Search for the SM Higgs Boson in the VH($b\bar{b}$) Channel at the CMS Detector

Michael Mooney

Princeton University

On behalf of the CMS Collaboration

APS DPF Meeting, Santa Cruz

August 15, 2013

Outline

- Introduction
- Analysis Strategy
- b-jet Energy Regression
- Control Samples
- BDT Shape Analysis
- Multi-BDT
- Results

~5 fb^{-1} @ 7 TeV
~19 fb^{-1} @ 8 TeV

CMS Physics Analysis Summary:

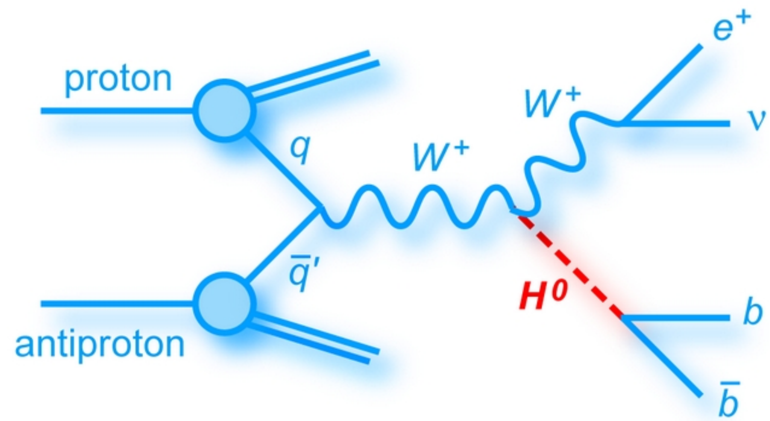
http://cms-physics.web.cern.ch/cms-physics/public/HIG-13-012-pas.pdf

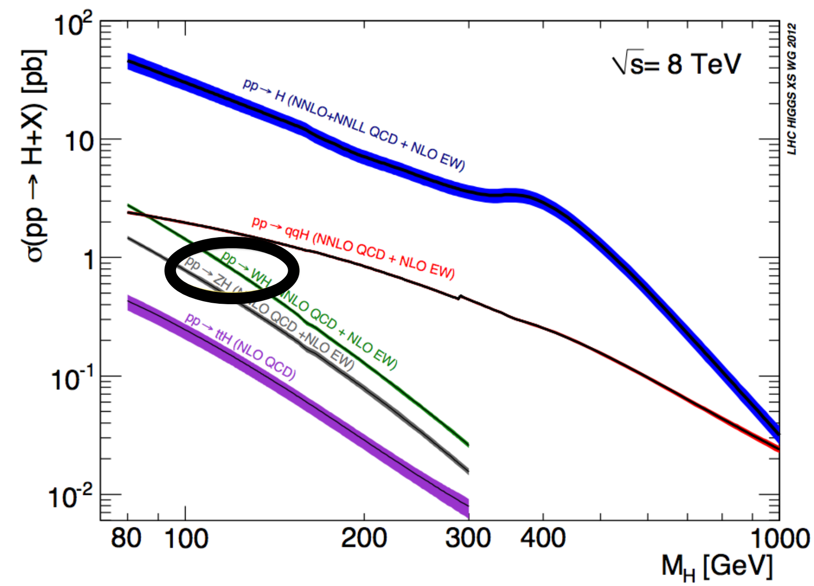
Public TWiki Page:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13012TWiki

Introduction

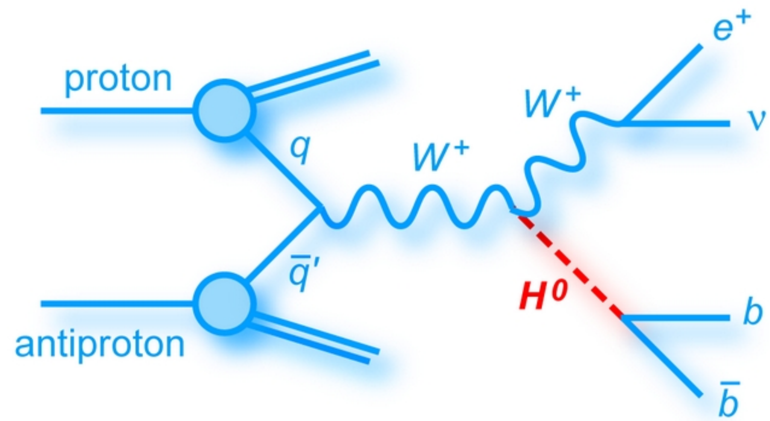
- Gluon-gluon fusion $H \rightarrow b\bar{b}$ analysis is hopeless! Need handle!
- For SM $H \rightarrow b\bar{b}$, best sensitivity is obtained with **VH($b\bar{b}$)**
- Advantages/features:
  - Negligible QCD (from V tag, cuts)
  - Efficient leptonic triggers
  - Boost $\rightarrow$ obtain gains with jet substructure (studies ongoing)
- Six unique final states (l = e, μ):
  - **W(lν)H($b\bar{b}$)**
  - **Z(l^+l^-)H($b\bar{b}$)**
  - **Z($\nu\bar{\nu}$)H($b\bar{b}$)**
  - **W(τν)H($b\bar{b}$) – NEW (8 TeV)**

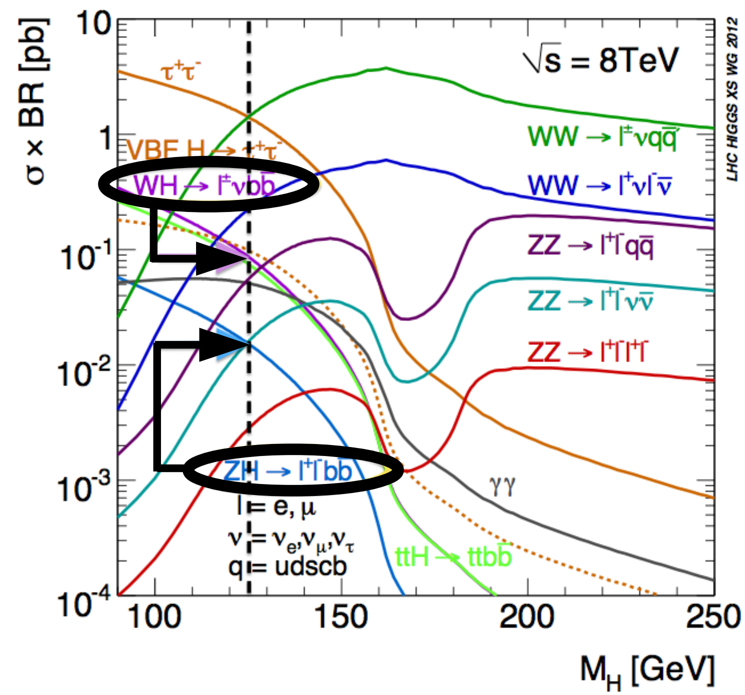




Introduction

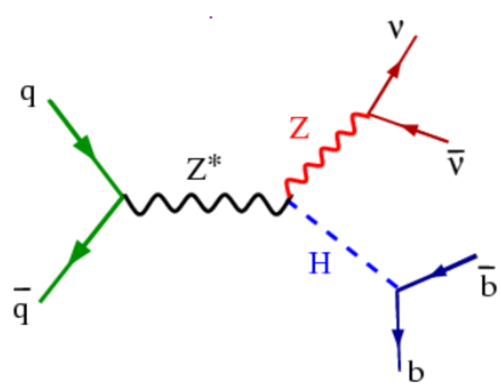
- Gluon-gluon fusion H $\rightarrow$ $b\bar{b}$ analysis is hopeless! Need handle!
- For SM H $\rightarrow$ $b\bar{b}$, best sensitivity is obtained with **VH($b\bar{b}$)**
- Advantages/features:
  - Negligible QCD (from V tag, cuts)
  - Efficient leptonic triggers
  - Boost $\rightarrow$ obtain gains with jet substructure (studies ongoing)
- Six unique final states (l = e, μ):
  - **W(lν)H($b\bar{b}$)**
  - **Z(l^+l^-)H($b\bar{b}$)**
  - **Z($\nu\bar{\nu}$)H($b\bar{b}$)**
  - **W(τν)H($b\bar{b}$) – NEW (8 TeV)**





Analysis Strategy

- Search strategy:
  - **Triggers**: one/two isolated lepton(s), MHT, or MET + two jets
  - **Two b-tagged jets** (corrected using b-jet energy regression)
    - AK5 jets ($p_T > 30$ GeV, $|\eta| < 2.5$) using CMS particle-flow
    - b-tagging with combined secondary vertex (CSV)
  - **Boosted W/Z decaying to leptons**
    - Isolated, central leptons (or large MET)
    - $p_T(e) > 30/20$ GeV (W/Z), $p_T(\mu) > 20$ GeV
    - $p_T(\tau) > 40$ GeV, 1-prong hadronic τ decays

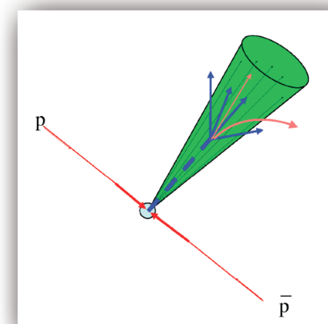


- Use MVA (TMVA): fit using **BDT shapes**
- Blind until approval in CMS Higgs group
  - BDT signal region blind
  - M(jj) window blind: 90 GeV < M(jj) < 150 GeV
  - Use control regions to validate data/MC agreement

b-jet Energy Regression

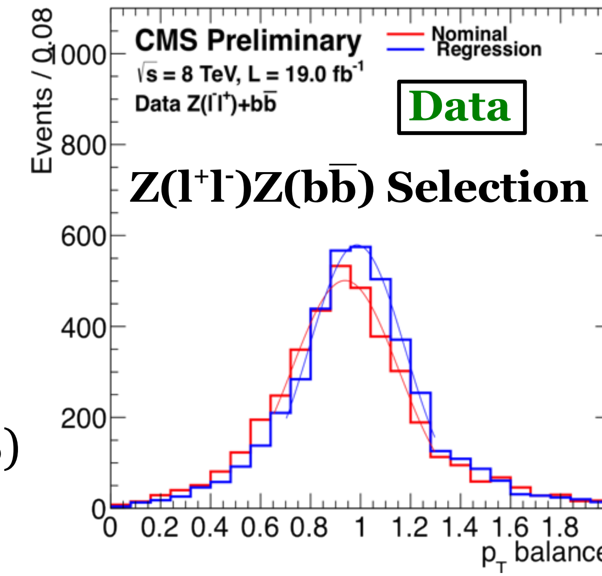
- Use dedicated b-jet energy regression on top of nominal jet corrections
- Train using VH signal MC (H b-jets), independently for each mode
- Common input variables and training parameters across modes
  - Only use MET in **$Z(l^+l^-)H(b\bar{b})$** (jet mis-measurement, not real MET)
- Also use soft lepton variables (semileptonic B decays)
  - Soft lepton must pass **loose ID cuts**

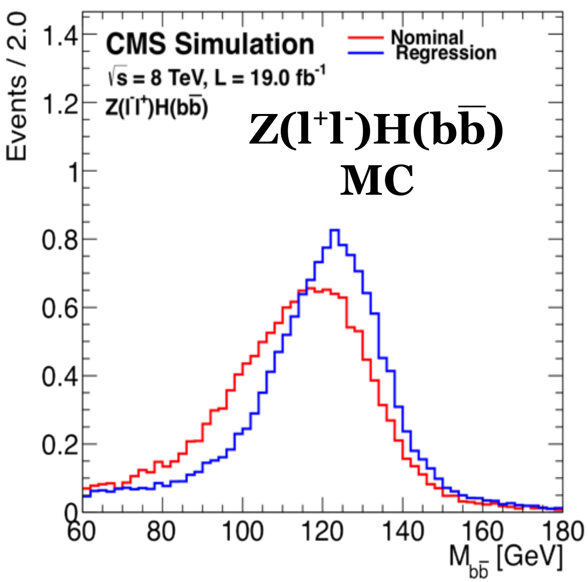
Variable Category	Variable
Jet Kinematics	p_T, η, raw p_T, E_T, m_T
Jet-related Properties	p_T(lead track), charged had. energy fraction, charged EM energy fraction, N(charged tracks), JEC uncertainty
Vertex	p_T(vtx), m(vtx), L_{3D}(vtx), ΔL_{3D}(vtx)
Soft Lepton	p_T(lep), $p_{T,rel}$(lep), ΔR(jet,lep)
$Z(l^+l^-)H(b\bar{b})$ Specific	MET, Δφ(jet,MET)

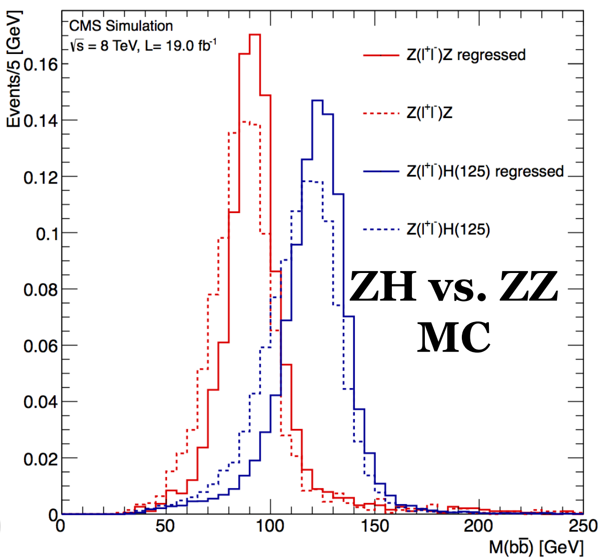


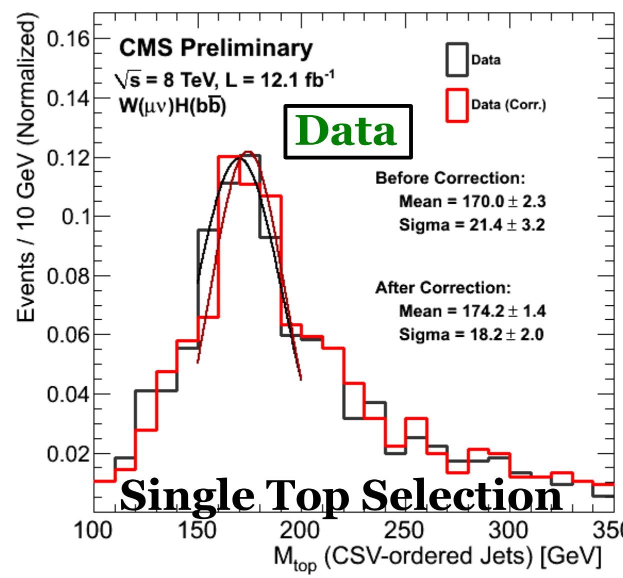
Regression Validation

- M(jj) resolution improvement:
  - **15-20%** for $Z(l^+l^-)H(b\bar{b})$
  - **7-12%** for $Z(\nu\bar{\nu})H(b\bar{b})$, $W(l\nu)H(b\bar{b})$
- Gain of **~15%** in analysis sensitivity
- Validate regression using **data**
  - $p_T(b\bar{b})/p_T(Z)$ balance ($Z(l^+l^-)Z(b\bar{b})$ enriched CS)
  - Top mass (single top enriched CS)





