Searches for the Higgs Boson Decaying to Bottom Quarks in the CMS Detector

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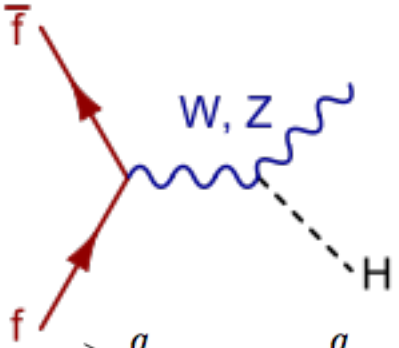
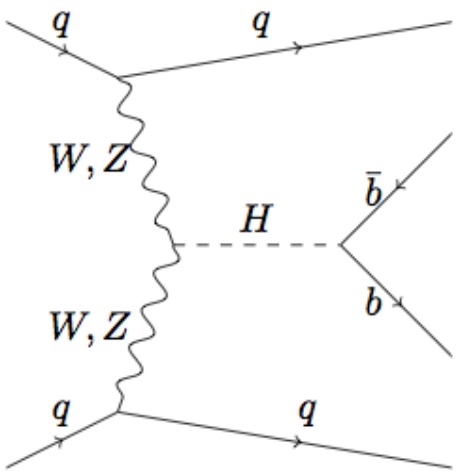
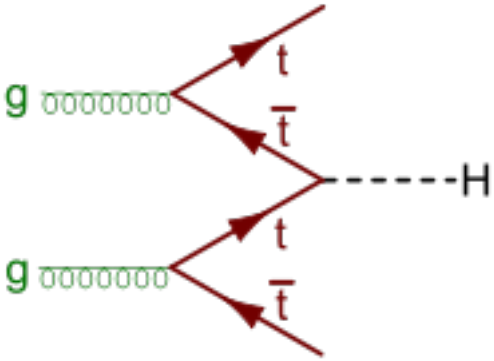
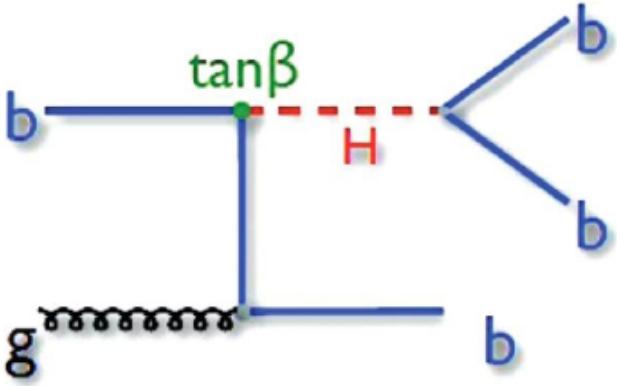
Overview

- H → bb in the Standard Model
  - VH → Vbb (5+19 fb^{-1})
  - VBF H → bb (19 fb^{-1})
  - ttH → ttbb (5 + New 19 fb^{-1})
- … And Beyond
  - bH+X, H → bb (2.7 - 4.8 fb^{-1})

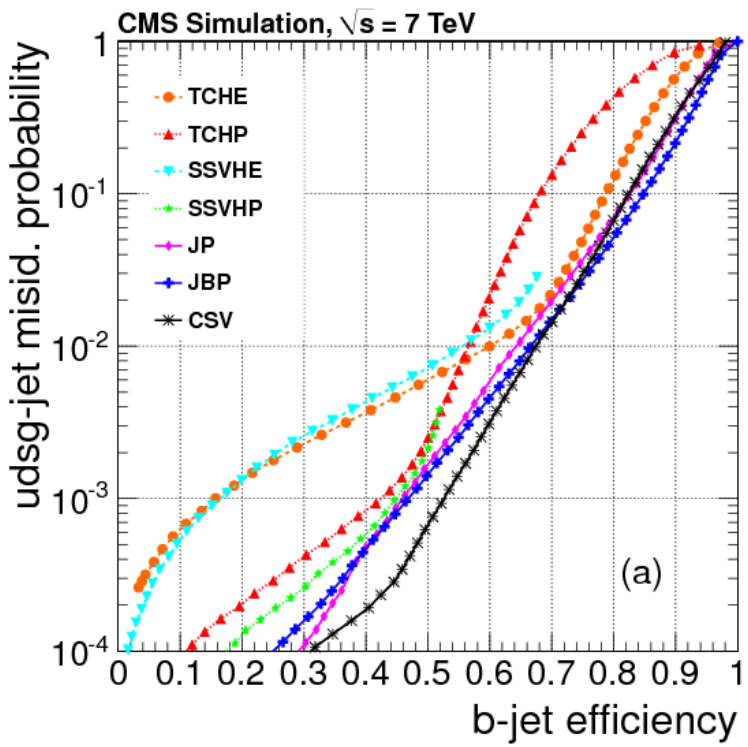


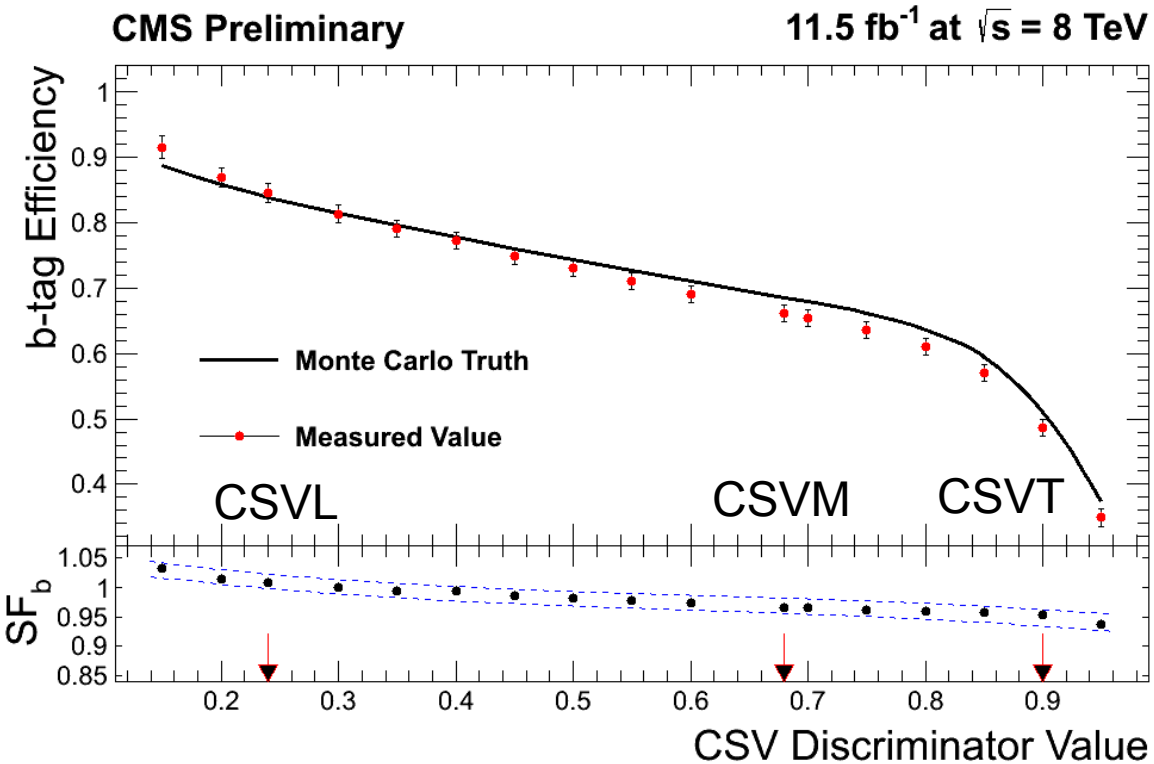






B-Tagging in CMS

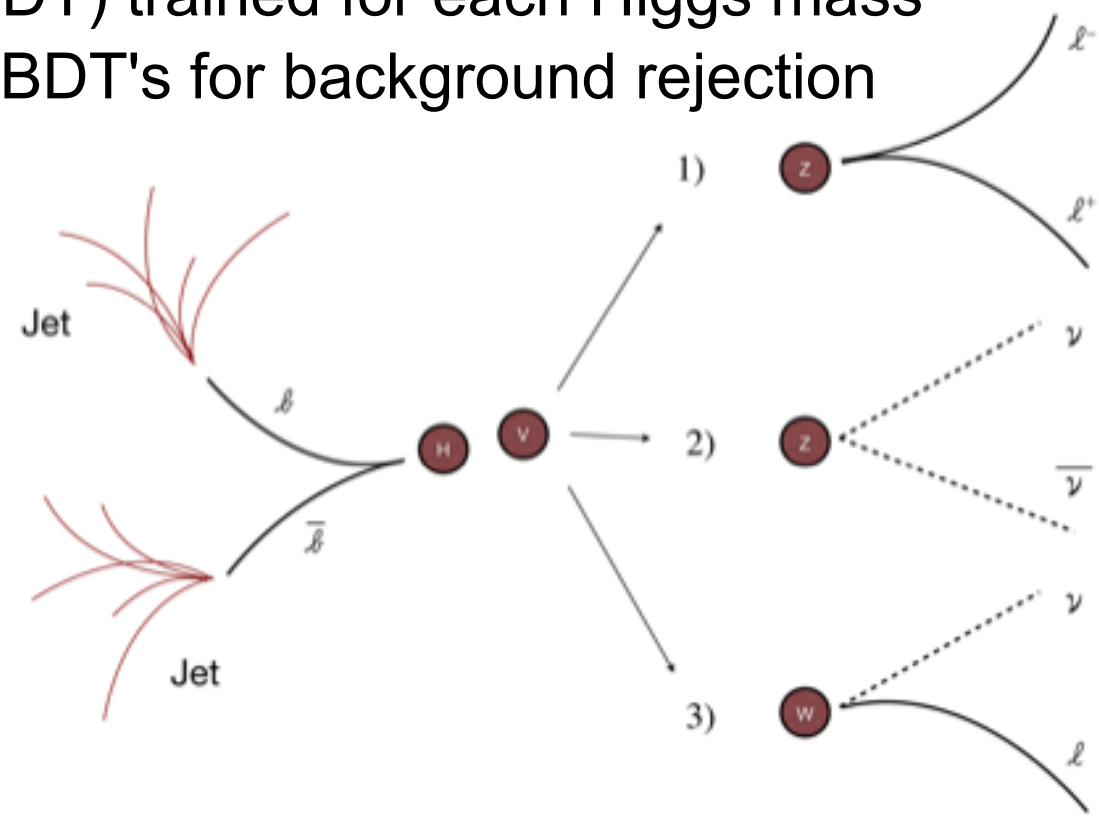




- Jets: particle flow inputs to anti-kT algorithm, R = 0.5
- B-tagging: Combined Secondary Vertex (CSV) discriminant
  - Explicitly reconstructed secondary vertex information
  - “Pseudovertex”: tracks with high impact parameter significance
  - Individual track IP's, jet and track kinematics

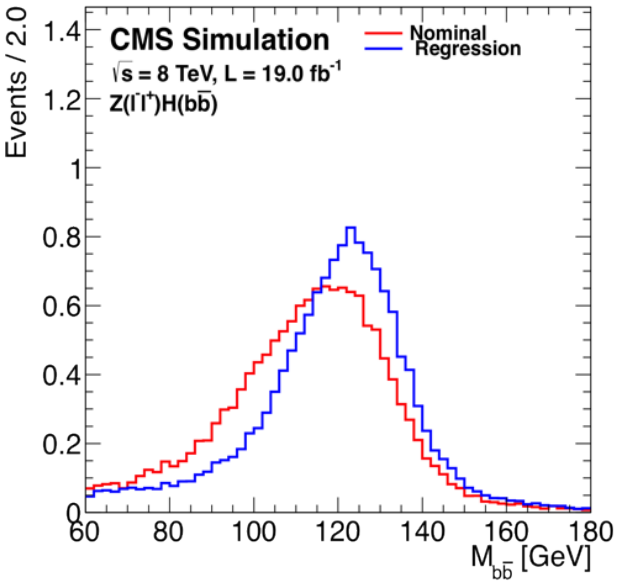
Analysis Strategy: VH → Vbb

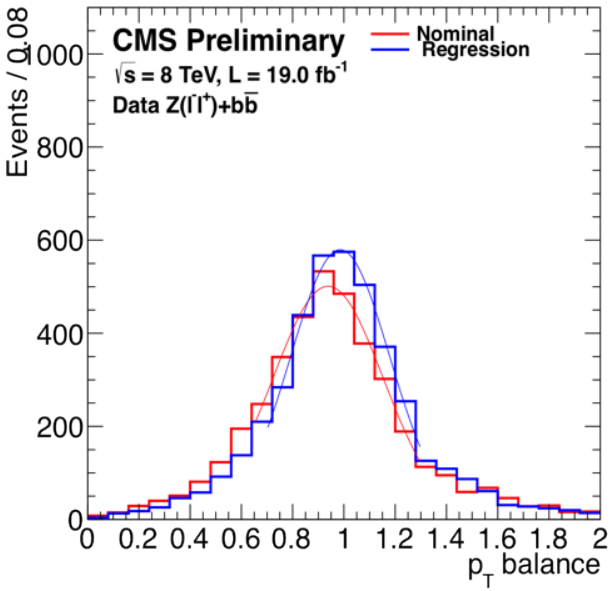
- Categorize by vector boson (V) decay: Z(νν), Z(ℓℓ), W(ℓν), W(τν)
- Require 2 b-tagged jets, leptons & MET as appropriate
- Bin in pT(V): signal-to-background increases at high pT
- Multivariate b-jet regression to improve bb mass resolution
- Boosted Decision Tree (BDT) trained for each Higgs mass
  - Additional specialized BDT's for background rejection
- Likelihood fit to BDT distributions
- Backgrounds: tt, V+bb, V+b, V+udscg, QCD, single top, VZ
- Dominant systematics: b-tagging, MC statistics, data-driven background normalization



