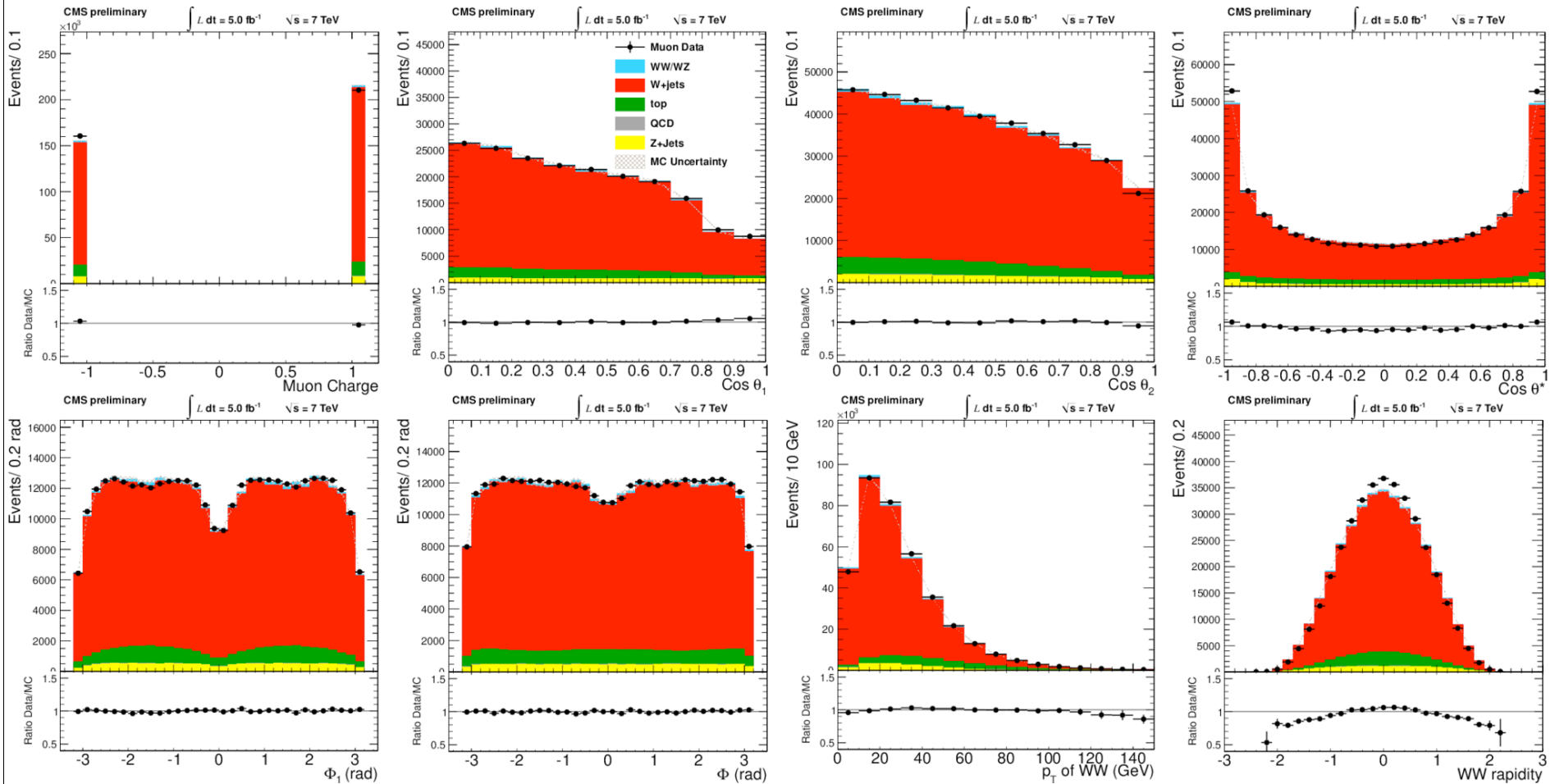
# Likelihood



- ◆ The Higgs production and decay kinematics are described by  $\{m_{WW}, m_{jj}, \theta_1, \theta_2, \theta^*, \phi, \phi_1\}$ .
  - $m_{WW}$  is used to set the limit.
  - $m_{jj}$  is used to normalize the backgrounds.
- ◆ We include the lepton sign as the background is charge asymmetric.
- ◆ We include  $p_T(WW)$  and  $y_{WW}$  for additional discrimination.
- ◆ All variables have negligibly small correlations.



# Inputs to the likelihood (muon data)



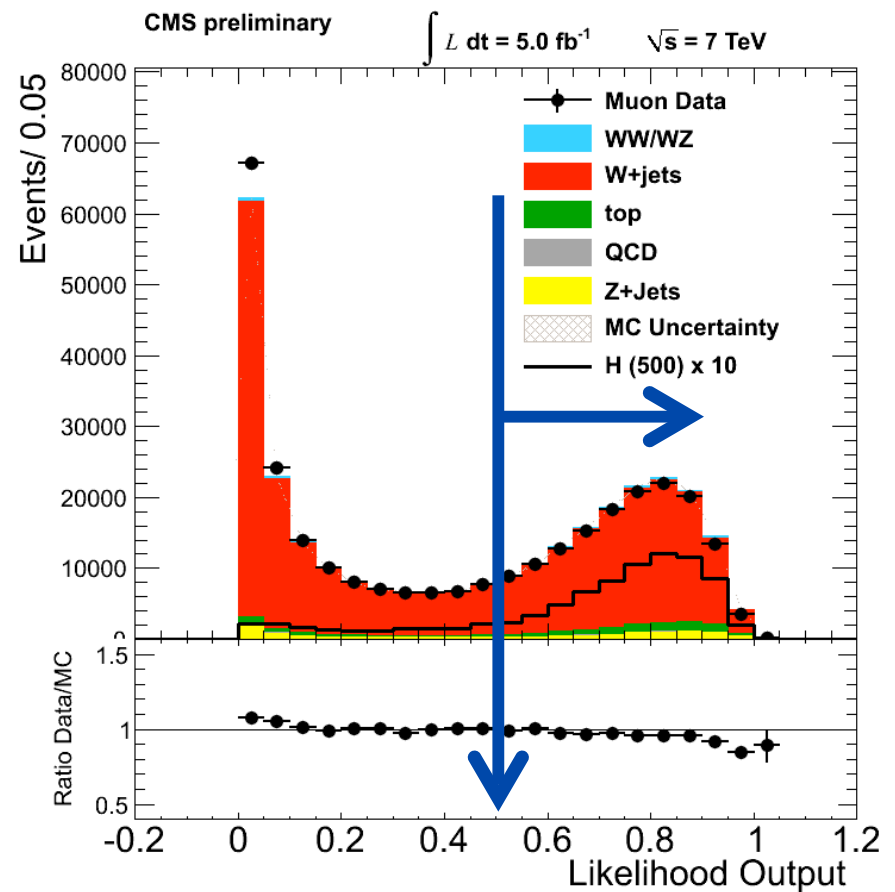
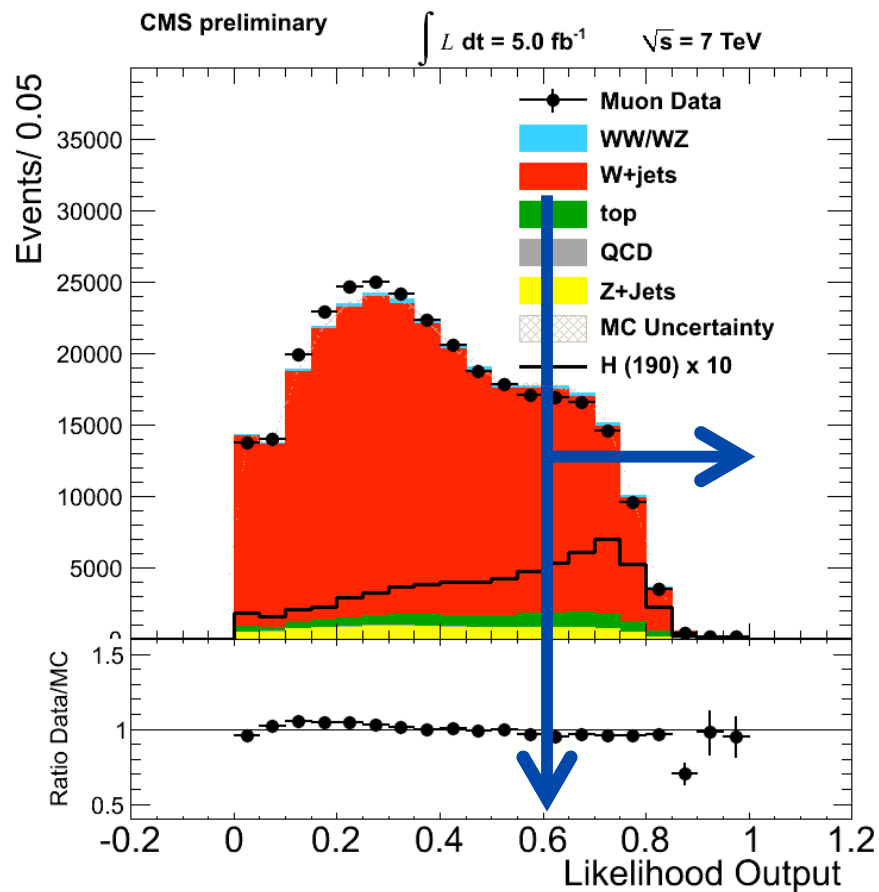
**Reasonable modeling of kinematics in simulation.**

# Likelihood output



muon, 2-jet,  $m_H = 190$  GeV

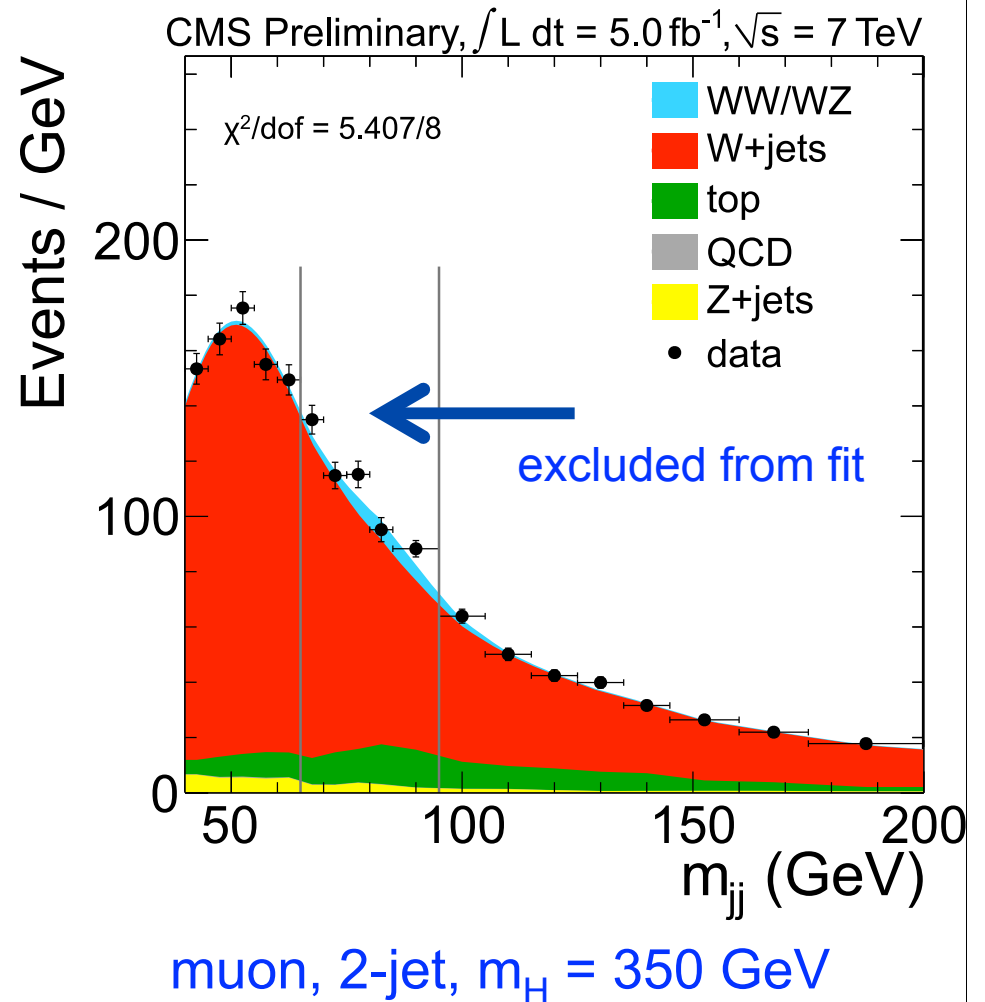
muon, 2-jet,  $m_H = 500$  GeV



# Relative normalization from fit to $m_{jj}$



- ◆ We determine the background composition in a 1D, unbinned, maximum likelihood fit to the di-jet invariant mass spectrum.
- ◆ The background shapes are taken from:
  - MC for all minor backgrounds (not for W+jets and QCD)
  - data-driven approach for QCD
  - analytic description or MC for W+jets

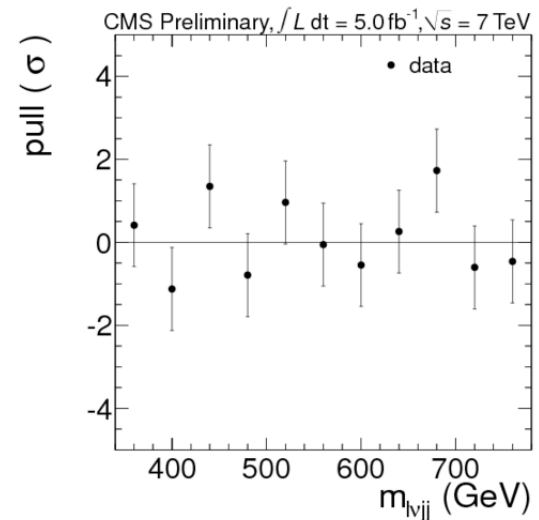
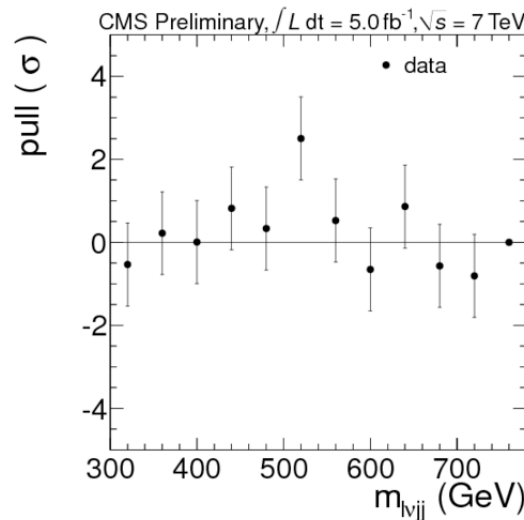
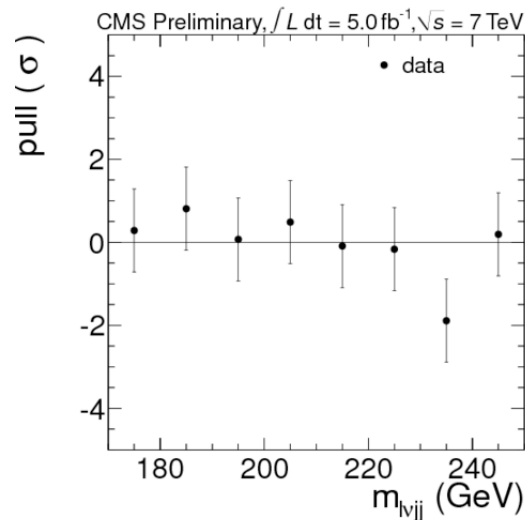
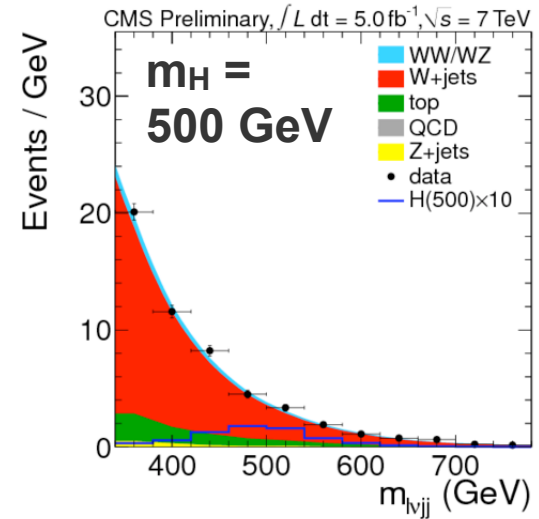
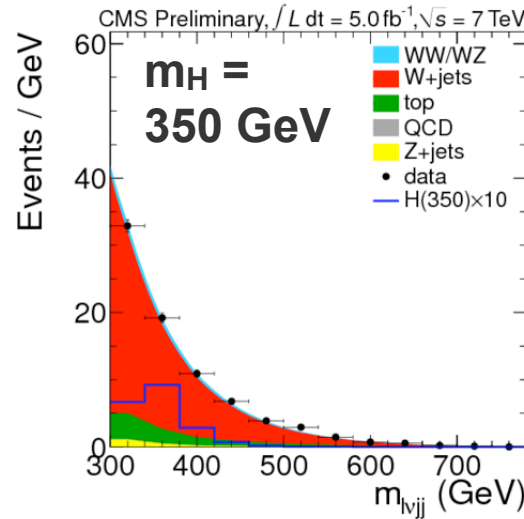
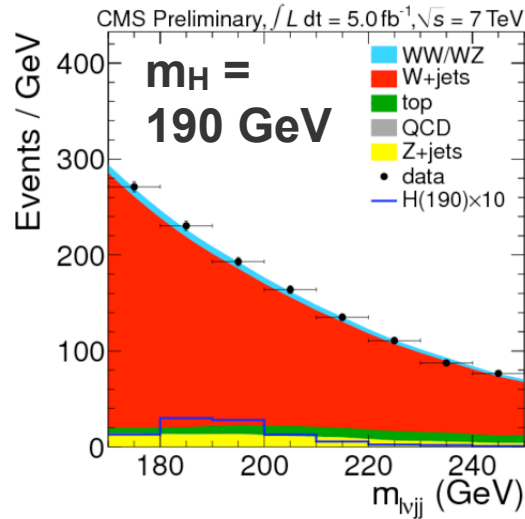


## Limit setting with the $m_{WW}$ spectrum



- ◆ The fit to the  $m_{jj}$  spectrum determines the relative normalization of the backgrounds.
- ◆ The background components are stacked up and compared with the data with the additional selection ( $65 < m_{jj} < 95$ ) GeV.
- ◆ Shapes of the minor backgrounds are taken from MC.
  - Again, QCD is taken from the data-driven sample.
  - The W+jets shape is constructed from the  $m_{jj}$  sidebands.

