THE UNIVERSITY *of* WISCONSIN MADISON

Higgs Couplings to Fermions at CMS

Isobel Ojalvo
on Behalf of
the CMS Collaboration

3/3/15

Overview

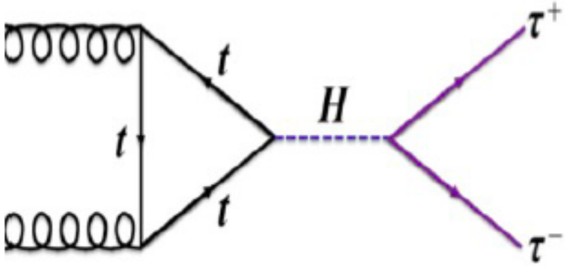
H->bb arXiv:1310.3687

ttH Combination arXiv:1408.1682

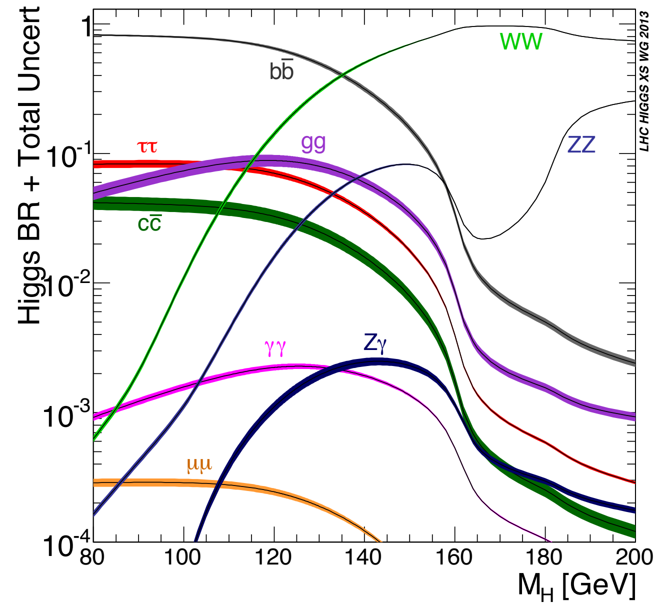
ttH H->bb with MEM arXiv:1502.02485

H->ττ arXiv:1401.5041

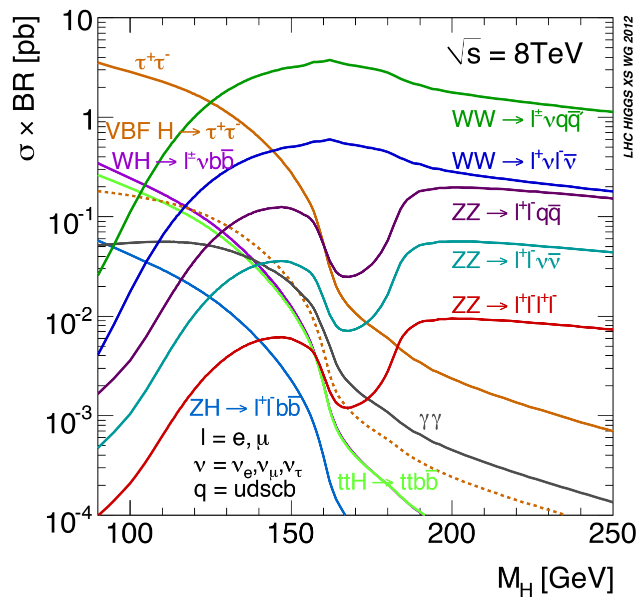
Overview



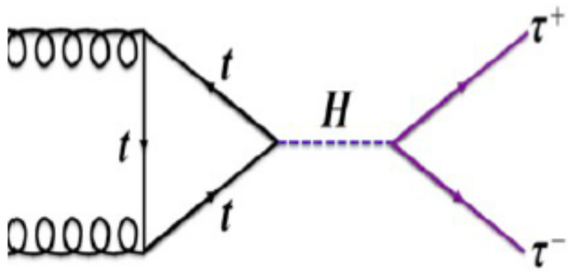
H→ττ



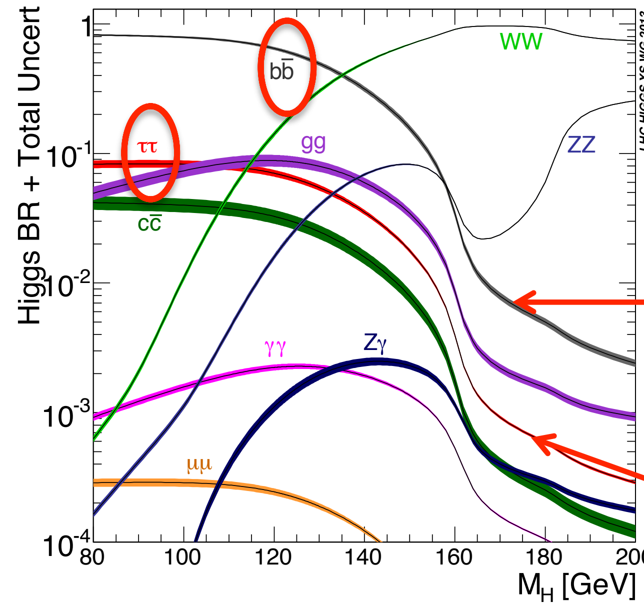
VH→bb



Overview



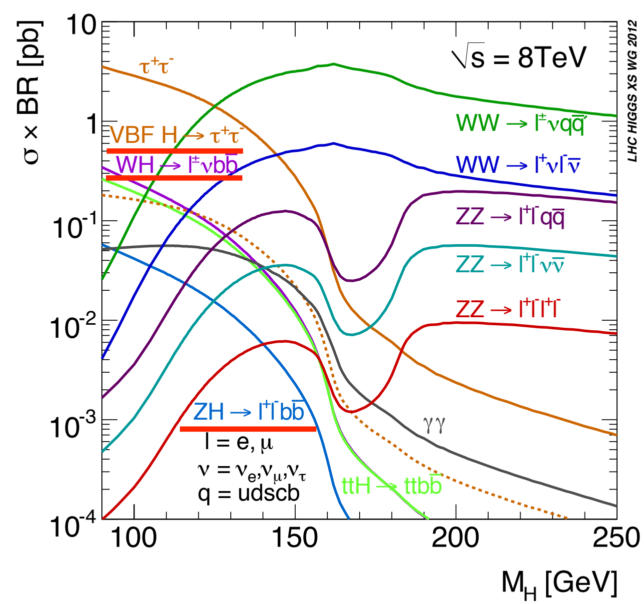
H→ττ



gg/qq->bb background

Z->ττ background

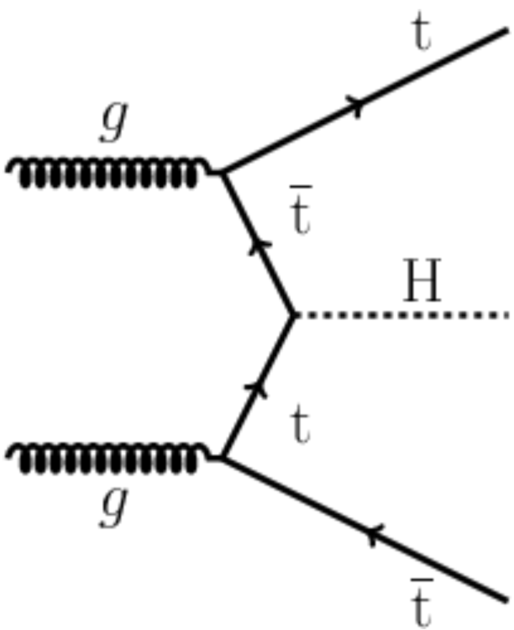
VH→bb



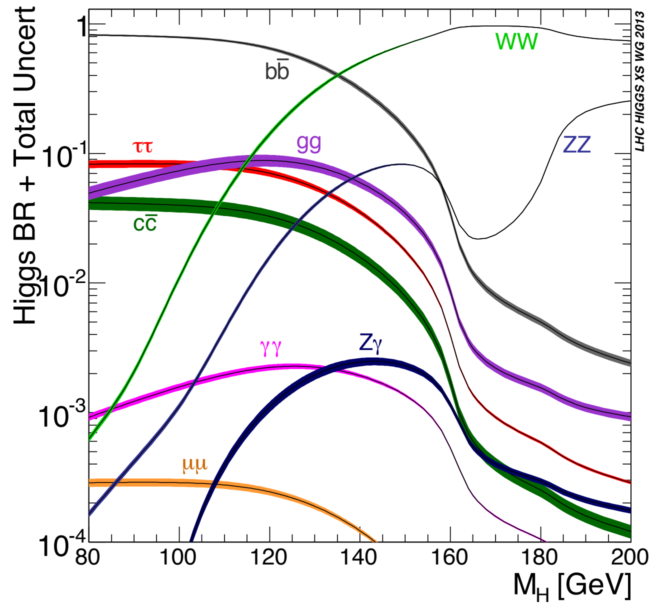
Associated production W/Z+H

Utilize VBF channel to reduce Z->ττ

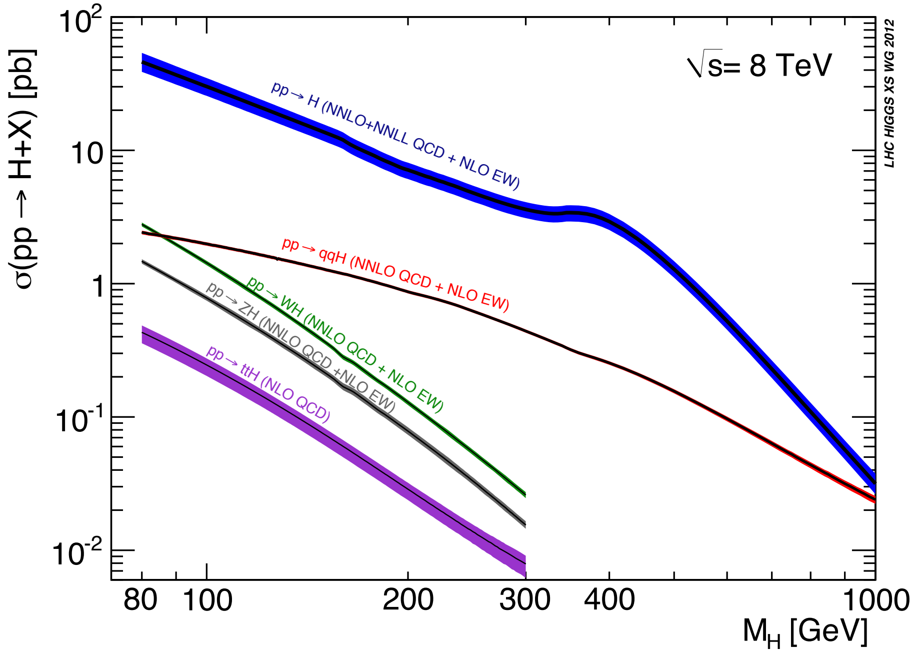
Overview



g
t
t̄
H
t
g
t̄

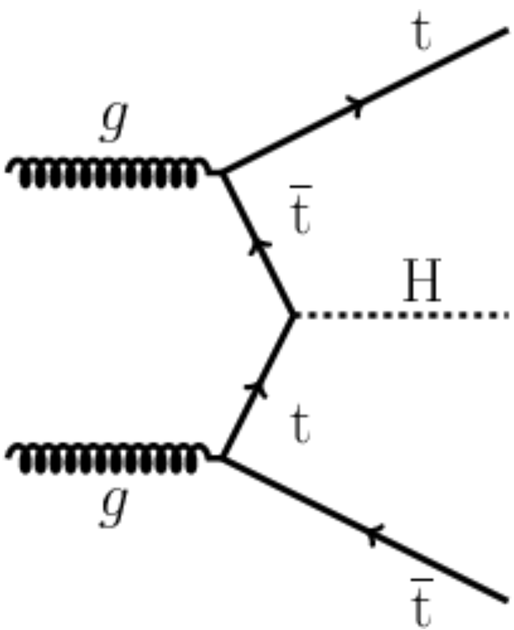


Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
bb̄
WW
ττ
gg
cc̄
ZZ
γγ
Zγ
μμ
M_H [GeV]

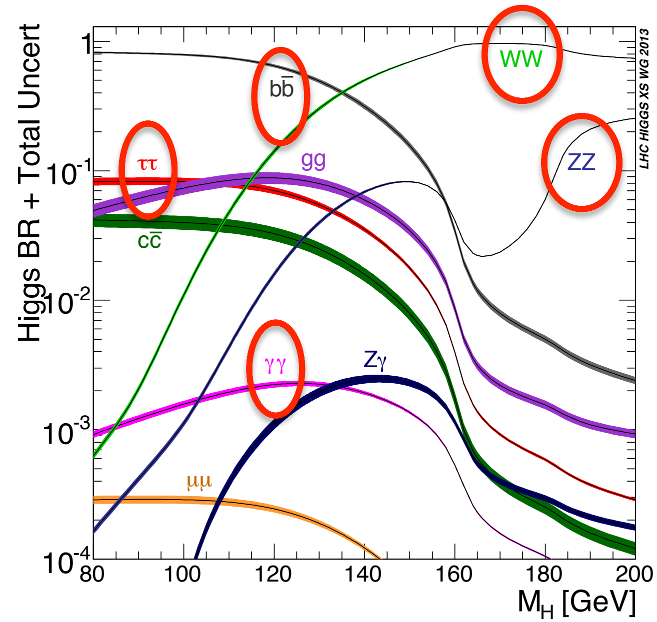


σ(pp → H+X) [pb]
√s= 8 TeV
LHC HIGGS XS WG 2012