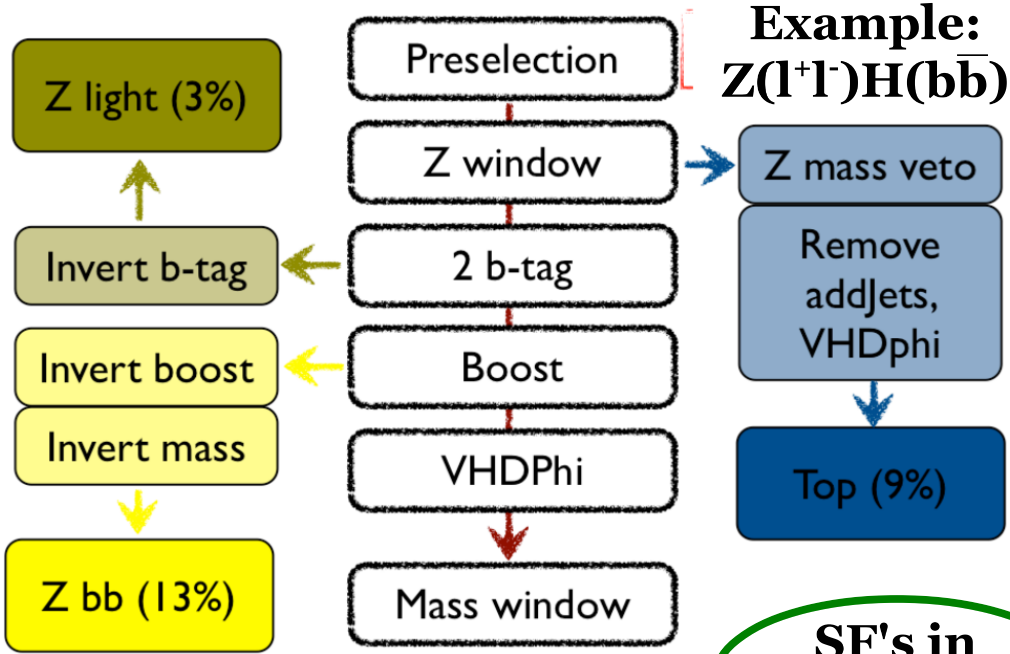




Control Samples

- Define control samples (CS's) to isolate and study backgrounds
- Use cuts as close as possible to signal region, but:
  - Invert some cuts to ensure orthogonality to signal region
  - Loosen some cuts to gain statistics

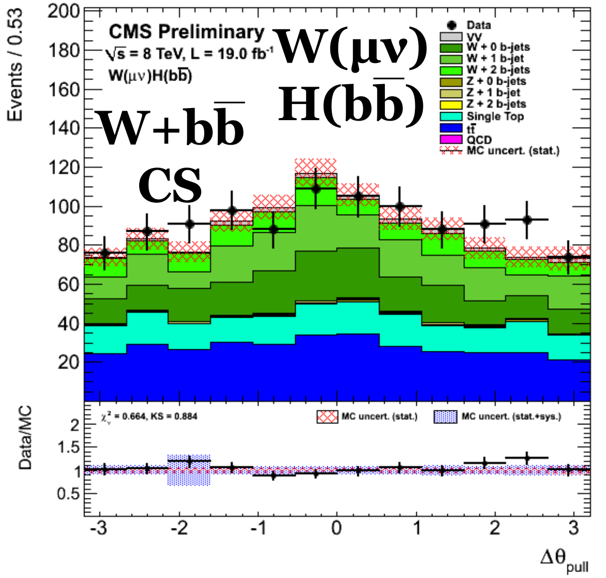
Example: $Z(l^+l^-)H(b\bar{b})$

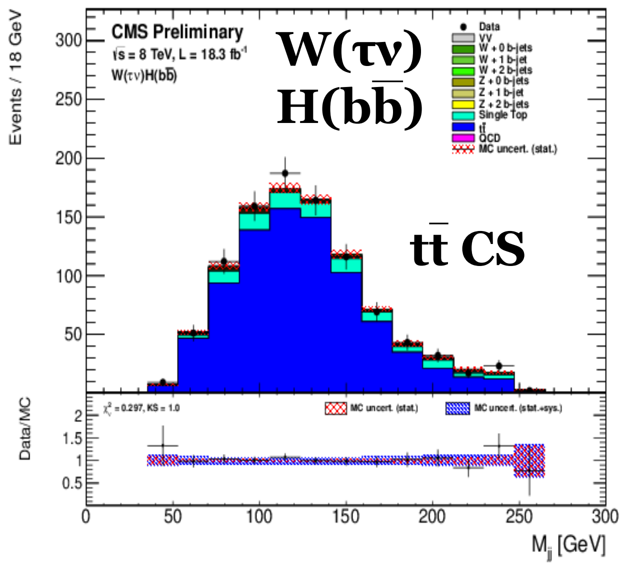


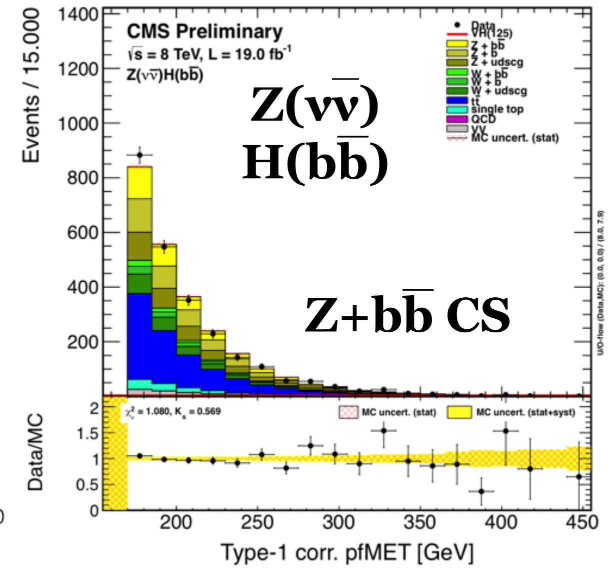
SF's in Backup

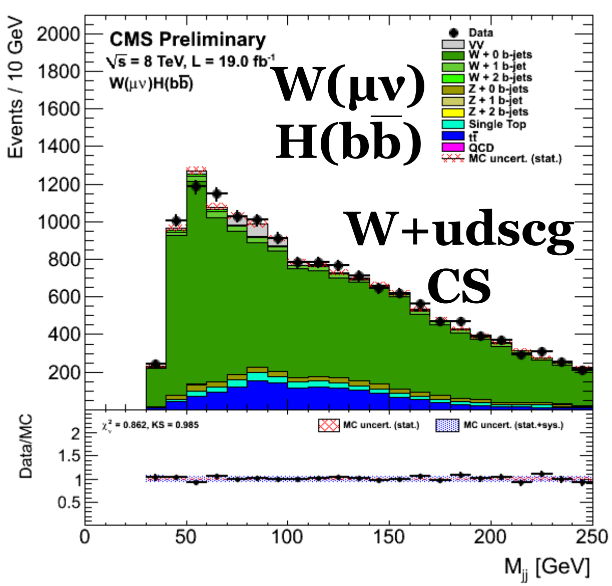
- Use to find **data/MC** scale factor (**SF**) for background yields in BDT signal region
- Three CS's: **V+udscg**, **V+$b\bar{b}$**, **$t\bar{t}$**
- Perform simultaneous fit to variables in all CS's to obtain SF's

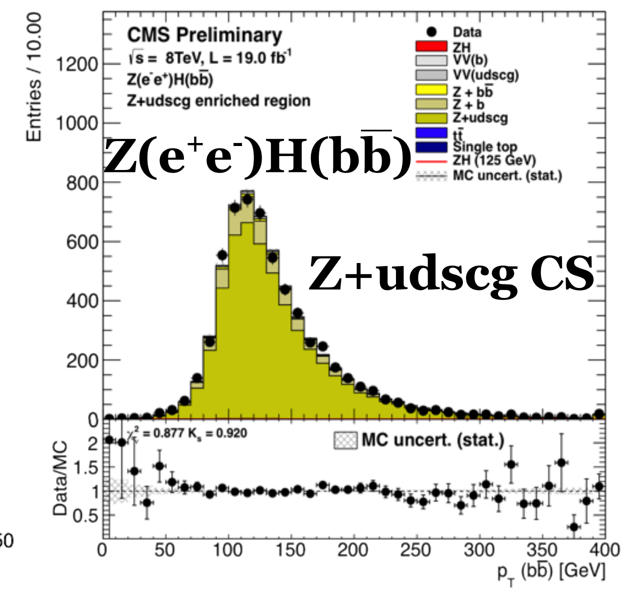
CS Data/MC Comparison

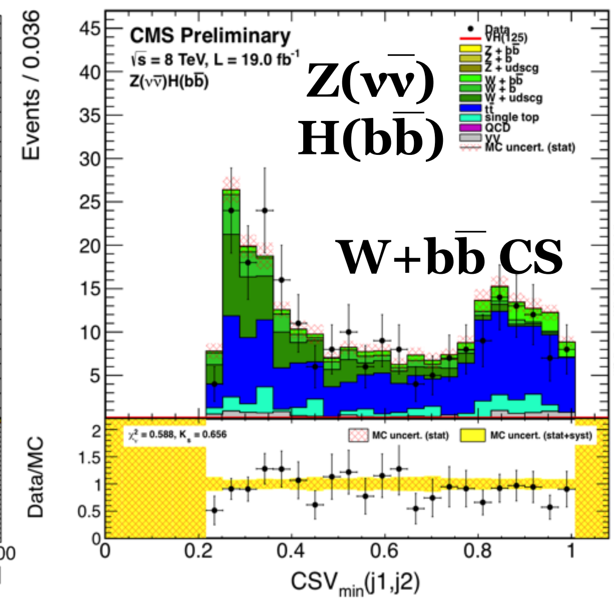




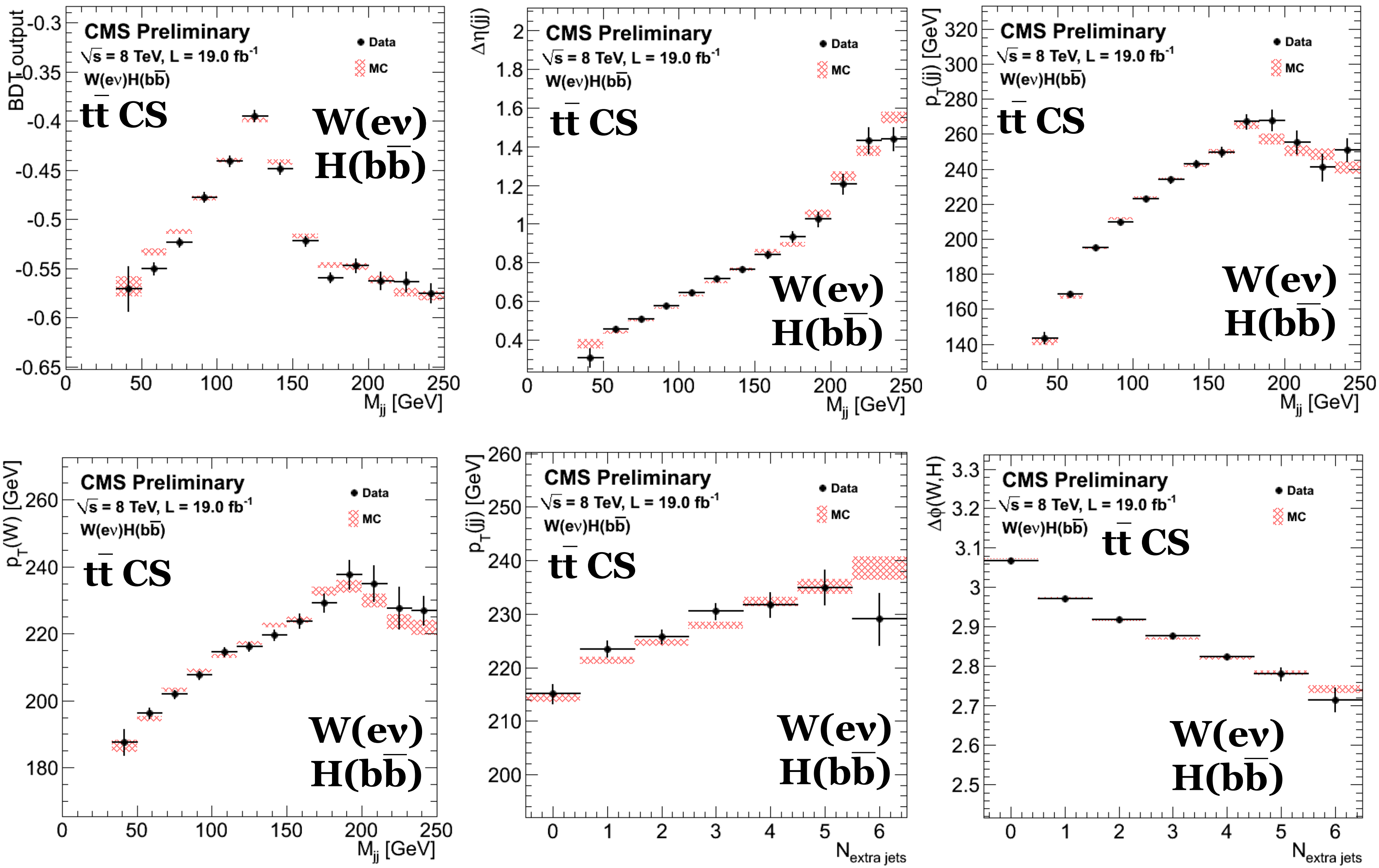








Correlations Check



Signal Region Definition

- Define signal-enriched region (for BDT shape fit) orthogonal to control regions, cutting out background primarily via boost, b-tagging, and QCD-targeted cuts
- Three different categories per mode (see later slide), split based on $p_T(V)$