B-Jet Regression

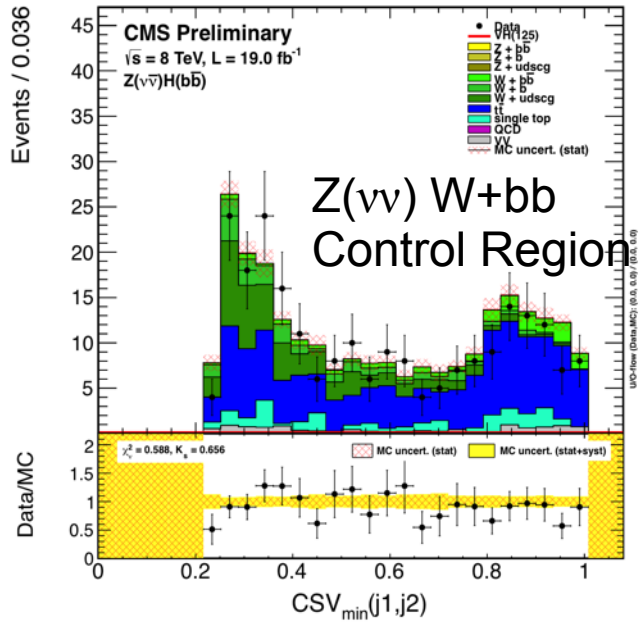
- Additional correction of b jet to parton energy, using BDT, to improve mass resolution
- Trained on simulated H → bb events
- Variables used:
  - Jet kinematics
  - Charged/neutral fraction, lead track pT, etc.
  - Vertex properties
  - Soft lepton properties
  - MET – Z(ll) only
- Improves Higgs mass resolution by ~15%
  → analysis sensitivity improved by 10-15%

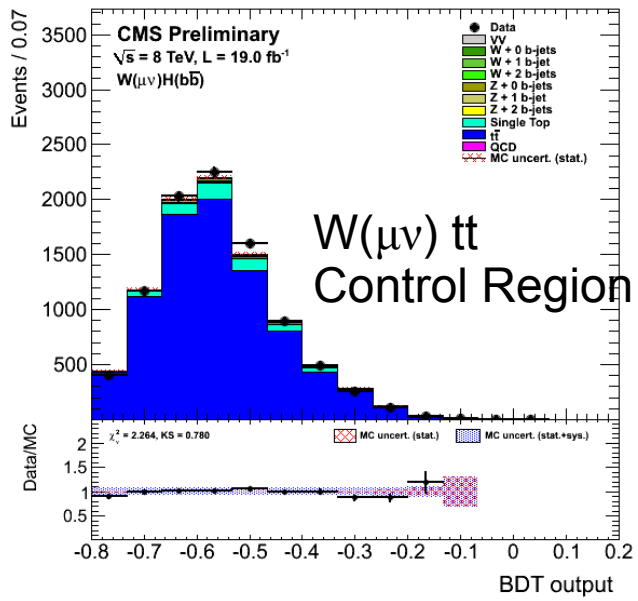


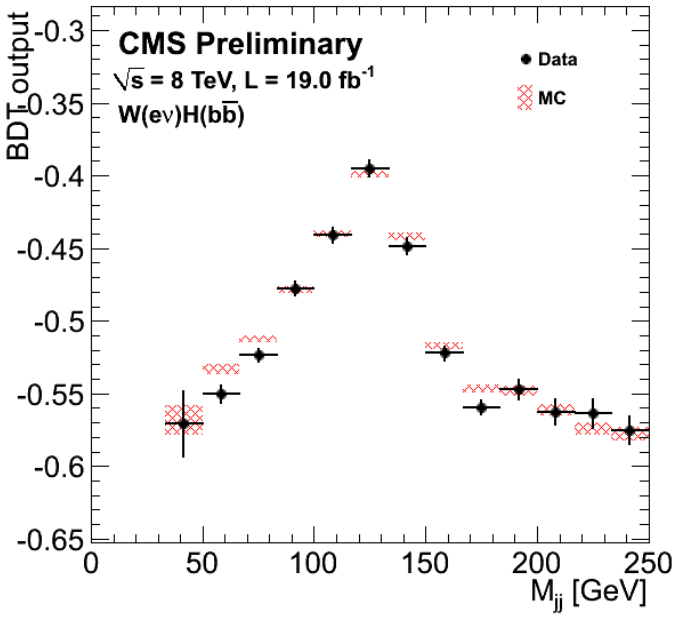


Boosted Decision Tree

- Trained for each channel and each Higgs mass
- Inputs
  - Higgs candidate jet pT and CSV
  - Dijet properties: ***m(jj)***, pT(jj), dEta(jj), dR(jj), color pull angle
  - Additional jets: Naj, max CSV, closest dR to Higgs candidate
  - dPhi(V,H), dPhi(E_T^{miss},j)
  - Angular variables of VH system