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
M_H [GeV]

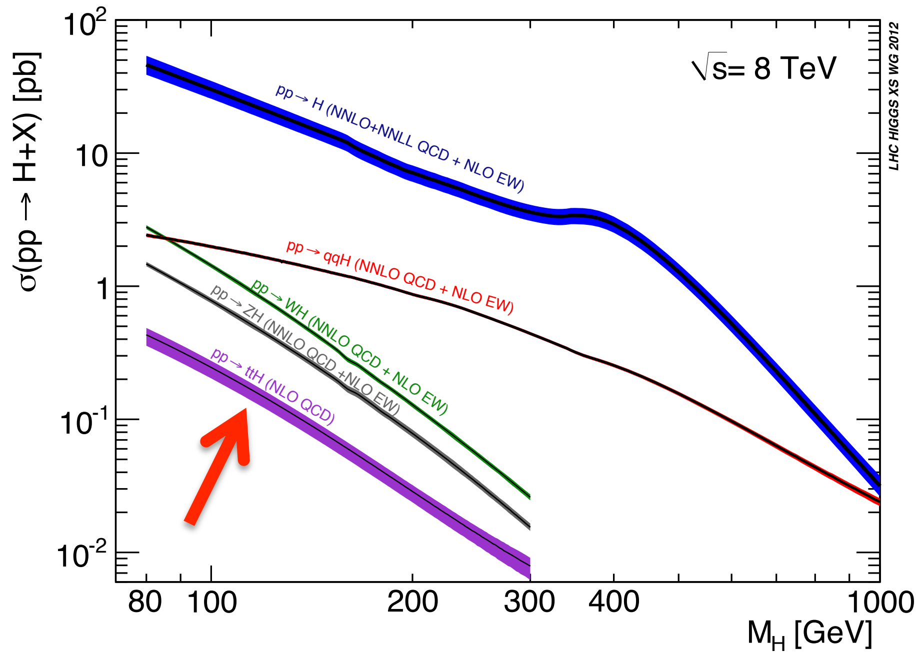
Overview



g
t
t̄
H
t
g
t̄



Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
bb̄
WW
ττ
gg
ZZ
cc̄
γγ
Zγ
μμ
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]



σ(pp → H+X) [pb]
LHC HIGGS XS WG 2012
√s= 8 TeV
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
10^2
10
1
10^{-1}
10^{-2}
80
100
200
300
400
1000
M_H [GeV]

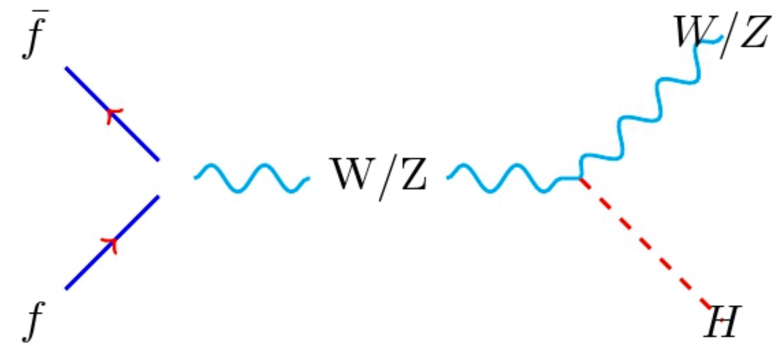
VH→bb: Overview

Motivation:

SM Higgs (125 GeV) has a high Branching Fraction to bb

Event Selection based on reconstruction of Vector Bosons + 2 b-Jets

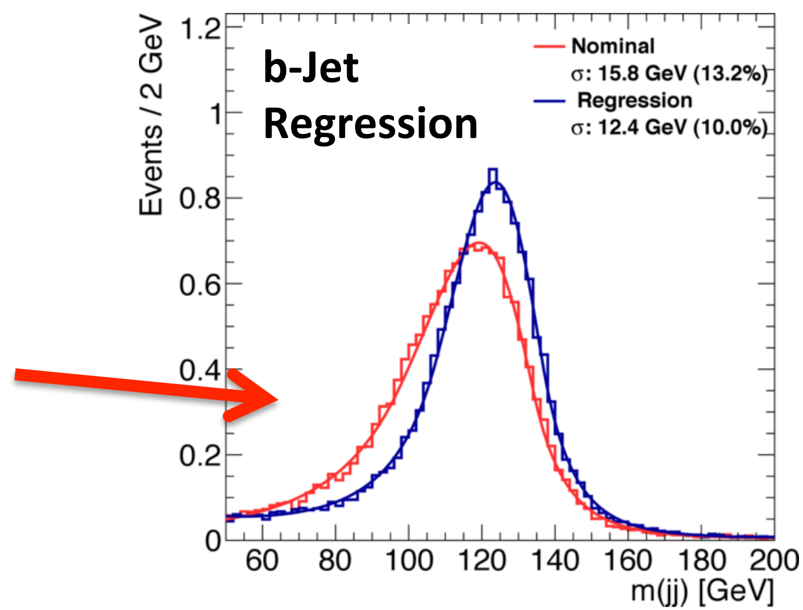
V and H bosons recoil away with large azimuthal opening angle ΔΦ (V,H)



Strategy:

Consider all W->leptons, Z->leptons channels

- Each channel has very different backgrounds, selects p_T(V) boost regions
- Reconstruction of H->bb decay is initiated by selecting di-jet pairs with highest p_T and then requiring b-tagging
- In order to improve the m(JJ) resolution, b-jet regression estimates the true p_T of the b-jet