# The $m_{WW}$ spectrum



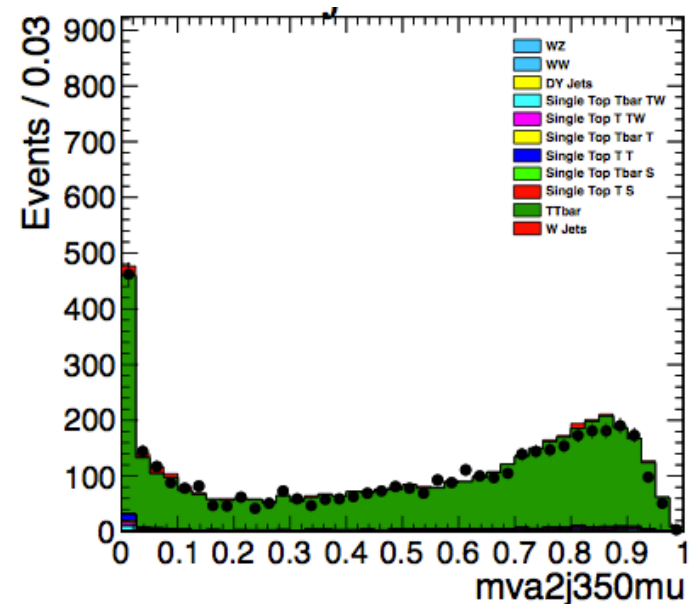
**Mass peak makes it straightforward to interpret any observed excess in data.**

# Signal systematic uncertainties



Source	uncertainty
Higgs line shape	0 – 30%
Signal cross-section	15 – 20%
Signal efficiency x acceptance	7% (13% for 500 GeV and up)
Luminosity	2.2%
Jet energy scale, resolution and MET	< 1%
Theory (PDFs)	1 – 2%
Lepton trigger efficiency	1%
Lepton selection efficiency	1 – 2%
Pile-up	< 1%

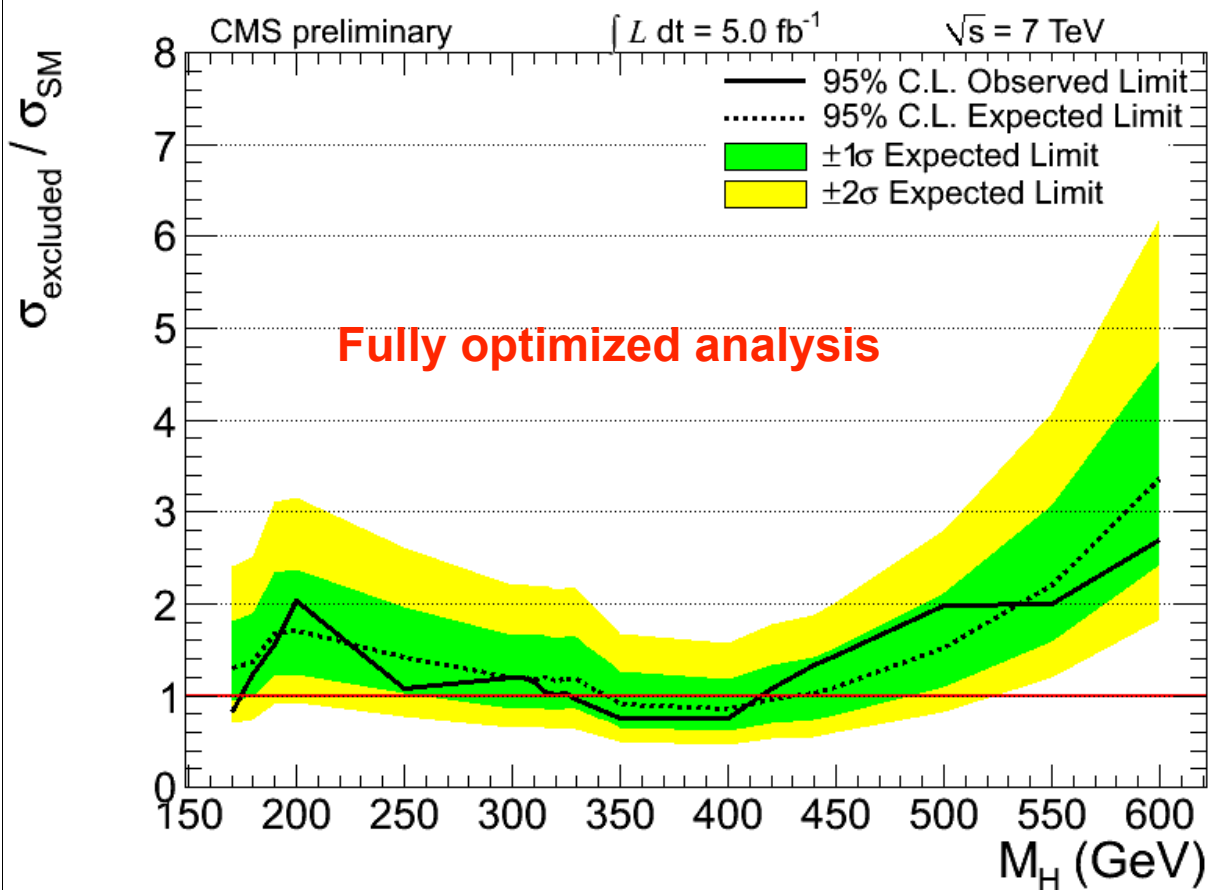
◆ Efficiency x acceptance syst. is evaluated using a pure top sample as the difference between data and MC.



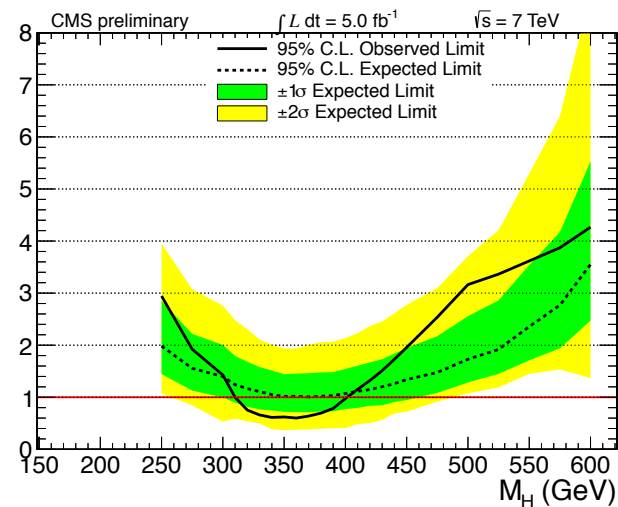
# Limit using 7 TeV data



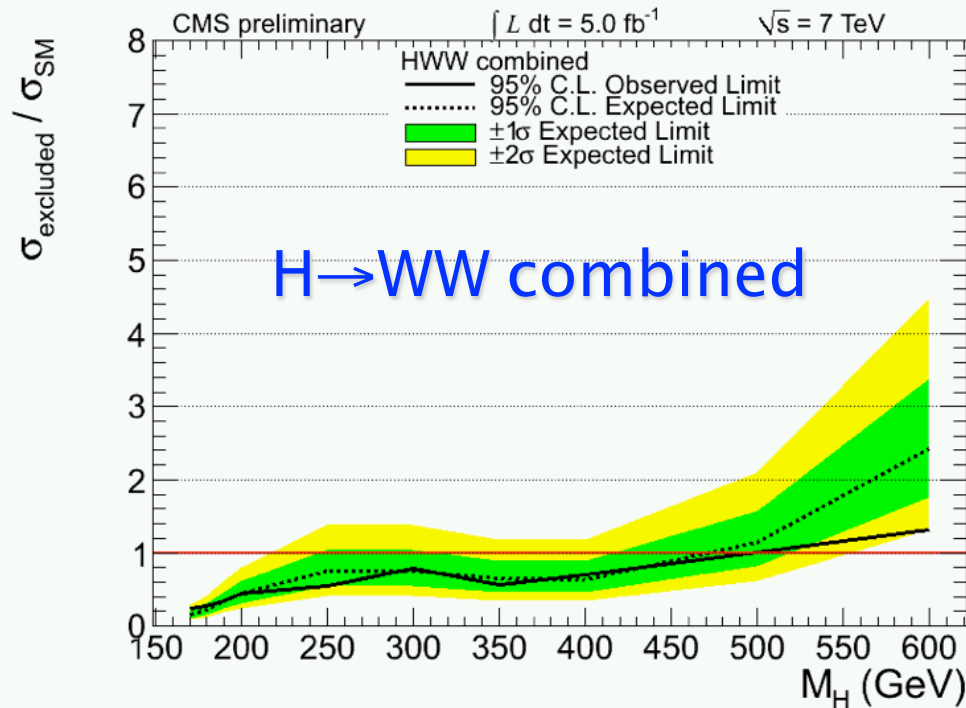
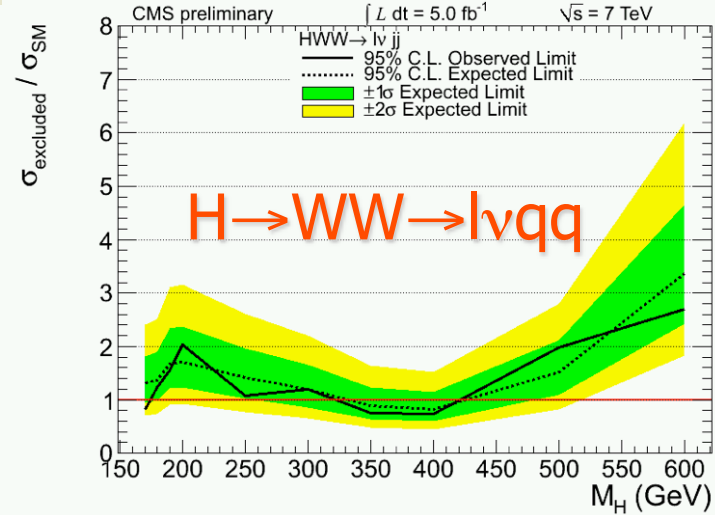
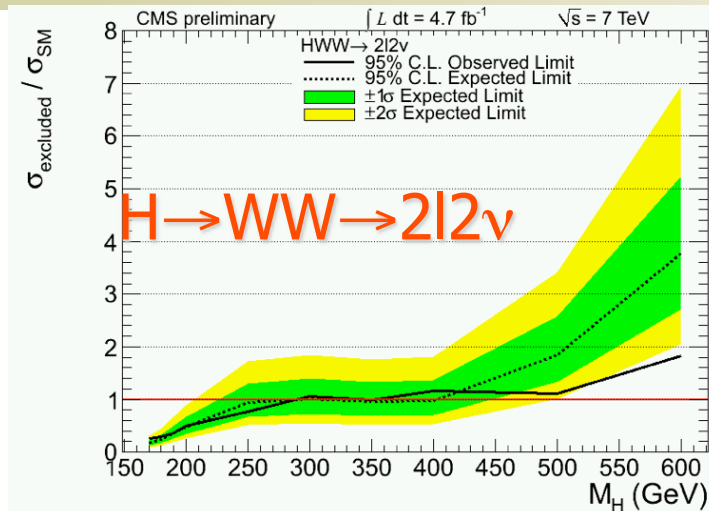
- ◆ expected exclusion: 340 – 440 GeV
- ◆ observed exclusion: 327 – 415 GeV



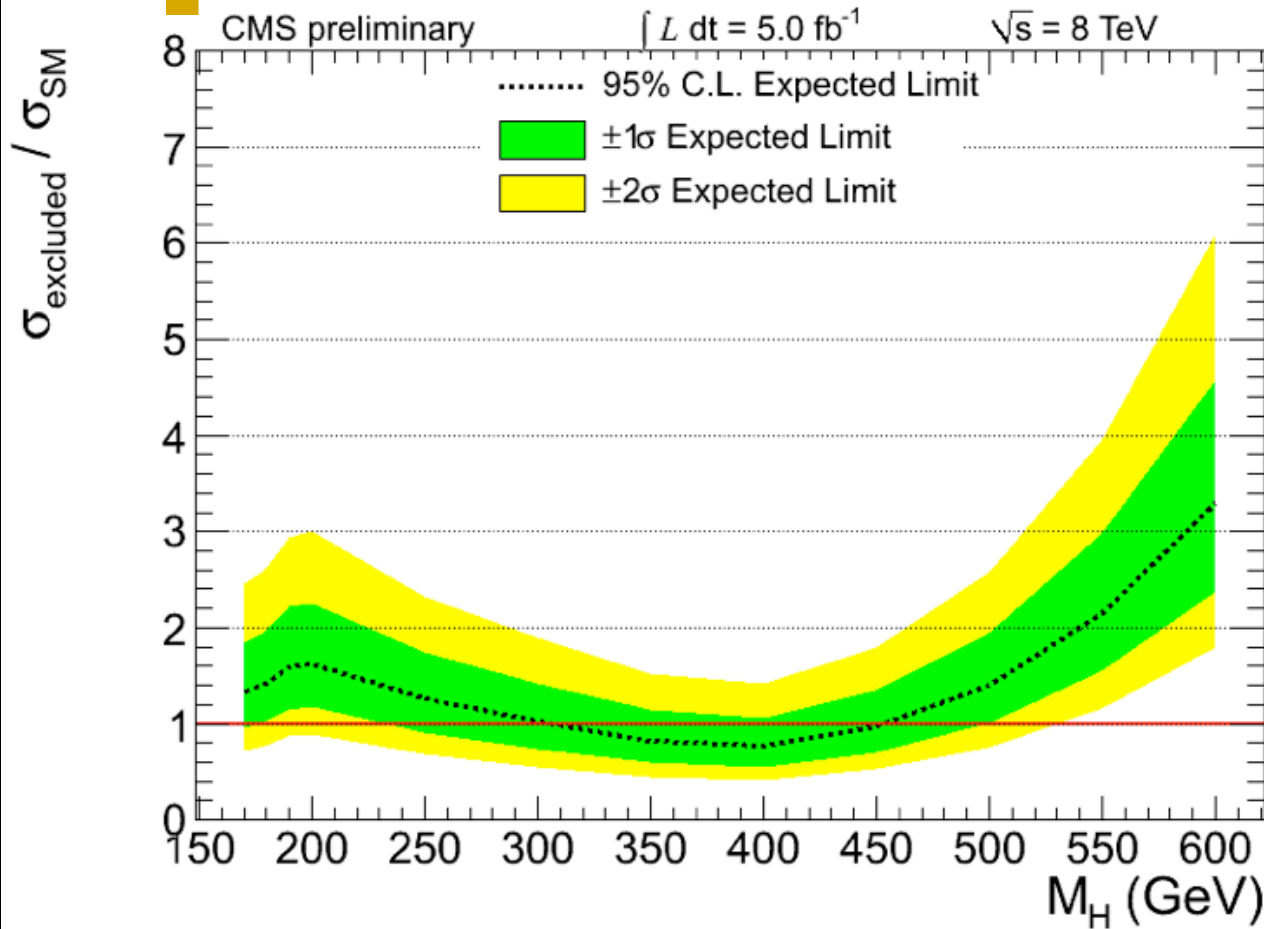
## Basic “cut & count”/fit analysis



# Combined limit $H \rightarrow WW \rightarrow 2l2\nu$ & $WW \rightarrow l\nu qq$



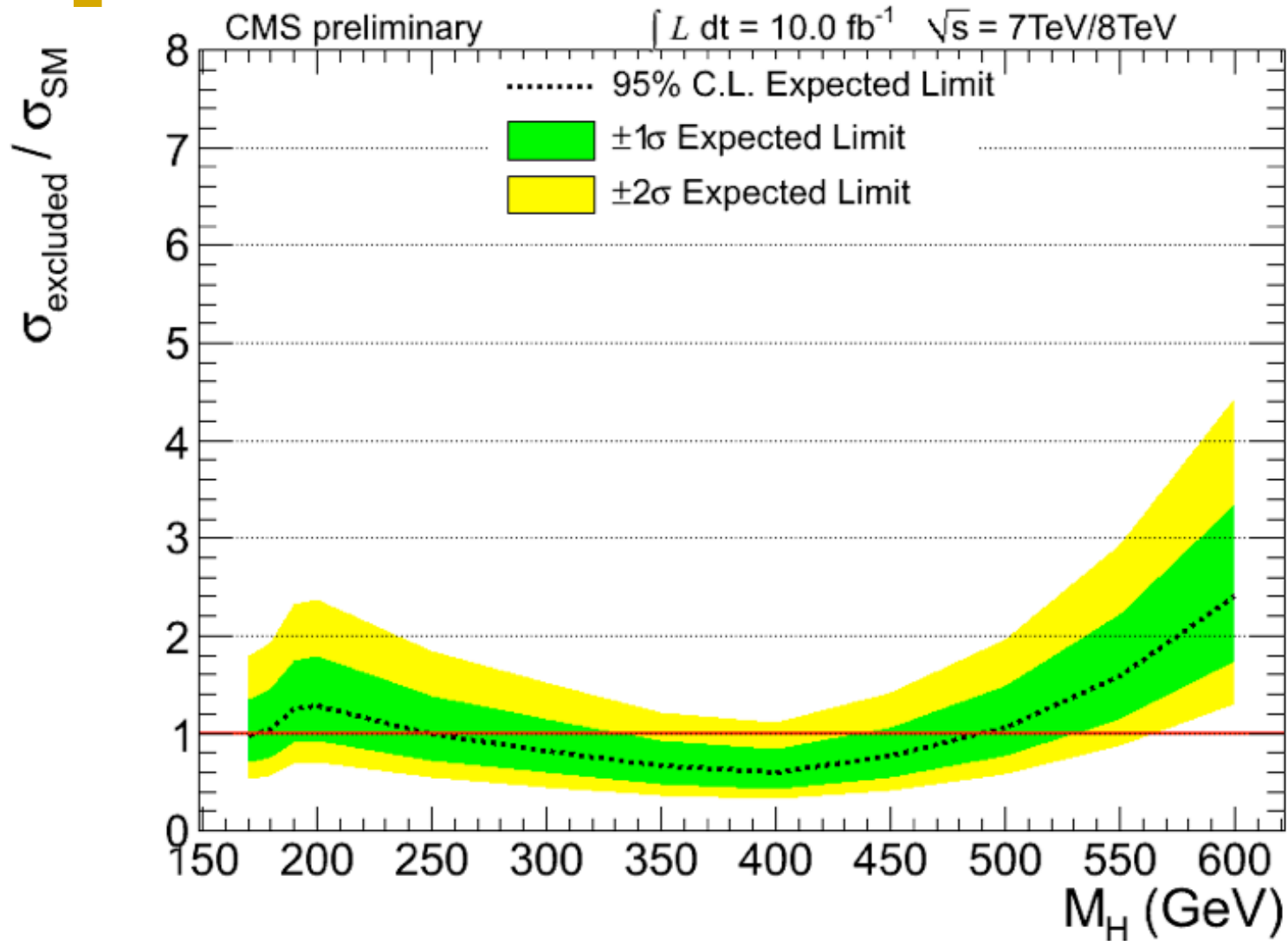
# Currently analyzing 8 TeV data: still blinded



- ◆ About 10–20% improvement over 2011 sensitivity
  - higher Higgs xsection at 8 TeV
  - improved trigger

To unblind 8 TeV data on June 15. Will show 8 TeV results and combination with 7 TeV data/ other channels during ICHEP.