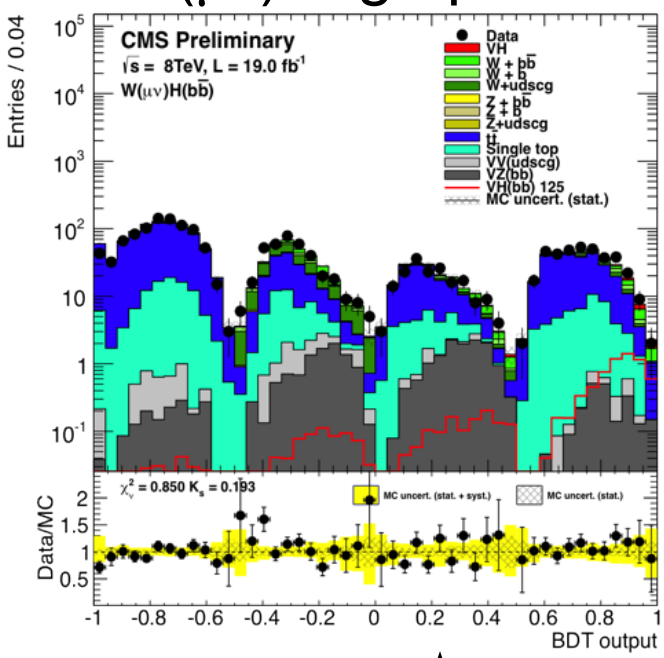




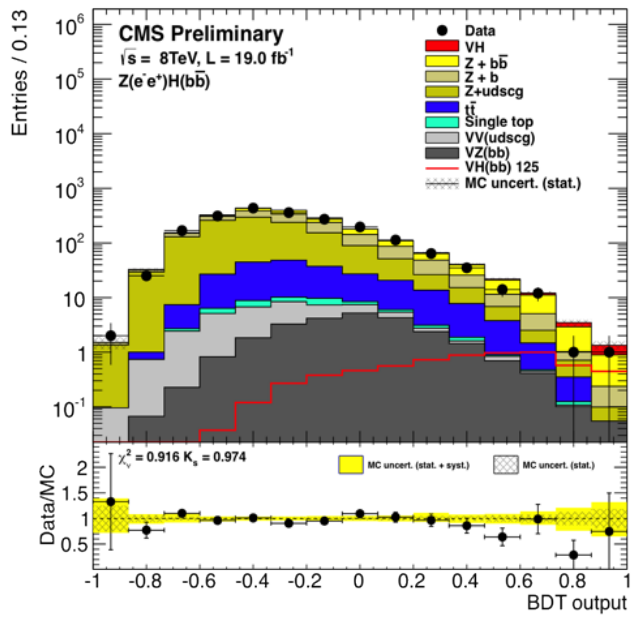


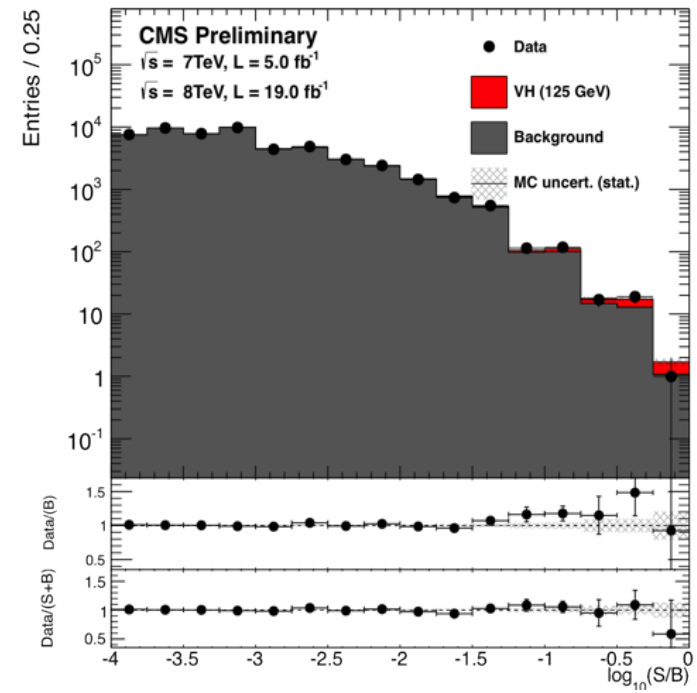
Signal Extraction

W(μν) High pT



Z(ee) High pT





"Fails" anti-tt MVA

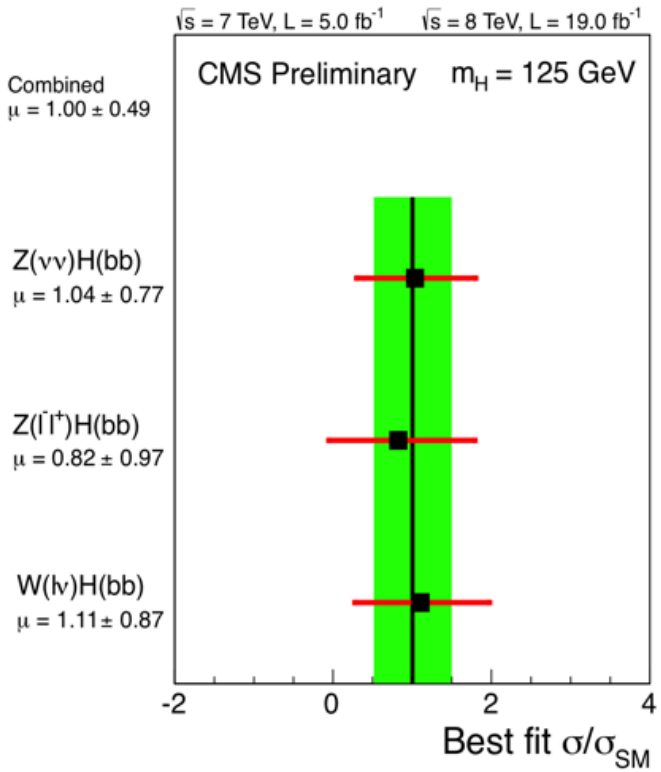
"Fails" anti-V+jets MVA

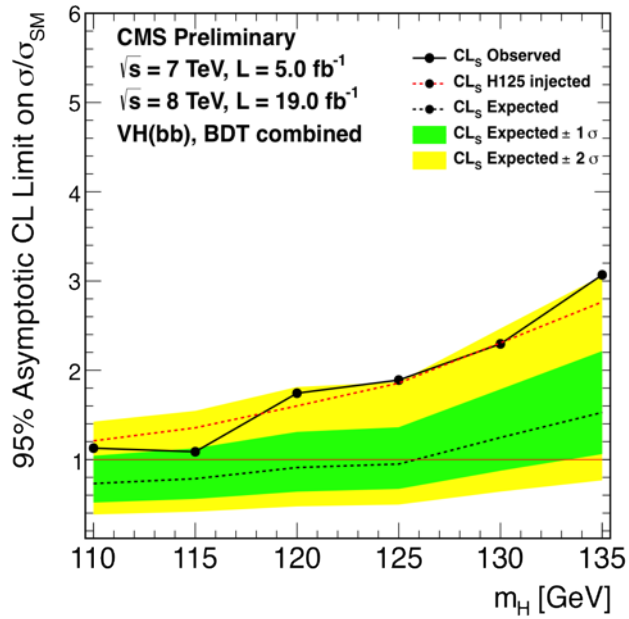
"Fails" Anti-VV MVA

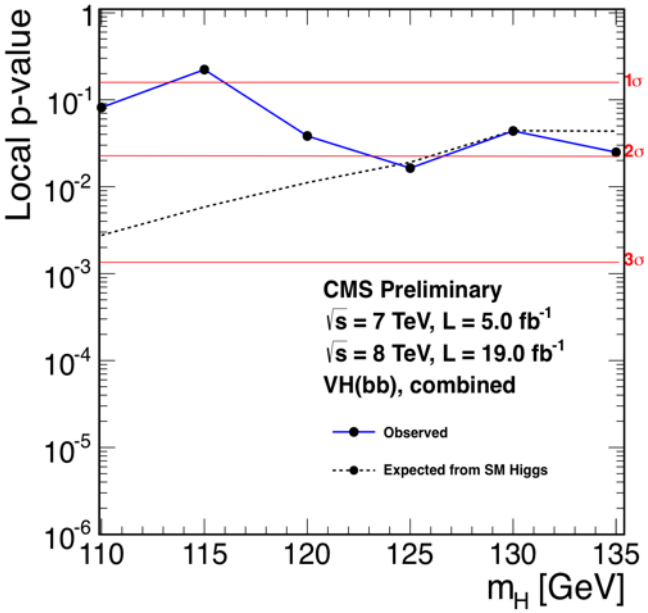
"Passes" all Background-Specific MVA's

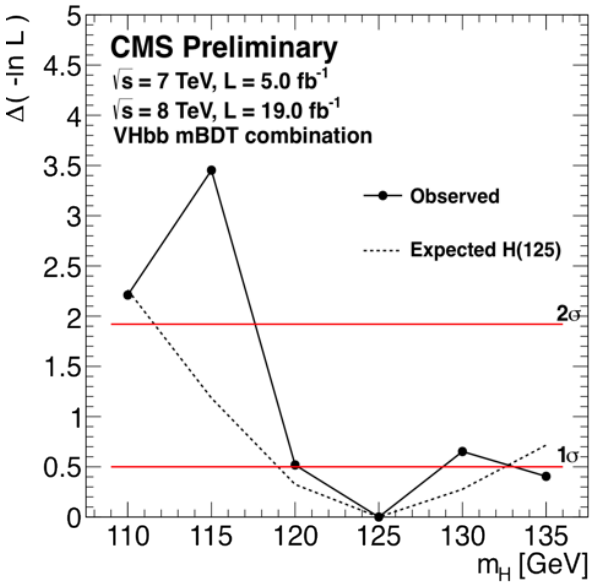
- Simultaneous fit in all 14 signal regions
  - Z(νν): 3, Z(ℓℓ): 4, W(ℓν): 6, W(τν): 1
- Visualize fit by summing bins by log(S/B)

VH → Vbb Results





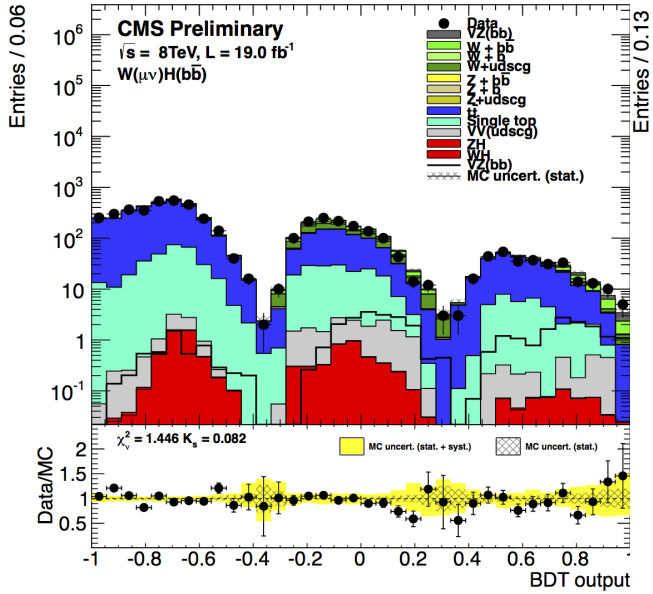


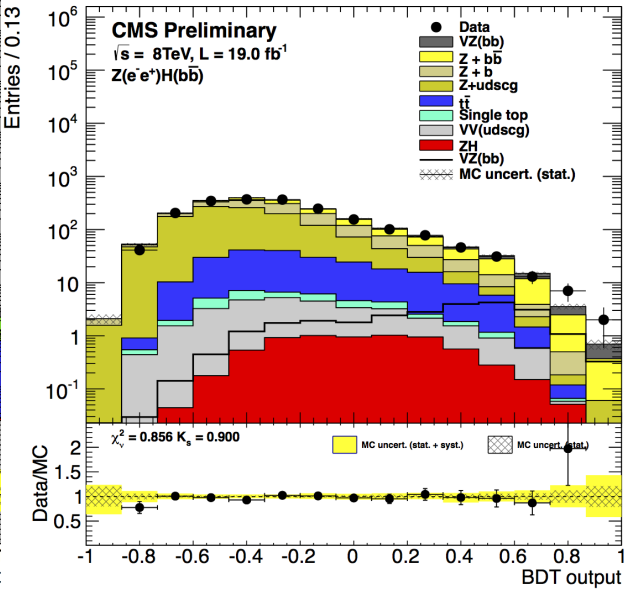


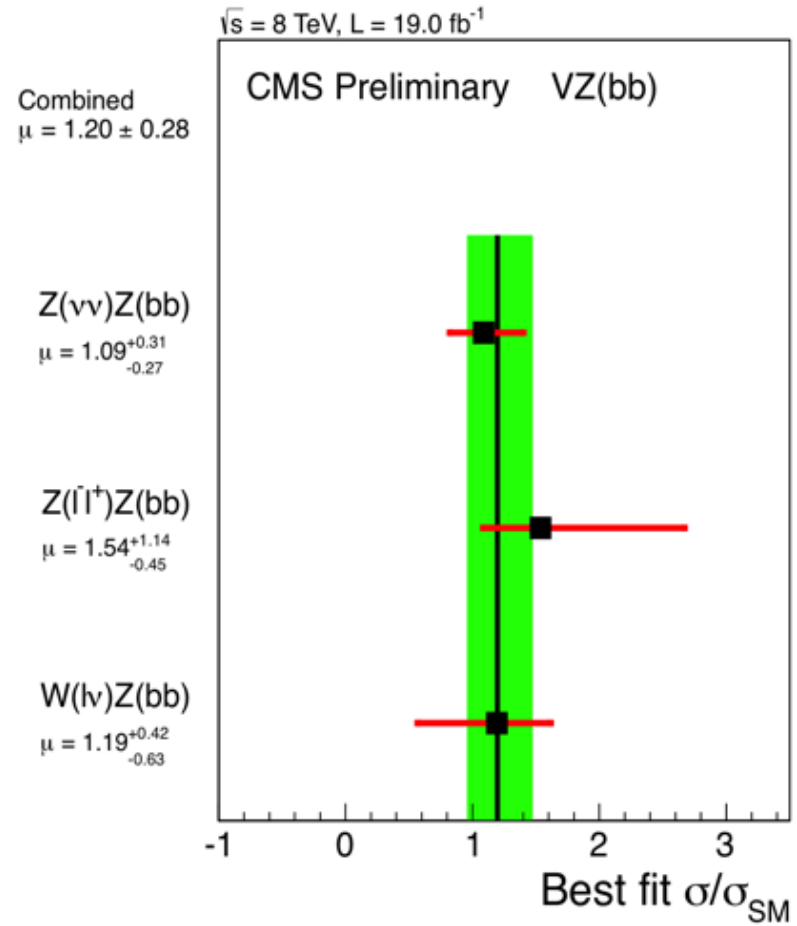
Results of BDT likelihood fit for 125 GeV Higgs:

- ***$\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.49$***
- Observed (expected) 95% CL limit: 0.95 (1.89)
- Observed (expected) significance: ***2.1σ***
- In combination with H → ττ: ***3.4σ***

Validation with VZ → Vbb



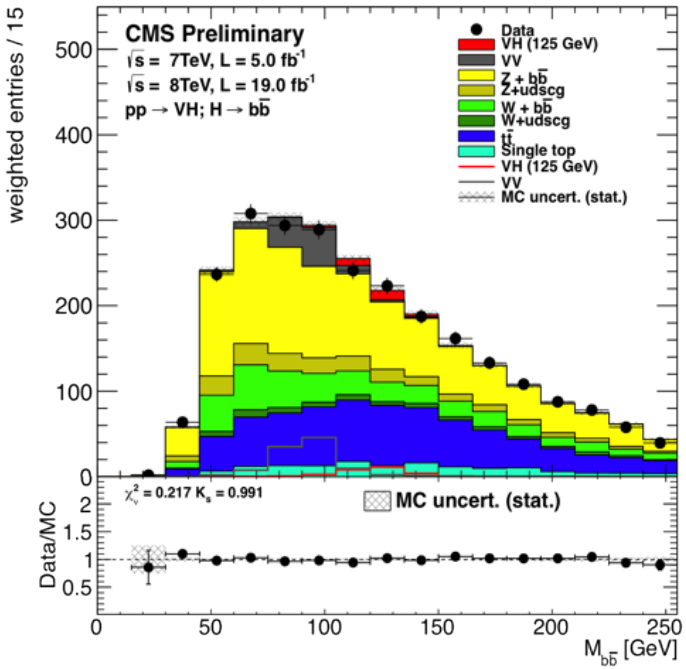


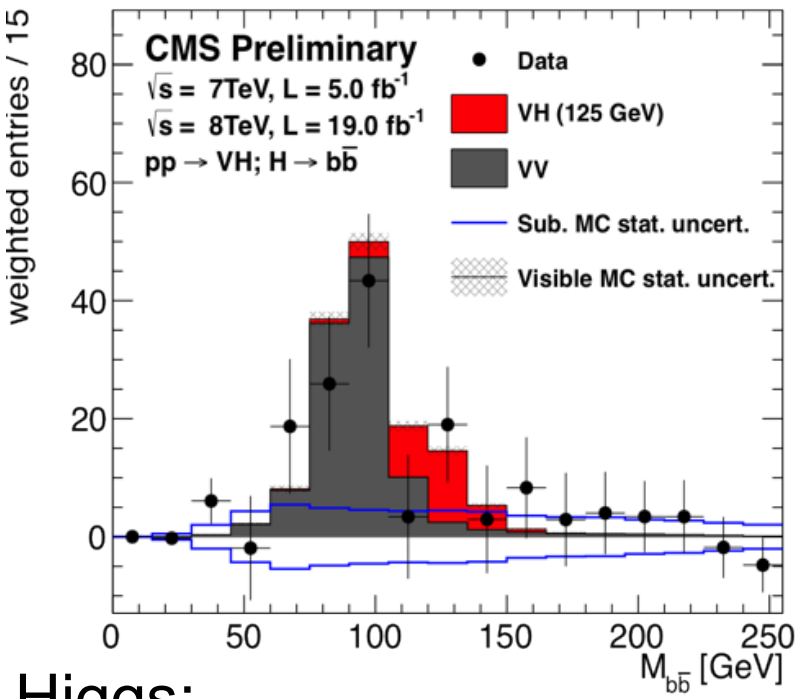


- Expected: 6.3σ
- Observed: 7.5σ
- Best fit μ: 1.20 ± 0.28
- Method gives correct SM result!

VH → Vbb Mass Analysis

- Tighten selection of BDT input variables
- To visualize: weight each category by S/(S+B)

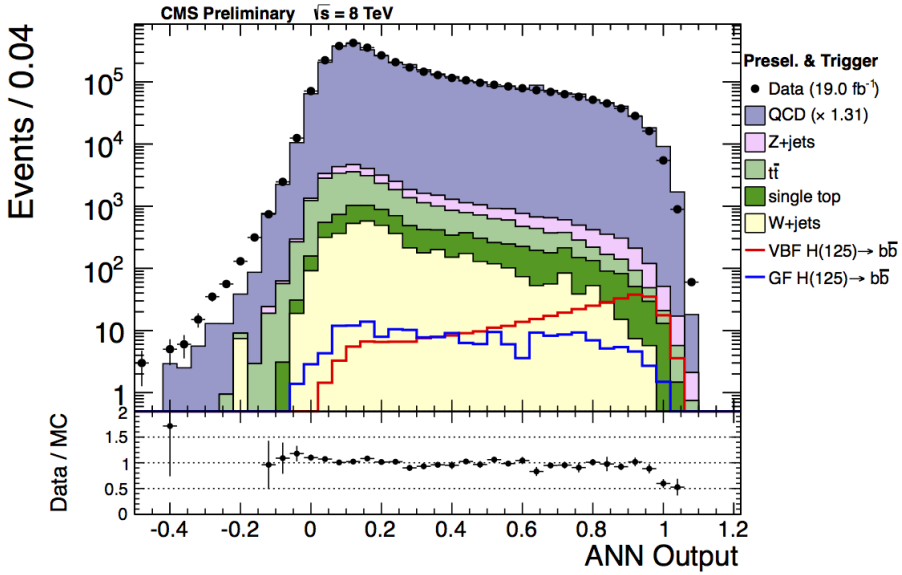


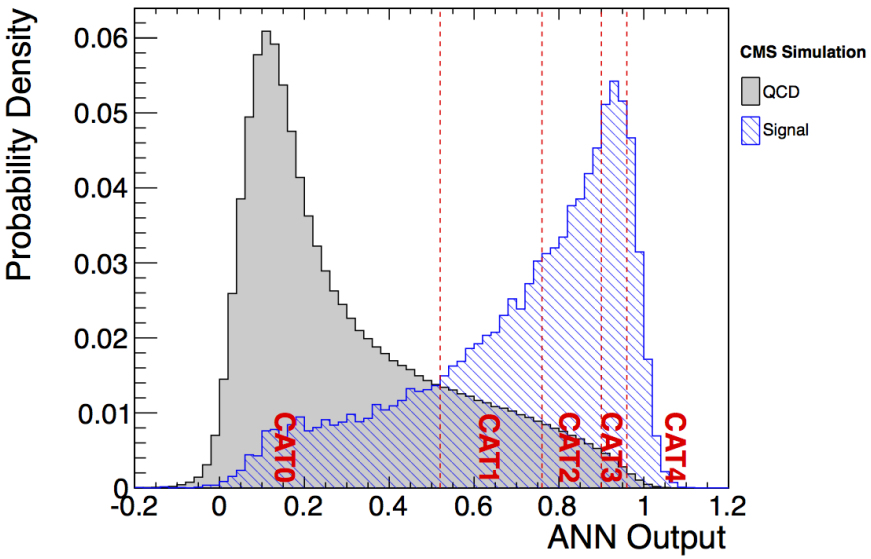


- Results of fit in M_{bb} for 125 GeV Higgs:
  - $\mu = 0.76^{+0.68}_{-0.66}$
  - Observed (expected) 95% CL Limit: 2.0 (1.4)
  - Similar to latest ATLAS results! (ATLAS-CONF-2013-079)