Multivariate discriminant based on BDT created from discriminating variables

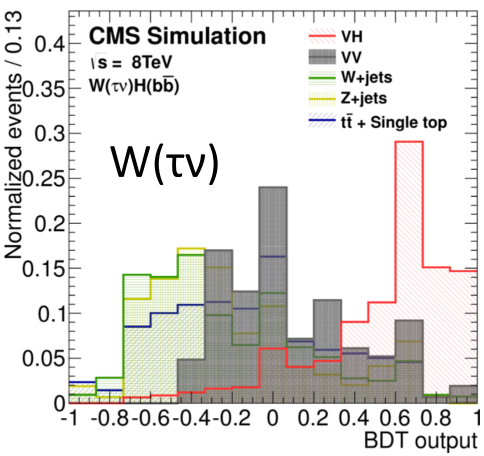
- **Used to extract signal**

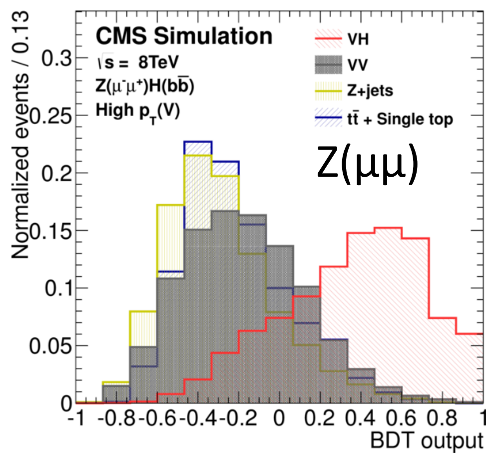
VH→bb: Analysis Channels

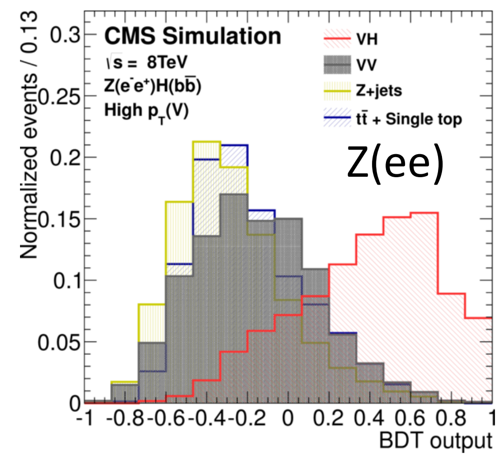
Channels Z(μμ) H, Z(ee) H, W(τν) H

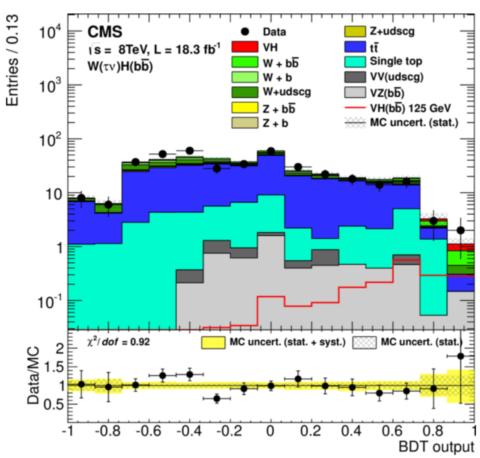
To Extract Signal: Single BDT using discriminating variables as the input

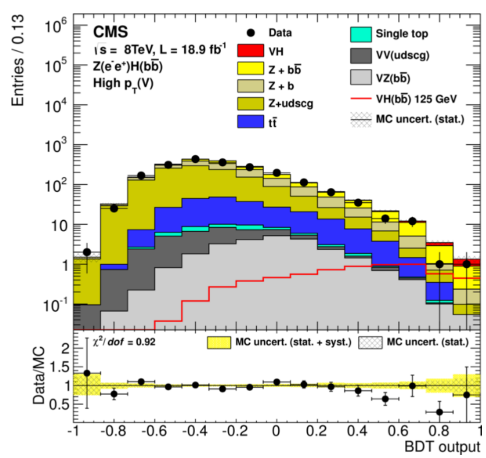
Jet p_T, m_{JJ}, $p_T(JJ)$, p_TV, b-tag value, ΔΦ(VH), M(ZH), (see backup)

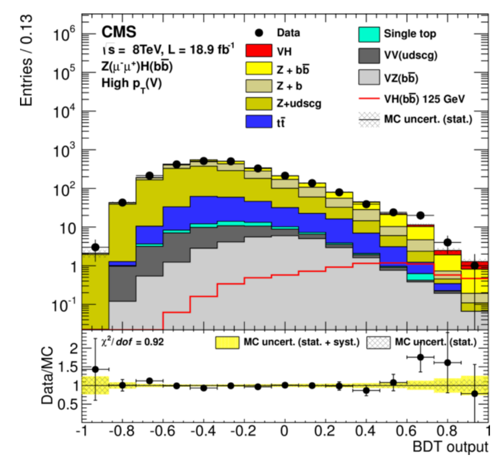










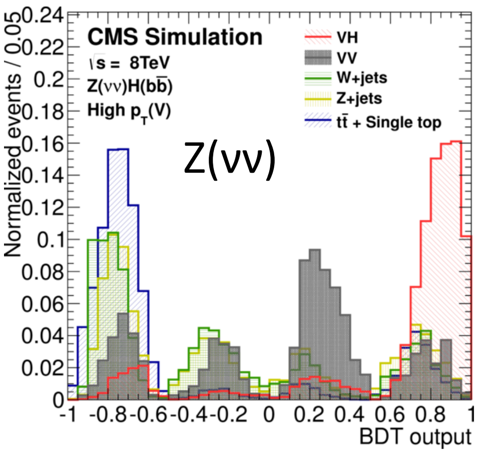


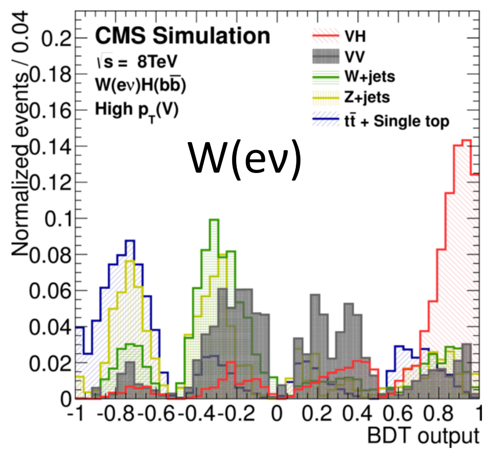
VH→bb: Analysis Channels

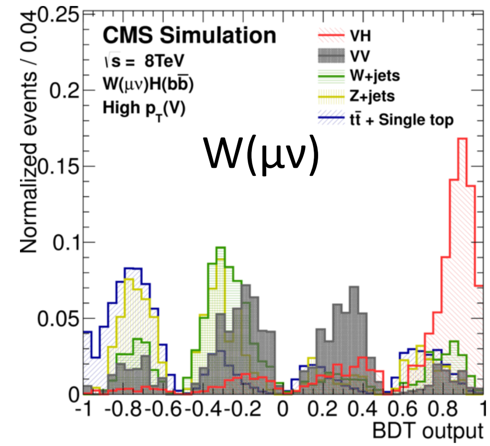
Channels W(μν)H, W(eν) H, Z(νν) H

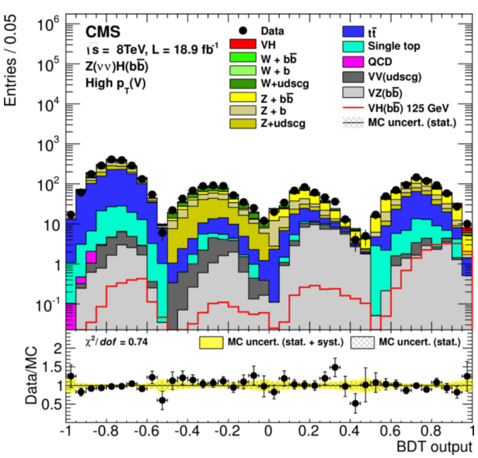
To Extract Signal: Divide into **four BDT subsets** enriched in **tt**, **V+jets**, **diBosons**, and **VH**

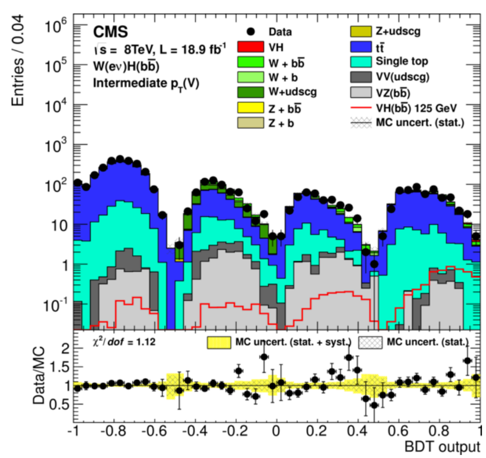
BDTs are trained for each subset-> better estimate of each background