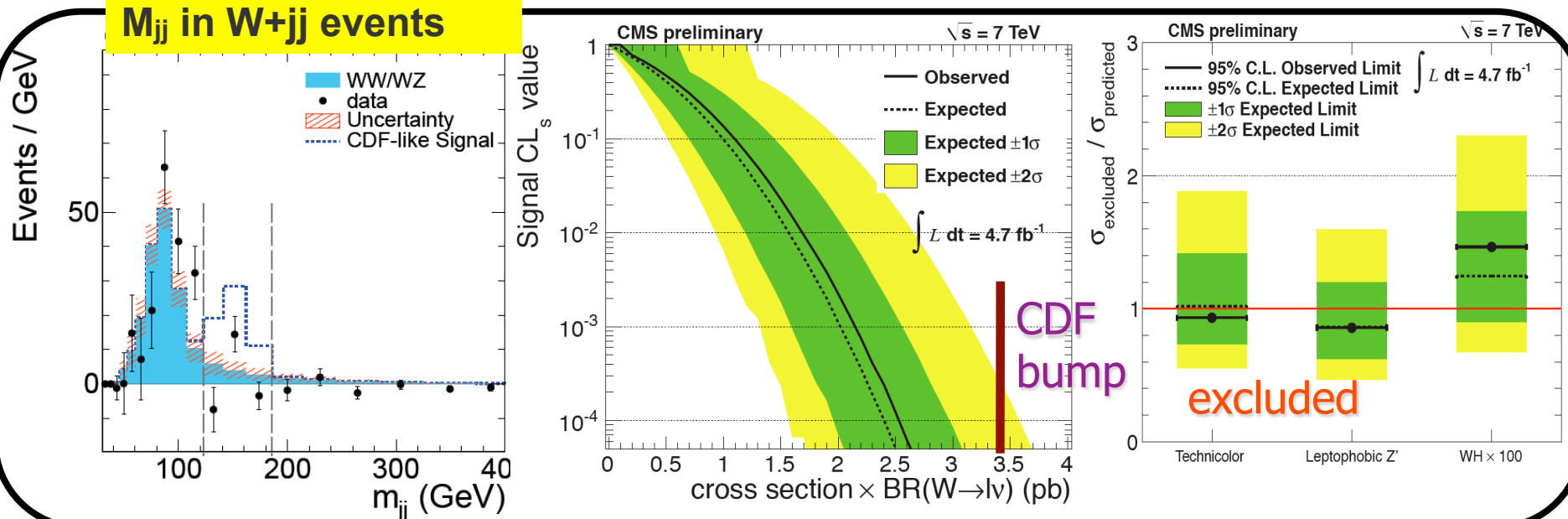
# Combination of 7 TeV and 8 TeV results



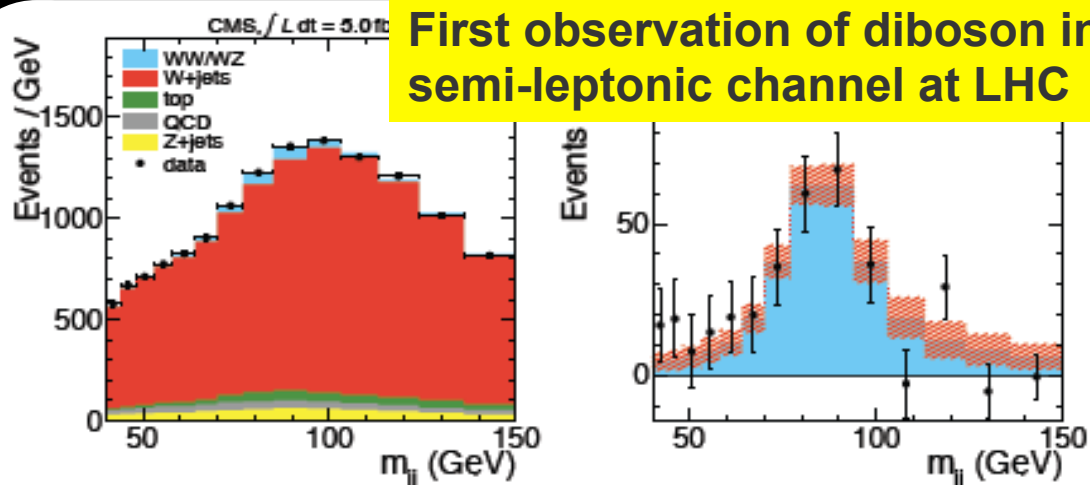
# Other achievements of this team



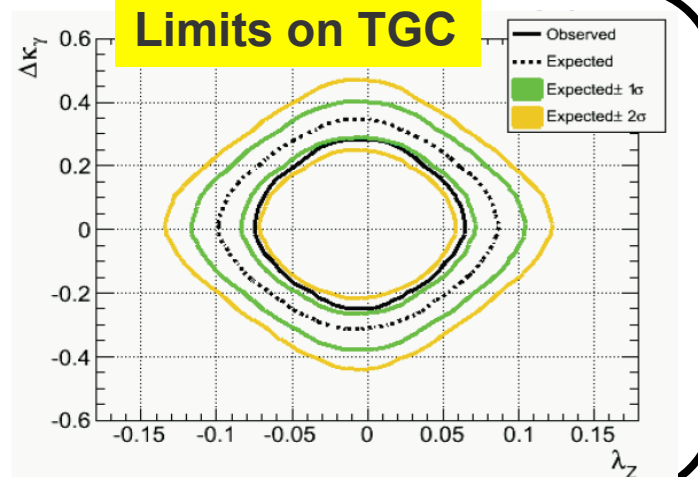
## $M_{jj}$ in W+jj events



## First observation of diboson in semi-leptonic channel at LHC



## Limits on TGC



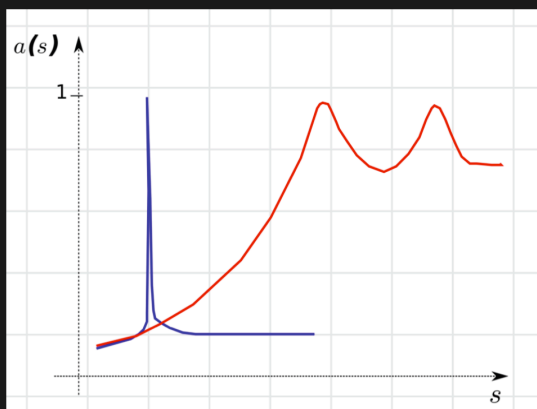
# Summary



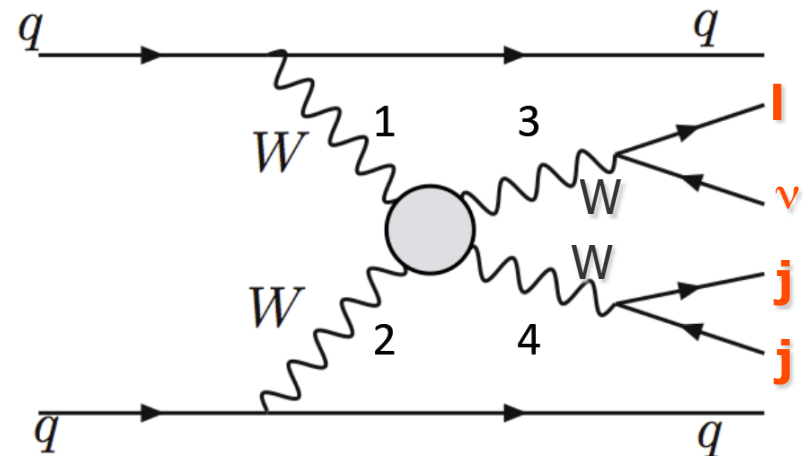
- ◆ We have set a world leading limit in  $H \rightarrow WW \rightarrow \ell \nu jj$  decays.
  - Poised to take advantage of the added statistics in 2012 to increase the mass reach of this important analysis
  - With 20 /fb data will have kinematic reach beyond 1 TeV
  - Sensitive to WW resonances at TeV scale

If the Higgs is found: VV scattering amps predicted to remain small  
Ultimate test of SM description of EWSB

If the Higgs is NOT found: VV scattering amps grow with  $s$  at “threshold”  
Nothing in the SM to tame this growth  
In the absence of new physics violate unitarity  $\sim 1.7$  TeV  
Best hunting ground for hints of new physics of EWSB

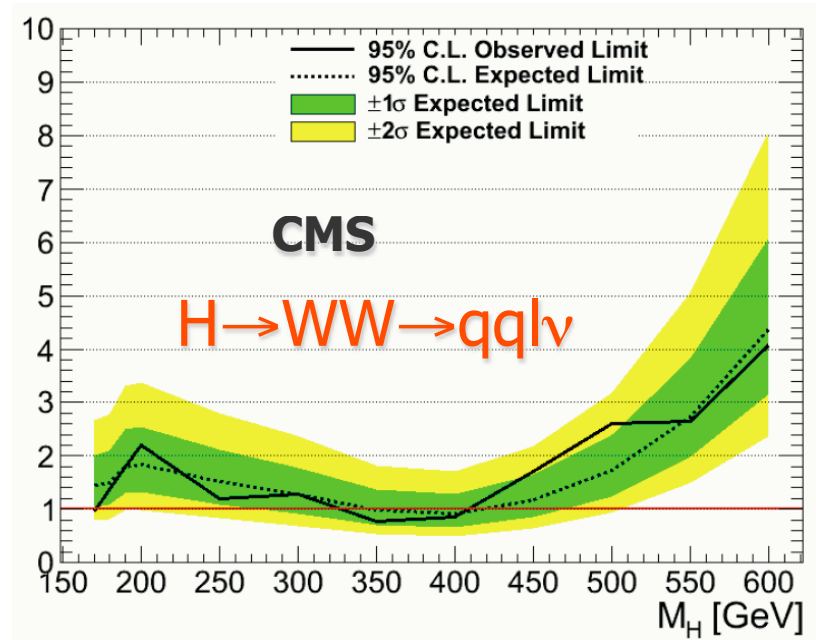
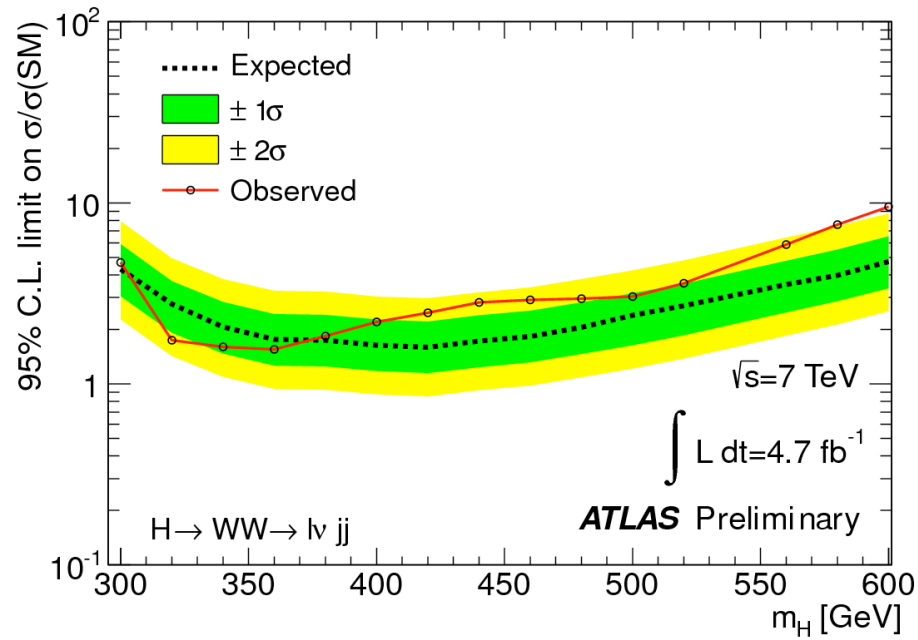


- High mass Higgs/ exotics in VBF
- WW scattering
- Merged jets from boosted W



backup slides

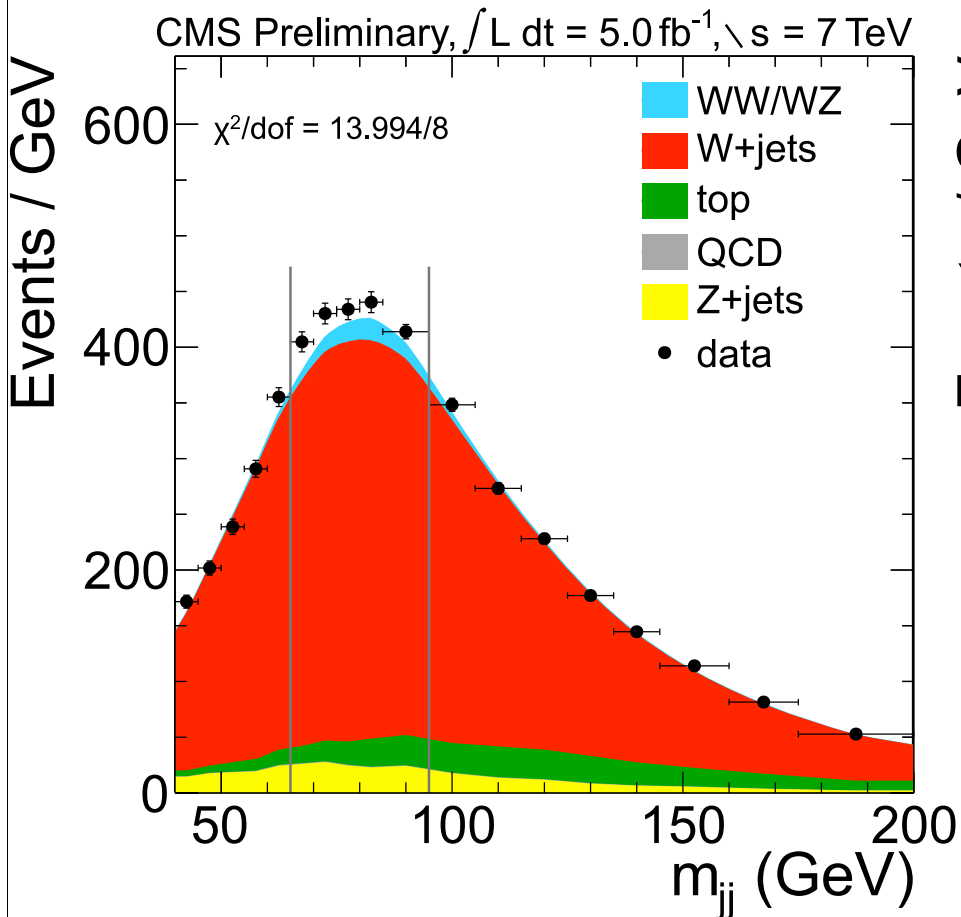
# CMS vs ATLAS



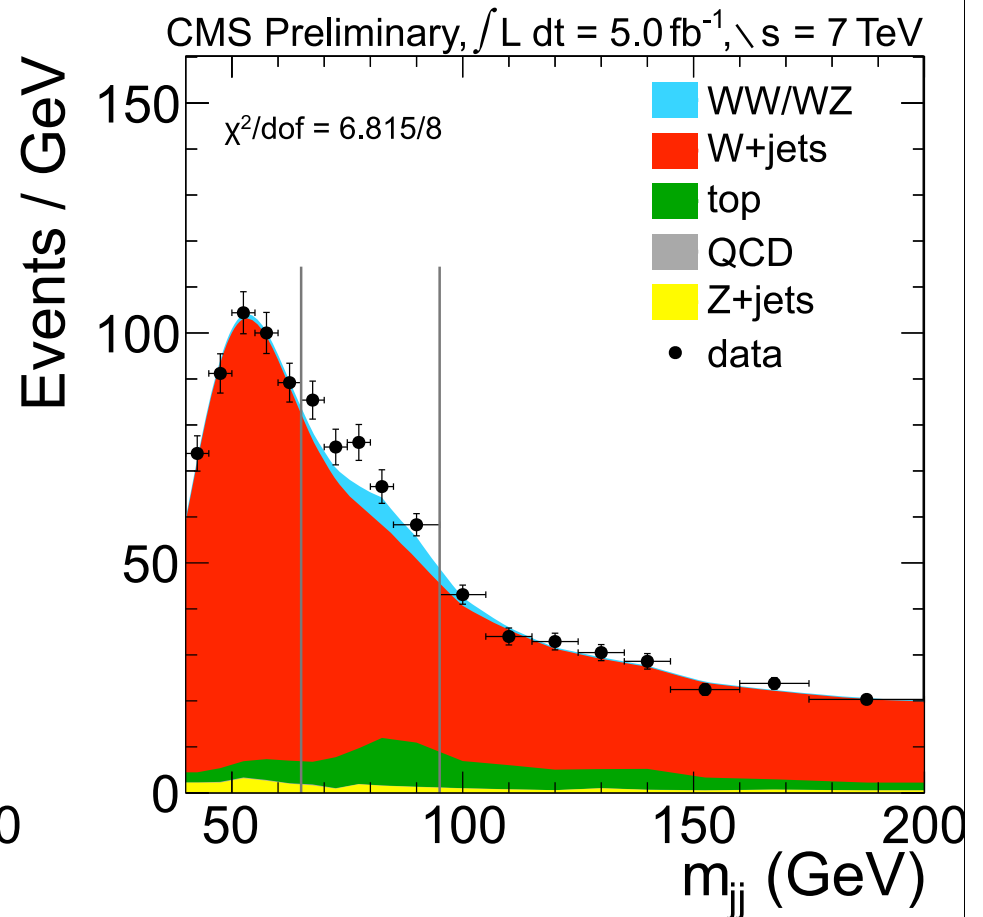
# Additional $m_{jj}$ examples



**muon, 2-jets,  $m_H = 190$  GeV**



**muon, 2-jets,  $m_H = 500$  GeV**



# Data samples

dataset name	run range	int. lumi
/SingleElectron/Run2011A-May10ReReco-v1/AOD /SingleMu/Run2011A-May10ReReco-v1/AOD	160404-153869	211 pb <sup>-1</sup>
/SingleElectron/Run2011A-PromptReco-v4/AOD /SingleMu/Run2011A-PromptReco-v4/AOD	165088-167913	930 pb <sup>-1</sup>
/SingleElectron/Run2011A-05Aug2011-v1/AOD /SingleMu/Run2011A-05Aug2011-v1/AOD	170249-172619	368 pb <sup>-1</sup>
/SingleElectron/Run2011A-PromptReco-v6/AOD /SingleMu/Run2011A-PromptReco-v6/AOD	172620-173692	659 pb <sup>-1</sup>
/SingleElectron/Run2011B-PromptReco-v1/AOD /SingleMu/Run2011B-PromptReco-v1/AOD	175832-180252	2512 pb <sup>-1</sup>
	<b>160404-180252</b>	<b>5.0 fb<sup>-1</sup></b>

- Certified “golden” JSON used

# MC samples

dataset name	x-sec (pb)	eq. lumi (fb <sup>-1</sup> )
<b>/WJetsToLNu_TuneZ2_7TeV-madgraph-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM</b>	<b>31314</b>	<b>2.5</b>
/DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	3048	11.3
/TTJets_TuneZ2_7TeV-madgraph-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	163	22.7
/T_TuneZ2_s-channel_7TeV-powheg-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	3.19	81.5
/T_TuneZ2_t-channel_7TeV-powheg-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	41.9	93.0
/T_TuneZ2_tW-channel-DR_7TeV-powheg-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	7.87	103
/Tbar_TuneZ2_s-channel_7TeV-powheg-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	1.44	95.8
/Tbar_TuneZ2_t-channel_7TeV-powheg-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	2.26	85.9
/Tbar_TuneZ2_tW-channel-DR_7TeV-powheg-tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	7.87	41.1
/WW_TuneZ2_7TeV_pythia6_tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	47.0	89.9
/WZ_TuneZ2_7TeV_pythia6_tauola/Fall11-PU_S6_START42_V14B-v1/AODSIM	18.2	234
/GluGluToHToWWToLNuQQ_M-XXX_7TeV-powheg-pythia6/Fall11-PU_S6_START42_V14B-v1/AODSIM	depends on Higgs mass	a lot
/GluGluToHToWWToTauNuQQ_M-XXX_7TeV-powheg-pythia6/Fall11-PU_S6_START42_V14B-v1/AODSIM		
/VBF_HToWWToLNuQQ_M-XXX_7TeV-powheg-pythia6/Fall11-PU_S6_START42_V14B-v1/AODSIM		
/VBF_HToWWToTauNuQQ_M-XXX_7TeV-powheg-pythia6/Fall11-PU_S6_START42_V14B-v1/AODSIM		