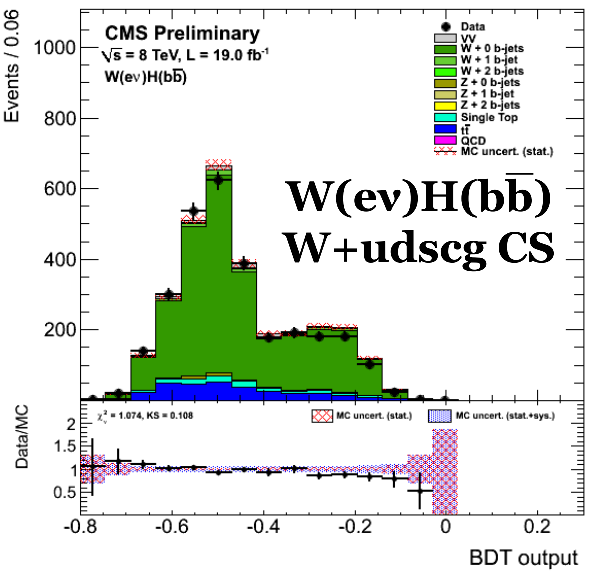
Variable	$W(\ell\nu)H$	$W(\tau\nu)H$	$Z(\ell\ell)H$	$Z(\nu\nu)H$
$p_T(V)$	[100 – 130] [130 – 180] [> 180]	[> 120]	[50 – 100] [> 100]	[100 – 130] [130 – 170] [> 170]
$m_{\ell\ell}$	–	–	[75 – 105]	–
$p_T(j_1)$	> 30	> 30	> 20	> 60
$p_T(j_2)$	> 30	> 30	> 20	> 30
$p_T(jj)$	> 100	> 120	–	[> 100] [> 130] [> 130]
$m(jj)$	< 250	< 250	[40 – 250] [< 250]	< 250
E_T^{miss}	> 45	> 80	–	–
$p_T(\tau)$	–	> 40	–	–
$p_T(track)$	–	> 20	–	–
CSV_{max}	> 0.40	> 0.40	[> 0.50] [> 0.244]	> 0.679
CSV_{min}	> 0.40	> 0.40	> 0.244	> 0.244
N_{aj}	–	–	–	[< 2] [–] [–]
N_{al}	= 0	= 0	–	= 0
$\Delta\phi(V,H)$	–	–	–	> 2.0
$\Delta\phi(E_T^{miss}, jet)$	–	–	–	[> 0.7] [> 0.7] [> 0.5]
$\Delta\phi(E_T^{miss}, E_T^{miss}(tracks))$	–	–	–	< 0.5
E_T^{miss} significance	–	–	–	[> 3] [–] [–]
$\Delta\phi(E_T^{miss}, \ell)$	$< \pi/2$	–	–	–

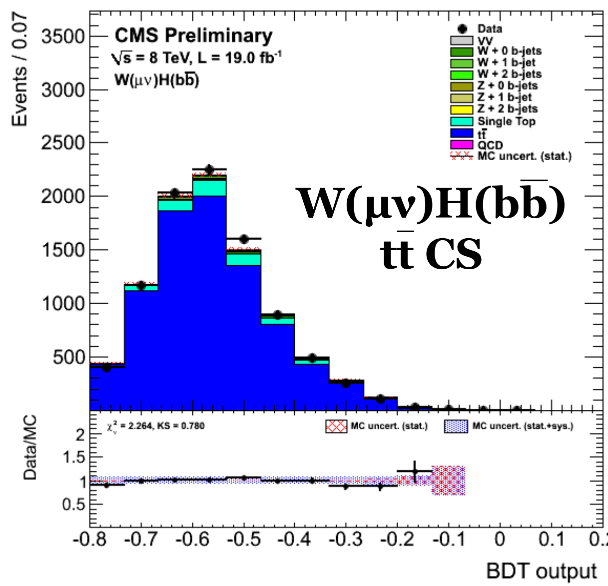
BDT Training

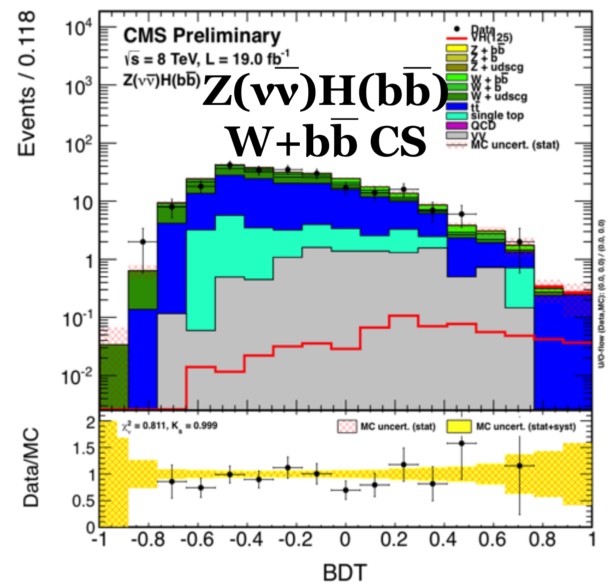
- Shape analysis using BDT classification output
- Train BDT separately for different signal modes, mass points
  - But combine **e** and **μ** modes for **W(lν)H($b\bar{b}$)**, **Z(l^+l^-)H($b\bar{b}$)**
- For final BDT shape fit, **reshape** BDT (binning transformation) to avoid too little background MC in any one bin

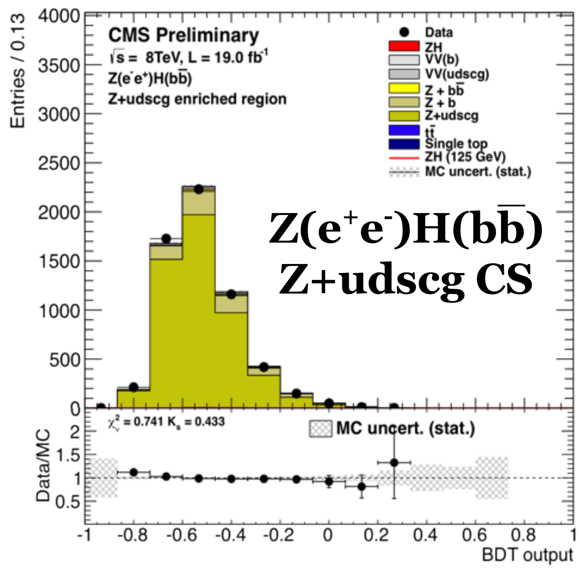
Variable
$p_T(j)$: transverse momentum of each Higgs daughter
m(jj): dijet invariant mass
p_T(jj): dijet transverse momentum
p_T(V): vector boson transverse momentum (or E_T^{miss})
N_{aj}: number of additional jets
CSV_{max}: value of CSV for the Higgs daughter with largest CSV value
CSV_{min}: value of CSV for the Higgs daughter with second largest CSV value
$\Delta\phi$(V, H): azimuthal angle between V (or E_T^{miss}) and dijet
$\|\Delta\eta(jj)\|$: difference in η between Higgs daughters
ΔR(jj): distance in η–ϕ between Higgs daughters
$\Delta\theta_{pull}$: color pull angle [35]
$\Delta\phi(E_T^{miss}, jet)$: azimuthal angle between E_T^{miss} and the closest jet (only for $Z(\nu\nu)$H)
$maxCSV_{aj}$: maximum CSV of the additional jets in an event (only for $Z(\nu\nu)$H and $W(\ell\nu)$H)
$min\Delta R$(H, aj): mimimum distance between an additional jet and the Higgs candidate (only for $Z(\nu\nu)$H and $W(\ell\nu)$H)
Angular variables: invariant mass of the VH system, angle Z-Z*, angle Z-l, angle H-jet (only for $Z(\ell\ell)$H)

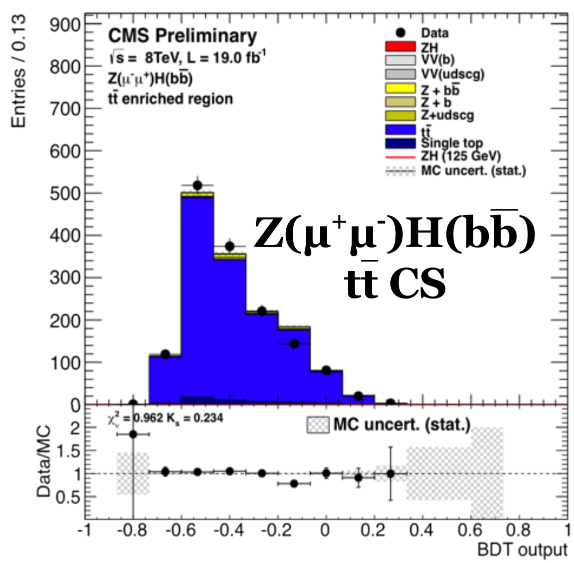
BDT Validation



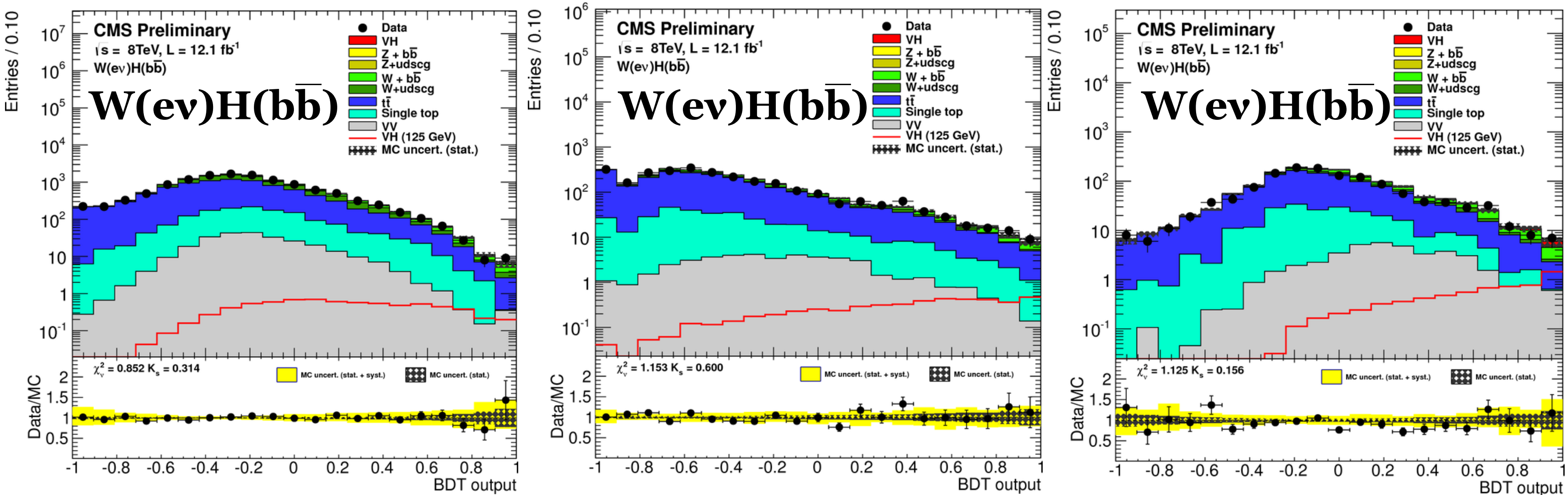








Event Categories



Low $p_T(V)$ | **Medium $p_T(V)$** | **High $p_T(V)$**

- Split events into three categories via $p_T(V)$ to increase sensitivity
  - Only two categories for $Z(l^+l^-)H(b\bar{b})$ – no sensitivity gain using three categories
- Example: $W(l\nu)H(b\bar{b})$
  - **Low $p_T(V)$**: 100 GeV < $p_T(W)$ < 130 GeV
  - **Medium $p_T(V)$**: 130 GeV < $p_T(W)$ < 180 GeV
  - **High $p_T(V)$**: $p_T(W)$ > 180 GeV

Multi-BDT Shape Analysis

- Use multiple BDT classifiers to separate signal from one background at a time (similar to **CDF**'s technique)
- Train 3 individual BDT's (targets: $t\bar{t}$, V+jets, VV) in addition to nominal "final BDT"
- Only used for **Z($\nu\bar{\nu}$)H($b\bar{b}$)** and **W($l\nu$)H($b\bar{b}$)** modes