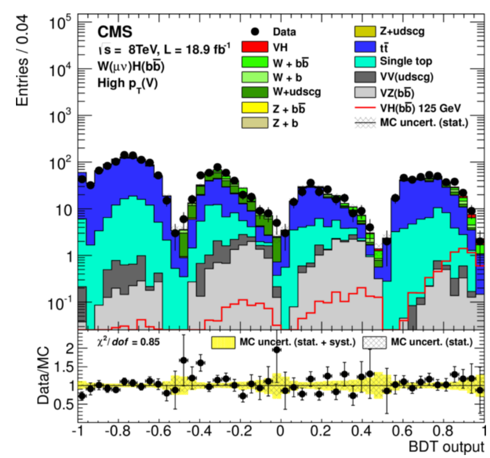






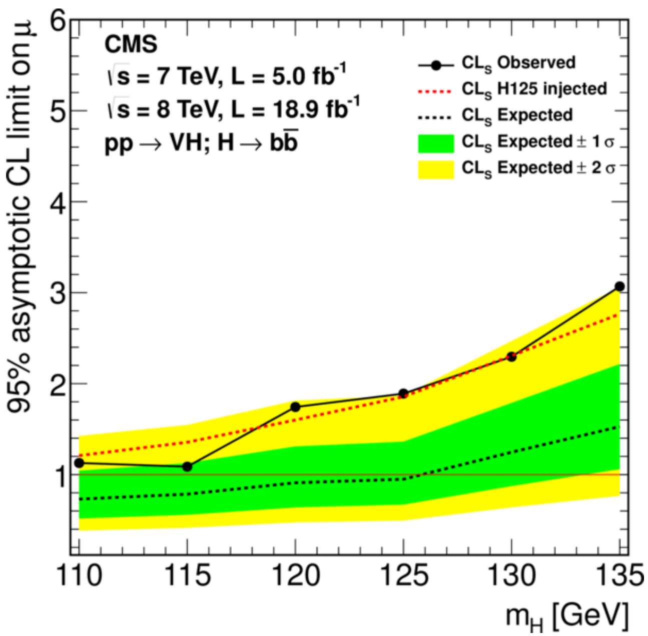


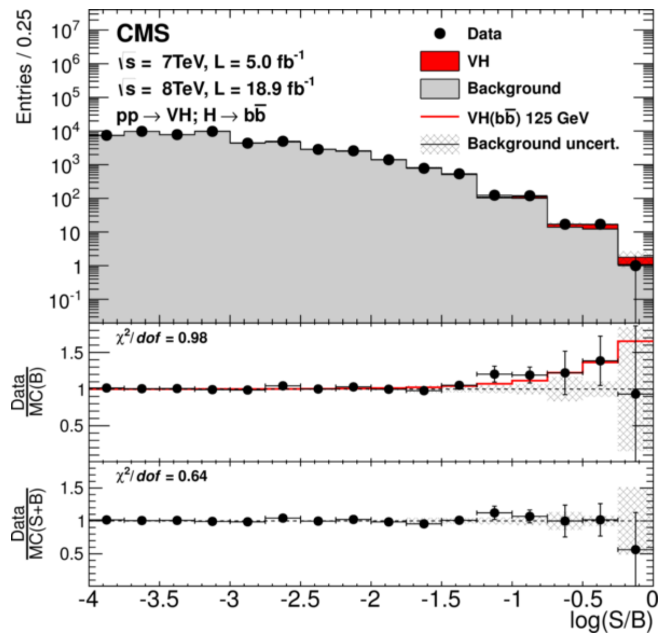


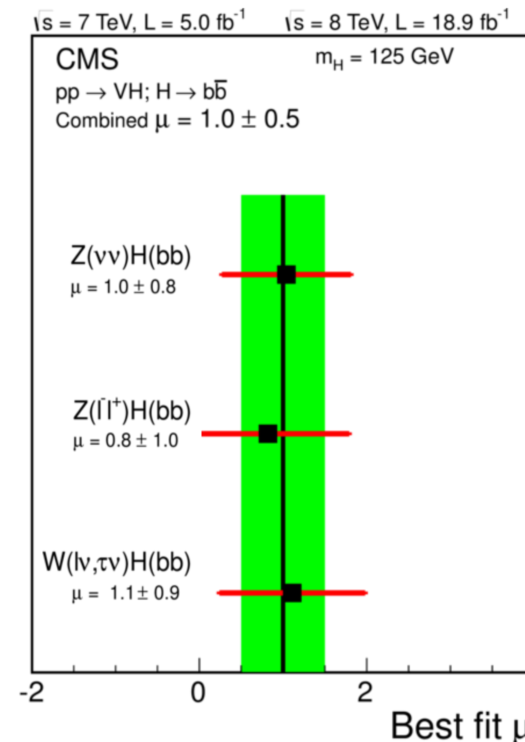


VH→bb: Results

Green (yellow) band show the 1σ (2σ) uncertainty







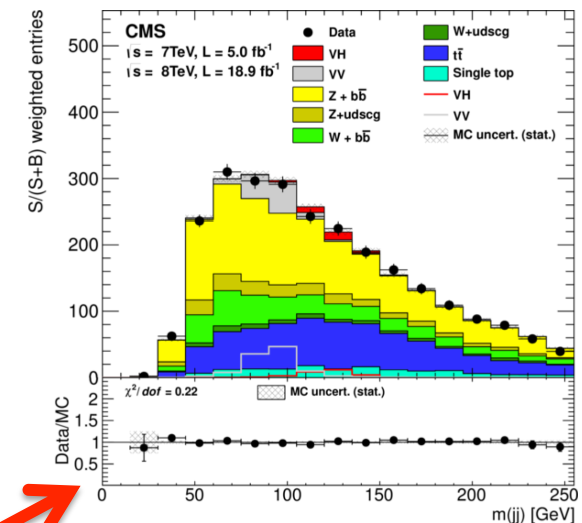
- Analysis is not yet very sensitive, slight excess O(2σ) present for a Higgs boson mass of 125 GeV
- The Signal Strength corresponding to this excess, relative to that of the SM higgs bosons is 1.0 +/-0.5
- ***Will be observed in Run II!***

VH→bb: Cut-based Cross-check

Cross-check to BDT based analysis:

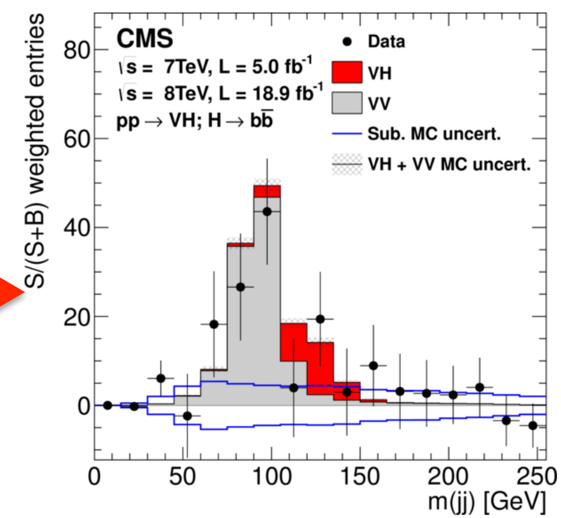
A fit is performed to the shape of the dijet invariant mass distribution (m_{JJ}) of the two jets associated with the Higgs

→This method is more restrictive and optimized for sensitivity in the m_{JJ} variable



Results:

- Diboson Signal Extraction W/Z + Z→bb
  $\mu_{VV}=1.19^{+0.28}_{-0.23}$
- For each channel the relative di-jet mass distribution weight is obtained from the ratio of S/(S+B)
- Background subtracted plot shows the Z(bb) peak and the H(bb) contribution
- The measured Higgs Signal Strength relative to that predicted by the SM is 0.8 +/- 0.7

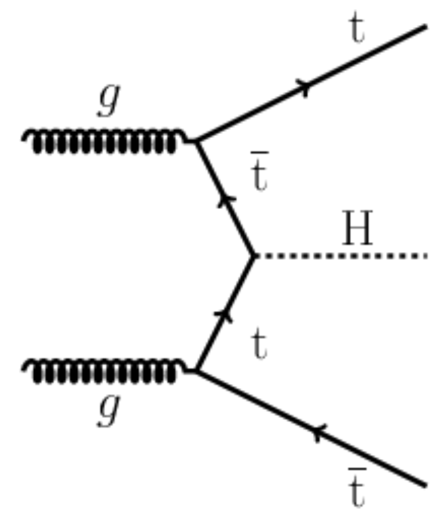


ttH: Overview arxiv:1408.1682v1

Motivations:

Striking feature of the SM Higgs boson is its strong coupling to the top quark relative to the other SM fermions

Current measurements of Higgs boson production via gluon fusion are consistent with SM expectation for the top-quark Yukawa coupling



Strategy:

Select tt by its decay t→b+W

Higgs decay modes with high S/(S+B) analyzed

Channels grouped by final state:

Category	Signature	Trigger	Signature
H → Hadrons H → $b\bar{b}$ H → $\tau_h\tau_h$ H → WW	Lepton + Jets ($t\bar{t}H \to \ell\nu jjbbbb$)	Single Lepton	1 e/μ, $p_T > 30$ GeV $\geq$4 jets + $\geq$2 b-tags, $p_T > 30$ GeV
	Dilepton ($t\bar{t}H \to \ell\nu\ell\nu bbbb$)	Dilepton	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV $\geq$3 jets + $\geq$2 b-tags, $p_T > 30$ GeV
	Hadronic τ ($t\bar{t}H \to \ell\nu\tau_h[\nu]\tau_h[\nu]jjbb$)	Single Lepton	1 e/μ, $p_T > 30$ GeV 2 τ_h, $p_T > 20$ GeV $\geq$2 jets + 1-2 b-tags, $p_T > 30$ GeV
H → Photons H → $\gamma\gamma$	Leptonic ($t\bar{t}H \to \ell\nu jjbb\gamma\gamma$, $t\bar{t}H \to \ell\nu\ell\nu bb\gamma\gamma$)	Diphoton	2 γ, $p_T > m_{\gamma\gamma}/2$ (25) GeV for 1st (2nd) $\geq$1 e/μ, $p_T > 20$ GeV $\geq$2 jets + $\geq$1 b-tags, $p_T > 25$ GeV
	Hadronic ($t\bar{t}H \to jjjjbb\gamma\gamma$)	Diphoton	2 γ, $p_T > m_{\gamma\gamma}/2$ (25) GeV for 1st (2nd) 0 e/μ, $p_T > 20$ GeV $\geq$4 jets + $\geq$1 b-tags, $p_T > 25$ GeV
H → Leptons H → WW H → $\tau\tau$ H → ZZ	Same-Sign Dilepton ($t\bar{t}H \to \ell^{\pm}\nu\ell^{\pm}[\nu]jjj[j]bb$)	Dilepton	2 e/μ, $p_T > 20$ GeV $\geq$4 jets + $\geq$1 b-tags, $p_T > 25$ GeV
	3 Lepton ($t\bar{t}H \to \ell\nu\ell[\nu]\ell[\nu]j[j]bb$)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 1 e(μ), $p_T > 7(5)$ GeV $\geq$2 jets + $\geq$1 b-tags, $p_T > 25$ GeV
	4 Lepton ($t\bar{t}H \to \ell\nu\ell\nu\ell[\nu]\ell[\nu]bb$)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 2 e(μ), $p_T > 7(5)$ GeV $\geq$2 jets + $\geq$1 b-tags, $p_T > 25$ GeV