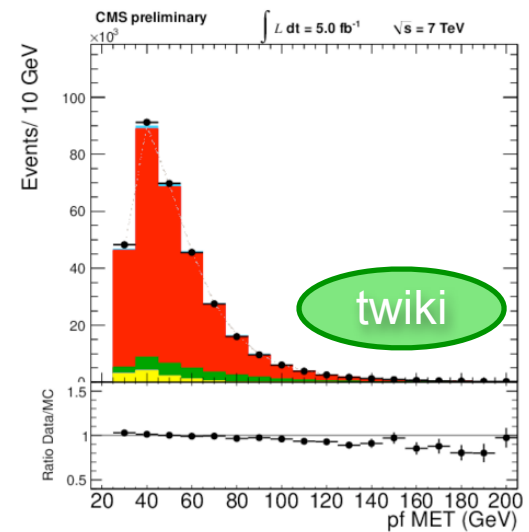
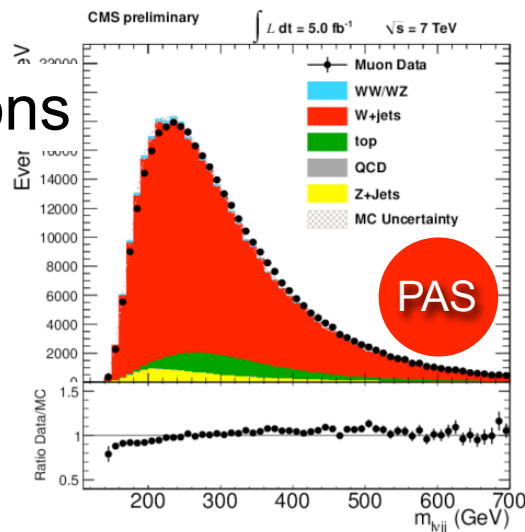
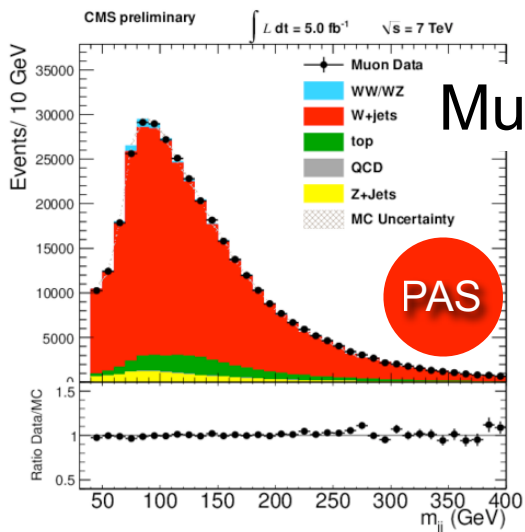
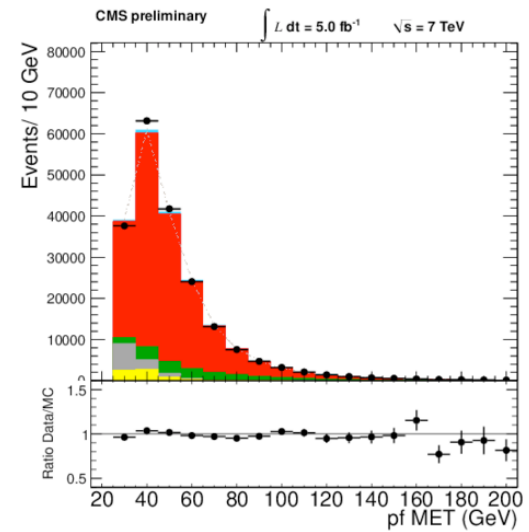
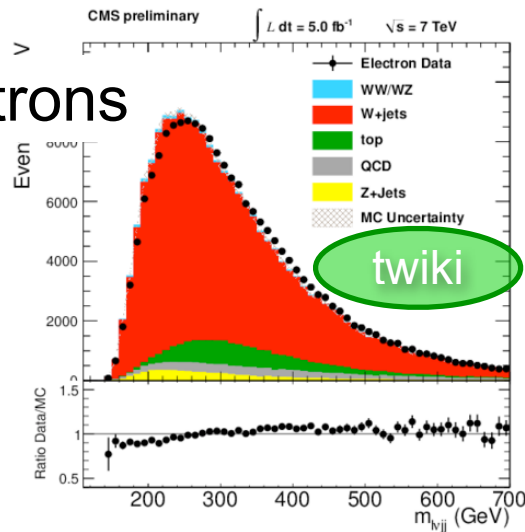
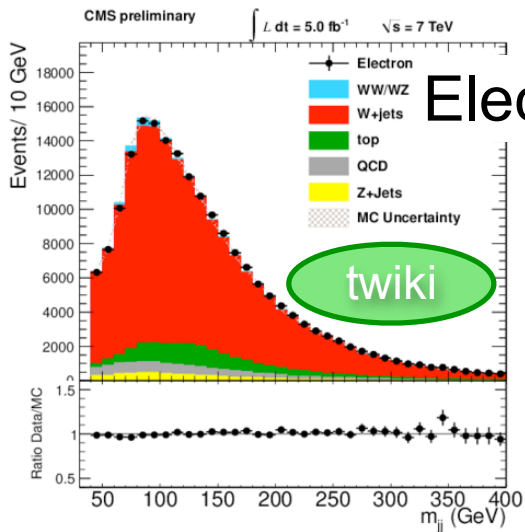
- All MC samples corrected for to account for different pile-up conditions in data
  - 3D pile-up re-weighting technique applied

# Trigger strategy

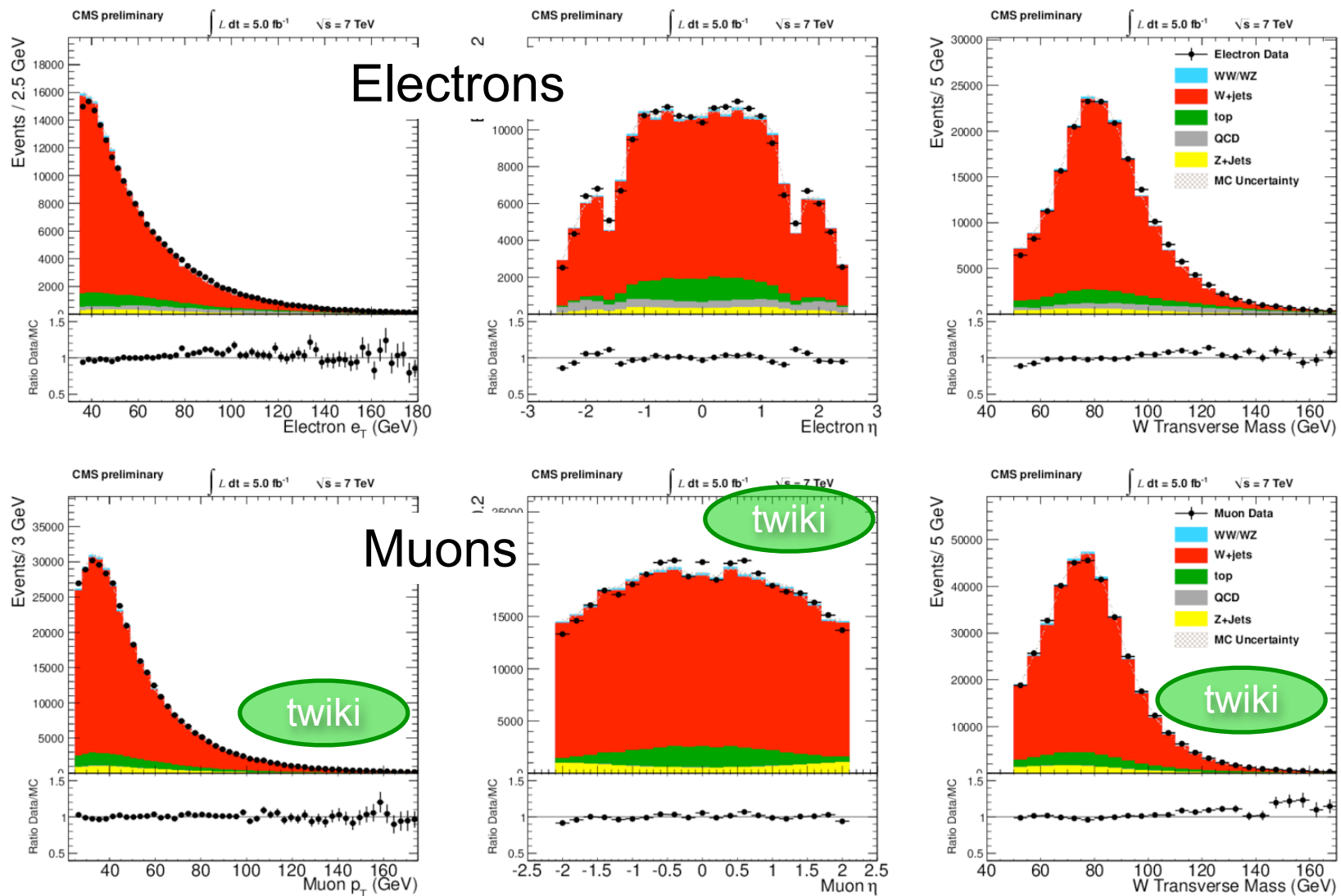
- Lepton as well as PFMT **HLT efficiencies** for electron events are **corrected** to account for data/MC differences by means of “Tag and Probe” with Z events
- Same technique is used to measure **reconstruction/identification scale factors**

electron trigger paths	run range
HLT_Ele27_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v*	160404-153869 (May10ReReco-v1)
HLT_Ele32_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v*	165088-167913 (PromptReco-v4)
HLT_Ele25_WP80_PFMT40_v*	
HLT_Ele27_WP80_PFMT50_v*	
HLT_Ele32_WP70_PFMT50_v*	170249-172619 (05Aug2011-v1)
HLT_Ele27_WP80_PFMT50_v*	172620-173629 (PromptReco-v6)
HLT_Ele27_WP80_PFMT50_v*	175832-180252 (PromptReco-v1)
muon trigger paths	run range
HLT_IsoMu17_v* OR HLT_Mu30_v*	160404-153869 (May10ReReco-v1)
HLT_IsoMu17_v* OR HLT_Mu30_v*	165088-167913 (PromptReco-v4)
HLT_IsoMu17_v* OR HLT_IsoMu20_v* OR HLT_IsoMu24_v*	170249-172619 (05Aug2011-v1)
HLT_IsoMu20_v* OR HLT_IsoMu24_eta2p1_v*	172620-173692 (PromptReco-v6)
HLT_IsoMu24_eta2p1_v* OR HLT_IsoMu30_eta2p1_v*	175832-180252 (PromptReco-v1)

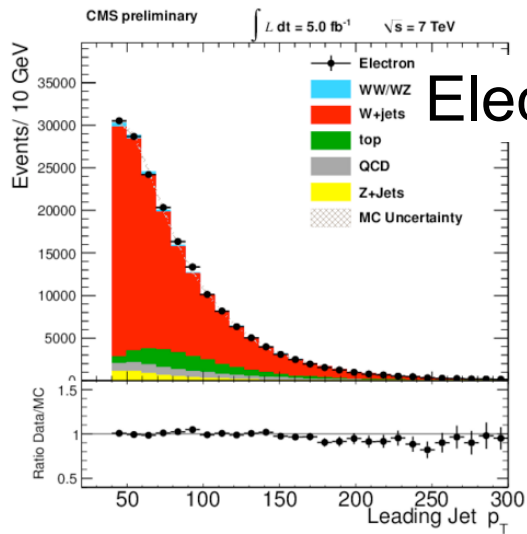
# Control plots - $m_{jj}$ / $m_{IVjj}$ / $E_T^{\text{miss}}$



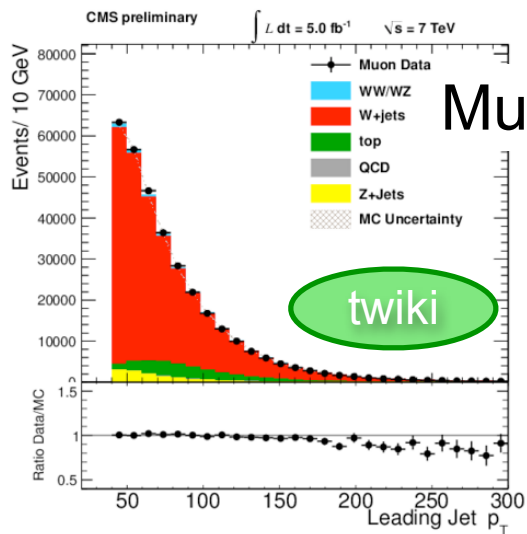
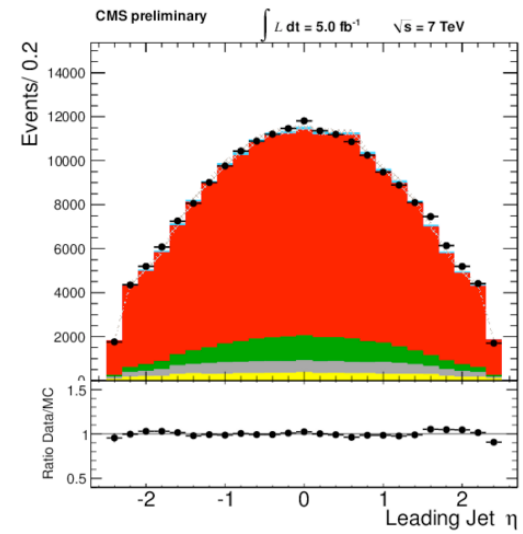
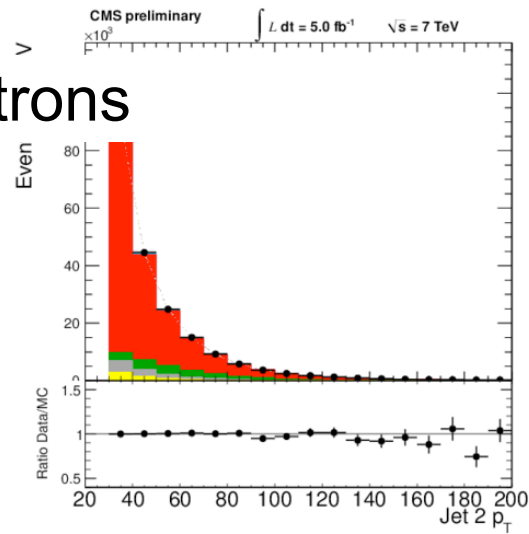
# Control plots - lepton



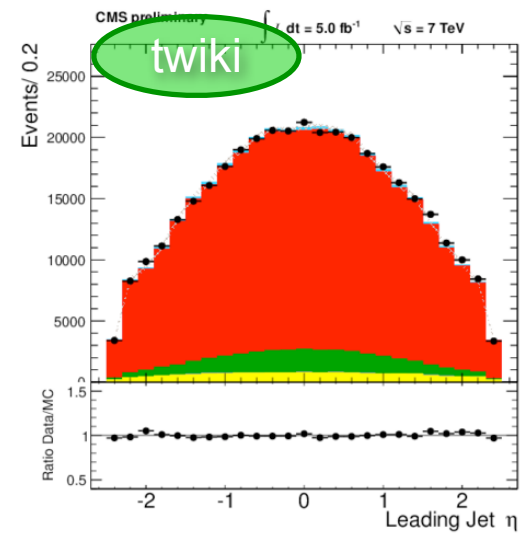
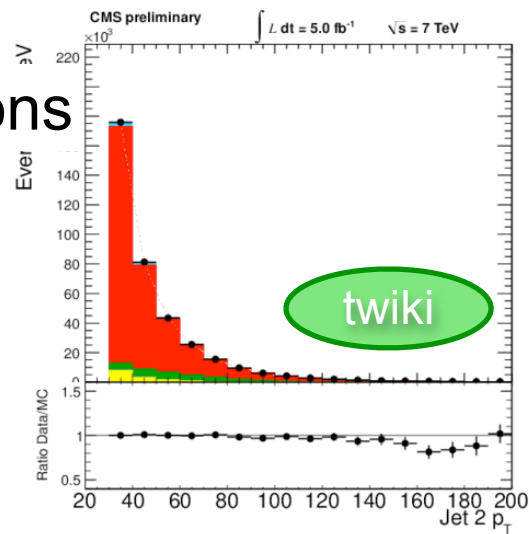
# Control plots - jets



Electrons



Muons



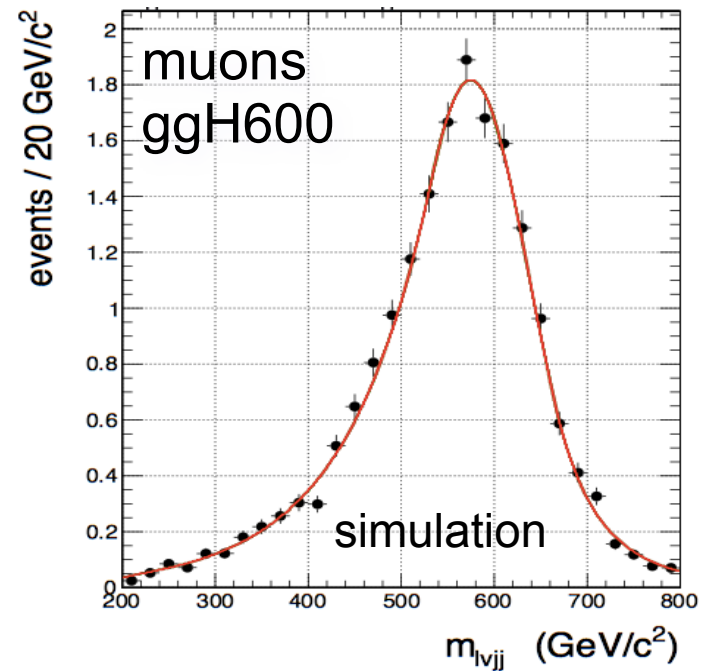
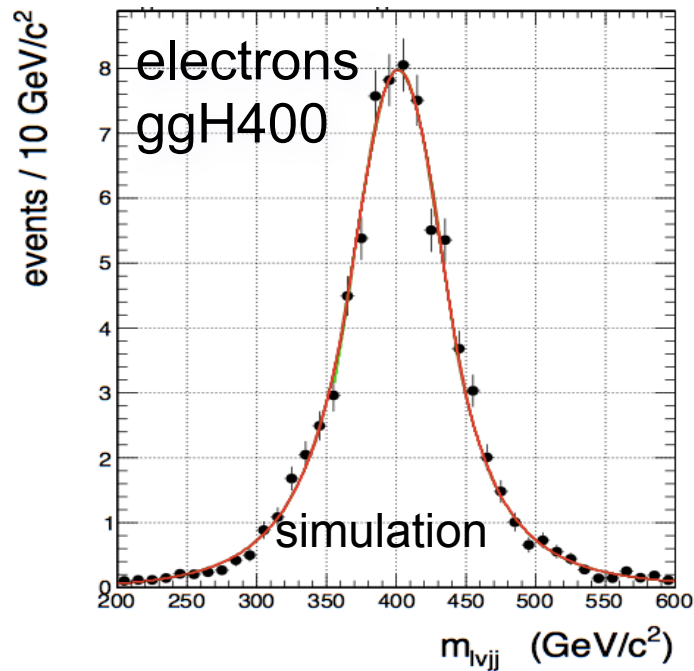
**Fit-based limit**