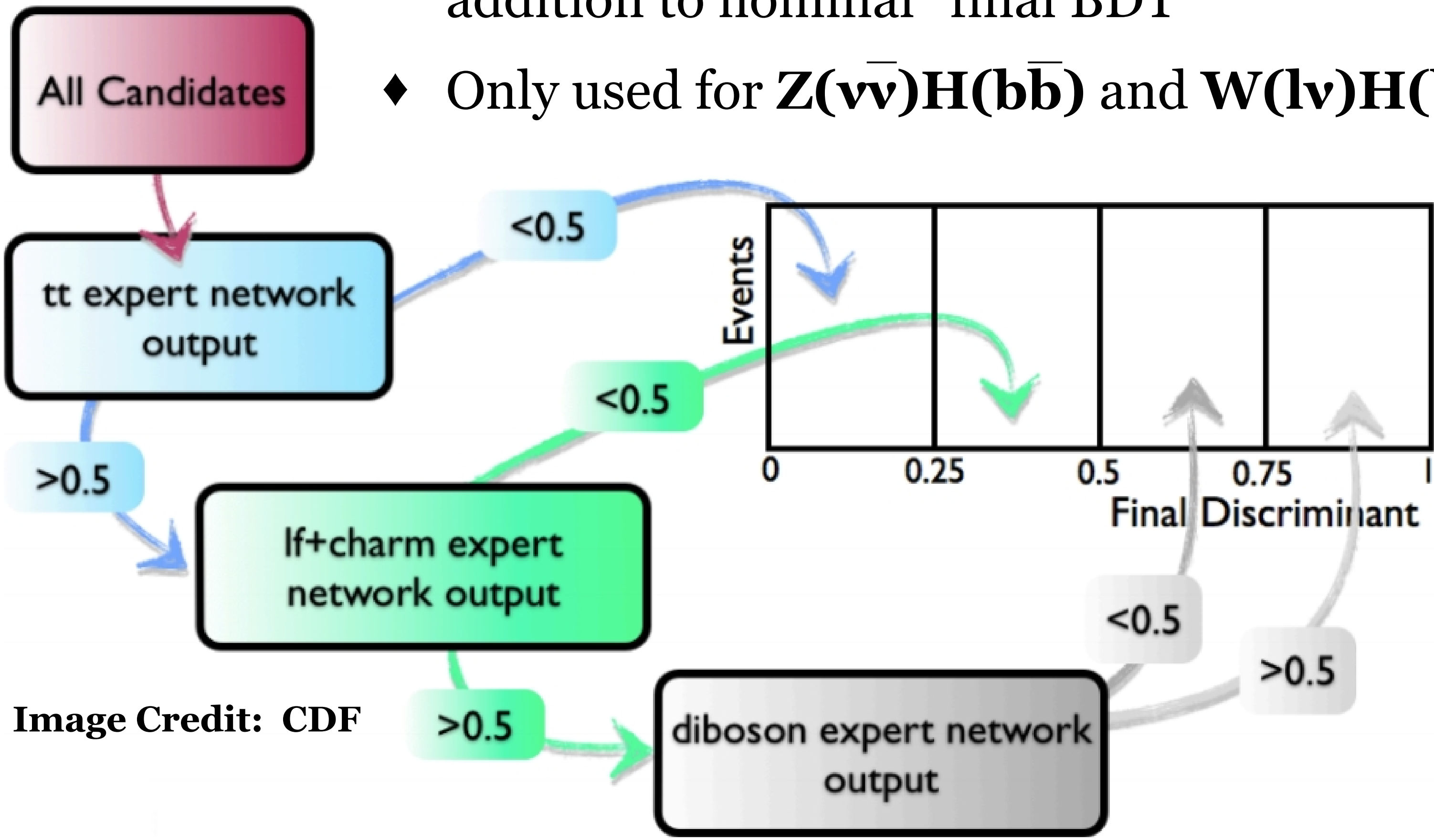
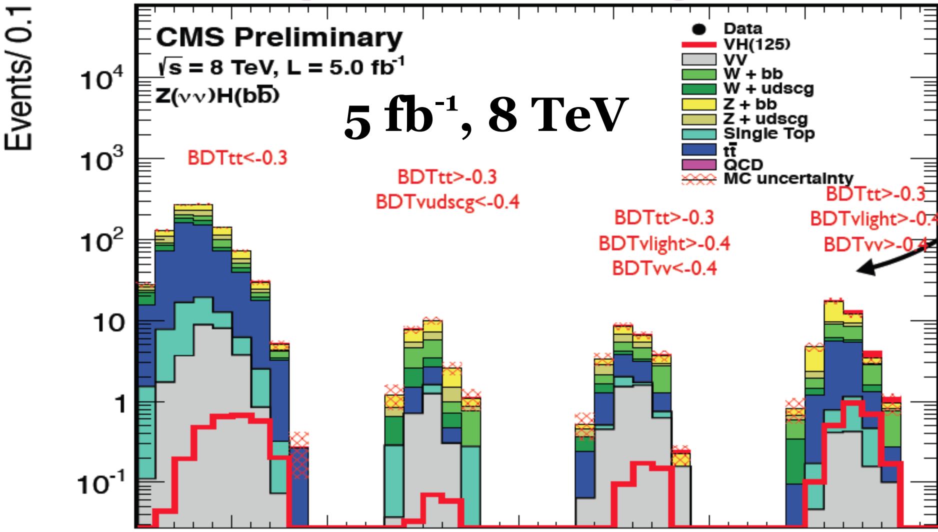


Image Credit: CDF

Multi-BDT Example

regular bdt trained with all bkgs

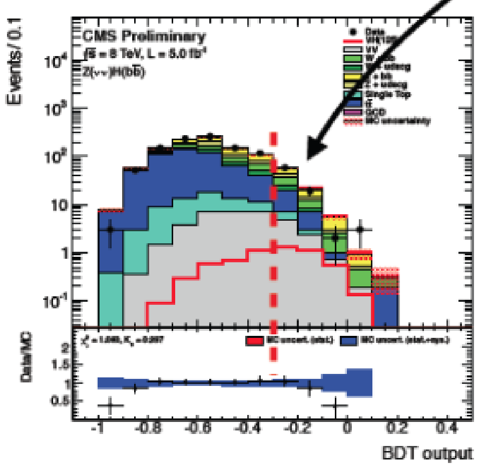


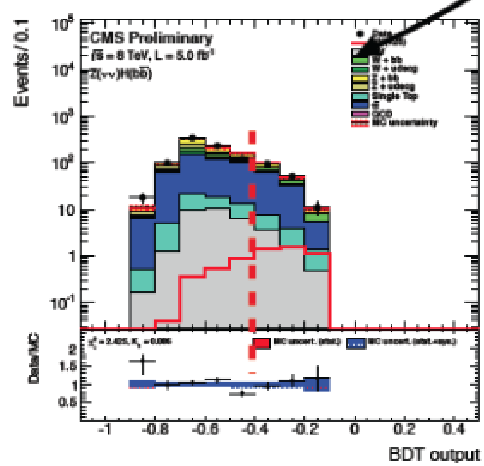
High S/B in last two bins

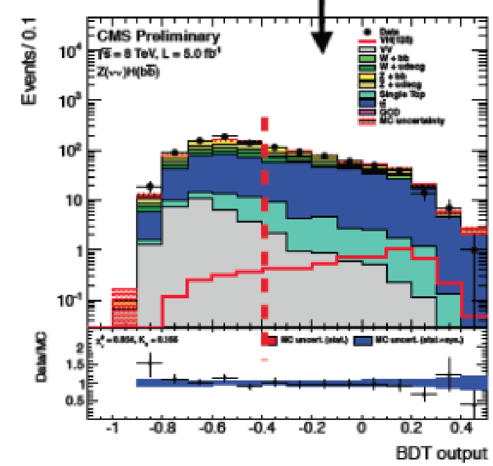
~10% Sensitivity Gain

Targeted Background →	$t\bar{t}$	Vudscg	VV
4 most discriminant variables	Jet multiplicity ΔΦ(j,MET) H.mass MinCsv	MinCsv MaxCsv H.mass Jet multiplicity	H.mass H.pt MET MinCSV

Z($\nu\bar{\nu}$)H($b\bar{b}$)