$t\bar{t}H$: Channels H->Hadrons

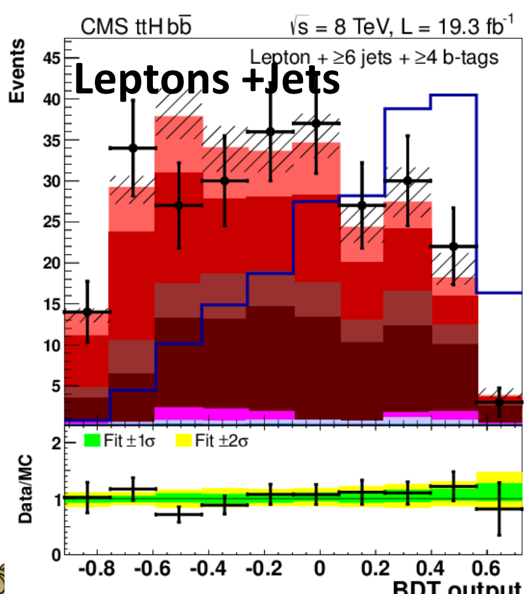
H->bb, H->$\tau_h\tau_h$, H->WW (W decays hadronically)

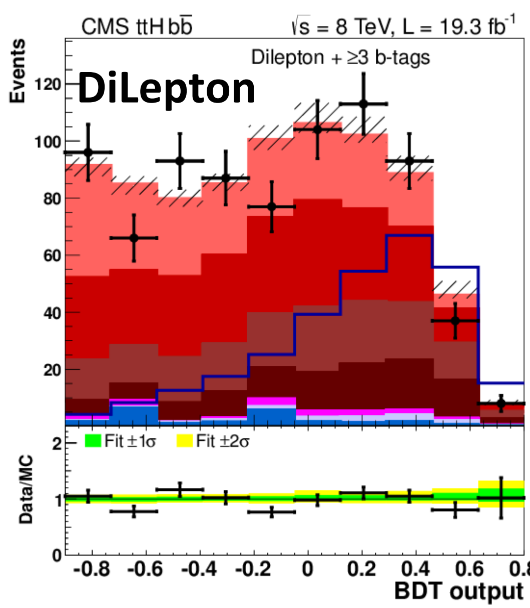
MVA used to tag jets coming from b-quarks or Tau-lepton decays and to separate ttH events from large tt+jets backgrounds

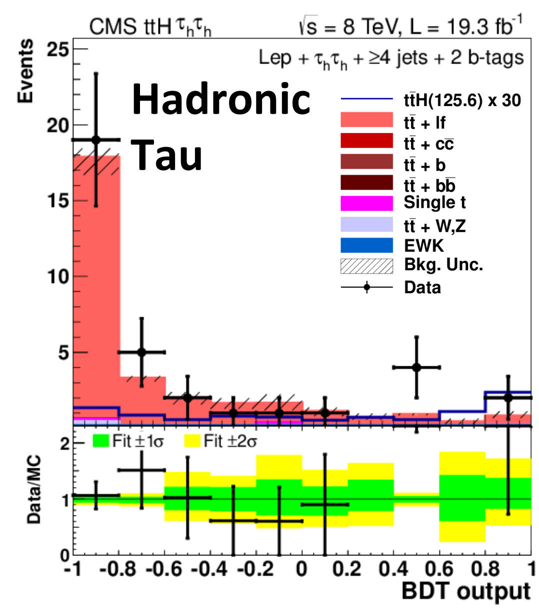
BDTs with 10-15 variables are trained using signal MC for each of the categories

→Output distributions are used for Signal Extraction

(more sensitive categories shown)







ttH: Channels H->γγ

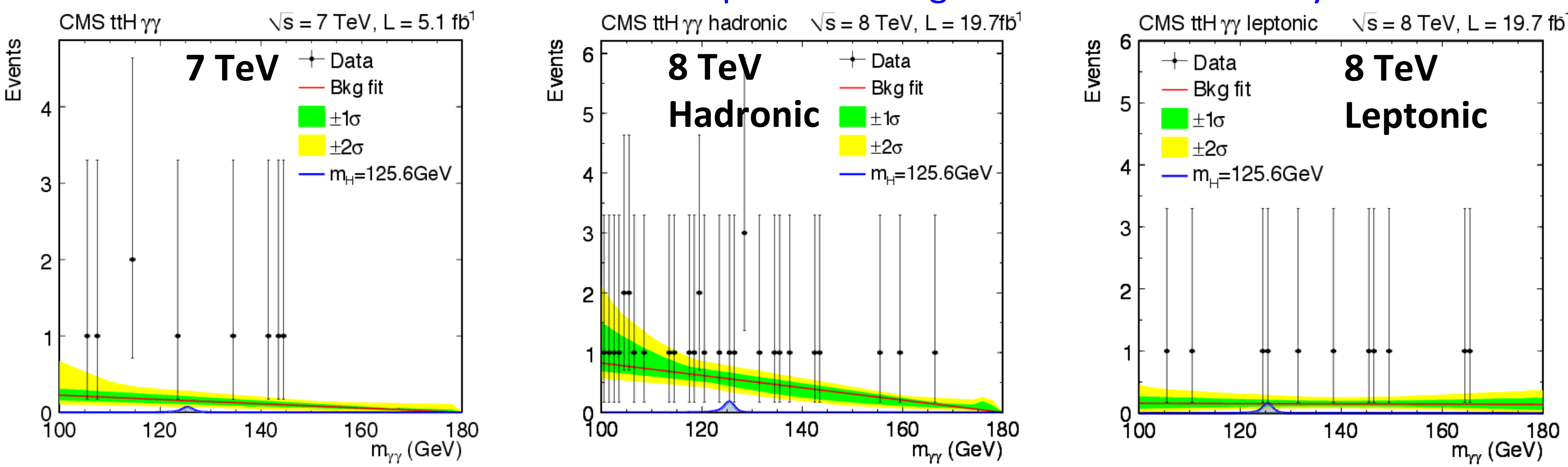
H->Photons, tt->lvjj or tt->lvlv

Photon invariant mass ($m_{\gamma\gamma}$) used to extract signal

→Powerful Discriminant due to the excellent photon energy resolution

Background obtained by fitting $m_{\gamma\gamma}$ in the range 100 GeV < mγγ < 180 GeV

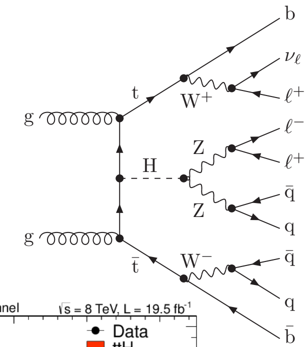
8 TeV split into categories based on tt decay



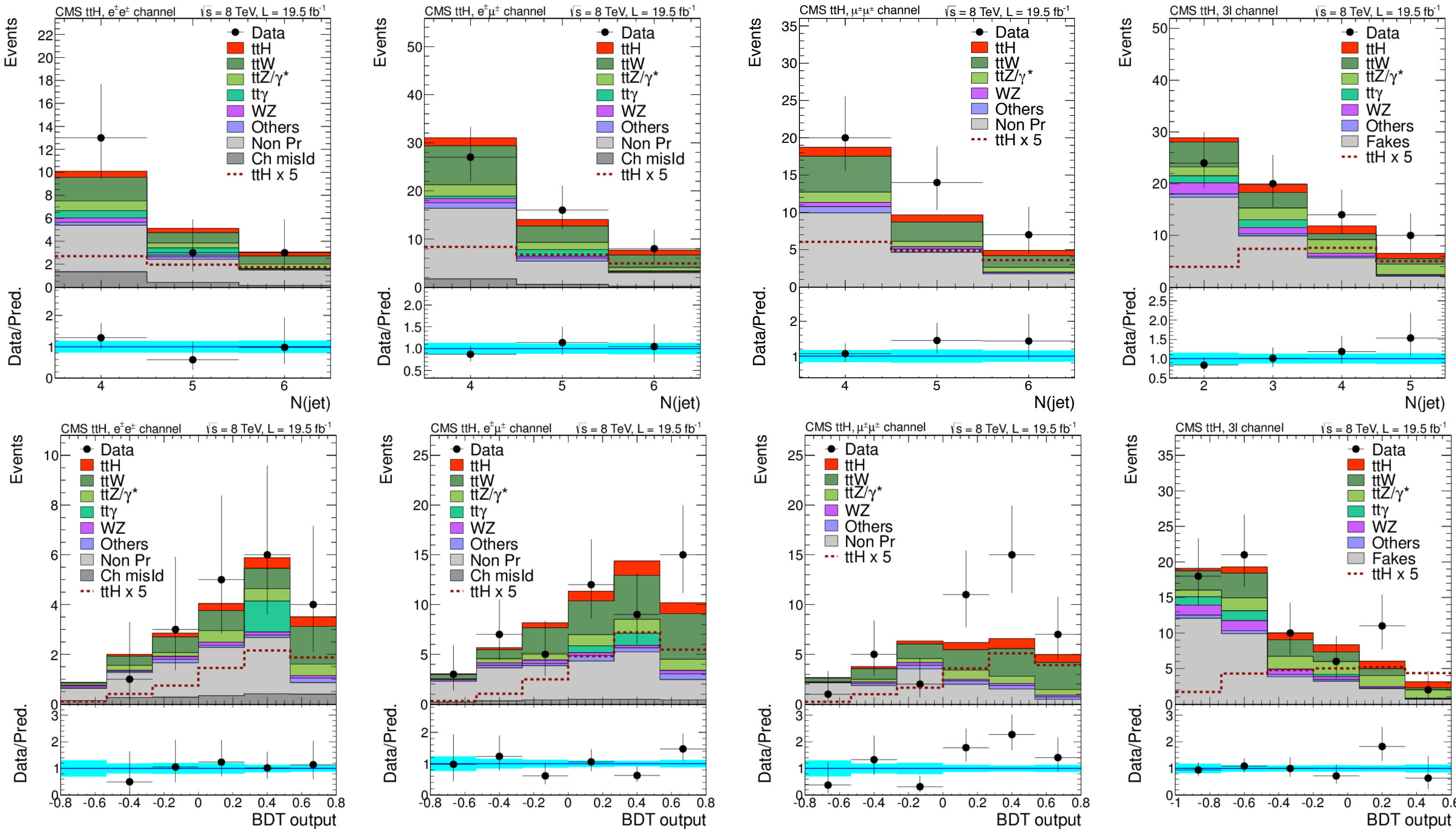
Green (yellow) band show the 1σ (2σ) uncertainty band