# The fit strategy

- Extract a limit on SM Higgs x-section just after common pre-selections
  - lots of events survive: ~20k (~30k) events in the electron (muon) channel
  - the signal shape is modeled by fitting the MC shapes (double crystal ball)
  - the background shape is modeled by a suitable analytic function (attenuated power law)
- Limit extracted performing shape analysis on  $m_{l\nu jj}$  spectrum
  - data are fitted within the combination tool with a  $B+\mu S$  hypothesis to calculate the test statistics
  - only Higgs mass points within 250 and 600 GeV are considered
- Only few additional cuts applied on top of pre-selections to enhance S/B:
  - centrality cuts:  $|\eta_{\text{lepton}}| < 1.5$ ,  $|\eta_{jj}| < 3.$ ,  $|\Delta\eta_{jj}| < 1.5$
  - $m_T > 50$  GeV relaxed to 30 GeV for muons
  - veto b-tags
  - cut on had. W resonance:  $(65 < m_{jj} < 95)$  GeV

# Signal modeling

- Signal shape in the limit extraction is modeled with a smooth function
  - Gaussian core with two power laws to describe the leading/trailing edge (double crystal-ball)
  - fitted to the signal MC samples for each mass



# Background modeling

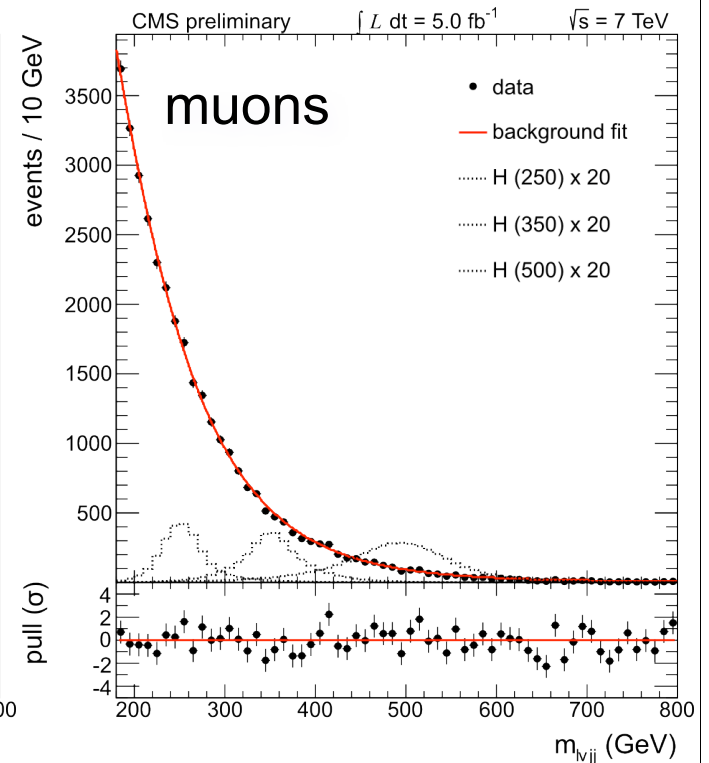
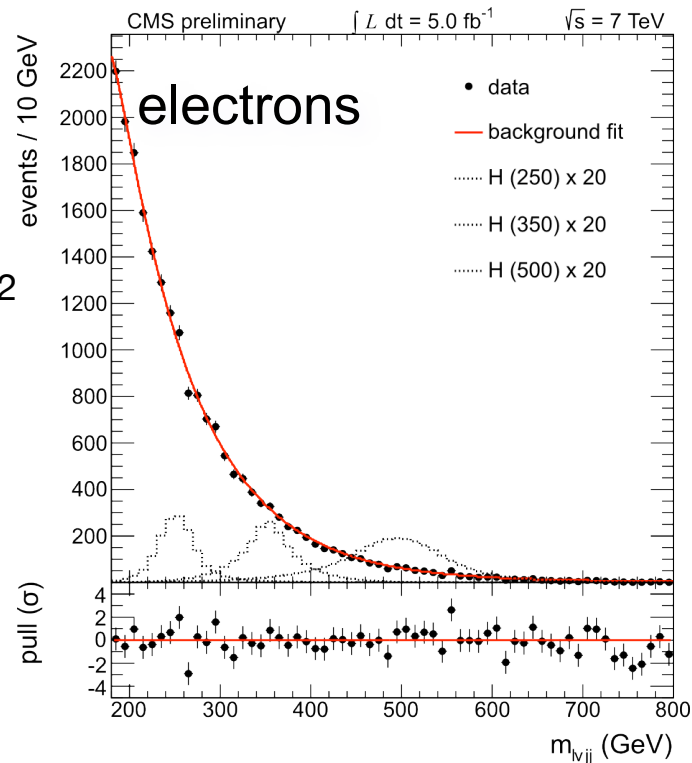
- An empirical attenuated power law shape is used to model the background

$$\mathcal{F}_B = \frac{1}{1 + e^{-(x-\mu)/\tau}} \cdot \left( \frac{500 + a}{x + a} \right)^n$$

- $\mu$ ,  $\tau$ ,  $a$  and  $n$  determined from data

**fit range:**  
180-800 GeV/c<sup>2</sup>

**bin size:**  
5 GeV/c<sup>2</sup>



# Systematics uncertainties

background model choice(*)	2-40%
inclusive cross-section	15-20%
gluon-fusion higgs line shape	10-30%
acceptance uncertainty due to pdfs	1-2%
luminosity	2.2%
jet energy scale and $E_T^{\text{miss}}$	2-3%
lepton efficiencies	1-2%
lepton trigger efficiencies	<1%
pile-up	<1%
PFMH <sub>T</sub> trigger efficiency (electron channel)	1-2%
b-tagging	< 1%

(\*) more on following slide

# Background model systematics

- We need to determine the systematic uncertainty related to choice of the background shape
- Our study:
  - We have a set of functions that describe the MC equally well.
  - We consider the differences with respect to the nominal functional form as the uncertainty on our choice.
- The background uncertainty is converted into an uncertainty on the signal.

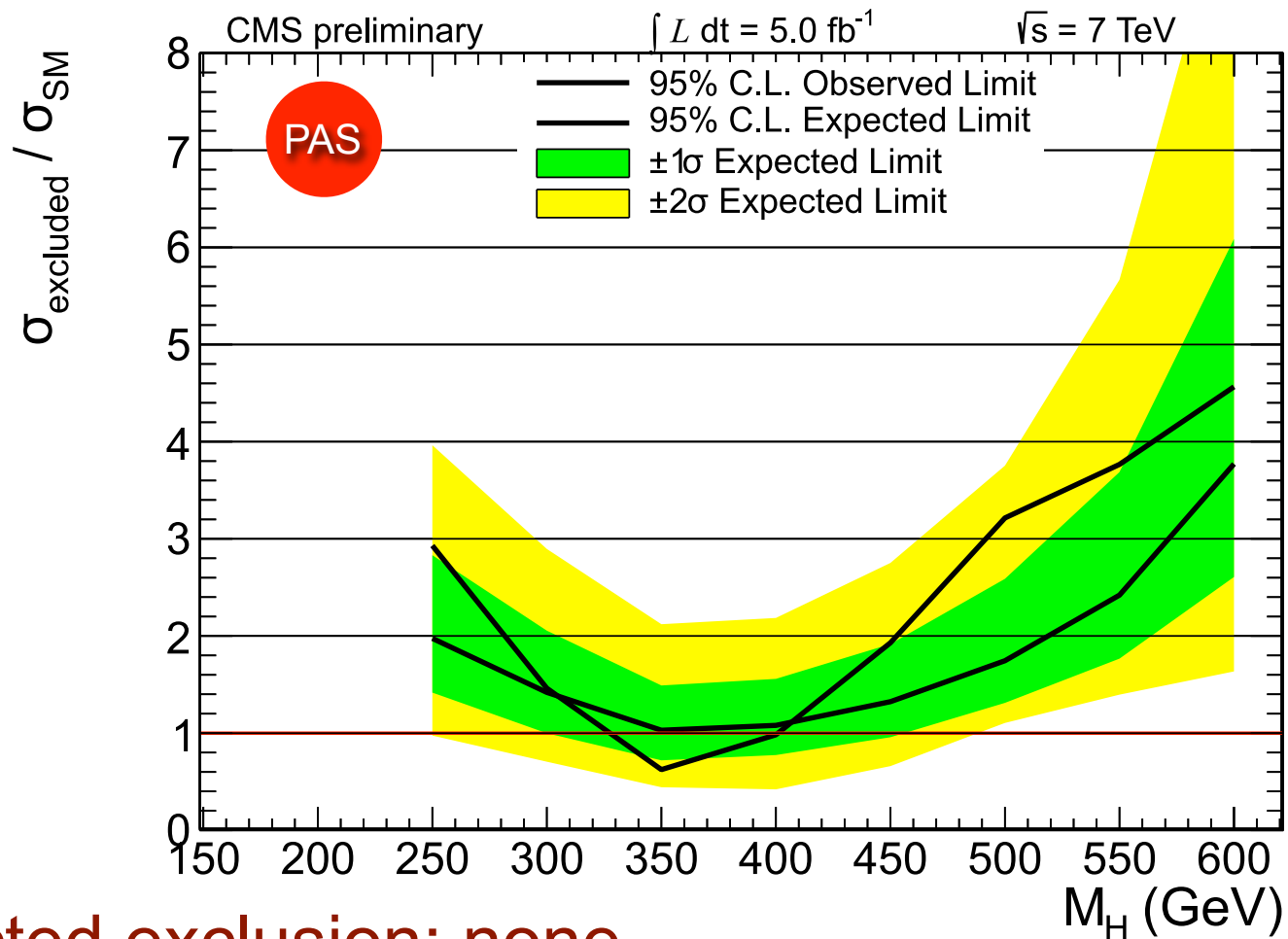
$$\mathcal{F}_B = \frac{1}{1 + e^{-(x-\mu)/\tau}} \cdot \left( \frac{500 + a}{x + a} \right)^n$$

$$\mathcal{F}_{B, \text{ alt}} = \frac{1}{1 + e^{-(x-\mu)/\tau}} \cdot \left( e^{ax^3 + bx^2 + cx} \right)$$

$$\mathcal{F}_{B, \text{ alt}} = \frac{1}{1 + e^{-(x-\mu)/\tau}} \cdot \left( e^{-\lambda_1 x} + N_2 e^{-\lambda_2 x} \right)$$

$m_H$	electrons unc.	muons unc.
250	13%	3.0%
300	17%	4.2%
350	14%	2.6%
400	4.5%	4.6%
450	4.3%	3.2%
500	14%	2.1%
550	24%	10%
600	38%	18%

# The limit



- Expected exclusion: none
- Observed exclusion: 325 – 400 GeV

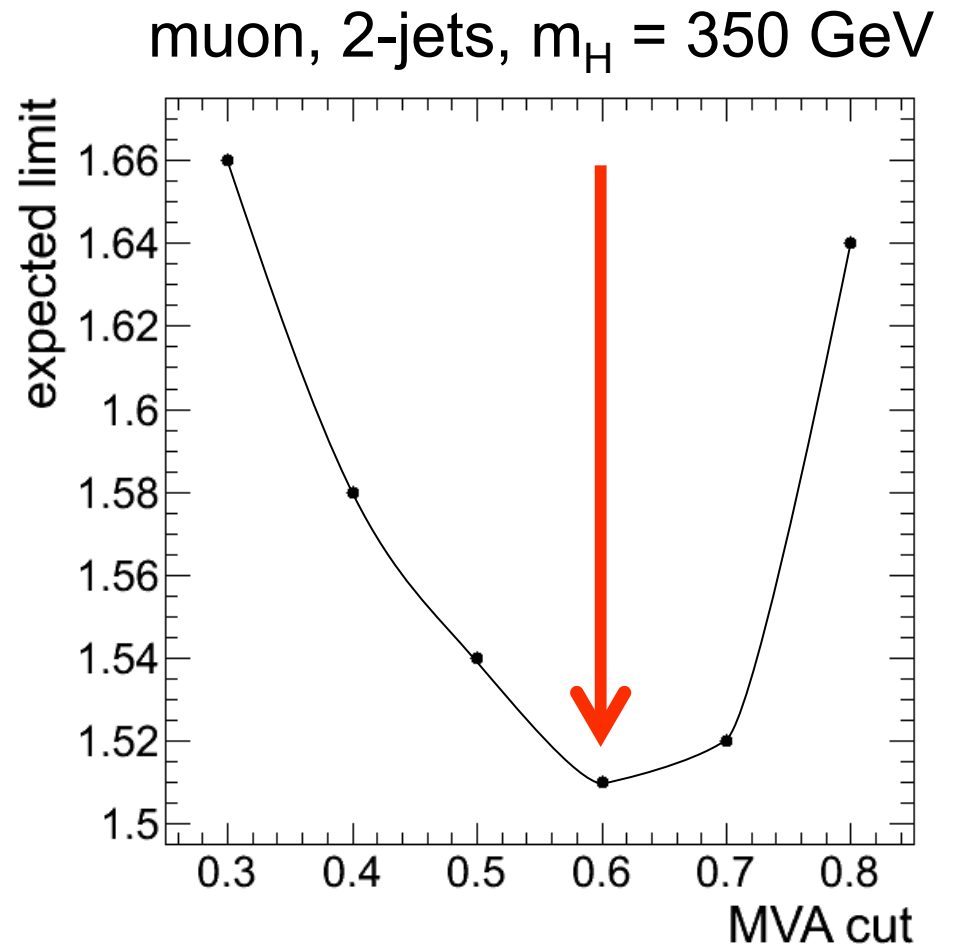
# MVA analysis

# Strategy

- **Goals**
  - Improve the sensitivity by significantly reducing the background and its inherent uncertainty.
  - Extend the mass reach of the analysis down as close to the kinematic edge as possible.
- **We exploit the kinematic information in the event to discriminate against  $W$ +jets production.**
  - Use TMVA package to build a **likelihood** discriminator
  - A separate discriminator for each of 12 mass points  $\times$  2 lepton flavors  $\times$  2 jet bins = 48 discriminators

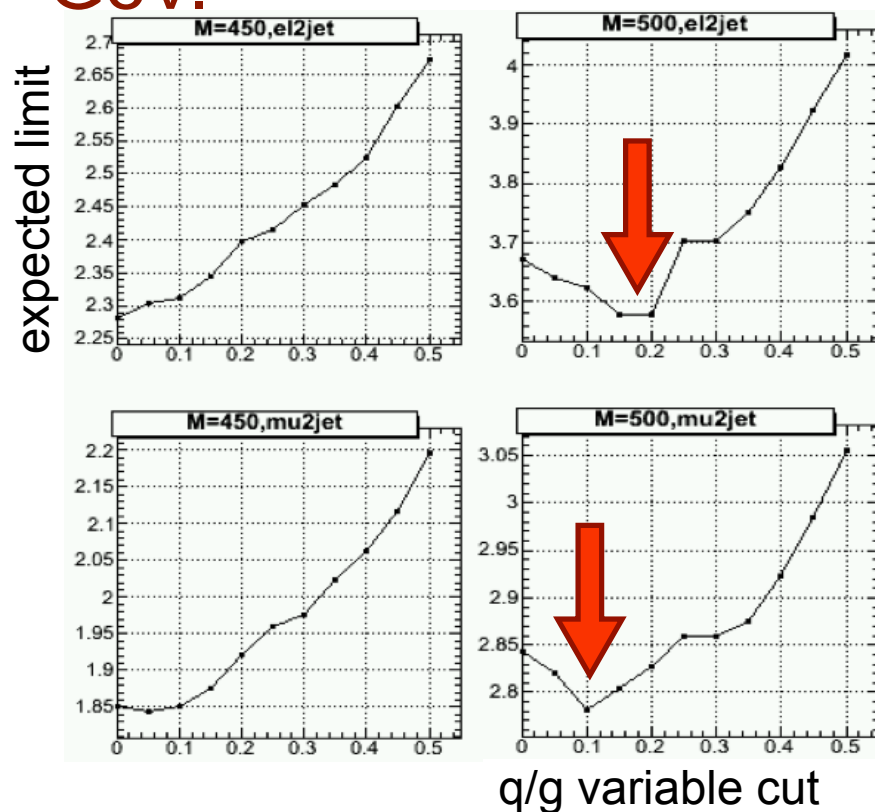
# MVA cut optimization

- We select the MVA cut value based on running the full asymptotic limit setting machinery and using the expected limit.
- Once the optimal cut is selected for each of the 48 analysis points they can be combined using the standard Higgs combination package.



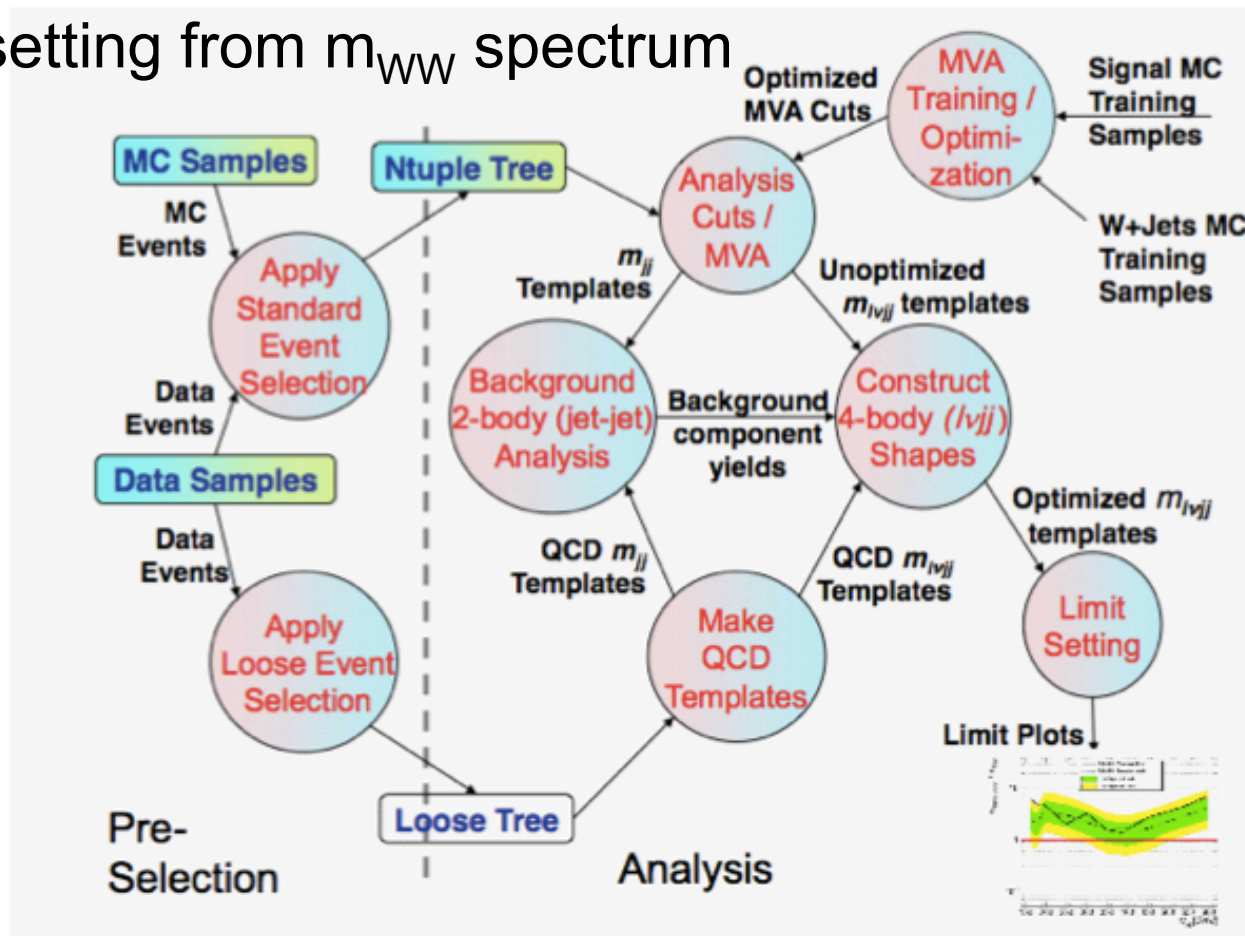
# Additional high mass cut

- In addition to the MVA cut we look at separating gluon-initiated jets from quark-initiated jets using a quark-gluon likelihood discriminator.
- Here again we optimize this cut based on the final expected limit.
- We don't find this cut to be advantageous for Higgs masses below 500 GeV.