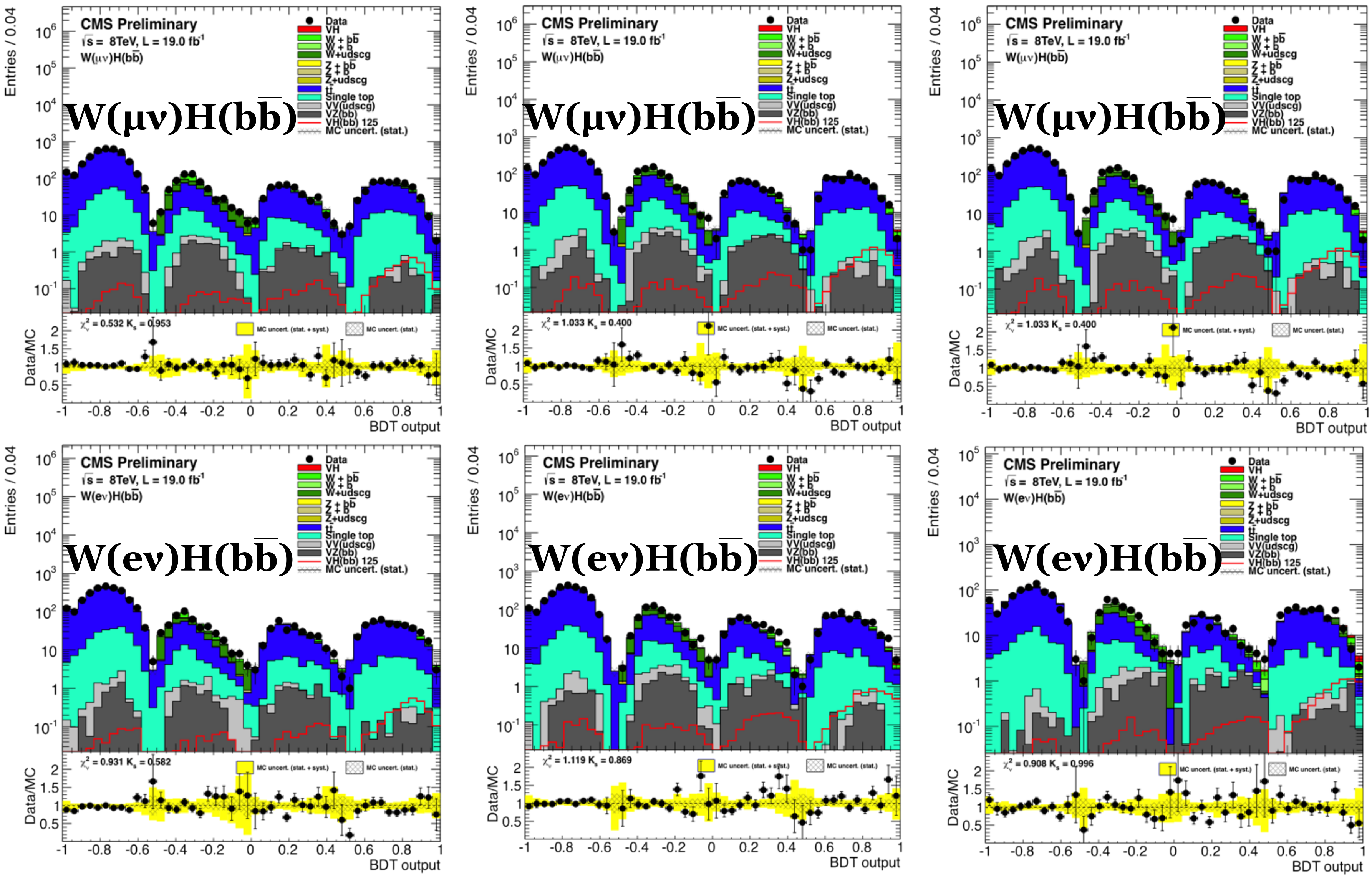






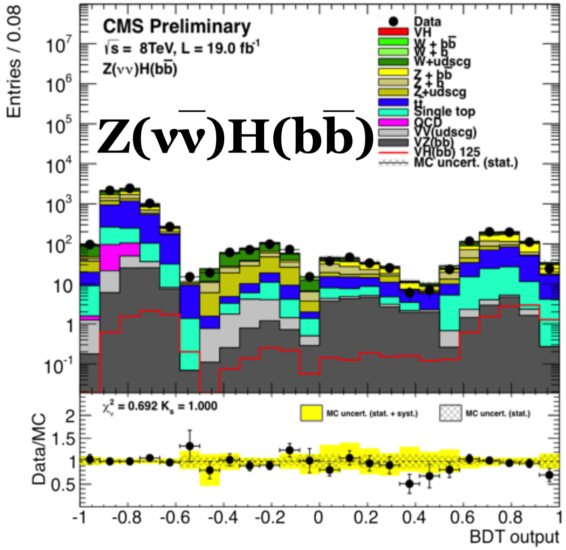
Post-fit BDT Plots

Low $p_T(V)$ | **Medium $p_T(V)$** | **High $p_T(V)$**

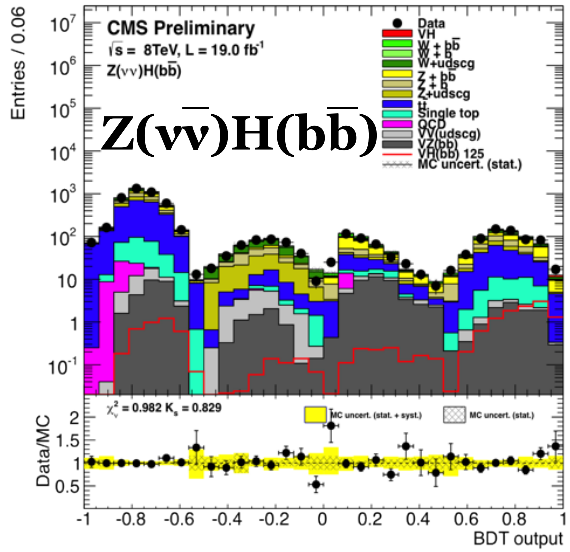


Post-fit BDT Plots

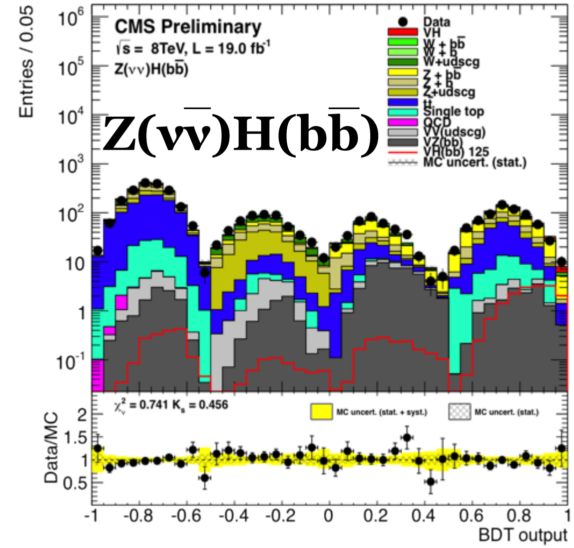
Low $p_T(V)$

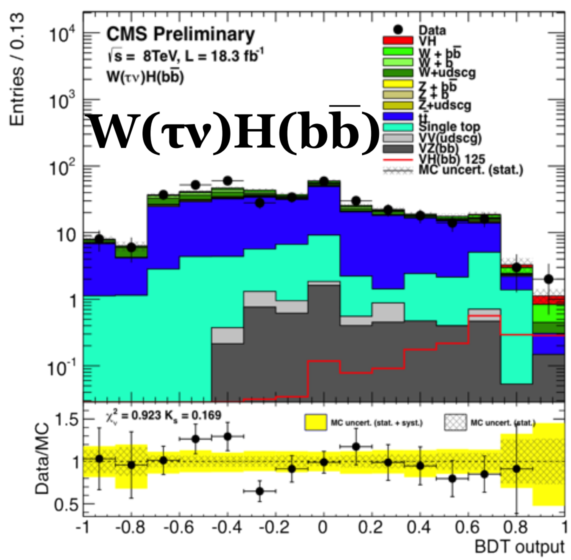


Medium $p_T(V)$



High $p_T(V)$

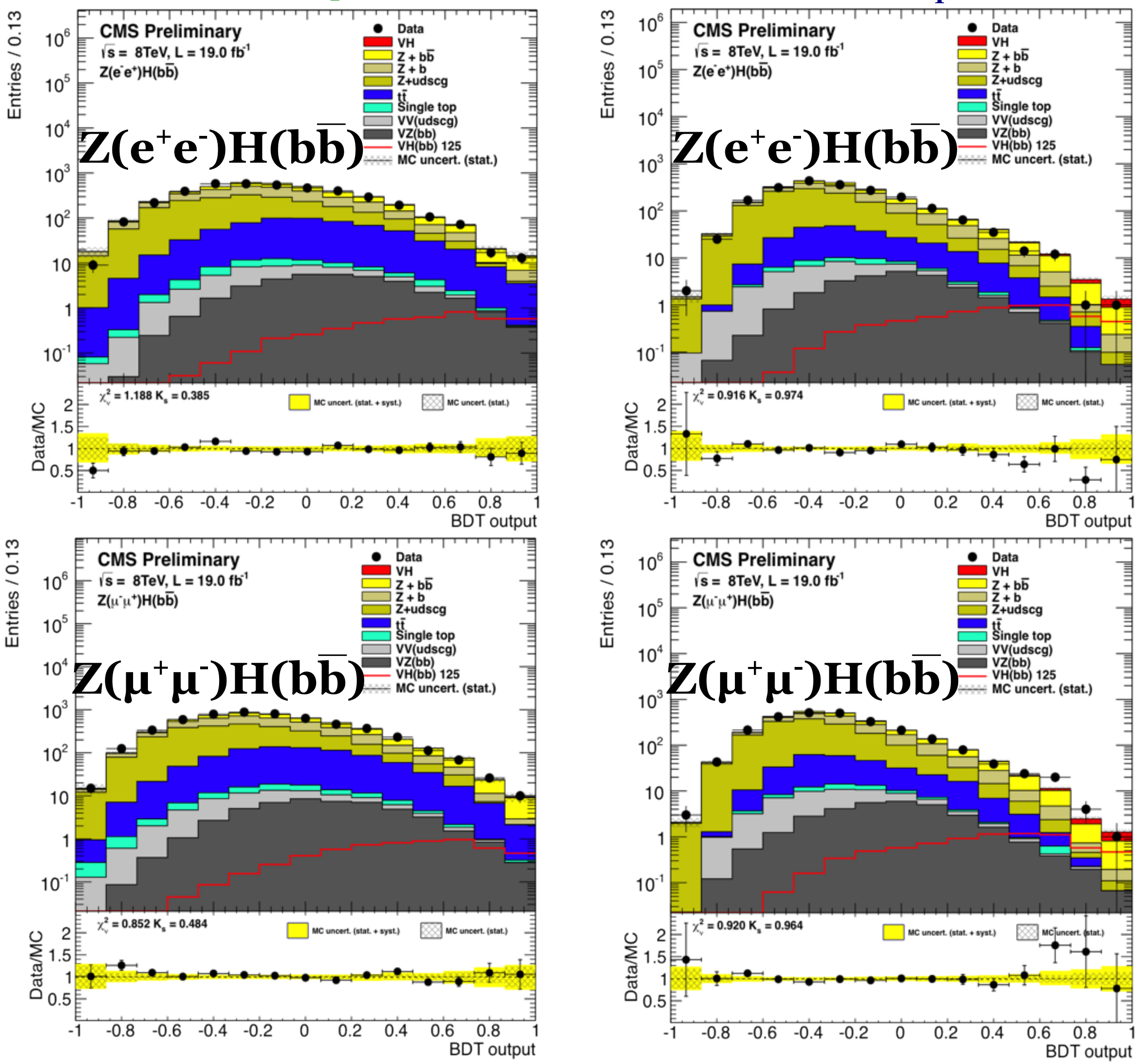




Only One Category for W(τν)H(bb̄) (120+ GeV)

Post-fit BDT Plots

Low $p_T(V)$ | **High $p_T(V)$**

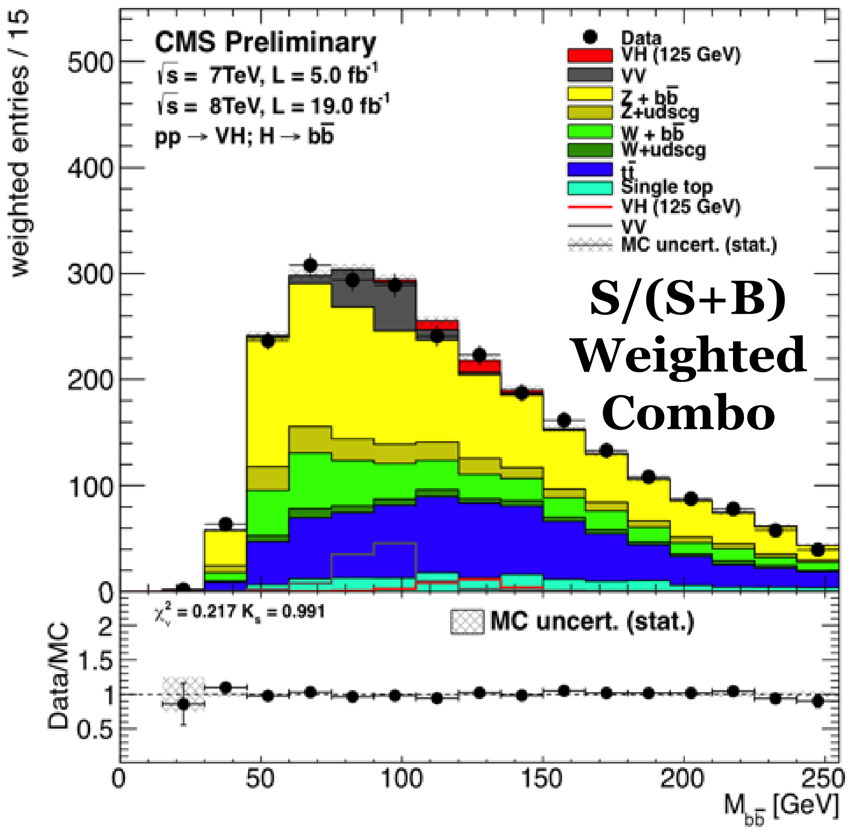


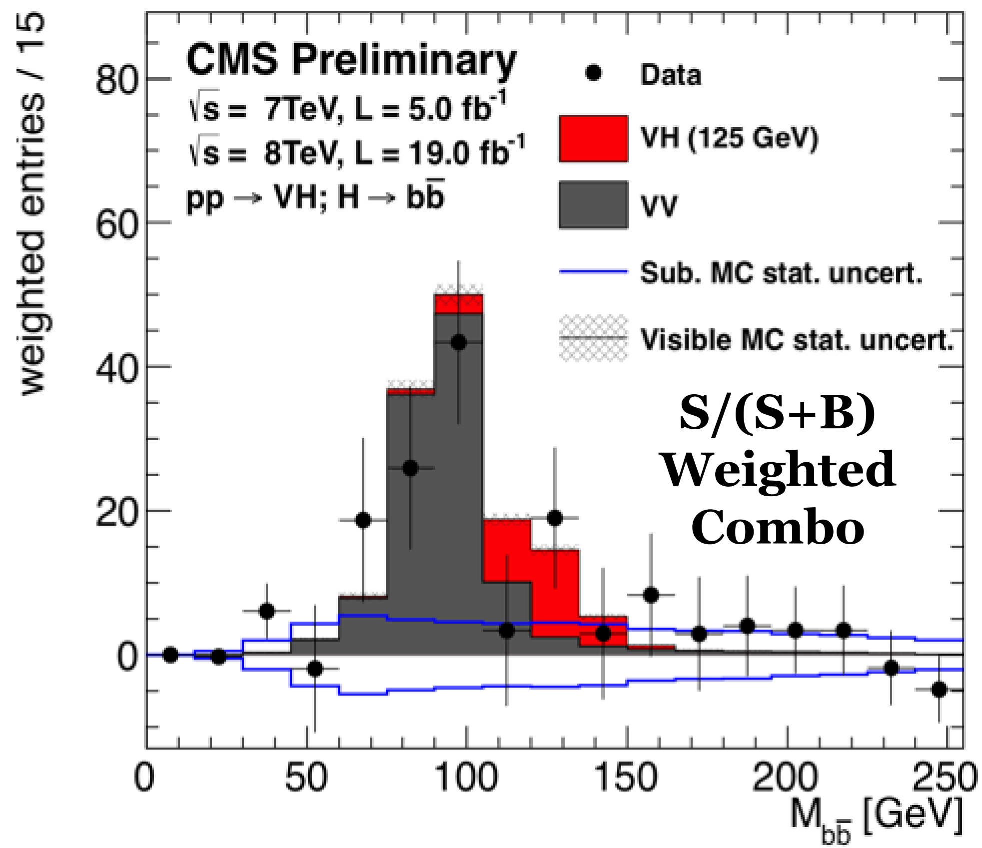
Systematics

- Use up/down **shape** systematics for MC BDT shapes in fit, obtained via propagation of mis-tag, b-tag, JES, JER, and PU uncertainties
- **Normalization** systematics for other contributions (including uncertainty on data/MC scale factors for background estimation)

Source	Type	Yield uncertainty (%) range	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
Luminosity	norm.	2.2–4.4	< 2	< 0.1
Lepton efficiency and trigger (per lepton)	norm.	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)	norm.	4	3.9	0.3
Signal cross section (p_T boost, EWK/QCD)	norm.	2/5	3.9	0.3
Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	norm.	10	15.9	5.2
Single-top (simulation estimate)	norm.	15	5.0	0.5
Dibosons (simulation estimate)	norm.	15	5.0	0.5
MC modeling (V+jets and $t\bar{t}$)	shape	10	7.4	1.1

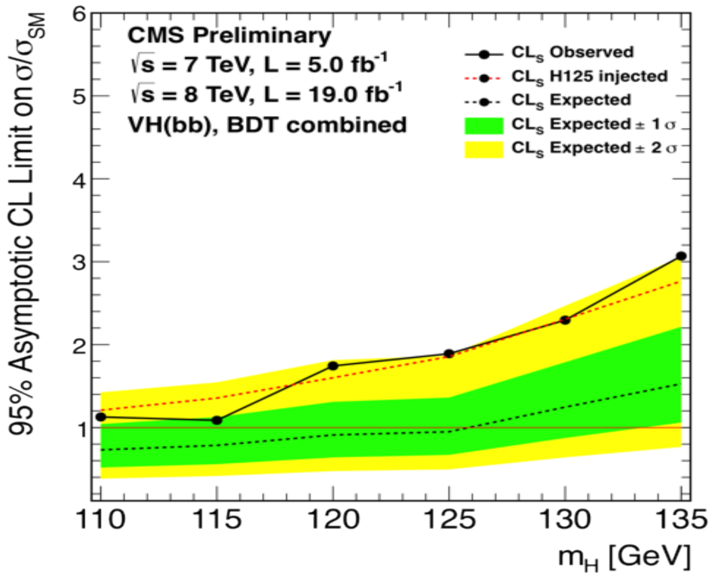
Combined M(jj) Distribution



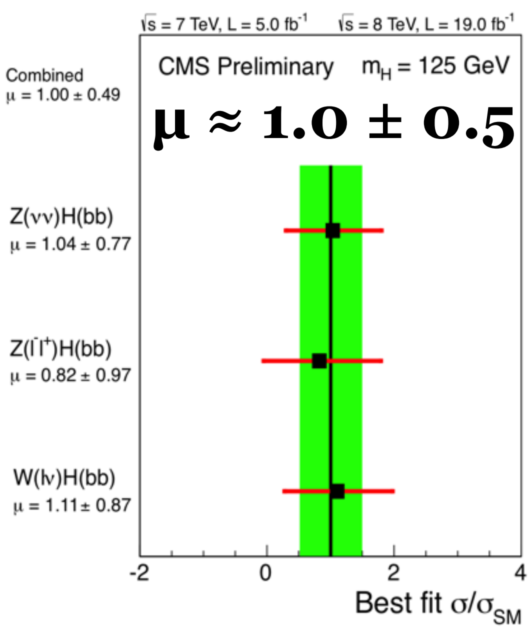


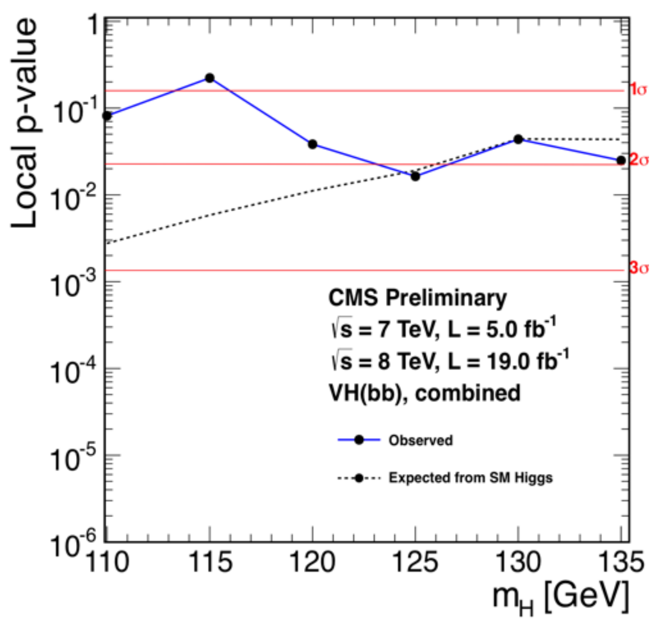
- Can see well-defined VV peak (**7.5 σ** with 8 TeV alone)
  - Measure **μ_{VV} ≈ 1.19 ± 0.25** – important cross-check for VH analysis
- Suggestive, small excess in neighborhood of 125 GeV