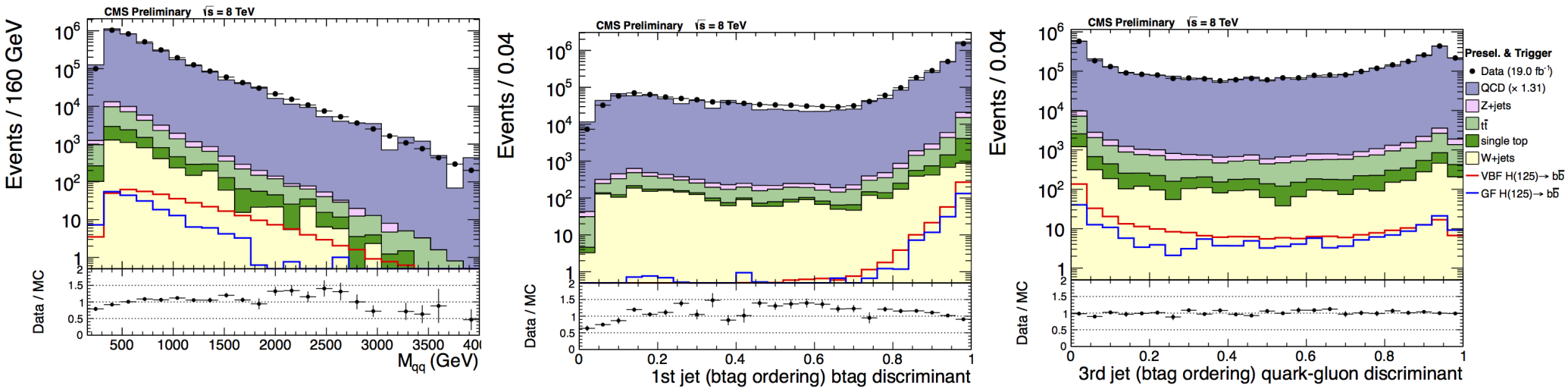
Analysis Strategy: VBF H → bb

- Jet pT > (85,70,60,40) GeV
- Quark jets from VBF required to have $\Delta\eta_{qq} > 2.5$, $m_{qq} > 300$ GeV
- Higgs candidate jets: $d\varphi_{bb} < 2$
- Construct Artificial Neural Network (ANN) to separate ***QCD-dominated*** background from VBF qqH → qqbb events
- Separate into categories and fit for background in each
  - Polynomial for QCD, templates for SM backgrounds



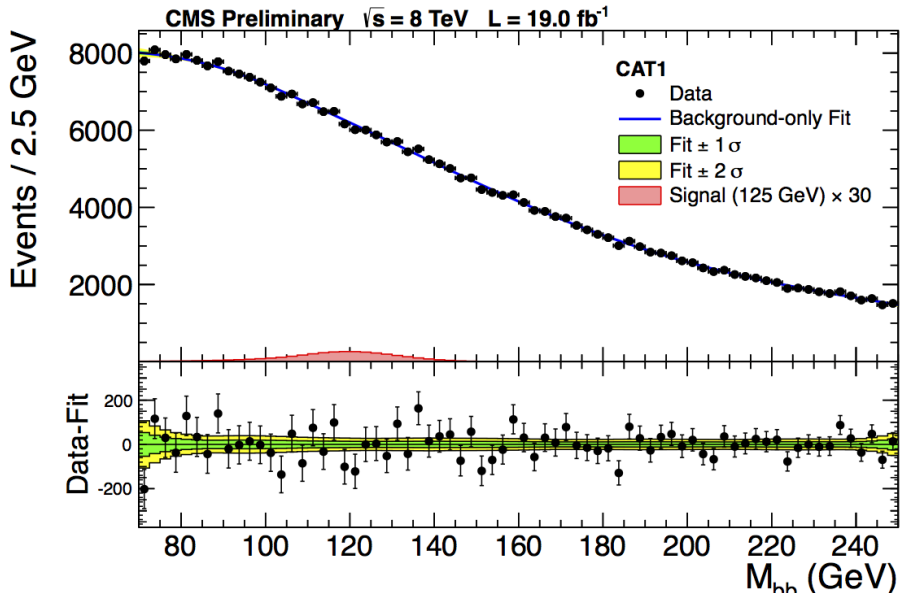


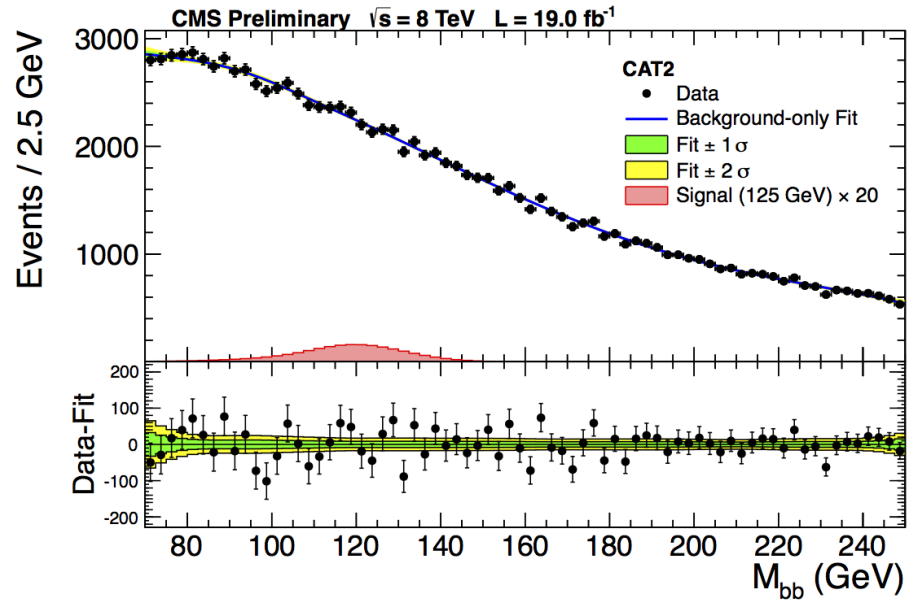
ANN Training and Inputs

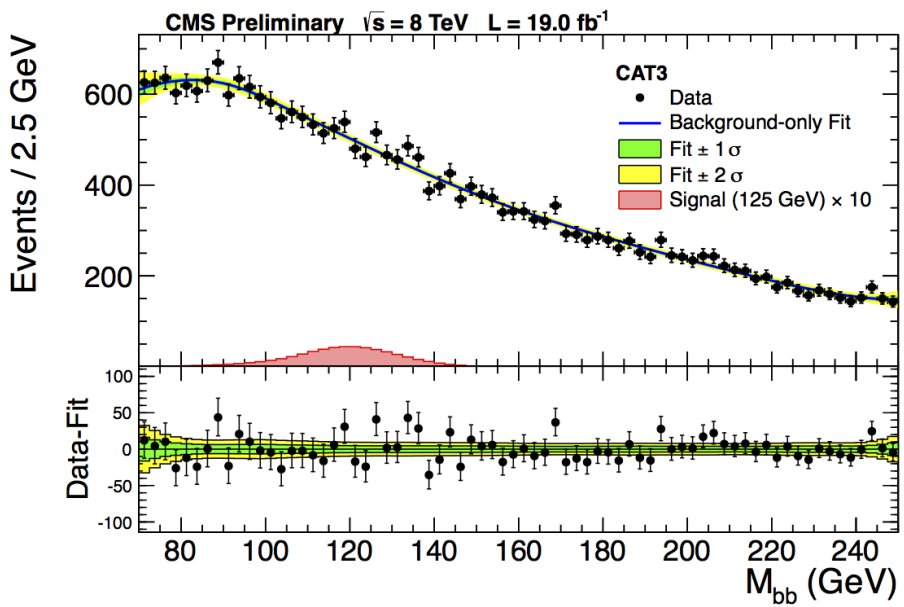


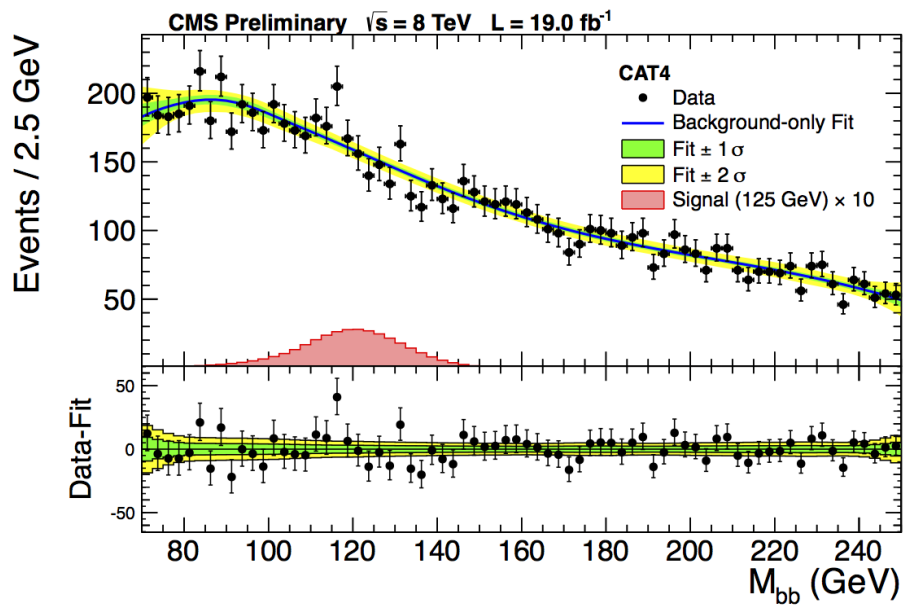
- Input variables – no strong correlations with m_{bb}
  - $\Delta\eta_{qq}$, $\delta\Delta\eta_{qq}$: separation b/w qq jets, difference from b-jets
  - Mass and pseudorapidity of qq pair system, η of 3rd jet
  - CSVs of b-tagged jets
  - Quark/gluon discriminant of q jets (constituent kinematics)
  - H_T – scalar sum of soft track jets in the event
  - Kinematics of bb system w.r.t. qq system (H/g separation)

Signal Extraction





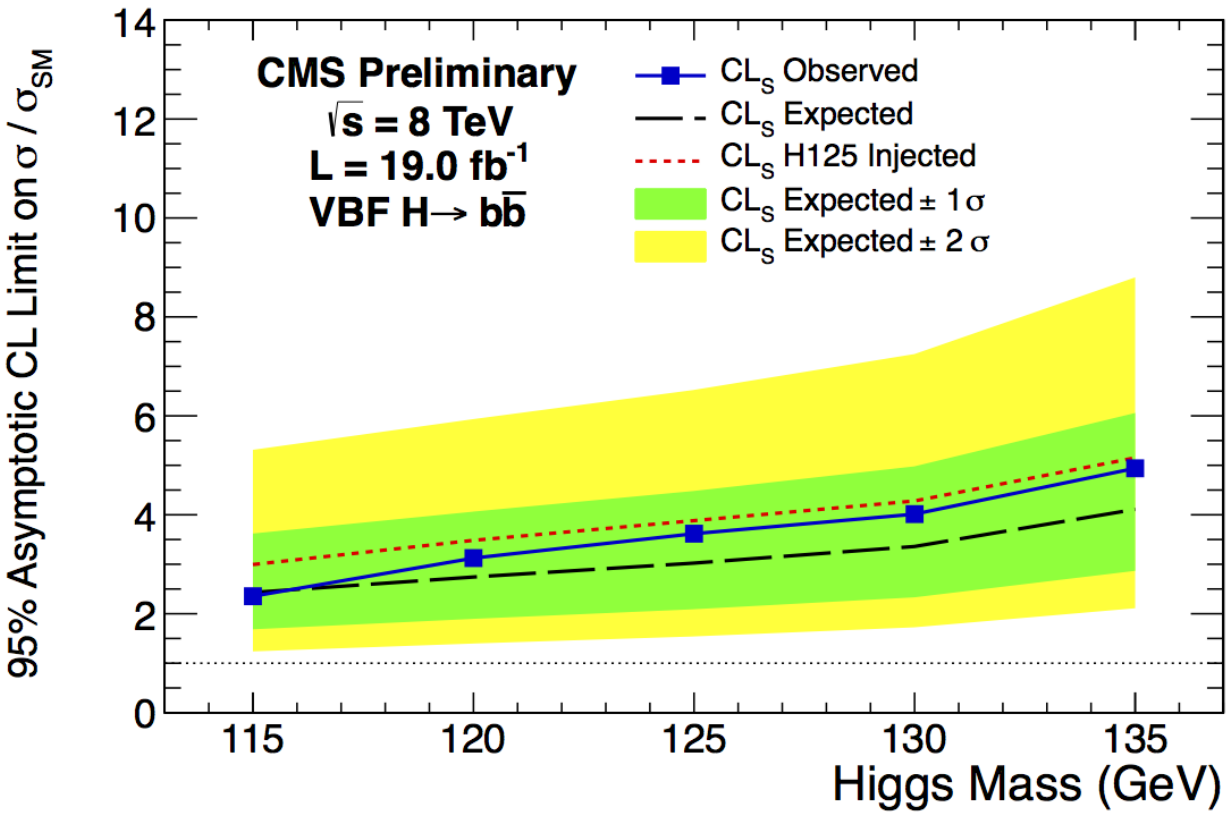




VBF Results

Results of fit for 125 GeV Higgs:

- $\mu = \sigma/\sigma_{SM} = 0.7 \pm 1.4$
- Observed (expected) 95% CL limit: 3.6 (3.0)
- Observed (expected) significance: 0.5σ (0.7σ)



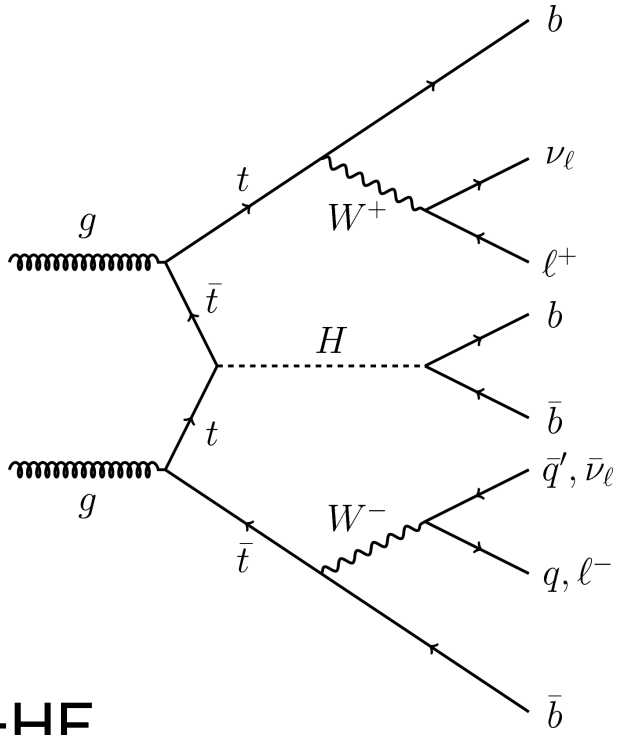
- Uncertainty dominated by background statistics
- All systematic uncertainties combined worsen limit by ~15%

Analysis Strategy: ttH → ttbb

- Lepton+Jets (lvlvbb), Dilepton (lvqqbb)
  - Subcategories: number of jets and b-tags (CSVM, p_T > 30 GeV)

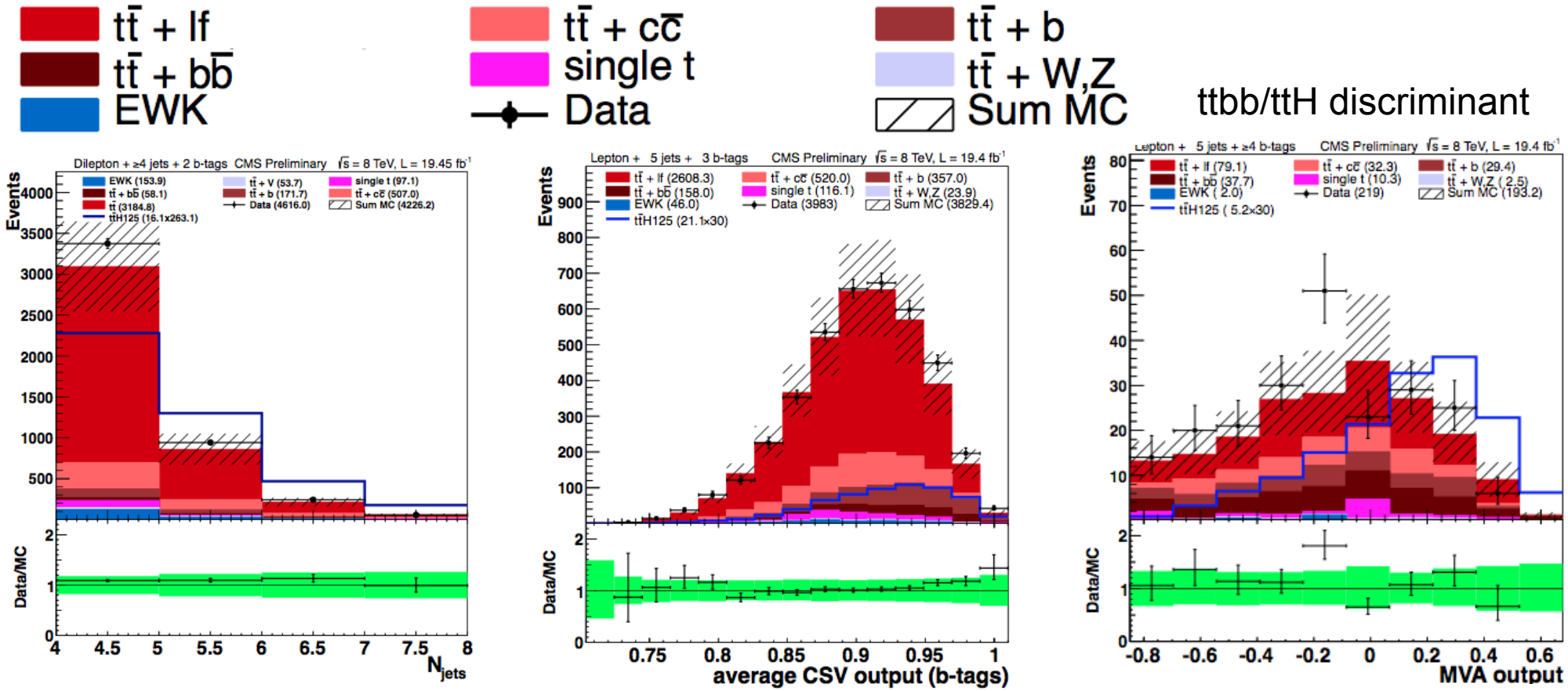
	Lepton+Jets							Dilepton	
Jets	≥6	4	5	≥6	4	5	≥6	2	≥3
Tags	2	3	3	3	4	≥4	≥4	2	≥3

- BDT tuned in each subcategory
  - Inputs: kinematics of single or combined objects, “best Higgs mass”, event shape, CSV discriminants of jets
- Global fit of BDT distributions
  - Includes ttH → ttττ for 8 TeV
- Systematic uncertainties
  - Experimental: b-tag efficiency and fake rate, Jet Energy Scale, ...
  - Theoretical: Q^2 on tt+jets, extra 50% on tt+HF, ...

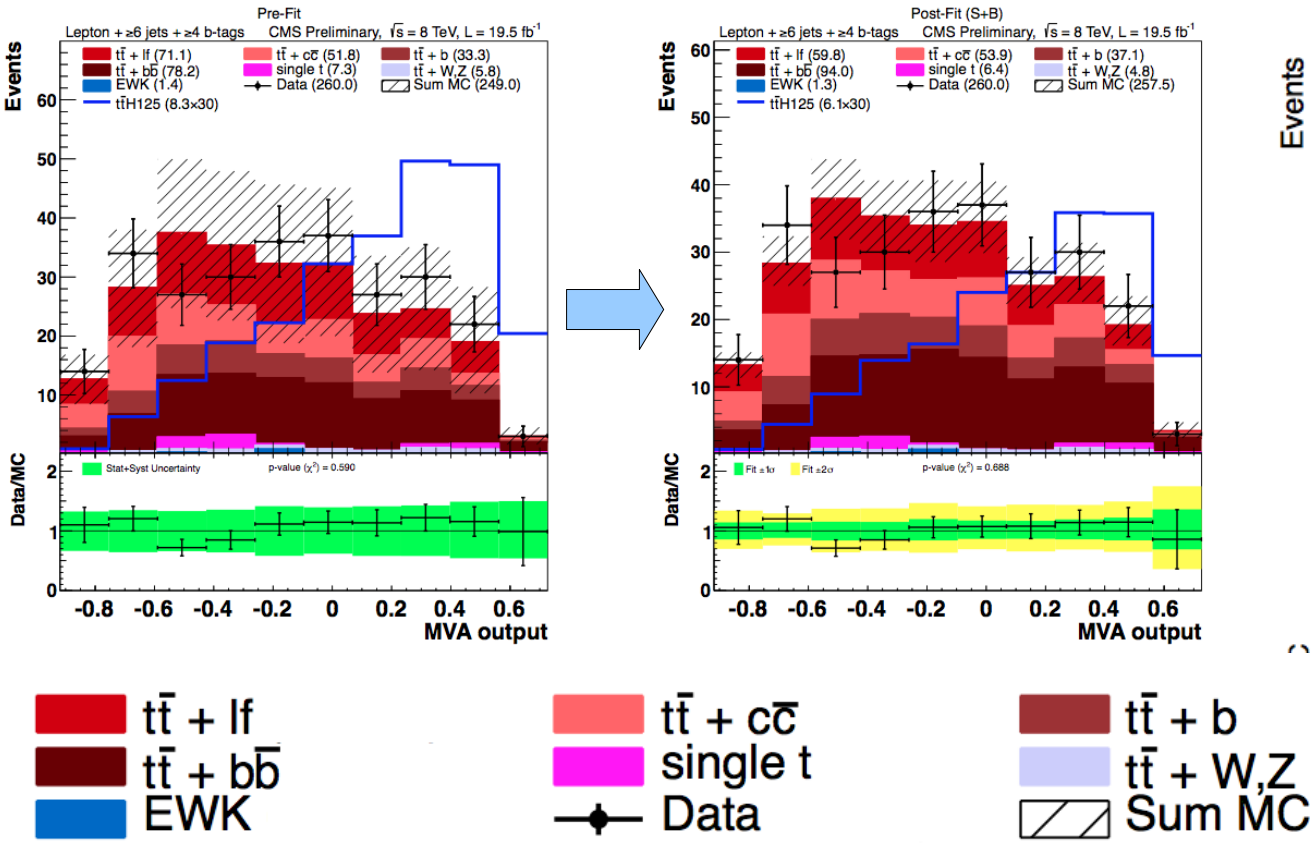


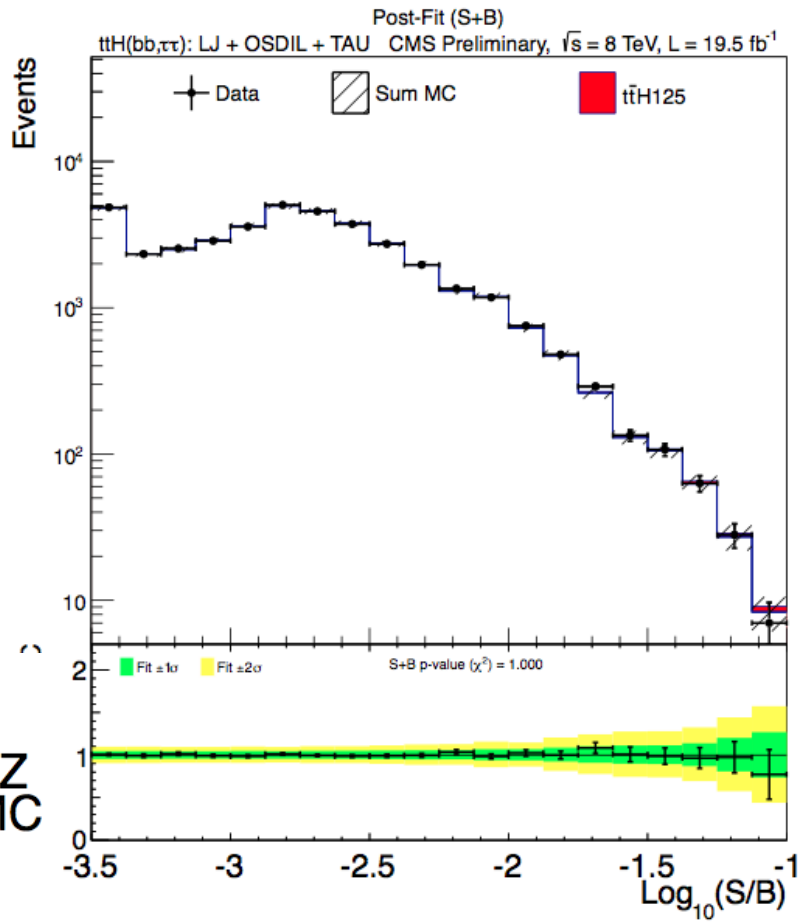
BDT Inputs and Training

- Training and variable selection separate for each channel
  - Up to 10 variables with highest 1D signal/background separation
- Specialized BDT trained against ttbb used as input for event-wide discriminant in most sensitive categories: 13% overall improvement