ttH: Channels H->Leptons

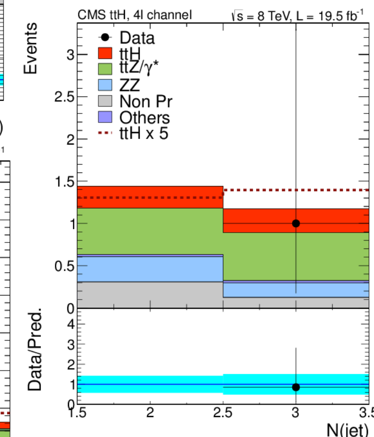
Multi-Lepton Final State



One of a few SS di-lepton diagrams

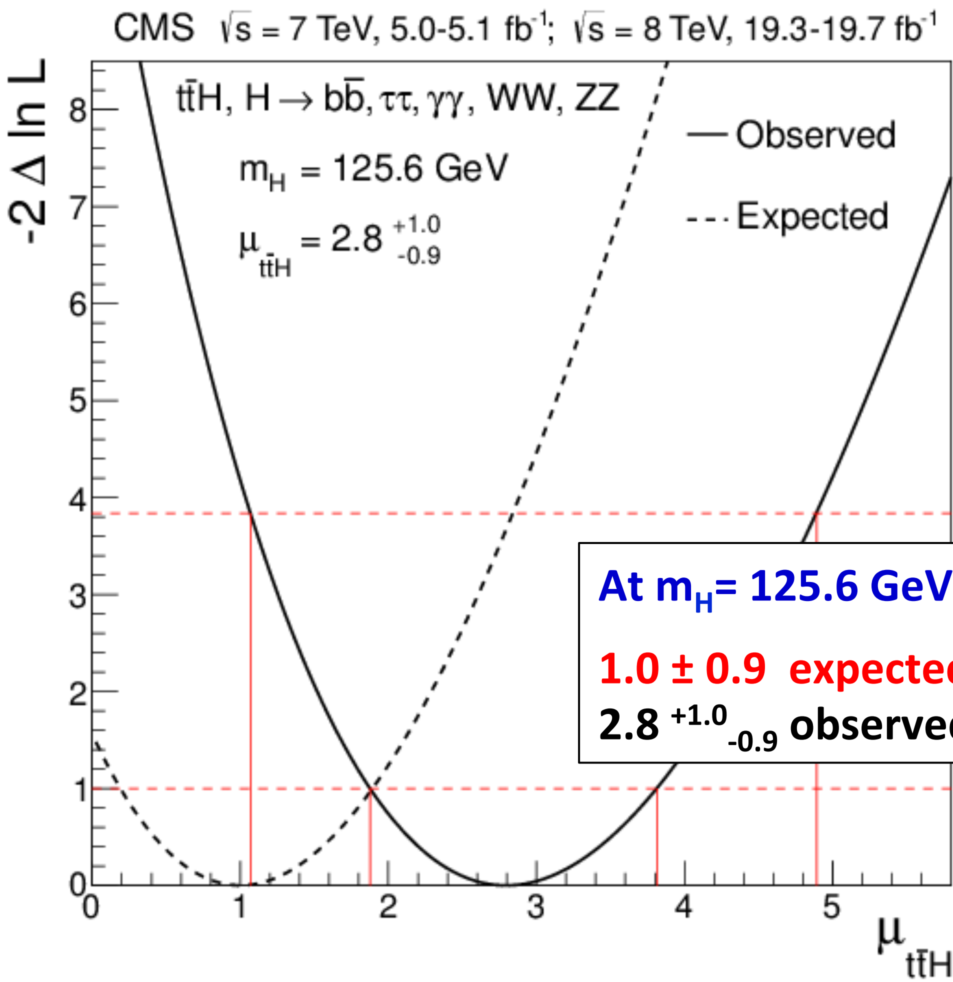


same-sign ee   same-sign eμ   same-sign μμ   tri-lepton



4-lepton

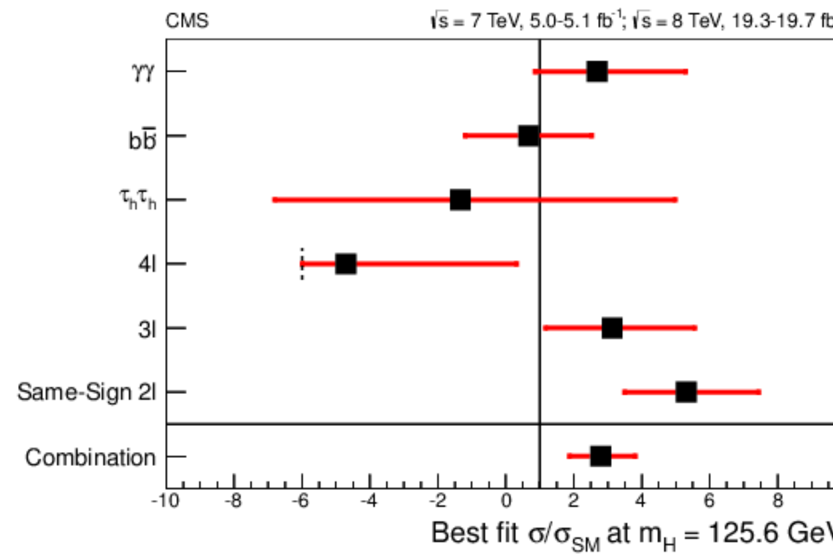
ttH: Results



At m_H= 125.6 GeV:

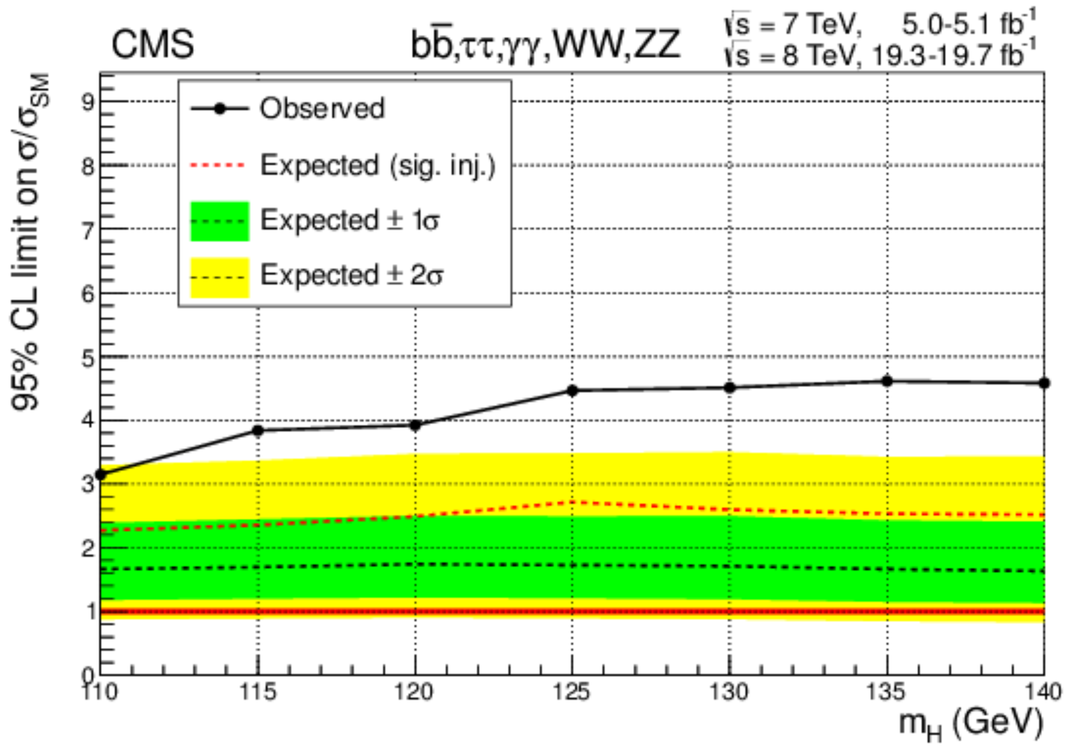
1.0 ± 0.9 expected

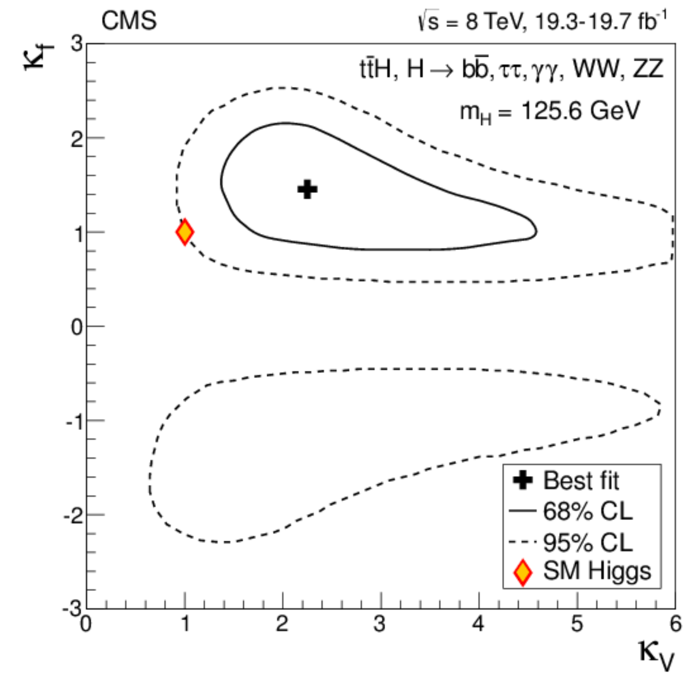
$2.8^{+1.0}_{-0.9}$ observed



Best fit σ/σ_{SM} by Higgs Decay Mode

$t\bar{t}$H: Results





2D Test Statistic $q(k_V,k_f)$

Excess on the order of 2σ above the expected SM Limit

->Will be watched closely in Run II

Vector and fermion couplings grouped

κ_V: $\kappa_W=\kappa_Z$ κ_F: $\kappa_t=\kappa_b=\kappa_\tau=\kappa_g$

ttH: H->bb with MEM arXiv:1502.02485

Matrix Element Method (used at D0/CDF)

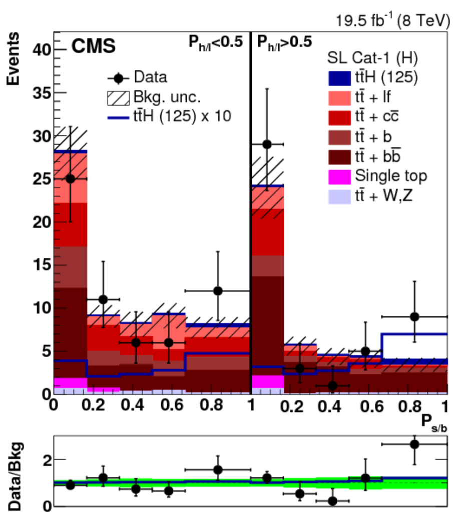
MEM Probability Density Function $w(\vec{y}|t\bar{t}H)$ + Combined Likelihood of b-Tagging $f(\vec{\xi}|t\bar{t}+hf)$

$$P_{s/b} = \frac{w(\vec{y}|t\bar{t}H)}{w(\vec{y}|t\bar{t}H) + k_{s/b}w(\vec{y}|t\bar{t}+b\bar{b})} \qquad P_{h/l} = \frac{f(\vec{\xi}|t\bar{t}+hf)}{f(\vec{\xi}|t\bar{t}+hf) + k_{h/l}f(\vec{\xi}|t\bar{t}+lf)}$$

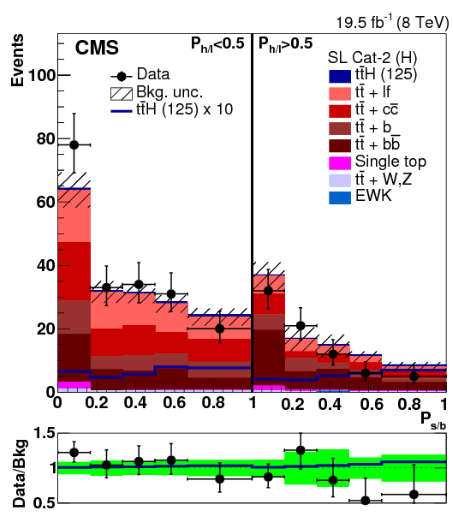
→2D fit!

Combined Likelihood Discriminant $P_{S/B}$ Distributions with $P_{h/l}$ profiled:

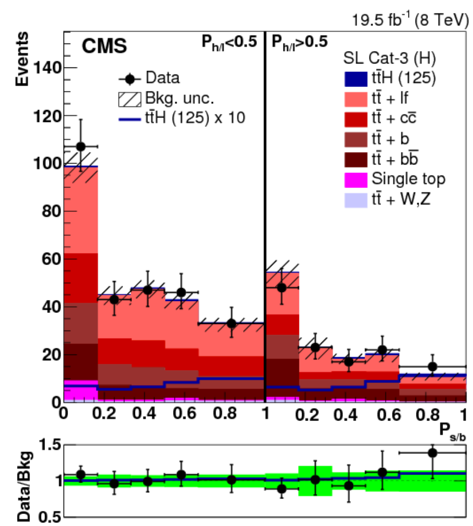
Single Lepton
6-Jets + W-Tag



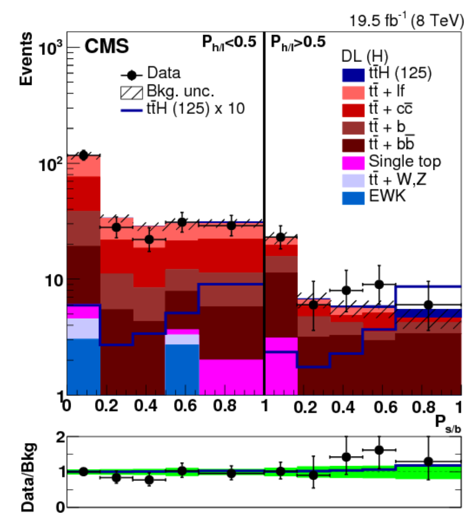
Single Lepton
> 6-Jets No W-Tag



Single Lepton
5-Jets



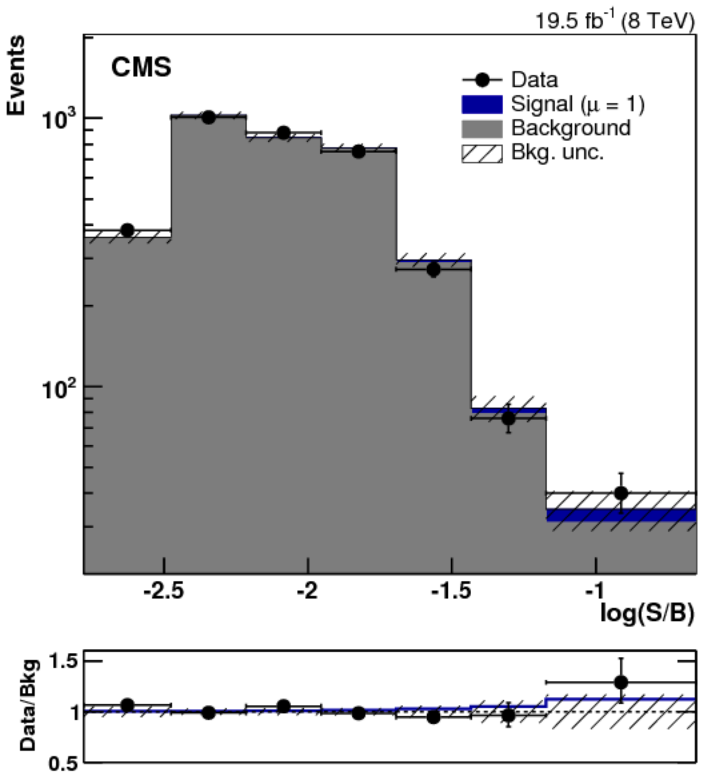
Double Lepton
4-Jets

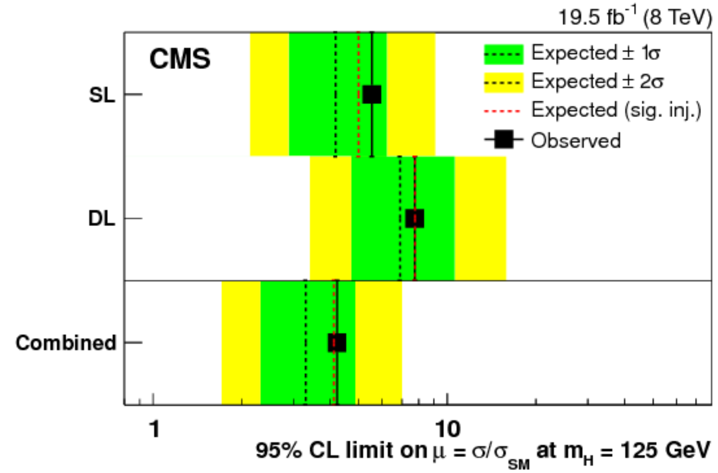


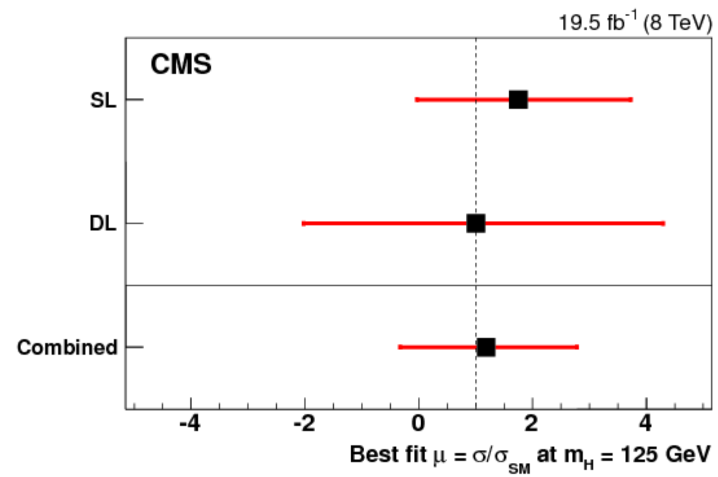
ttH: H->bb with MEM

Slight excess seen, in agreement with SM H
Observed (expected) limit of $\mu < 4.2$ (3.3)