Results



- Compute limits and p-values using full CL_s frequentist calculation
- Find broad **excess** for 120+ GeV
- Expected limit (125 GeV): **0.95*SM**
- Observed limit (125 GeV): **1.89*SM**

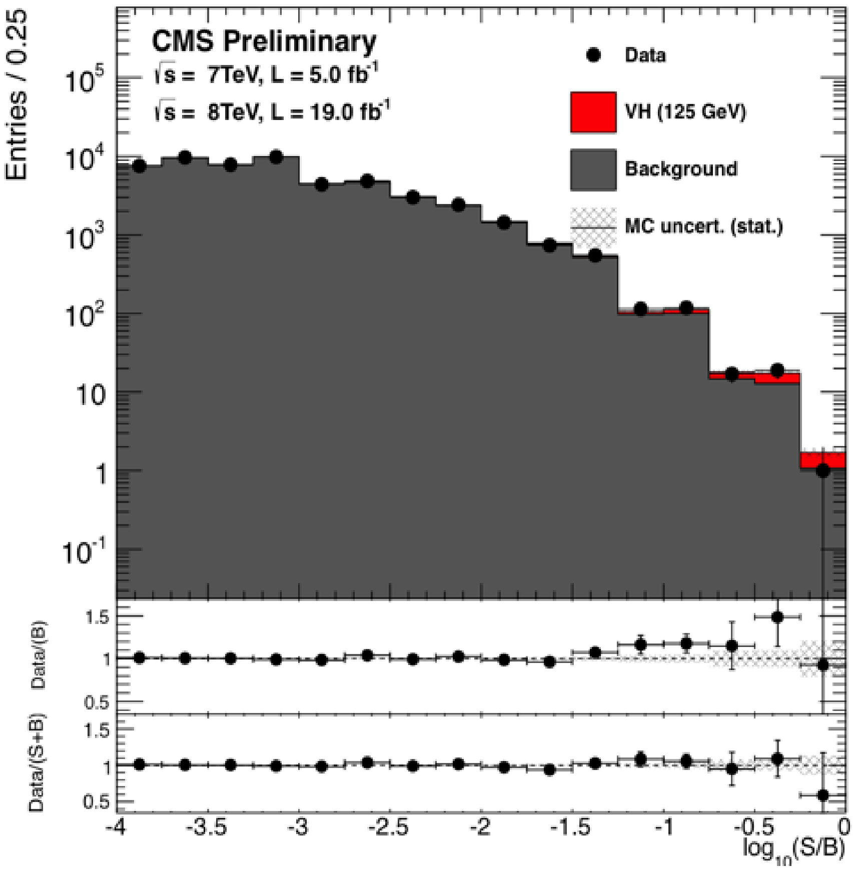




- Expected signif. (125 GeV): **2.1 σ**
- Observed signif. (125 GeV): **2.1 σ**
- Find similar signal strength in all modes @ 125 GeV

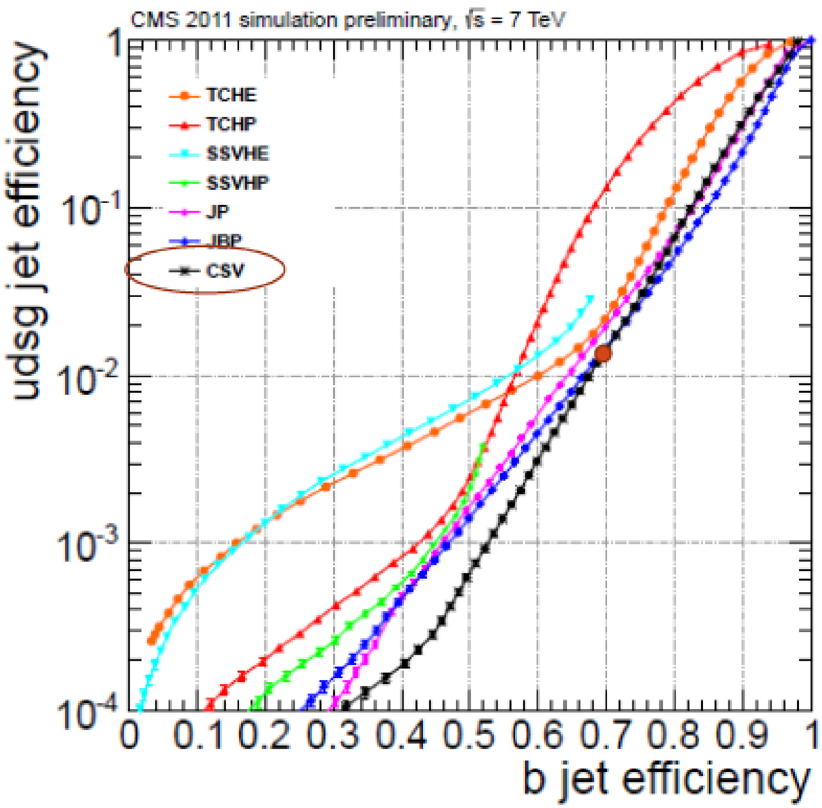
Summary

- **VH($b\bar{b}$) search results:**
  - 125 GeV signal strength: **1.0 ± 0.5**
  - 125 GeV limits:
    - Expected: **0.95**
    - Observed: **1.89**
  - 125 GeV significance:
    - Expected: **2.1 σ**
    - Observed: **2.1 σ**
- **VV($b\bar{b}$) cross-check results:**
  - Signal strength: **1.19 ± 0.25**
  - Expected significance: **6.1 σ**
  - Observed significance: **7.5 σ**

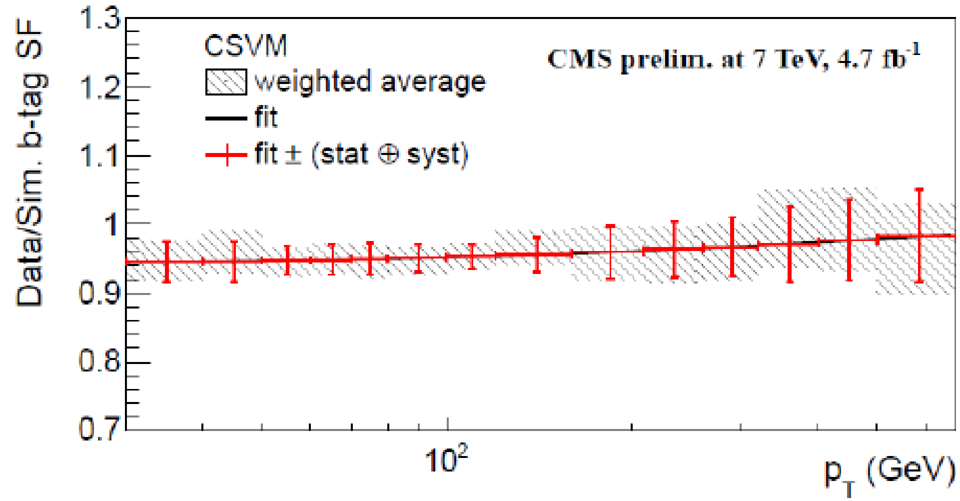


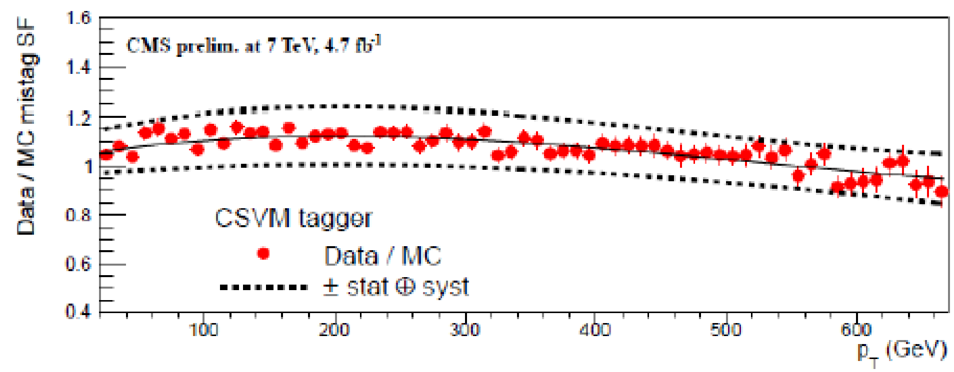
BACKUP SLIDES

b-tagging Performance



Calibrated on ttbar data up to pT(j) > 600 GeV





Typical working point:

- Eff(sig) ~ 70%
- Eff(bkg) ~ 1%

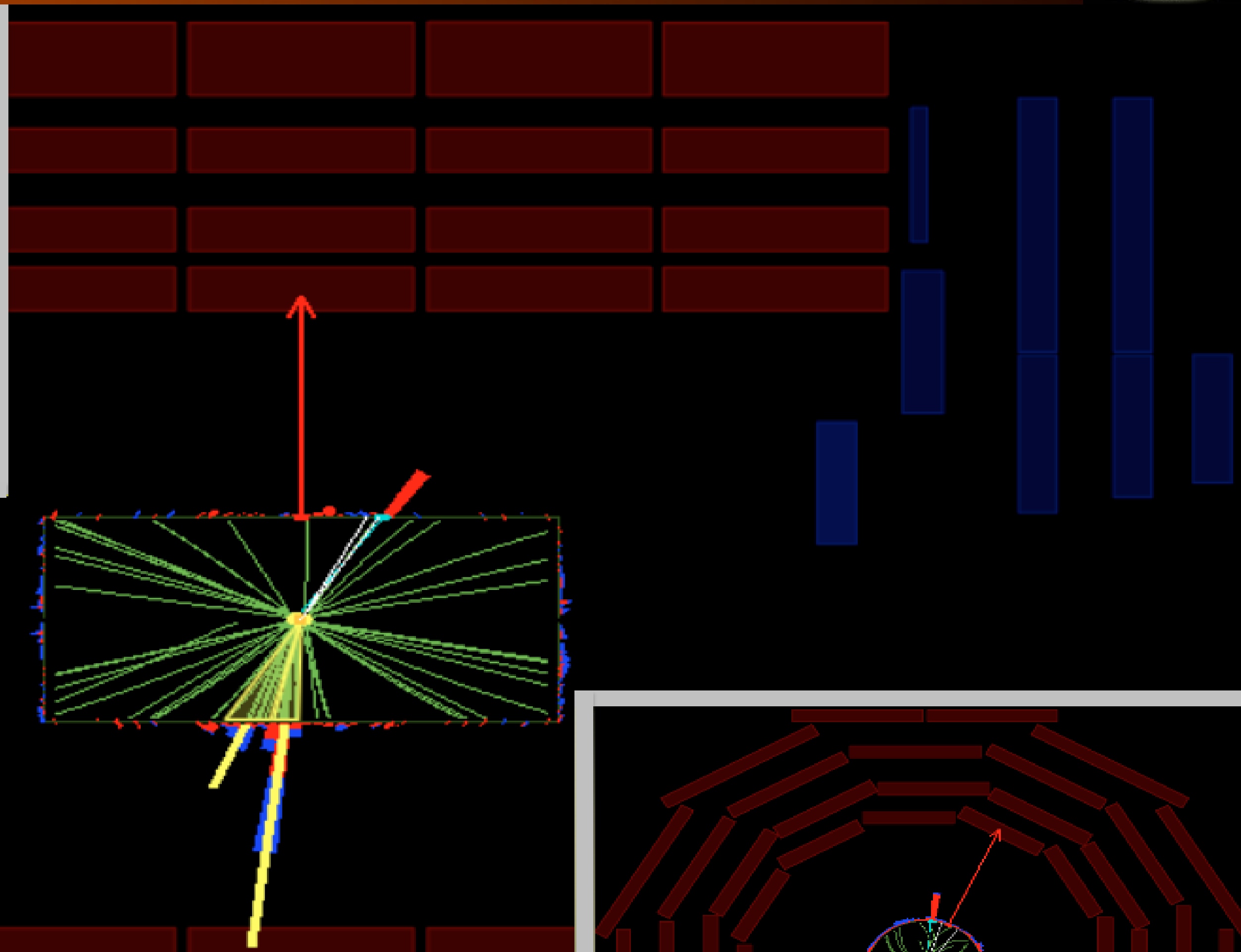
Corrected shapes used as input to BDT

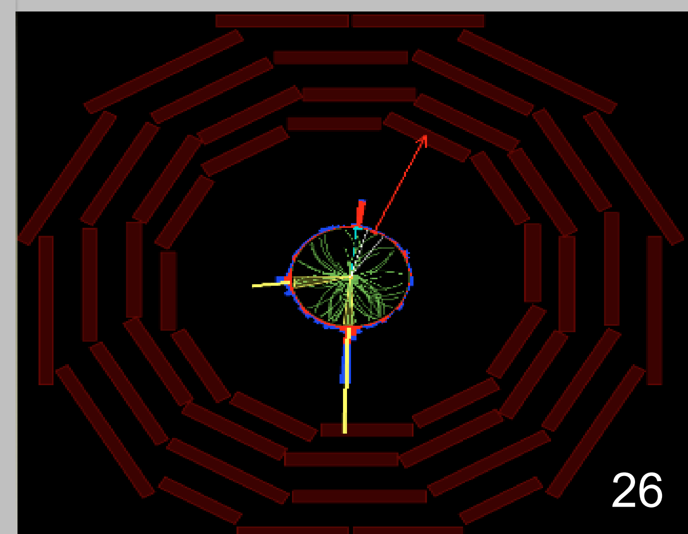
W(eν)H($b\bar{b}$) Event Display

W(eν)H($b\bar{b}$) Candidate

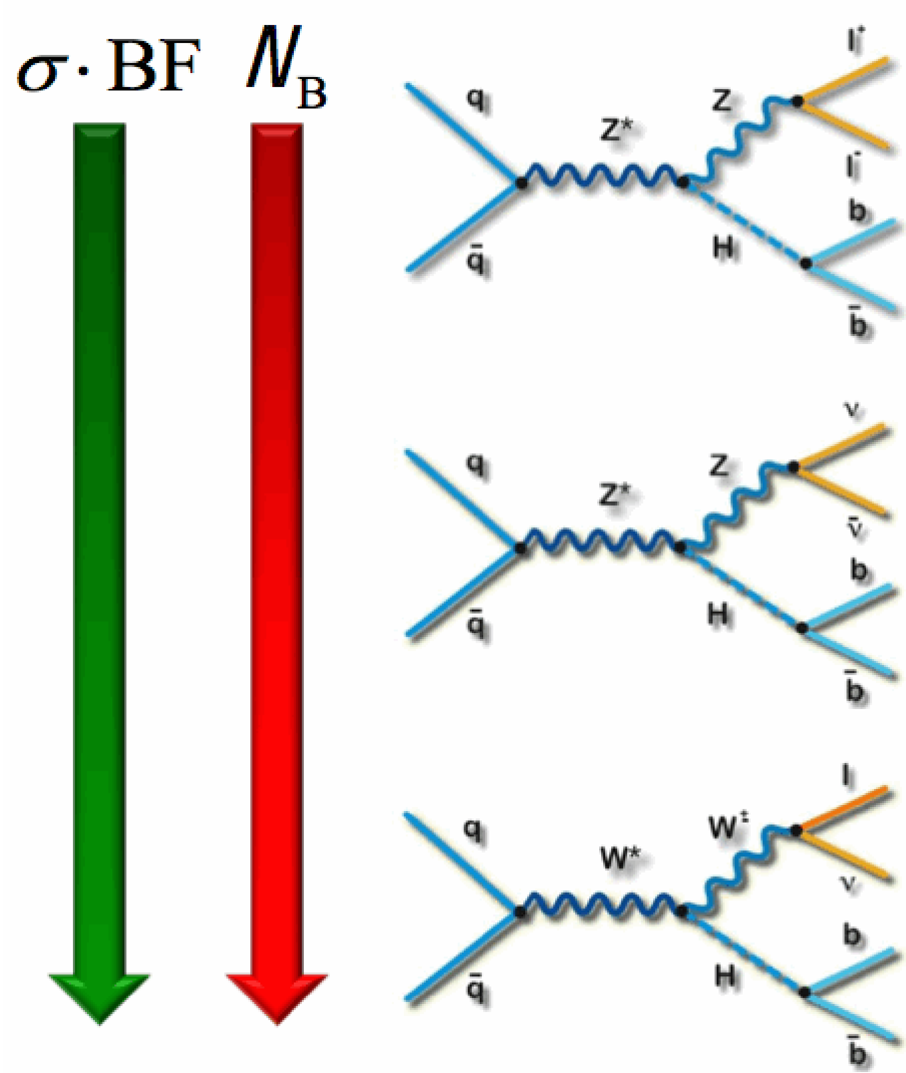
Run: 173389
Lumi: 485
Event: 654261640

M(jj): 114.5 GeV/c²
p_T(jj): 162.3 GeV/c
p_T(W): 187.6 GeV/c





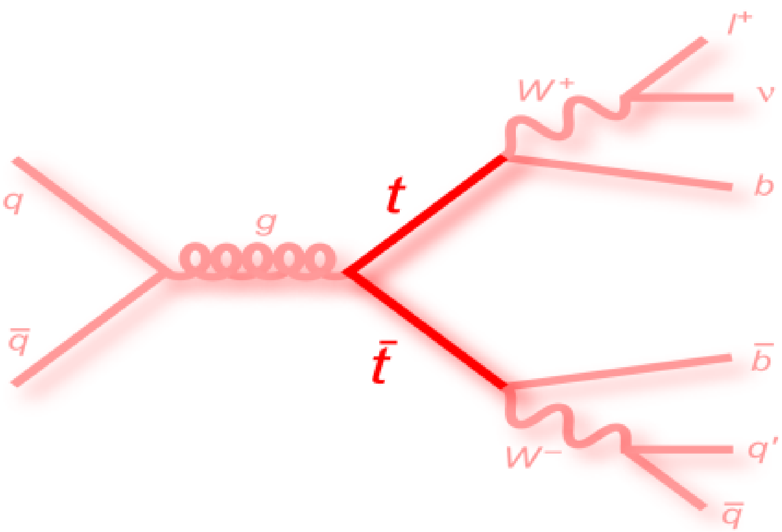
Signal



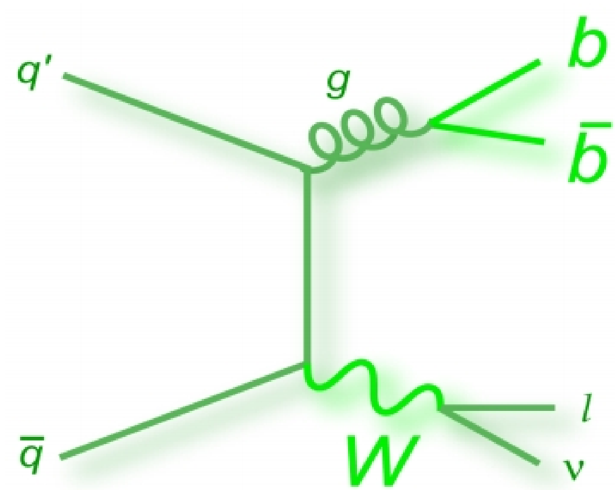
- **Z(l⁺l⁻)H(bb̄)**:
  - Cleanest mode
  - Least significant mode
  - Main bkg: Z+jets
- **Z(νν̄)H(bb̄)**:
  - High MET required (boosted $Z \rightarrow \nu\bar{\nu}$)
  - Main bkg: W/Z+jets, $t\bar{t}$
- **W(lν)H(bb̄)**:
  - Most significant mode
  - Main bkg: W+jets, $t\bar{t}$

Backgrounds

- **Reducible backgrounds**:
  - QCD (isolated leptons, $\Delta\varphi$(V,H), MET, b-tagging, $\Delta\varphi$(MET,$j_{nearest}$))
  - V+udscg (b-tagging, boost)
  - $t\bar{t}$ (additional jets)
  - Single top (additional jets)



- **Irreducible backgrounds**:
  - V+$b\bar{b}$ (boost)
  - Z(ll,νν)Z($b\bar{b}$) (M(jj))
  - W(lν)Z($b\bar{b}$) (M(jj))



Scale Factors (HCP)

Process	W($\ell\nu$)H	W($\ell\nu$)H	Z($\ell\ell$)H	Z($\ell\ell$)H	Z($\nu\nu$)H	Z($\nu\nu$)H
Low p_T	7 TeV	8 TeV	7 TeV	8 TeV	7 TeV	8 TeV
W + udscg	$0.88 \pm 0.01 \pm 0.03$	$1.01 \pm 0.02 \pm 0.01$	–	–	$0.89 \pm 0.01 \pm 0.03$	$0.96 \pm 0.06 \pm 0.03$
W$b\bar{b}$	$1.91 \pm 0.14 \pm 0.31$	$2.07 \pm 0.15 \pm 0.10$	–	–	$1.36 \pm 0.10 \pm 0.15$	$1.30 \pm 0.17 \pm 0.10$
Z + udscg	–	–	$1.11 \pm 0.03 \pm 0.11$	$1.10 \pm 0.02 \pm 0.06$	$0.87 \pm 0.01 \pm 0.03$	$1.15 \pm 0.07 \pm 0.03$
Z$b\bar{b}$	–	–	$0.98 \pm 0.05 \pm 0.12$	$1.08 \pm 0.04 \pm 0.08$	$0.96 \pm 0.02 \pm 0.03$	$1.12 \pm 0.10 \pm 0.04$
$t\bar{t}$	$0.93 \pm 0.02 \pm 0.05$	$1.07 \pm 0.01 \pm 0.01$	$1.03 \pm 0.04 \pm 0.11$	$1.01 \pm 0.02 \pm 0.06$	$0.97 \pm 0.02 \pm 0.04$	$1.05 \pm 0.07 \pm 0.03$
High p_T	7 TeV	8 TeV	7 TeV	8 TeV	7 TeV	8 TeV
W + udscg	$0.79 \pm 0.01 \pm 0.02$	$0.94 \pm 0.02 \pm 0.01$	–	–	$0.78 \pm 0.02 \pm 0.03$	$0.95 \pm 0.05 \pm 0.02$
W$b\bar{b}$	$1.49 \pm 0.14 \pm 0.19$	$1.72 \pm 0.16 \pm 0.08$	–	–	$1.48 \pm 0.15 \pm 0.20$	$1.27 \pm 0.18 \pm 0.10$
Z + udscg	–	–	$1.11 \pm 0.03 \pm 0.11$	$1.10 \pm 0.02 \pm 0.06$	$0.97 \pm 0.02 \pm 0.04$	$1.04 \pm 0.07 \pm 0.02$
Z$b\bar{b}$	–	–	$0.98 \pm 0.05 \pm 0.12$	$1.08 \pm 0.04 \pm 0.08$	$1.08 \pm 0.09 \pm 0.06$	$1.15 \pm 0.10 \pm 0.04$
$t\bar{t}$	$0.84 \pm 0.02 \pm 0.03$	$0.99 \pm 0.01 \pm 0.01$	$1.03 \pm 0.04 \pm 0.11$	$1.01 \pm 0.02 \pm 0.06$	$0.97 \pm 0.02 \pm 0.04$	$1.03 \pm 0.07 \pm 0.03$

Scale Factors (LHCp)

Process	$W(\ell\nu)H$	$Z(\ell\ell)H$	$Z(\nu\nu)H$
Low $p_T(V)$			
$W + udscg$	$1.03 \pm 0.01 \pm 0.05$	–	$0.83 \pm 0.02 \pm 0.04$
$W + b$	$2.22 \pm 0.25 \pm 0.20$	–	$2.30 \pm 0.21 \pm 0.11$
$W + b\bar{b}$	$1.58 \pm 0.26 \pm 0.24$	–	$0.85 \pm 0.24 \pm 0.14$
$Z + udscg$	–	$1.11 \pm 0.04 \pm 0.06$	$1.24 \pm 0.03 \pm 0.09$
$Z + b$	–	$1.59 \pm 0.07 \pm 0.08$	$2.06 \pm 0.06 \pm 0.09$
$Z + b\bar{b}$	–	$0.98 \pm 0.10 \pm 0.08$	$1.25 \pm 0.05 \pm 0.11$
$t\bar{t}$	$1.03 \pm 0.01 \pm 0.04$	$1.10 \pm 0.05 \pm 0.06$	$1.01 \pm 0.02 \pm 0.04$
Intermediate $p_T(V)$			
$W + udscg$	$1.02 \pm 0.01 \pm 0.07$	–	$0.93 \pm 0.02 \pm 0.04$
$W + b$	$2.90 \pm 0.26 \pm 0.20$	–	$2.08 \pm 0.20 \pm 0.12$
$W + b\bar{b}$	$1.30 \pm 0.23 \pm 0.14$	–	$0.75 \pm 0.26 \pm 0.11$
$Z + udscg$	–	–	$1.19 \pm 0.03 \pm 0.07$
$Z + b$	–	–	$2.30 \pm 0.07 \pm 0.08$
$Z + b\bar{b}$	–	–	$1.11 \pm 0.06 \pm 0.12$
$t\bar{t}$	$1.02 \pm 0.01 \pm 0.15$	–	$0.99 \pm 0.02 \pm 0.03$
High $p_T(V)$			
$W + udscg$	$1.04 \pm 0.01 \pm 0.07$	–	$0.93 \pm 0.02 \pm 0.03$
$W + b$	$2.46 \pm 0.33 \pm 0.22$	–	$2.12 \pm 0.22 \pm 0.10$
$W + b\bar{b}$	$0.77 \pm 0.25 \pm 0.08$	–	$0.71 \pm 0.25 \pm 0.15$
$Z + udscg$	–	$1.11 \pm 0.04 \pm 0.06$	$1.17 \pm 0.02 \pm 0.08$
$Z + b$	–	$1.59 \pm 0.07 \pm 0.08$	$2.13 \pm 0.05 \pm 0.07$
$Z + b\bar{b}$	–	$0.98 \pm 0.10 \pm 0.08$	$1.12 \pm 0.04 \pm 0.10$
$t\bar{t}$	$1.00 \pm 0.01 \pm 0.11$	$1.10 \pm 0.05 \pm 0.06$	$0.99 \pm 0.02 \pm 0.03$

Triggers

Triggers	7 TeV (2011)	8 TeV (2012)
W(μν)H Z(μμ)H	≥ 1 (isolated) muon $p_T^{\mu} > 17–40$ GeV/c	≥ 1 (isolated) muon $p_T^{\mu} > 24–40$ GeV/c
W(eν)H	≥ 1 isolated electron $p_T^{e} > 17–30$ GeV/c (≥ 2 jets for lower threshold)	≥ 1 isolated electron $p_T^{e} > 27$ GeV/c
Z(ee)H	≥ 2 isolated electrons $p_T^{e,1st} > 17$ GeV/c $p_T^{e,2nd} > 8$ GeV/c	≥ 2 isolated electrons $p_T^{e,1st} > 17$ GeV/c $p_T^{e,2nd} > 8$ GeV/c
Z(νν)H	MHT > 150 GeV OR ≥ 2 central jets pT > 20 GeV MET > 80-100 GeV	MHT > 150 GeV OR ≥ 2 central jets pT > 30 GeV, MET > 80 GeV