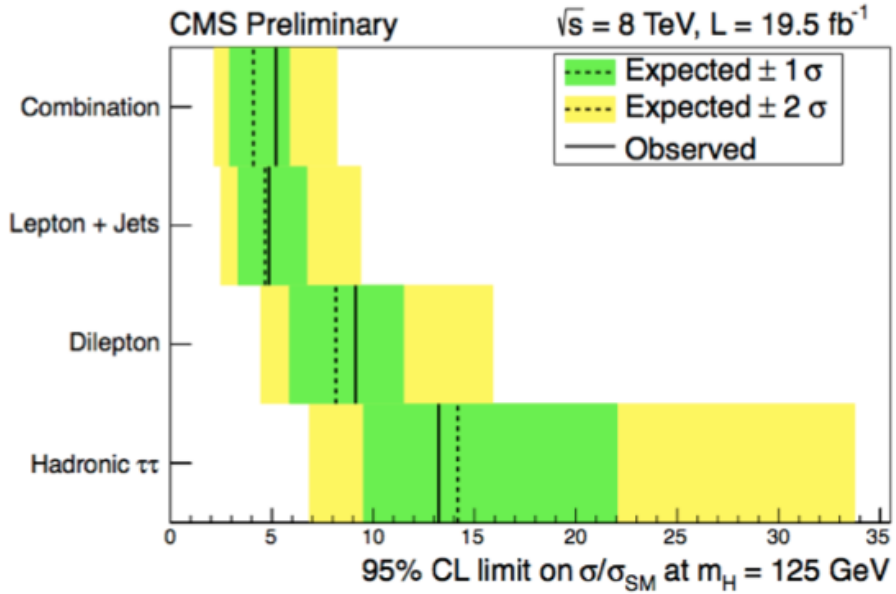
Signal Extraction

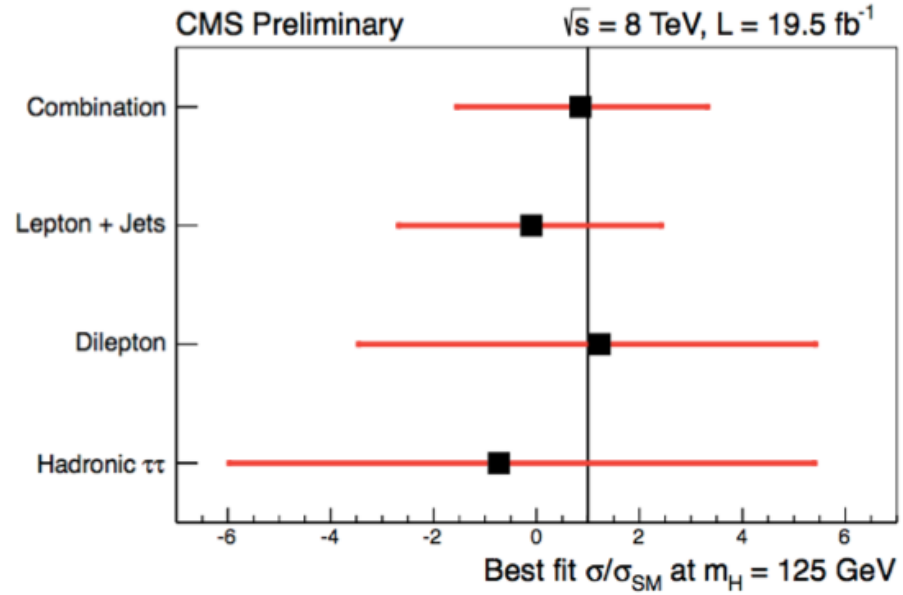




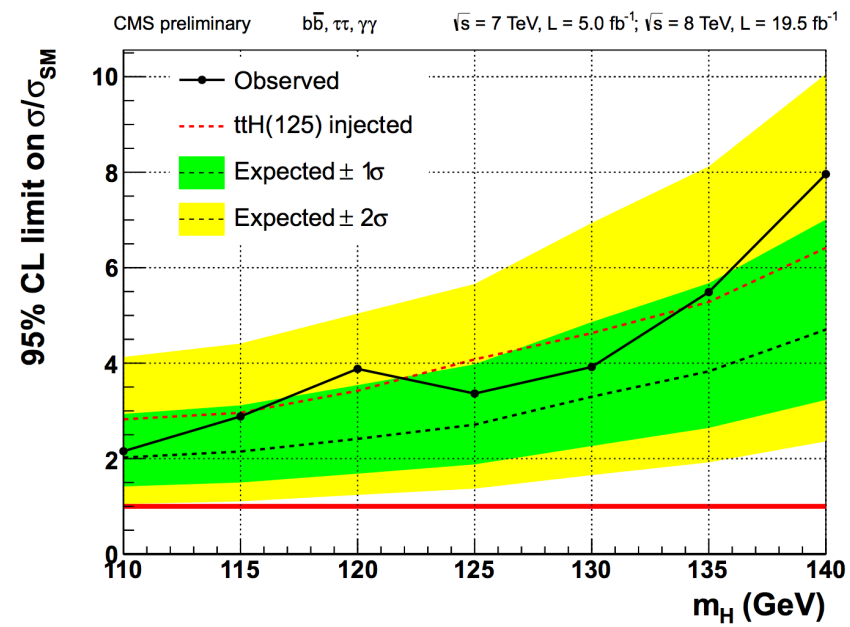
- Simultaneous fit in all categories, including tau
- Visualize fit by summing bins by log(S/B)

ttH → ttbb Results





- Observed (expected) 95% CL limit for 8 TeV at 125 GeV:
  - Combined [ττ,bb]: 5.2 (4.1)
  - Lepton+Jets: 4.9 (4.7)
  - Dilepton: 9.1 (8.2)
- Combined 7+8 TeV ttH(bb) + 8 TeV ttH(ττ,γγ): 3.3 (3.9)

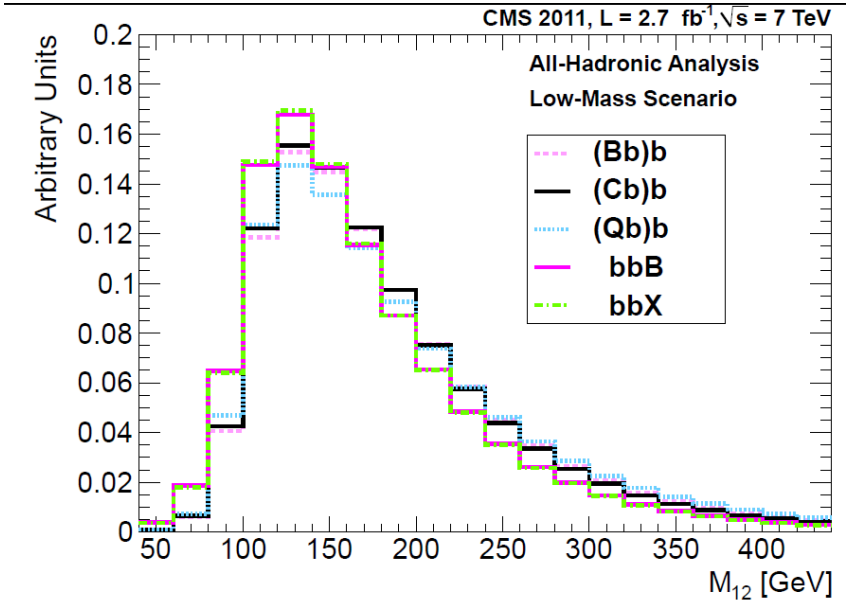


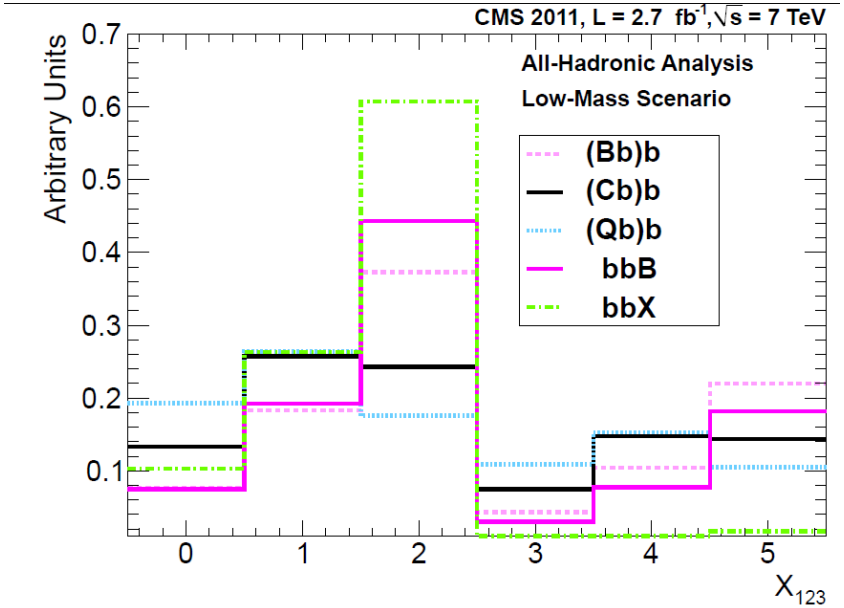
Analysis Strategy: bH → bbb

- All-Hadronic analysis
  - 3 reconstructed jets with |eta| < 2.2
  - 2 online b-tags required for trigger
  - Low-mass: pT(j1,j2,j3) > (46,38,20) GeV – 2.7 fb^{-1}
  - Medium-mass: pT(j1,j2,j3) > (60,53,20) GeV – 4.0 fb^{-1}
- Semi-leptonic analysis
  - Require muon (pT > 15 GeV) from semi-leptonic b decay
  - Reduce trigger rate, allow jet pT(j1,j2,j3) < (30,30,20)
- Derive QCD background in 3 b-tag signal sample using events with 1-2 b-tags
- Dominant systematics: trigger and b-tagging efficiency, jet energy scale, factorization/renormalization QCD scale

All-Hadronic Background

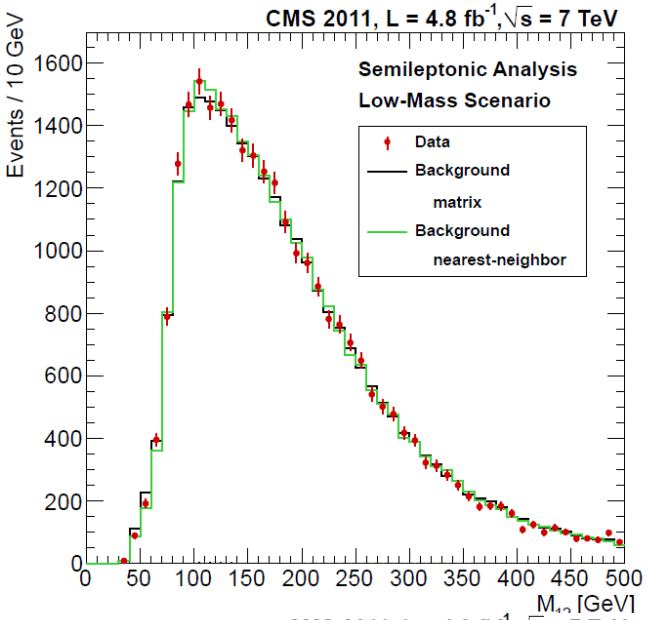
- Construct 2 variables for fits:
  - Dijet mass of 2 leading jets
  - Event Btag variable X_{123}
    - Defined based on masses of reconstructed b-vertices
    - Sufficient statistics in all bins
- In 2 b-tag sample, define templates using assumed flavor of untagged jet
  - B-tagging efficiency from MC
    - Function of (p_T,η)
    - Data/MC scale factors
  - Additional simulation-derived corrections for non-bb contribution (3-4%), online btagging