# Fitting and limit setting

- The analysis has two major parts
  - Fit to the  $m_{jj}$  spectrum to determine the backgrounds
  - limit setting from  $m_{WW}$  spectrum



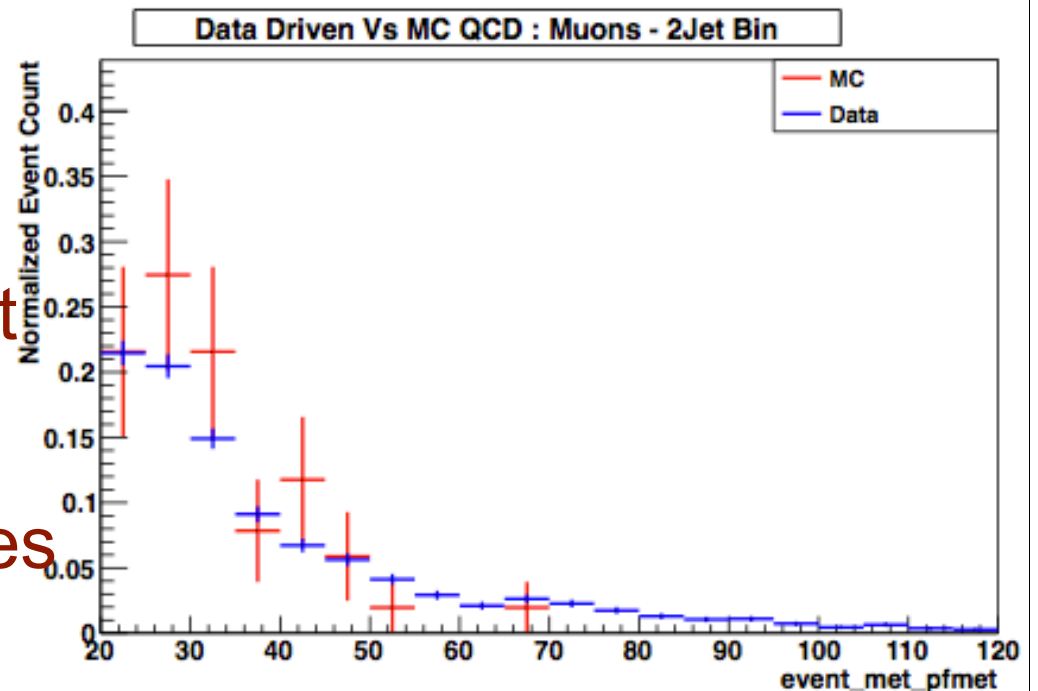
- The background yields in the fit are:

- Constrained to the best MC cross-section including error for all minor backgrounds.
- QCD constrained from the data.
- W+jets is unconstrained.

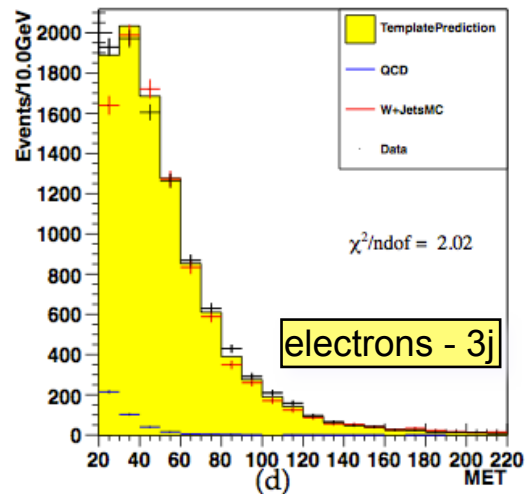
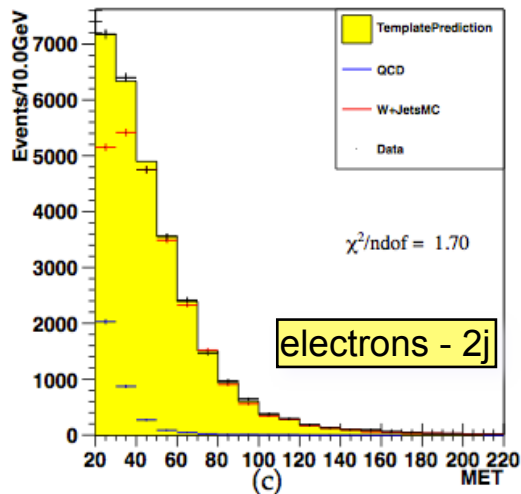
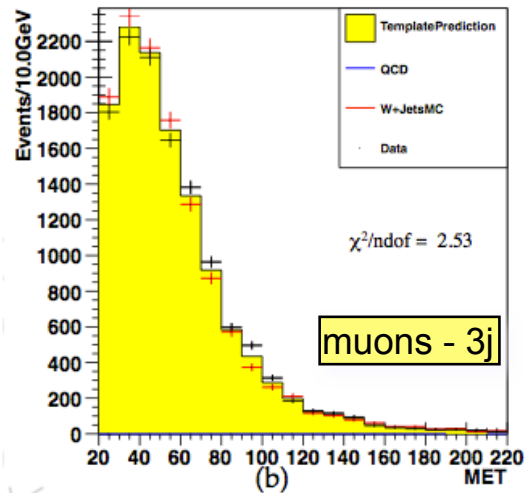
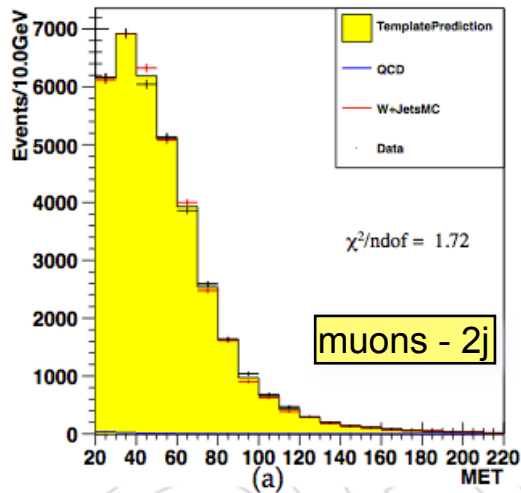
Process	Shape	External constraint on normalization
W+jets	MC/data	Unconstrained
Diboson	MC	Constrained: (NLO) $61.2 \text{ pb} \pm 10\%$ [47]
$t\bar{t}$	MC	Constrained: (NLO) $163 \text{ pb} \pm 7\%$ [48]
Single top	MC	Constrained: (NNLO) [49–51] $\pm 5\%$
Drell-Yan+jets	MC	Constrained: (NLO, $m_{ll} > 50 \text{ GeV}$ ) $3048 \text{ pb} \pm 4.3\%$ [47]
Multijet	data	Constrained: $E_T$ fit in data $\pm 50\%$ (100%) for electron (muon)

# Data driven QCD estimation

- We derive the QCD shape and normalization from the data.
  - invert the isolation requirements
  - relax ID requirements
  - relax the MET cut
- We can fit the MET distribution in data to get the normalization of the QCD contribution after accounting for differences due to the MET cut.
- The shape is also taken from this data as the MC is statistics starved.



# QCD $E_T^{\text{miss}}$ fit results



## QCD fractions in data

	2 jets	3 jets
electron	$6.2 \pm 0.4\%$	$2.1 \pm 0.7\%$
muon	$0.2 \pm 0.4\%$	$0.0 \pm 0.4\%$

statistical fit errors only!

## Uncertainty on QCD normalization

	2 jets	3 jets
electron	50%	50%
muon	>100%	>100%

# W+jets background

- The W+jets process is the dominant background.
  - For  $m_H \leq 180$  GeV, MC is used as the shape template, because statistics in this case are plentiful.
  - For higher masses MC statistics are much lower so we take an analytic approach.
- The shapes are inspired by MC but ultimately the parameters of the functions are determined from the fit to the data.

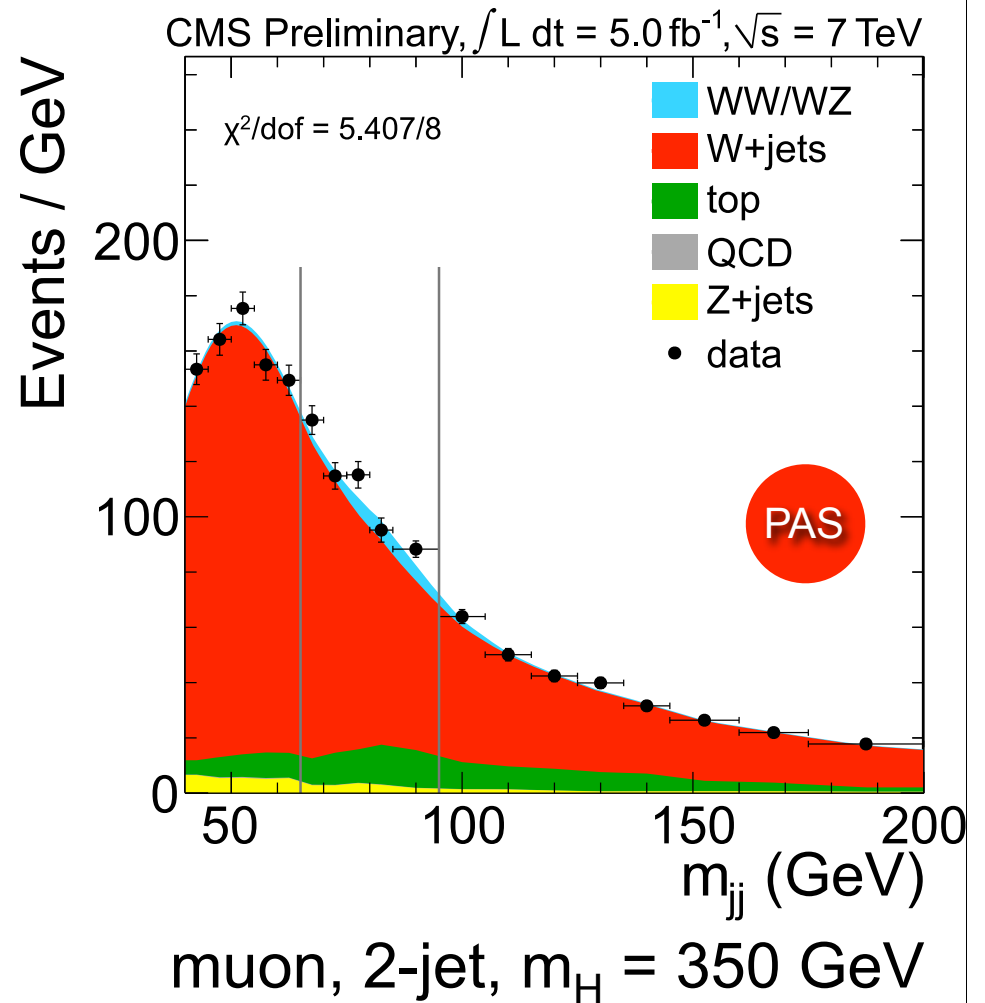
$$\mathcal{F}_{W+jets} = \text{erf}(m_{jj}; m_0, \sigma) \times \left[ (m_{jj})^{-\alpha - \beta \ln(m_{jj}/\sqrt{s})} \right]$$

$$\mathcal{F}_{W+jets, 2-jets}^{\text{low mass}} = \text{erf}(m_{jj}; m_0, \sigma) \times (m_{jj})^{-\alpha} \times e^{m_{jj}\tau}$$

$$\mathcal{F}_{W+jets, 3-jets}^{\text{low mass}} = (m_{jj})^{-\alpha - \beta \ln(m_{jj}/\sqrt{s})} \times e^{m_{jj}\tau}$$

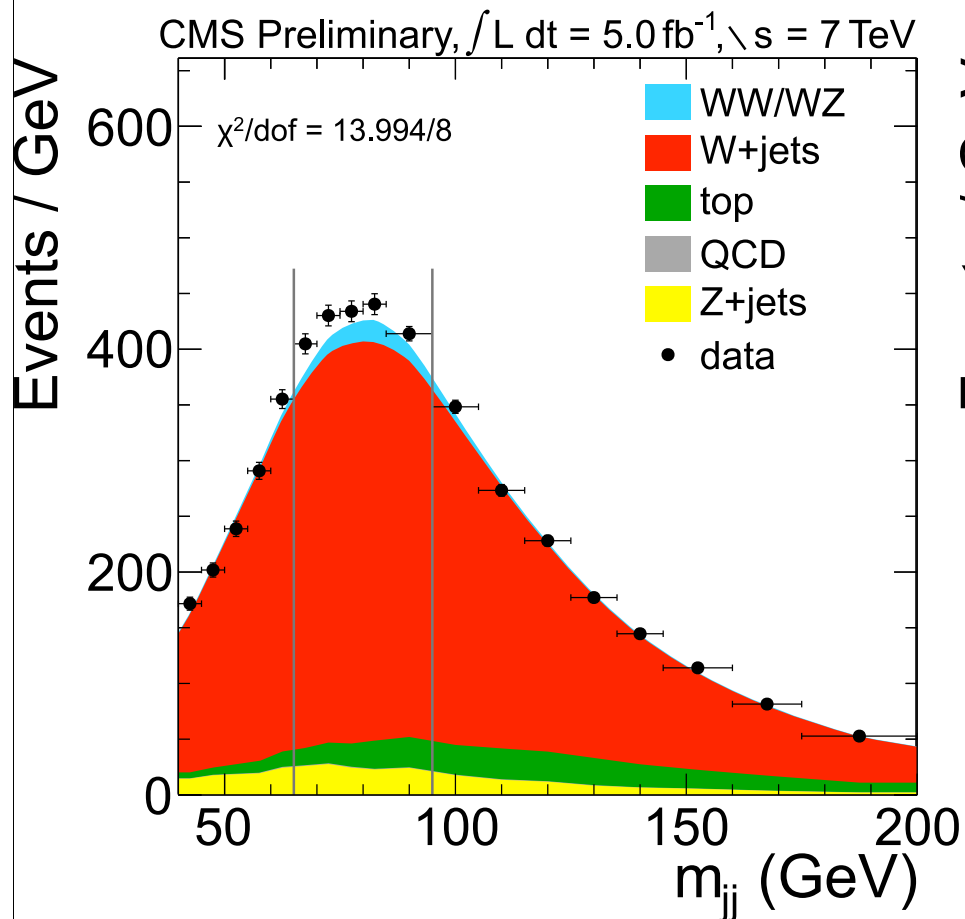
# The background composition

- **We exclude the region from 65 – 95 GeV excluded from the fit.**
- We see good agreement between the fitted composition and the data.
- The normalizations are extrapolated into the signal region of the fit and passed to the next stage for limit setting.