MC Generator Summary

Process	MC Generator
VH	Powheg
V+jets	Madgraph/Herwig
tt	Madgraph, Powheg (7 TeV, 8 TeV)
Single top	Powheg
VV	Pythia/Madgraph
QCD multijet	Pythia

CS Definitions

W(lν)H($b\bar{b}$)

Variable	W+LF	$t\bar{t}$	W+HF
$p_T(V)$	$[100-130][130,180][>180]$	$[100-130][130,180][>180]$	$[100-130][130,180][>180]$
$p_T(j_1)$	>30	>30	>30
$p_T(j_2)$	>30	>30	>30
$p_T(jj)$	>120	>120	>120
$m(jj)$	<250	<250	$<250, \notin [90-150]$
CSV_{max}	$[0.244-0.898]$	>0.898	>0.898
N_{aj}	<2	>1	$=0$
N_{al}	$=0$	$=0$	$=0$
E_T^{miss}	>45	>45	>45
E_T^{miss} significance	$>2.0(\mu)$ $>3.0(e)$	–	–

CS Definitions

$Z(l^+l^-)H(b\bar{b})$

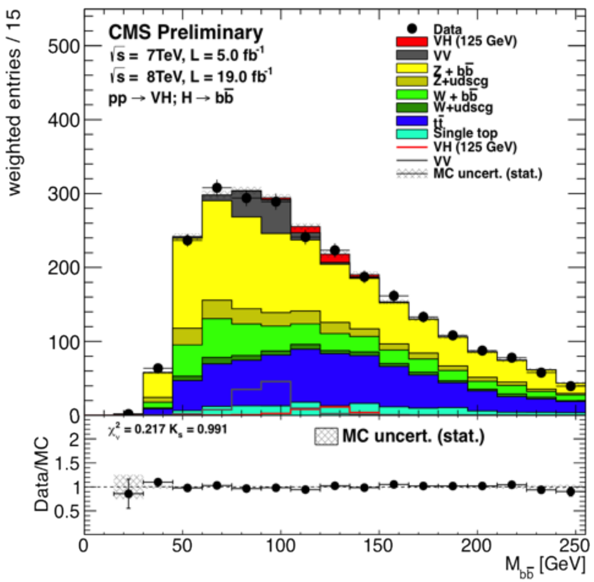
Variable	Z+jets	$t\bar{t}$
$m_{\ell\ell}$	$[75-105]$	$\notin [75-105]$
$p_T(j_1)$	> 20	> 20
$p_T(j_2)$	> 20	> 20
$p_T(V)$	> 50	$[50-100]$
$m(jj)$	$< 250, \notin [80-150]$	$< 250, \notin [80-150]$
CSV_{max}	> 0.244	> 0.244
CSV_{min}	> 0.244	> 0.244

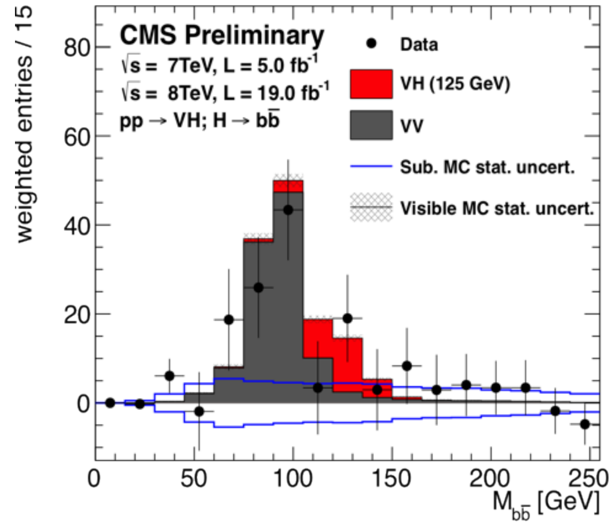
CS Definitions

$Z(\nu\bar{\nu})H(b\bar{b})$

Variable	Z+LF	Z+HF	$t\bar{t}$	W+LF	W+HF
E_T^{miss}	[100 – 130] [130 – 170] [> 170]	[100 – 130] [130 – 170] [> 170]	[100 – 130] [130 – 170] [> 170]	[100 – 130] [130 – 170] [> 170]	[100 – 130] [130 – 170] [> 170]
$p_T(j_1)$	> 60	> 60	> 60	> 60	> 60
$p_T(j_2)$	> 30	> 30	> 30	> 30	> 30
$p_T(jj)$	[> 100][> 130] [> 130]	[> 100][> 130] [> 130]	[> 100][> 130] [> 130]	[> 100][> 130] [> 130]	[> 100][> 130] [> 130]
$m(jj)$	< 250	< 250, ∉ [100 – 140]	< 250, ∉ [100 – 140]	< 250	< 250, ∉ [100 – 140]
CSV_{max}	[0.244 – 0.898]	> 0.679	> 0.898	[0.244 – 0.898]	> 0.679
CSV_{min}	–	> 0.244	–	–	> 0.244
N_{aj}	[< 2] [–] [–]	[< 2] [–] [–]	≥ 1	= 0	= 0
N_{al}	= 0	= 0	= 1	= 1	= 1
$\Delta\phi(V, H)$	–	> 2.0	–	–	> 2.0
$\Delta\phi(E_T^{miss}, jet)$	[> 0.7] [> 0.7] [> 0.5]	[> 0.7] [> 0.7] [> 0.5]	[> 0.7] [> 0.7] [> 0.5]	[> 0.7] [> 0.7] [> 0.5]	[> 0.7] [> 0.7] [> 0.5]
$\Delta\phi(E_T^{miss}, E_T^{miss}(tracks))$	< 0.5	< 0.5	–	–	–
E_T^{miss} significance	[> 3] [–] [–]	[> 3] [–] [–]	[> 3] [–] [–]	[> 3] [–] [–]	[> 3] [–] [–]

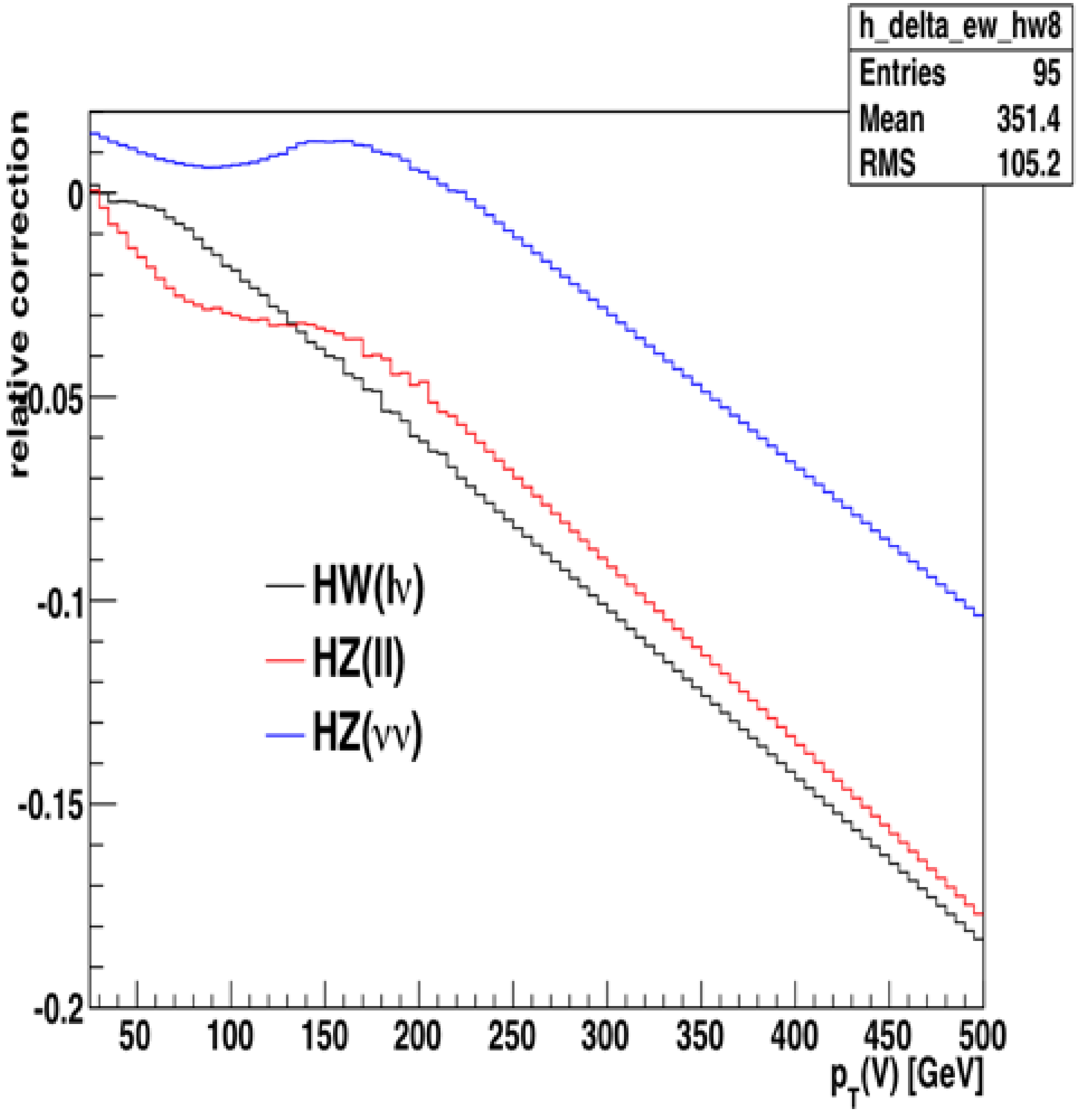
$M(b\bar{b})$ Plot Selection



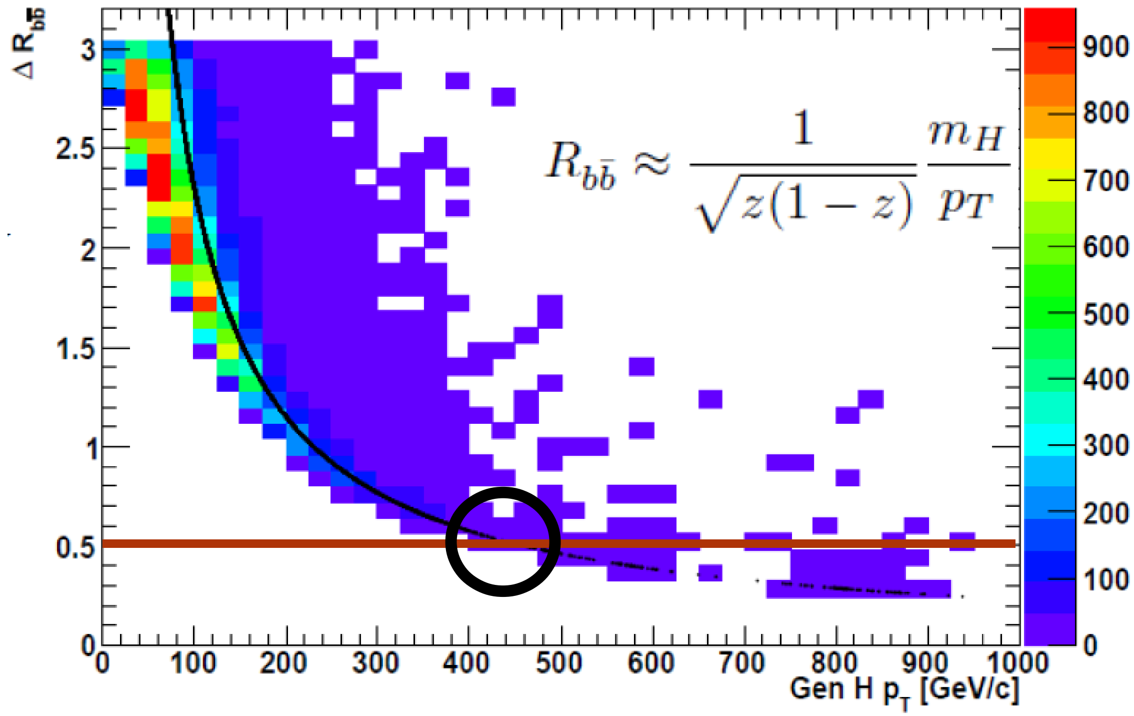


Variable	$W(\mu\nu)H$	$W(e\nu)H$	$W(\tau\nu)H$	$Z(\ell\ell)H$	$Z(\nu\nu)H$
$p_T(V)$	$[100-130][130-180][>180]$	$[100-150][>150]$	$[<250]$	$[50-100][100-150][>150]$	$[100-130][130-170][>170]$
$m_{\ell\ell}$	–	–	–	$75 < m_{\ell\ell} < 105$	–
$p_T(j_1)$	>30	>30	>30	>20	$[>60][>60][>80]$
$p_T(j_2)$	>30	>30	>30	>20	>30
$p_T(jj)$	>100	>100	>120	–	$[>110][>140][>190]$
N_{aj}	$=0$	$=0$	$=0$	–	$=0$
N_{al}	$=0$	$=0$	>80	–	$=0$
E_T^{miss}	>45	>45	–	$<60.$	–
$p_T(\tau)$	–	–	>40	–	–
$p_T(track)$	–	–	>20	–	–
CSV_{max}	0.898	0.898	0.898	0.679	0.898
CSV_{min}	>0.5	>0.5	>0.4	>0.5	>0.5
$\Delta\phi(V,H)$	>2.95	>2.95	>2.95	–	>2.95
$\Delta R(jj)$	–	–	$=0$	$[-][-][<1.6]$	–
$\Delta\phi(E_T^{miss}, jet)$	–	–	–	–	$[>0.7][>0.7][>0.5]$
$\Delta\phi(E_T^{miss}, E_T^{miss}(tracks))$	–	–	–	–	<0.5
$\Delta\phi(E_T^{miss}, \ell)$	$<\pi/2$	$<\pi/2$	–	–	–

New EWK NLO Corrections



Jet Sub-structure



- For AK5 jets, b-jets from Higgs decay begin merging above 400 GeV
- Sub-structure not necessary at 8 TeV but sensitivity gains are possible even now (5-10%, preliminary)
- First attempts are reasonably straight-forward (additional BDT training variables) but more complex ideas are being investigated