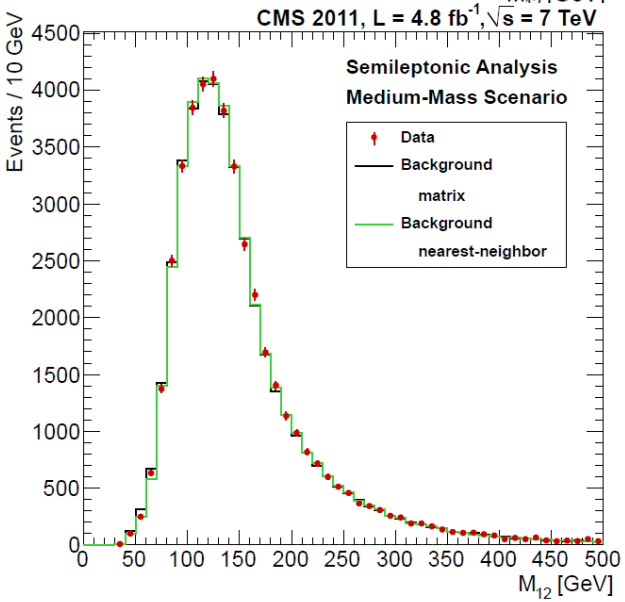




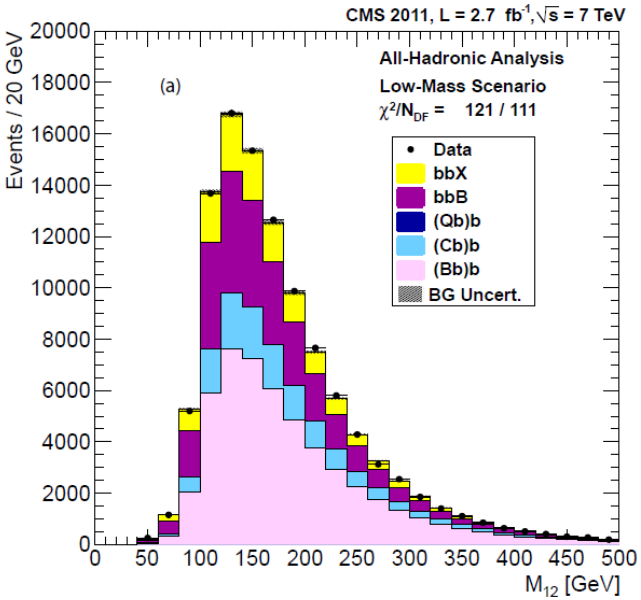
Semi-Leptonic Background

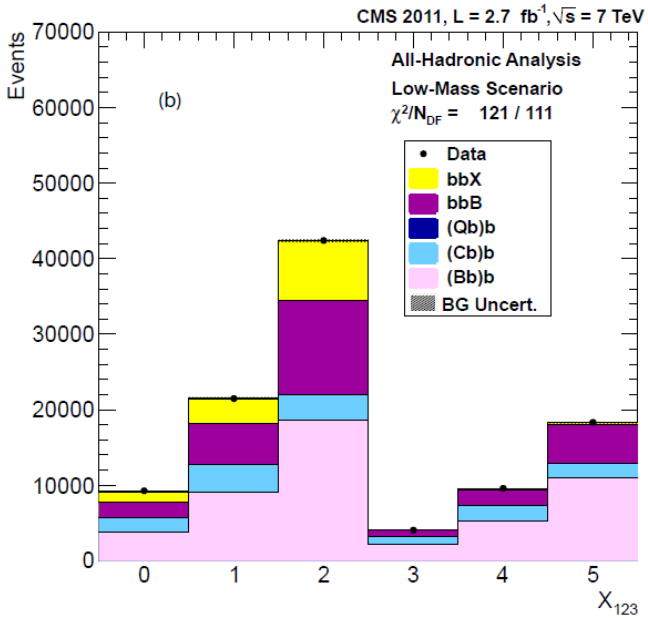
- Templates derived using two methods using disjoint samples: bbj, bjj
- Likelihood ratio to differentiate background-like from signal-like events
  - Jet pT, separation of lead jets in (η,φ), and separation from 3rd jet
- Matrix Method: template from bbj events; b-tagging probabilities for 3rd jet
- Nearest Neighbor method: use kinematically-similar background events in control region to predict bjj → bbb probability
- Good agreement between methods!

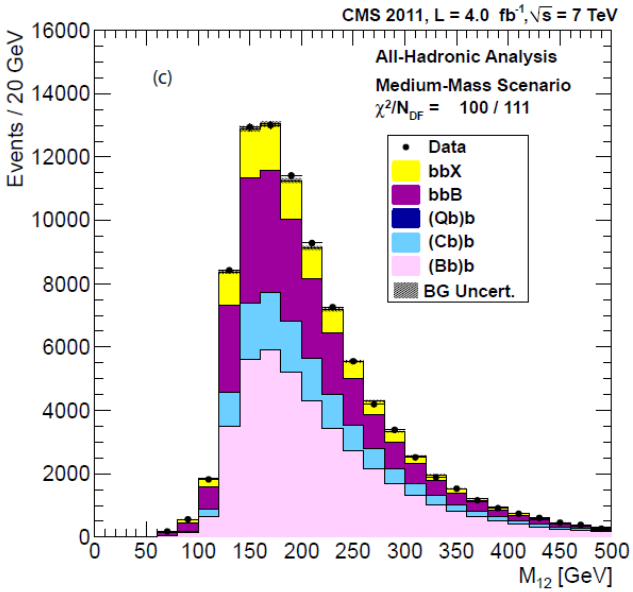


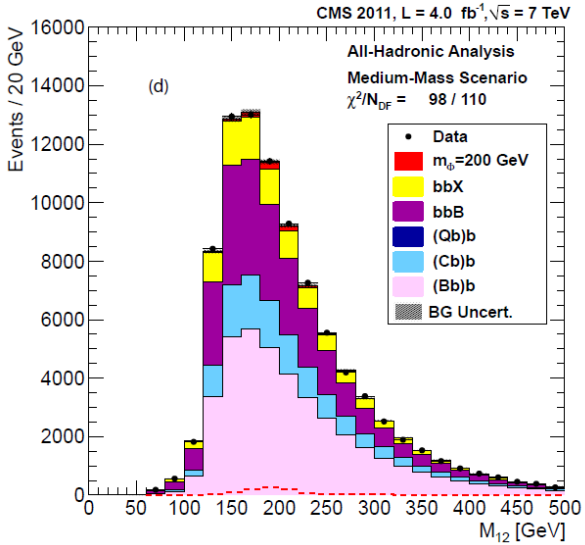


All-Hadronic Signal Extraction



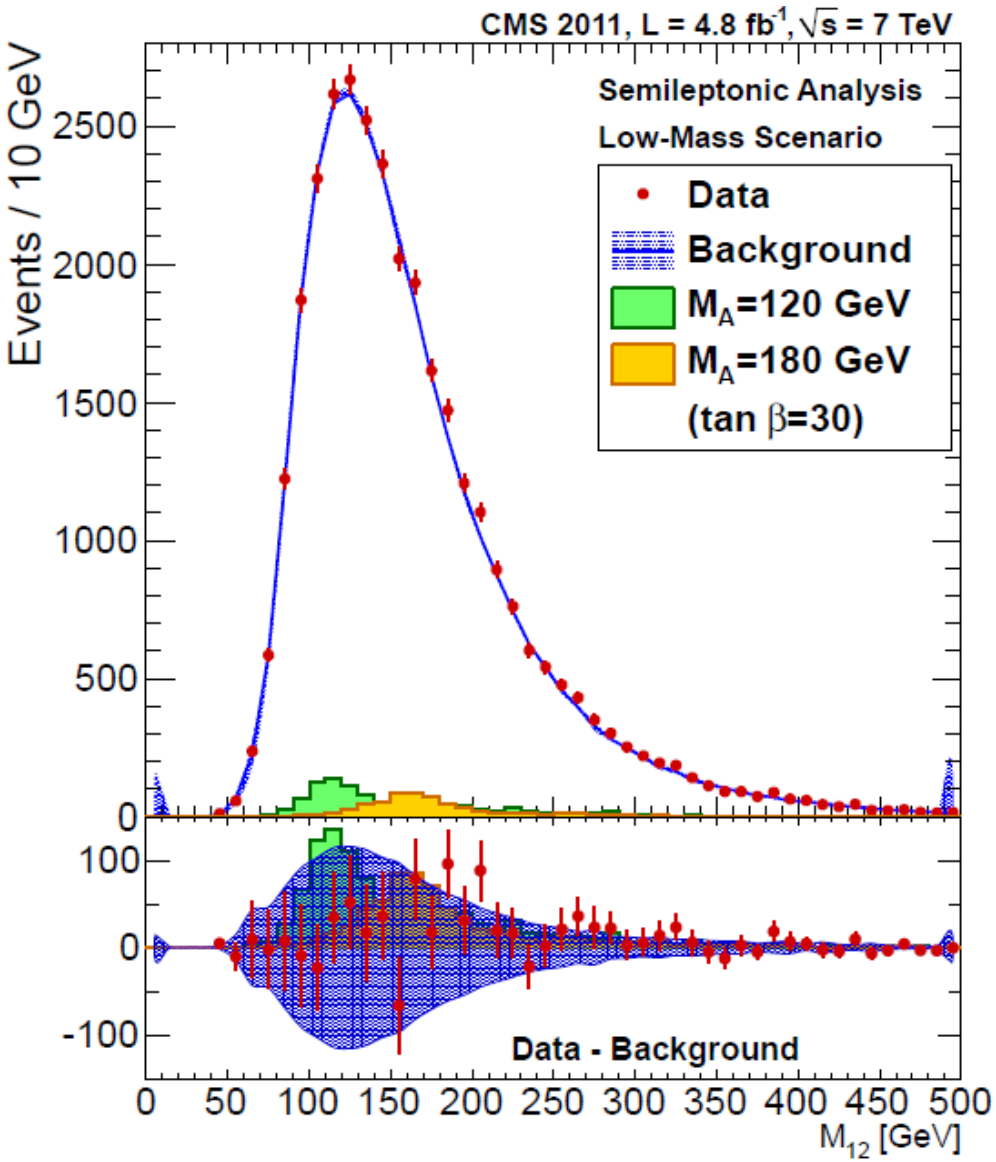


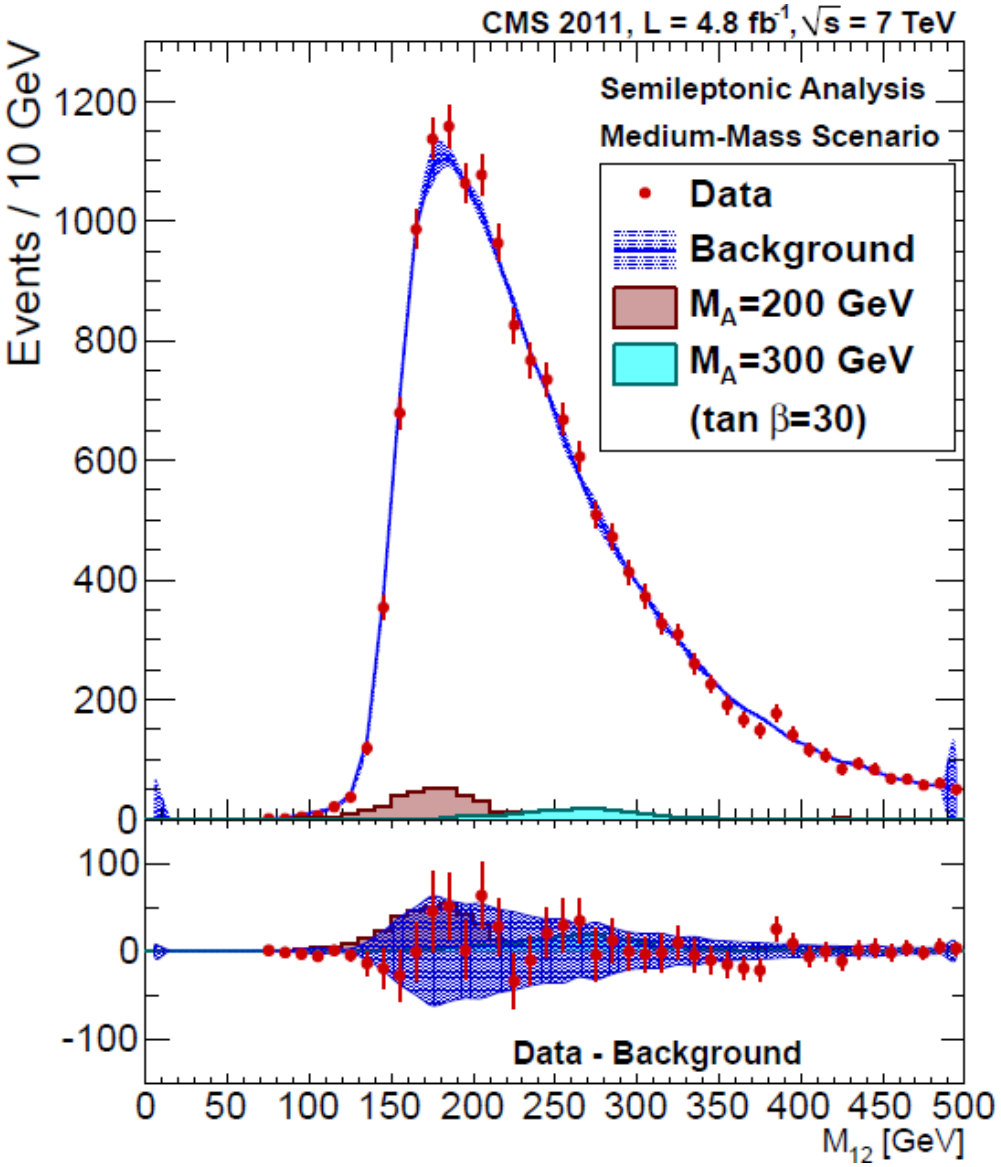




- Low-mass fit in M_{bb} and X_{123}
- High-mass fit in Mbb
  - No signal - left
  - With signal - right