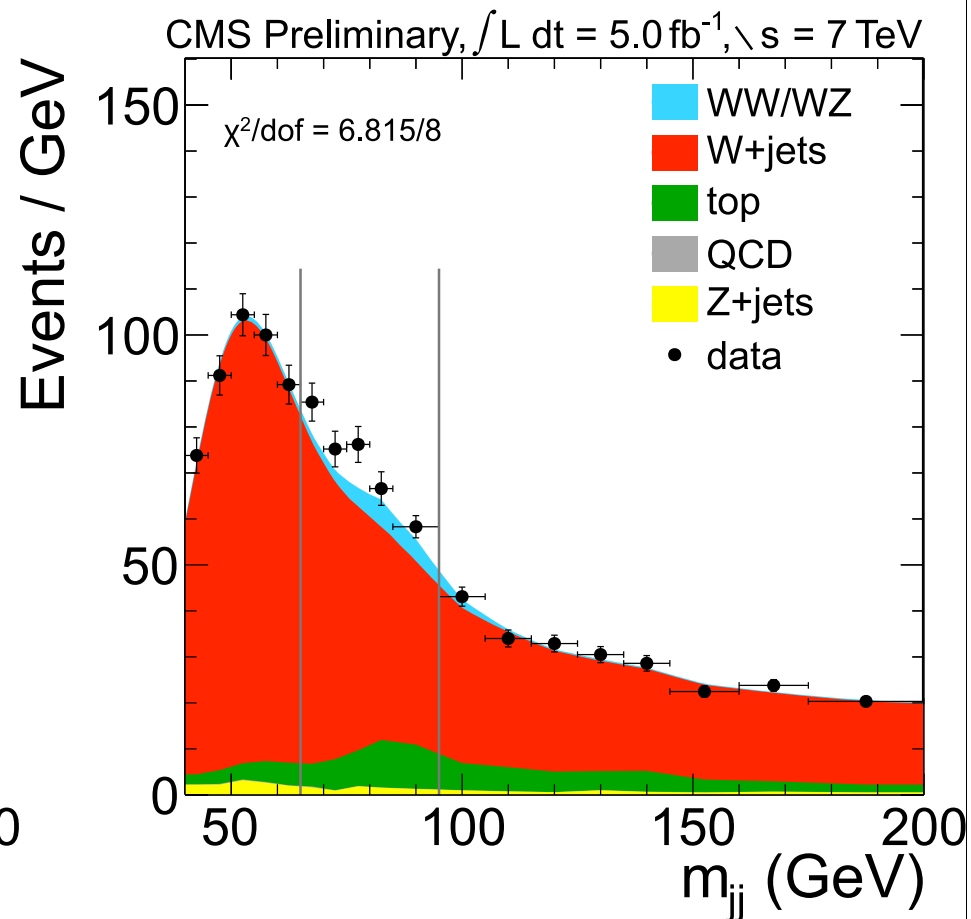


# Additional $m_{jj}$ examples

**muon, 2-jets,  $m_H = 190$  GeV**



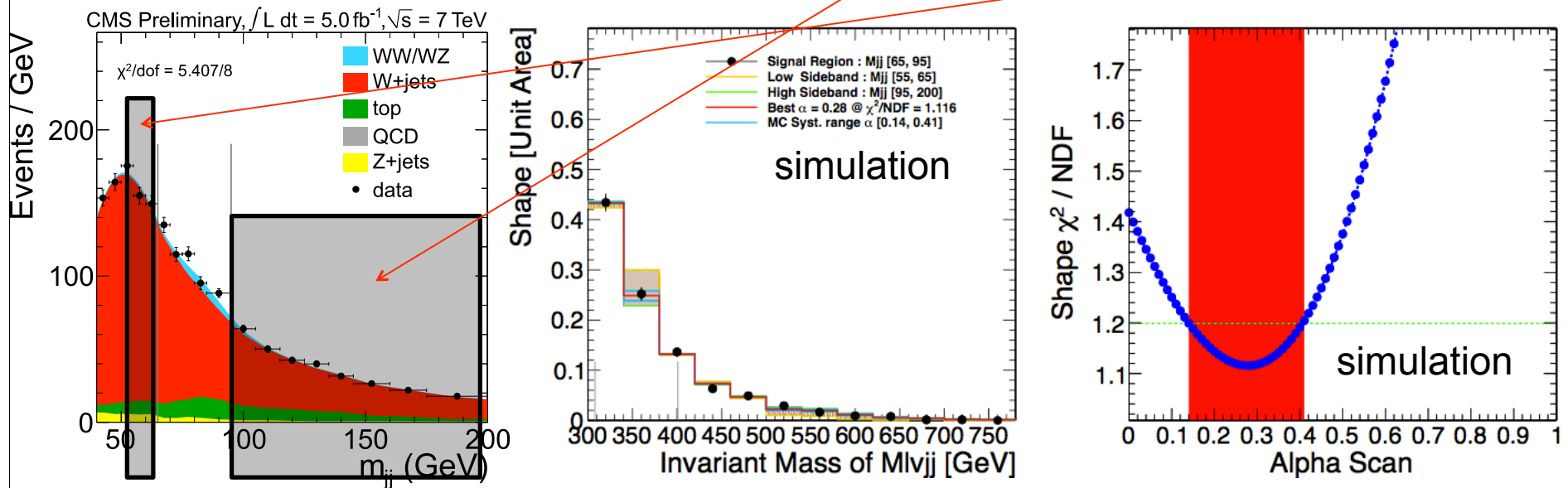
**muon, 2-jets,  $m_H = 500$  GeV**



# The $\ell\nu jj$ $W$ +jets shape

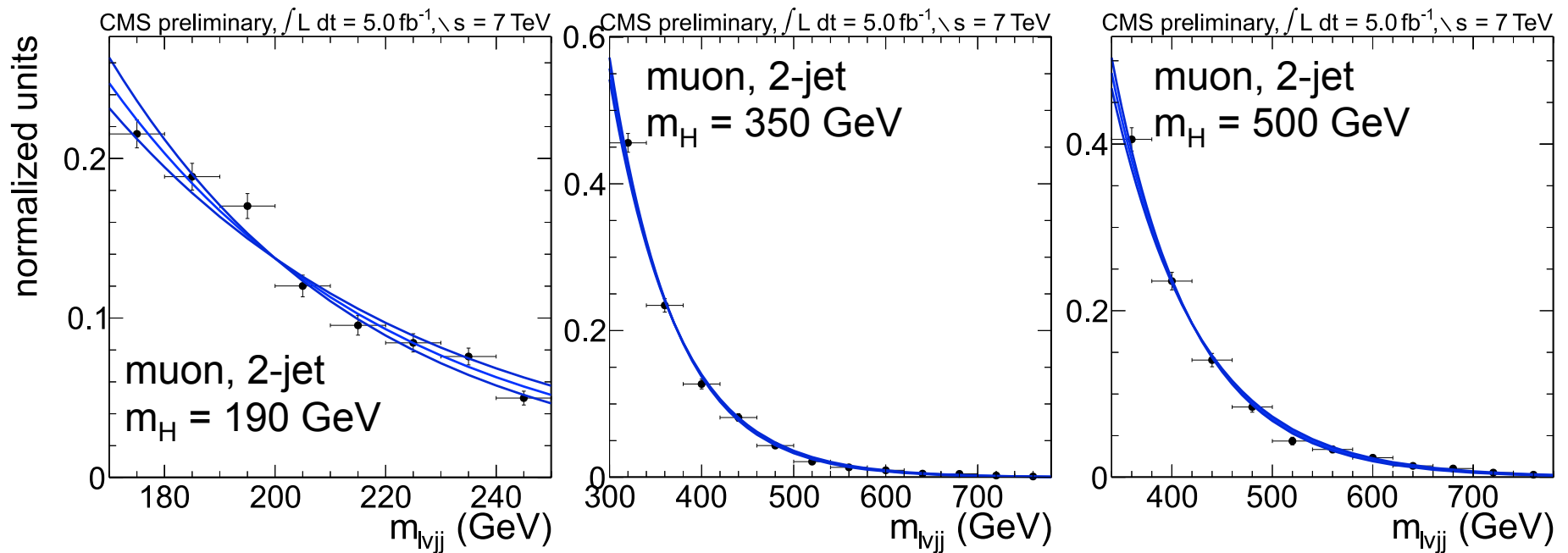
- We use the background-subtracted sidebands to derive a data driven  $W$ +jets shape.
  - separate  $\alpha$  for each of the 48 channels
  - $\alpha$  determined from MC
  - uncertainty on alpha from MC used as systematic error.

$$\mathcal{F}_{\ell\nu jj}^{W+jets} = (1 - \alpha)\mathcal{F}_{HSB} + \alpha\mathcal{F}_{LSB}$$

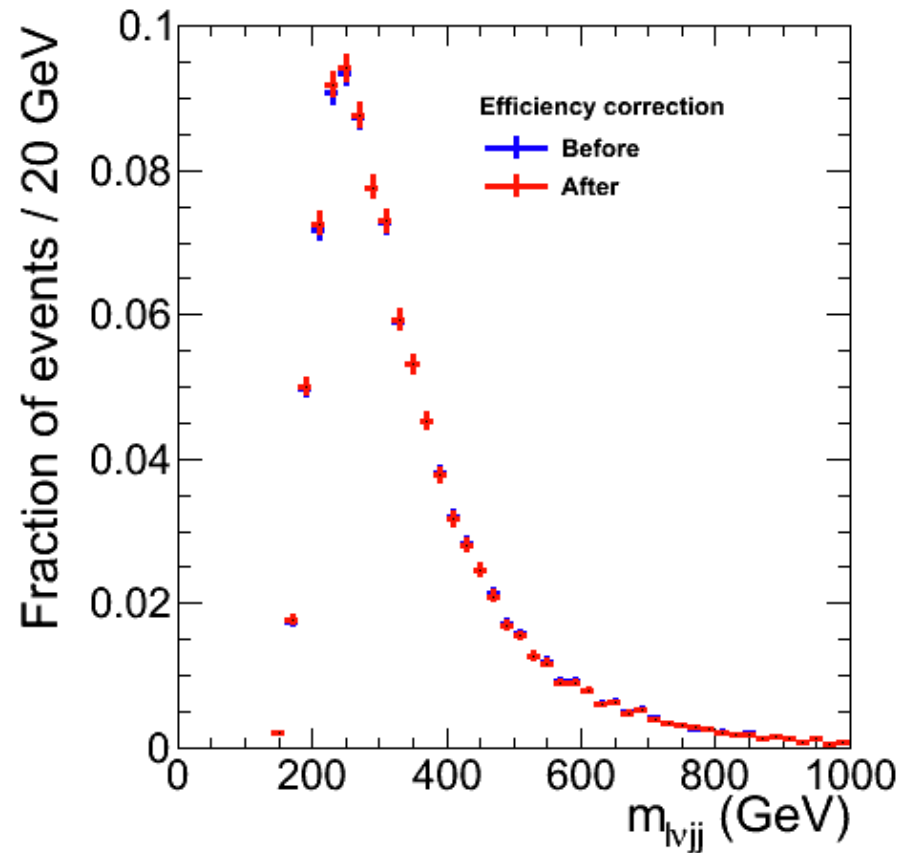
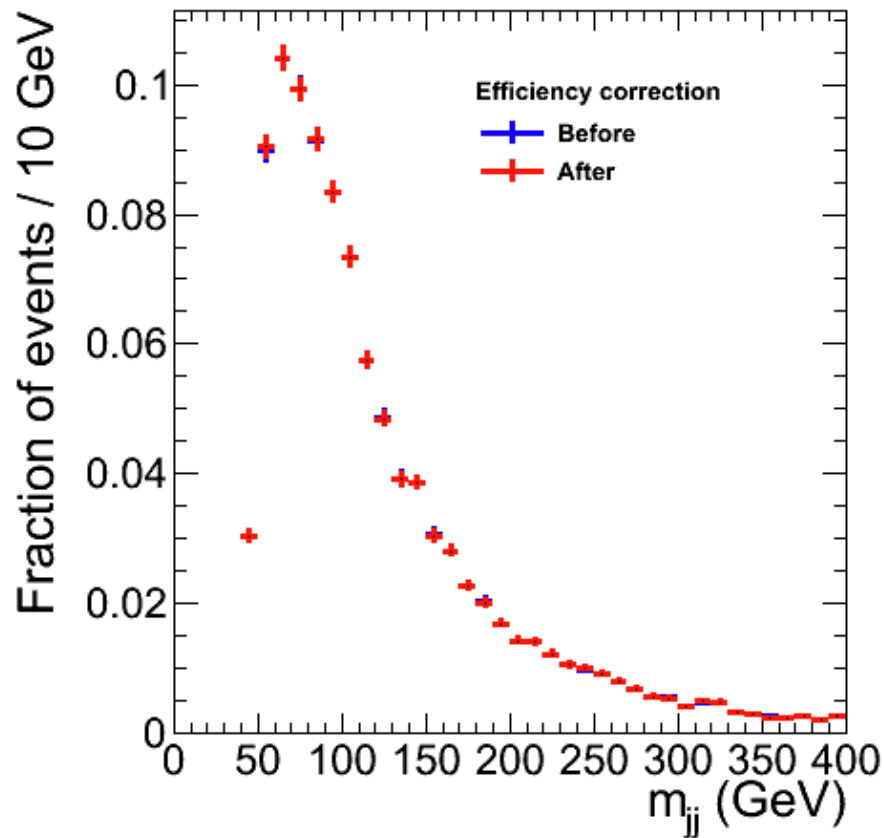


# The $\ell\nu jj$ $W$ +jets shape (II)

- The background-subtracted, alpha-combined sideband shape from data is smoothed using an exponential function.
  - The statistical uncertainty of the smoothing is combined with the uncertainty due to  $\alpha$  and used as a systematic error.

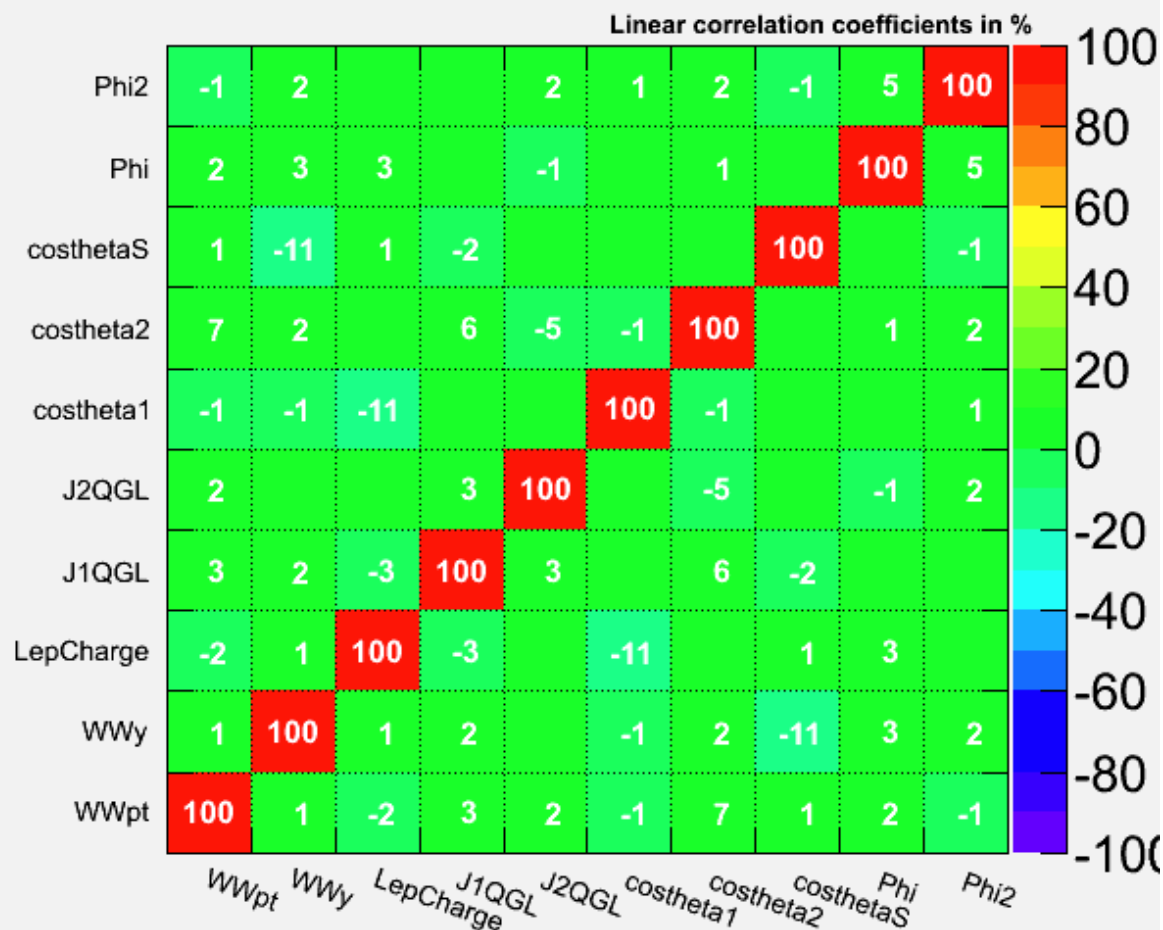


# Trigger effect on key distributions

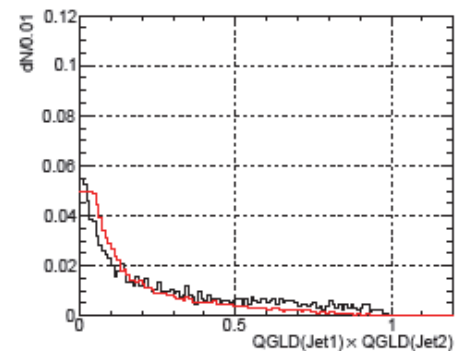
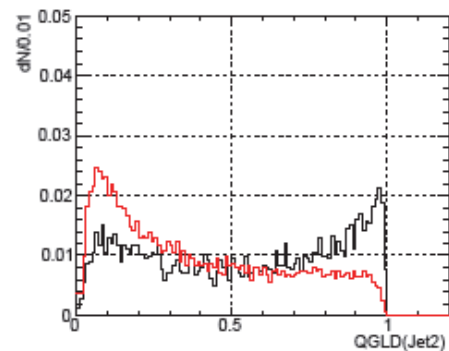
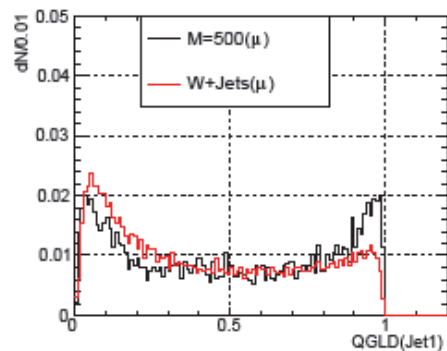
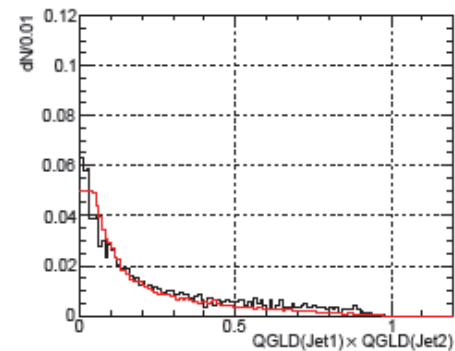
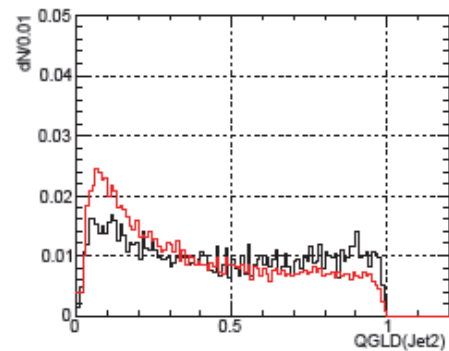
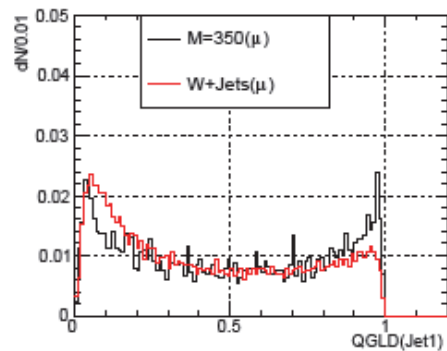
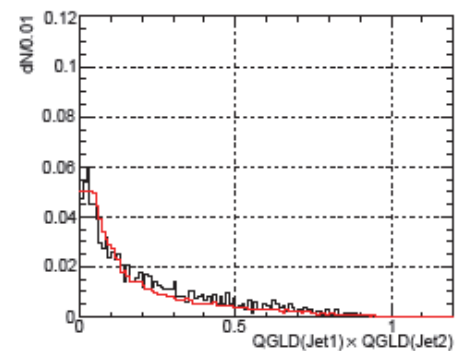
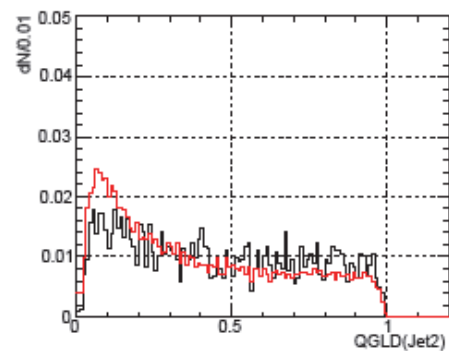
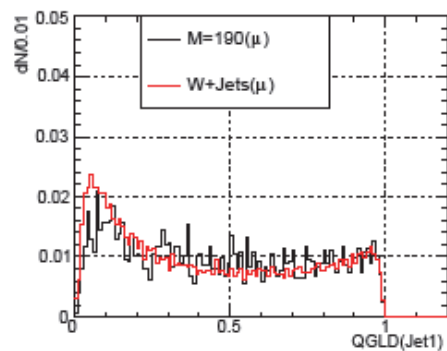


# MVA correlations

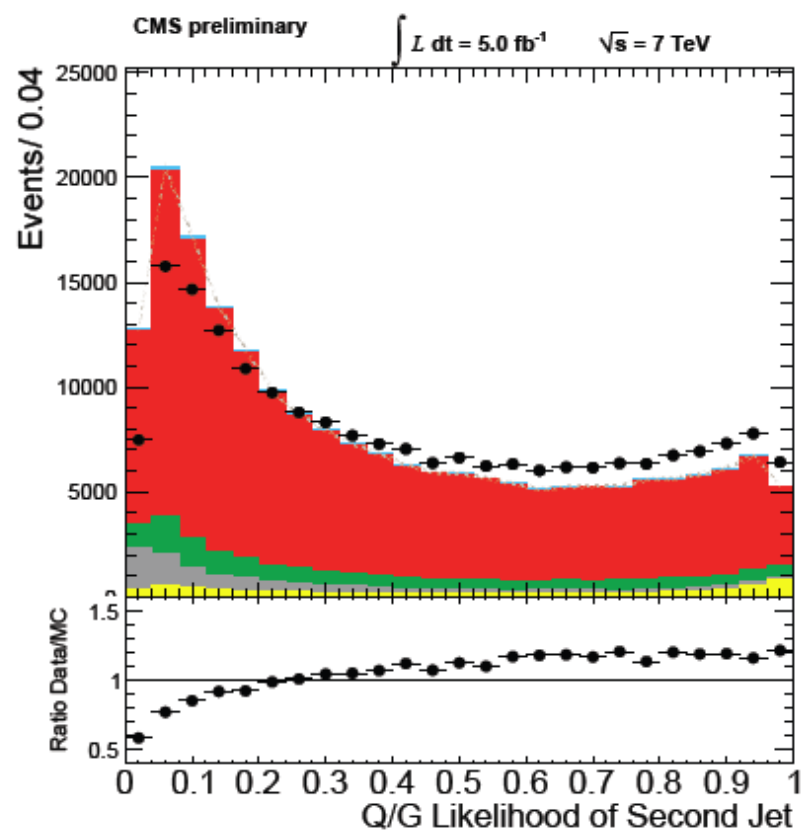
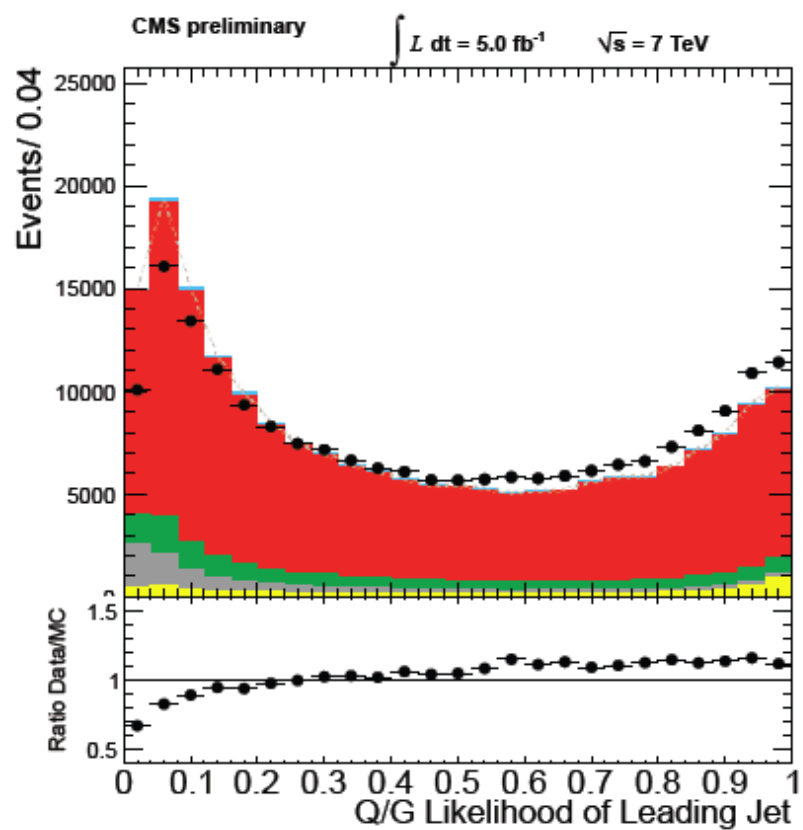
Correlation Matrix (signal)



# q/g likelihood



# q/g likelihood data / MC

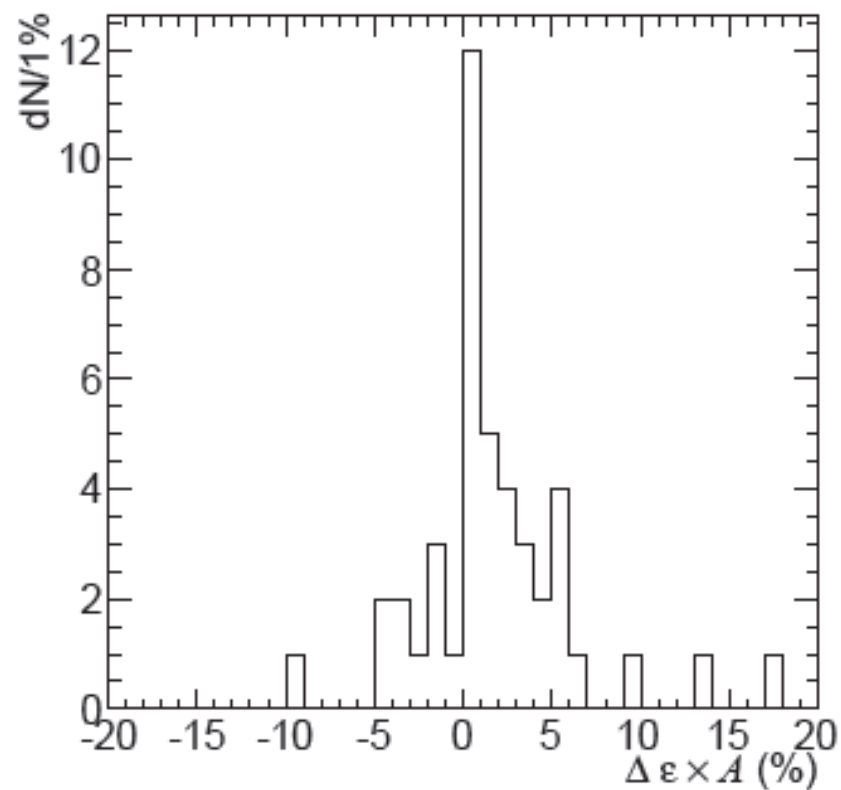
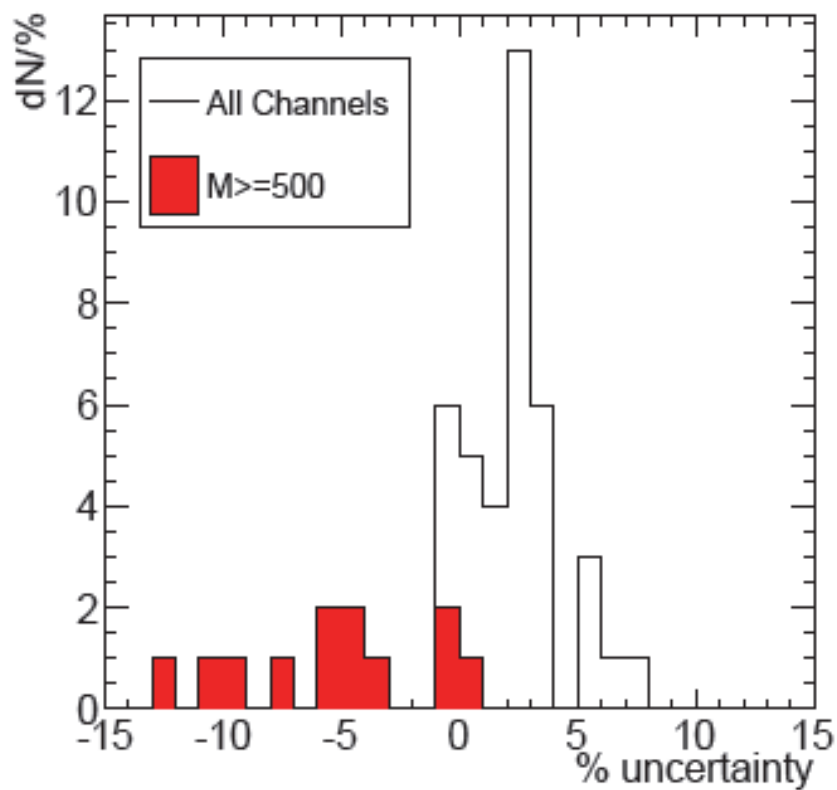


# Initial and final yields

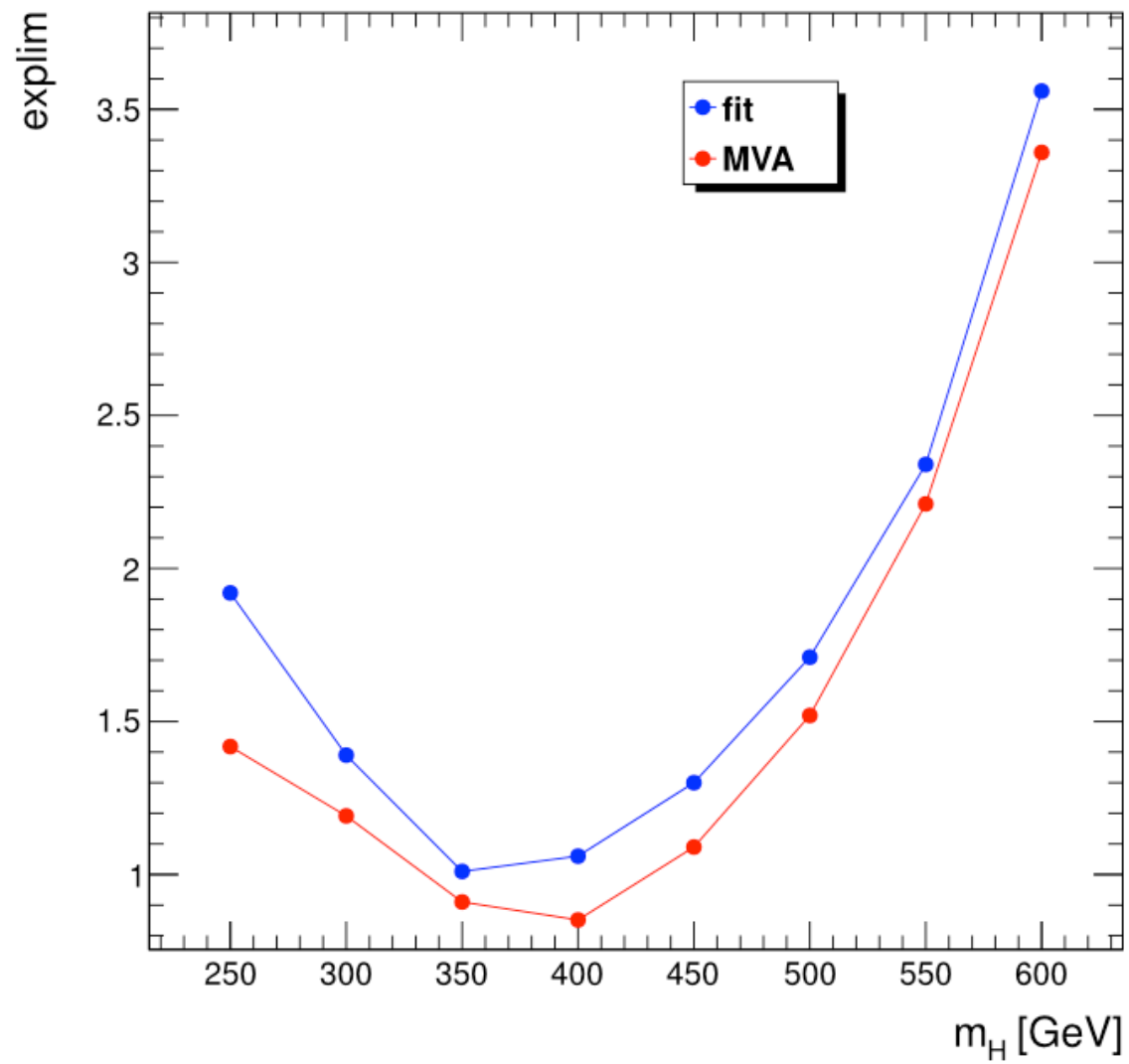
muon, 2-jets,  $m_H = 350$

<b>Parameter</b>	<b>Initial</b>	<b>Final</b>
nDiboson	270	269.93 +/- 9.18
nQCD	17.26	16.769 +/- 44.6
nSingleTop	200.8	200.82 +/- 10
nTTbar	908.5	908.81 +/- 63.5
nWjets	10282	8828.5 +/- 167
nZjets	305	305.01 +/- 13.1

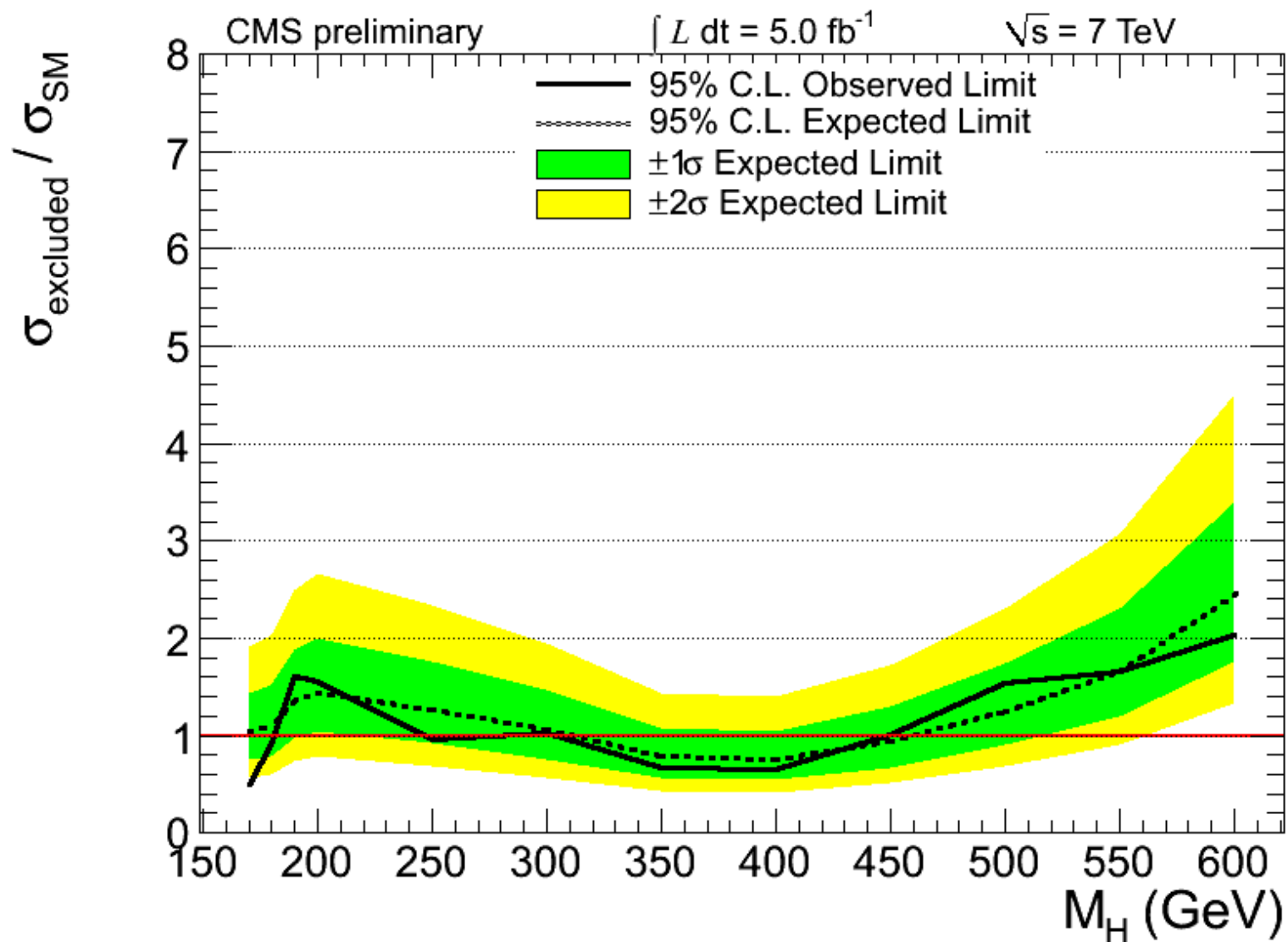
# Likelihood selection efficiency



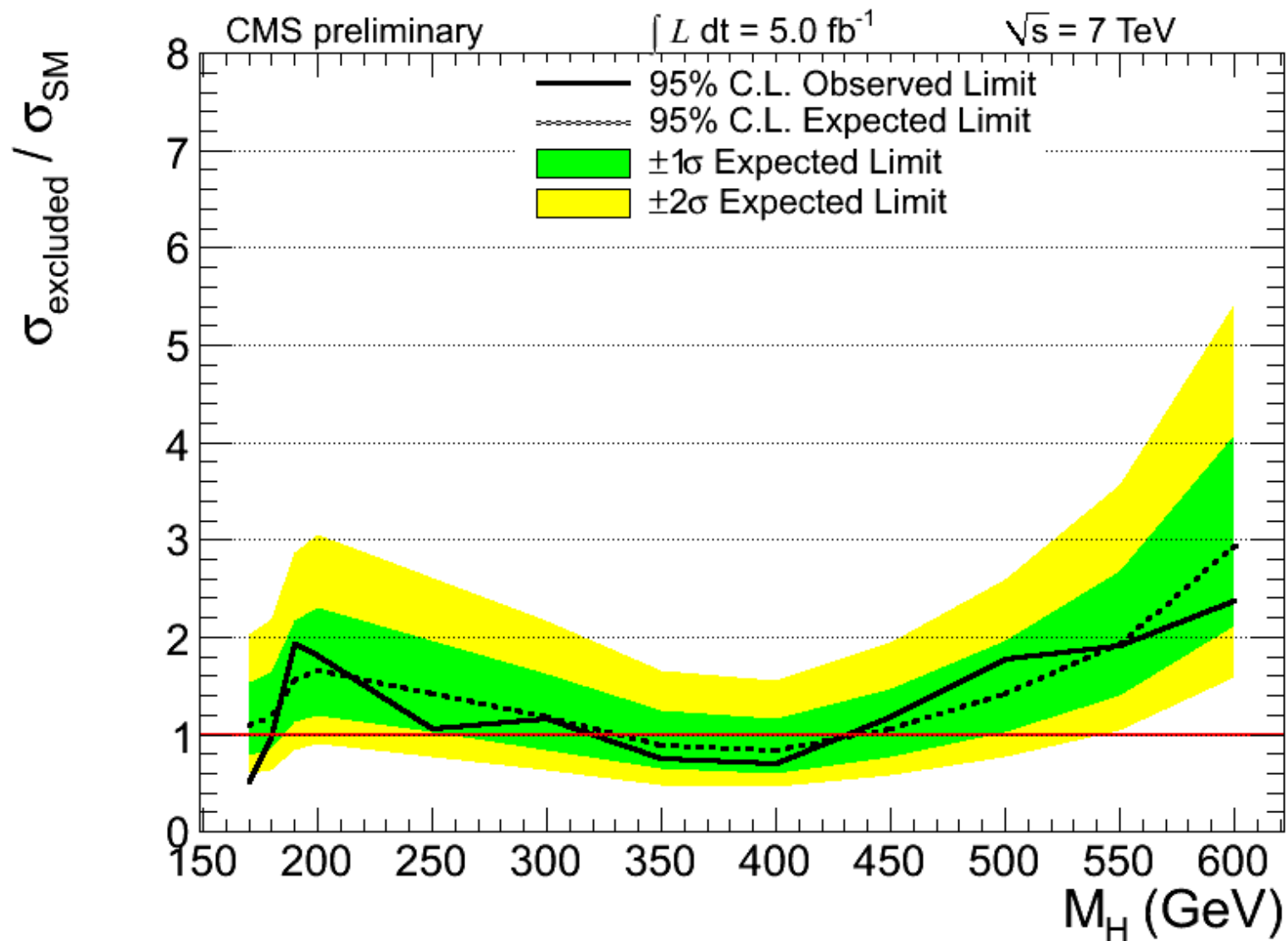
# Fit vs. MVA



# No systematic limit



# No shape systematic limit



# all systematic limit