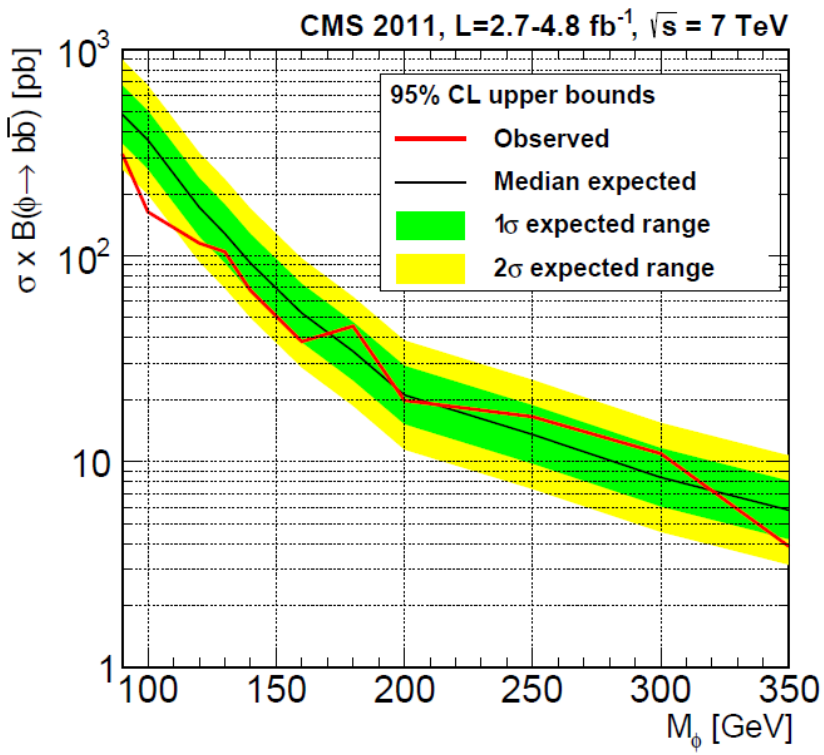
Semi-Leptonic Signal Extraction

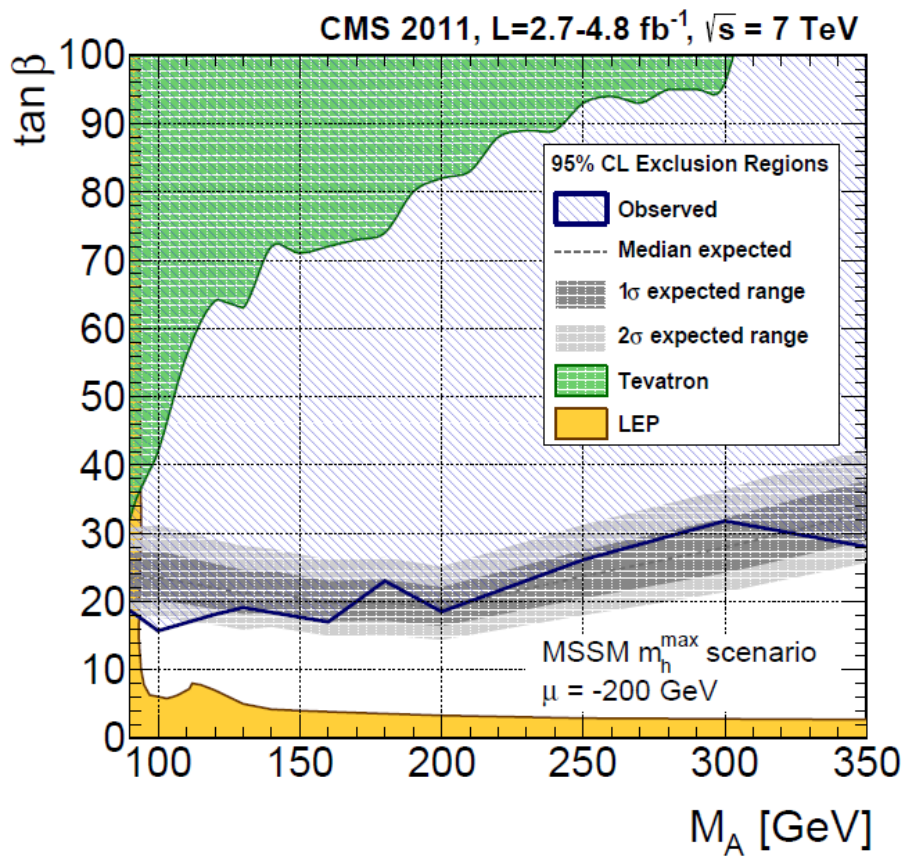




bH → bbb Results

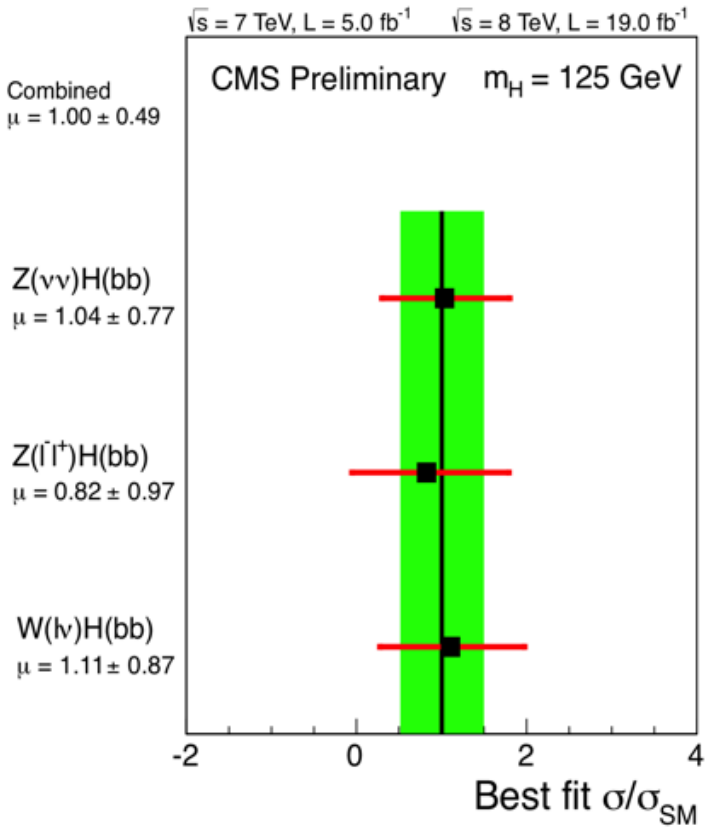
- Limits placed on cross section for bH+X cross section times H → bb branching ratio
- Interpreted as limits on parameters in the MSSM m_h^{max} benchmark scenario

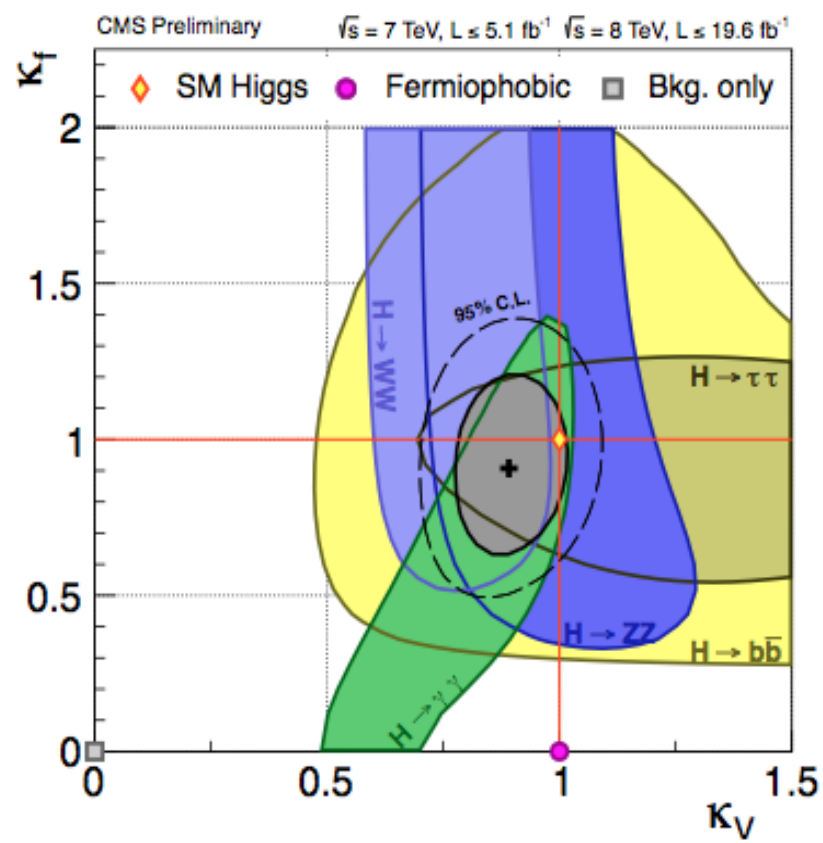




Conclusions

- Broad, well-developed CMS H → bb Program
  - All possible SM production mechanisms exploited
  - Multivariate techniques maximize kinematic information
- Everything consistent with Standard Model so far!





Extras

VH Systematic Uncertainties

Source	Type	Yield uncertainty (%) range	Contribution to uncertainty (%)	Removal effect on total uncertainty (%)
Luminosity	normalization	2.2-4.4	< 2	< 0.1
Lepton efficiency and trigger (per lepton)	normalization	3	< 2	< 0.1
$Z(\nu\nu)H$ triggers	shape	3	< 2	< 0.1
Jet energy scale	shape	2–3	5.0	0.5
Jet energy resolution	shape	3–6	5.9	0.7
Missing transverse energy	shape	3	3.2	0.2
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	normalization	4	3.9	0.3
Signal cross section (p_T boost, EWK/QCD)	normalization	2/5	3.9	0.3
Signal Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	normlization	10	15.9	5.2
Single-top (simulation estimate)	normalization	15	5.0	0.5
Dibosons (simulation estimate)	normalization	15	5.0	0.5
MC modeling (V+jets and $t\bar{t}$)	shape	10	7.4	1.1

VBF Systematic Uncertainties

Source	Uncertainty
Background fit	depending on the statistics of each category
Z+jets cross section	$\pm 20\%$
top cross section	$\pm 20\%$
Signal and Z peak position (JES)	$\pm 1.5\%$
Signal and Z resolution	$\pm 10\%$
Luminosity	$\pm 4.4\%$
Trigger efficiency	$\pm 5 - 8\%$
Signal acceptance due to JES	$\pm 10\%$
Signal acceptance due to JER	$\pm 2\%$
VBF cross section	$\pm 3\%$
VBF Monte Carlo acceptance	$\pm 10\%$
PDF	$\pm 5\%$
VBF ANN shape due to b-tag	$\pm 2\%$
VBF ANN shape due to quark-gluon discriminator	$\pm 2\%$
VBF ANN shape due to UE modeling	$-8 - +2\%$
GF cross section	$\pm 15\%$
GF Monte Carlo acceptance	$\pm 50\%$
GF ANN shape	$\pm 50\%$

ttH Systematic Uncertainties

Source	Shape	Remarks
Luminosity	No	Signal and all backgrounds
Lepton ID/Trig	No	Signal and all backgrounds
Pileup	No	Signal and all backgrounds
Top p_T reweighting	Yes	Only $t\bar{t}$ background
Jet Energy Resolution	No	Signal and all backgrounds
Jet Energy Scale	Yes	Signal and all backgrounds
b-Tag hf fraction	Yes	Signal and all backgrounds
b-Tag hf stats (linear)	Yes	Signal and all backgrounds
b-Tag hf stats (quadratic)	Yes	Signal and all backgrounds
b-Tag lf fraction	Yes	Signal and all backgrounds
b-Tag lf stats (linear)	Yes	Signal and all backgrounds
b-Tag lf stats (quadratic)	Yes	Signal and all backgrounds
b-Tag Charm (linear)	Yes	Signal and all backgrounds
b-Tag Charm (quadratic)	Yes	Signal and all backgrounds
QCD Scale ($t\bar{t}H$)	No	Scale uncertainty for NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	No	Scale uncertainty for NLO $t\bar{t}$ and single top predictions
QCD Scale (V)	No	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	No	Scale uncertainty for NLO diboson prediction
pdf (gg)	No	Pdf uncertainty for gg initiated processes ($t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$)
pdf ($q\bar{q}$)	No	Pdf uncertainty for $q\bar{q}$ initiated processes ($t\bar{t}W$, W, Z).
pdf (qg)	No	Pdf uncertainty for qg initiated processes (single top)
Madgraph Q^2 Scale ($t\bar{t}$+0p,1p,2p)	Yes	Madgraph Q^2 scale uncertainty for $t\bar{t}$+jets split by parton number. There is one nuisance parameter per parton multiplicity and they are uncorrelated.
Madgraph Q^2 Scale ($t\bar{t}$+b/$b\bar{b}$/$c\bar{c}$)	Yes	Madgraph Q^2 scale uncertainty for $t\bar{t}$+b/$b\bar{b}$/$c\bar{c}$.
Madgraph Q^2 Scale (V)	No	Varies by jet bin.
Extra $t\bar{t}$+hf rate uncertainty	No	A 50% uncertainty on the rate of $t\bar{t}$+b, $t\bar{t}+b\bar{b}$, $t\bar{t}+c\bar{c}$.

bH Systematic Uncertainties

Source	all-hadronic	semi-leptonic	type
Trigger efficiency	10%	$3-5\%$	rate
Online b-tagging efficiency	32%	-	rate
b-tagging efficiency	$10-13\%^{\dagger}$	12%	shape/rate
b-tagging efficiency dependence on topology	6%	-	rate
Jet Energy Scale	$1.4-6.8\%$	$^{+2.5}_{-3.1}\%$	shape/rate
Jet Energy Resolution	$0.6-1.3\%$	1.9%	shape/rate
Muon momentum scale	-	0.2%	rate
Muon momentum resolution	-	0.6%	rate
Signal Monte Carlo statistics	$1.1-2.6\%$		rate
Integrated luminosity	2.2%		rate
PDF and α_s uncertainties*	$3-6\%$	$^{+(2.5-4.7)}_{-(2.7-4.4)}\%$	rate
Renormalisation and fragmentation QCD scale*	$6-28\%$		rate
Underlying event and parton showering*	4%		rate