The best fit value on the signal strength modifier (σ/σ_{SM}) is $\mu = 1.2^{+1.6}_{-1.5}$







H->ττ: Overview

Motivations

Higgs to ττ decay mode is a promising channel due to its strong coupling to the higgs and smaller contribution from background with respect to bb

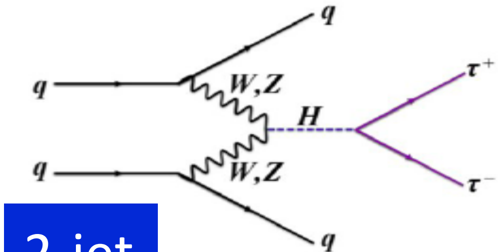
Strategy:

Divide H->ττ channels by Production Modes

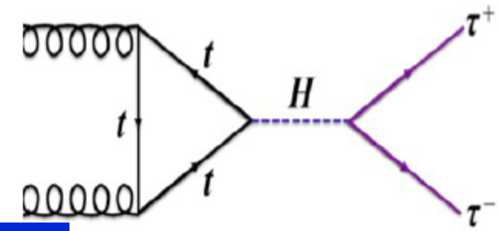
- Optimize Selection of each Mode

Combine Taus + ME_T to estimate $m_{\tau\tau}$

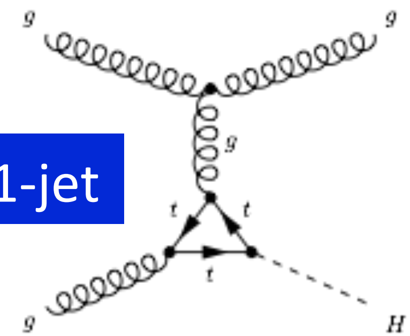
- Used for signal extraction in all final states except $\tau_e\tau_e$, $\tau_\mu\tau_\mu$ or WH



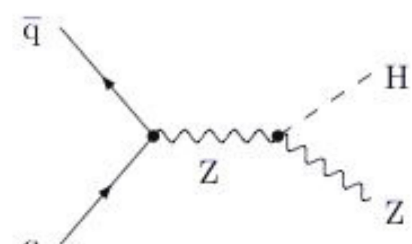
2-jet



0-jet

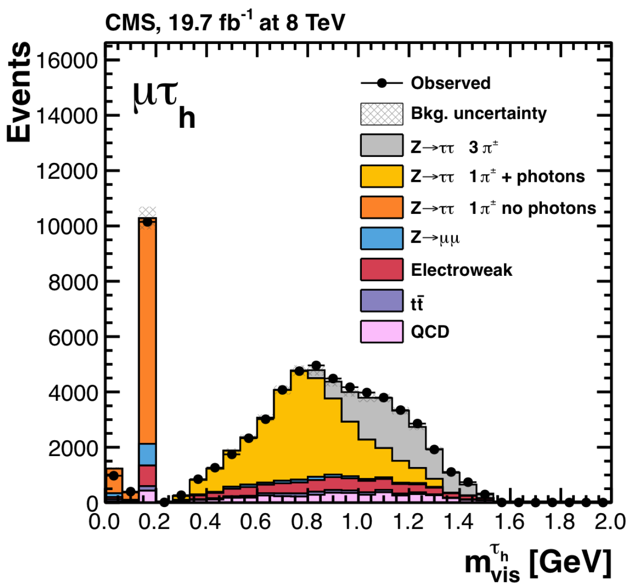


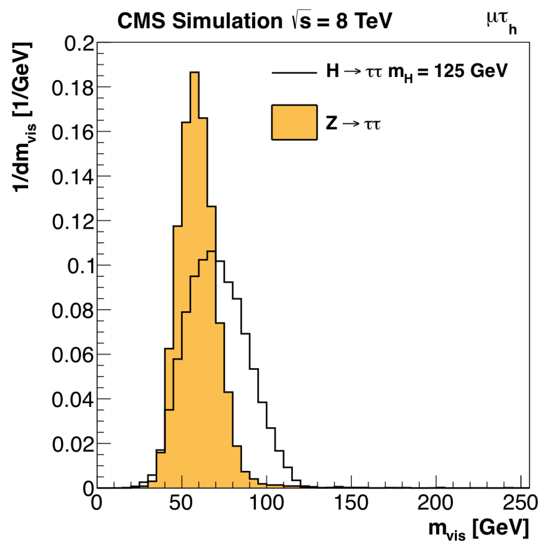
1-jet

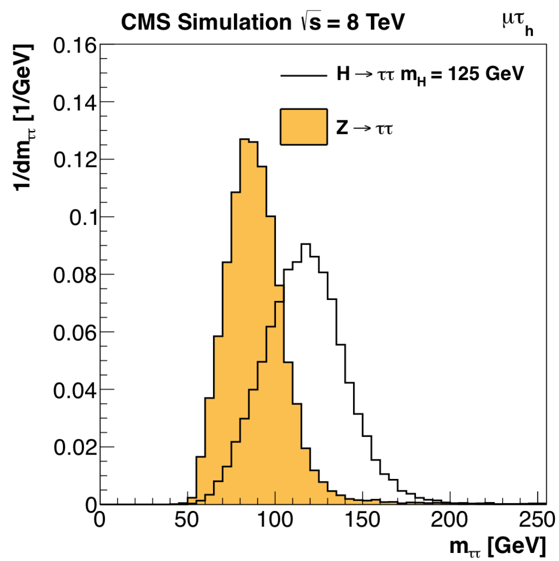


VH

H->ττ: τ_h Mass, SV-fit Mass





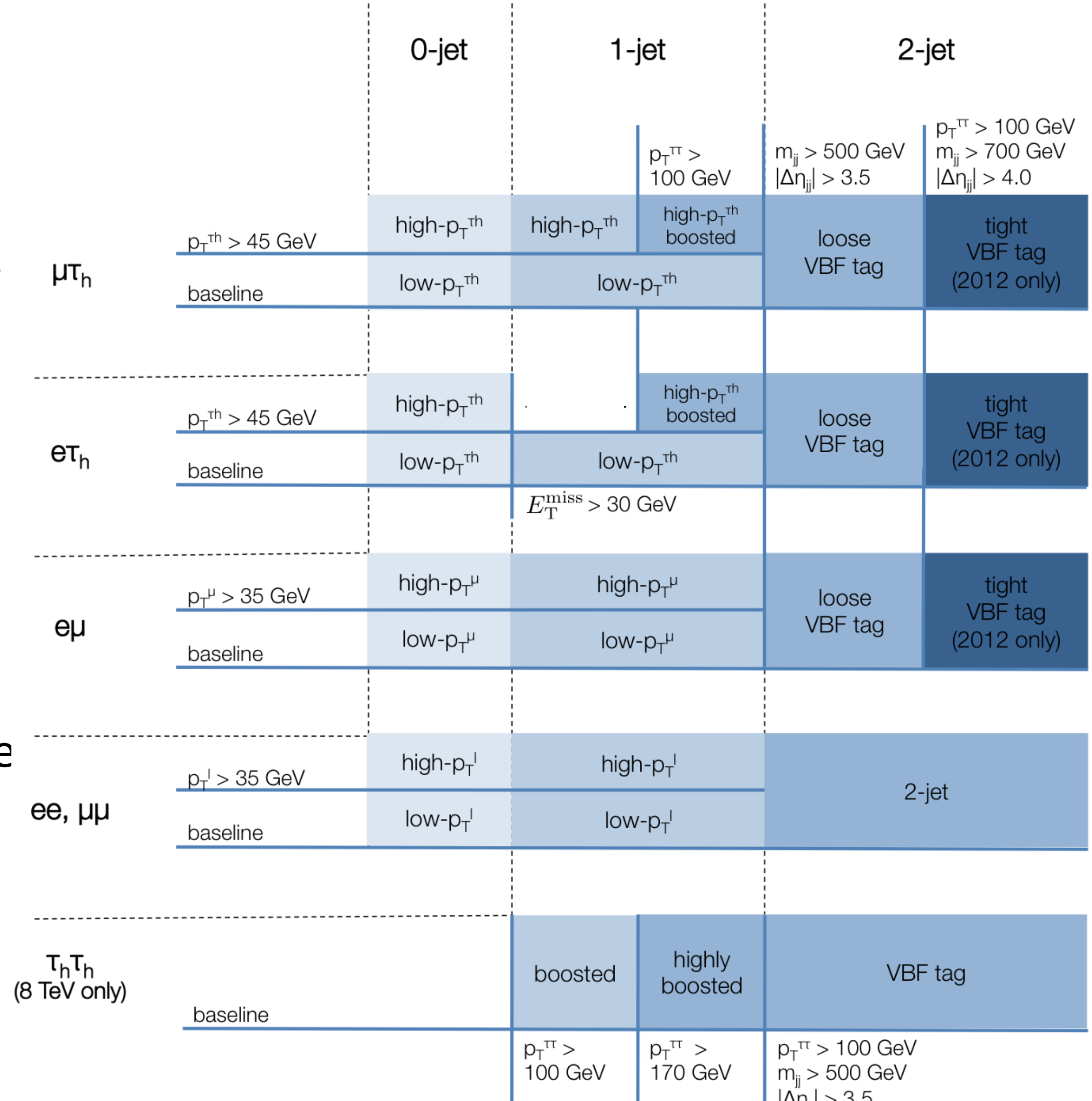


Maximum Likelihood fit using the visible τ kinematics combined with the MET to estimate the energy carried away by the neutrino

H->ττ: Non-VH

All τ final states considered

- 2-Jet designed to select for VBF, suppresses gluon fusion background
- 1-jet fails 2-jet category selection
- 0-Jet used to estimate large Z->ττ background

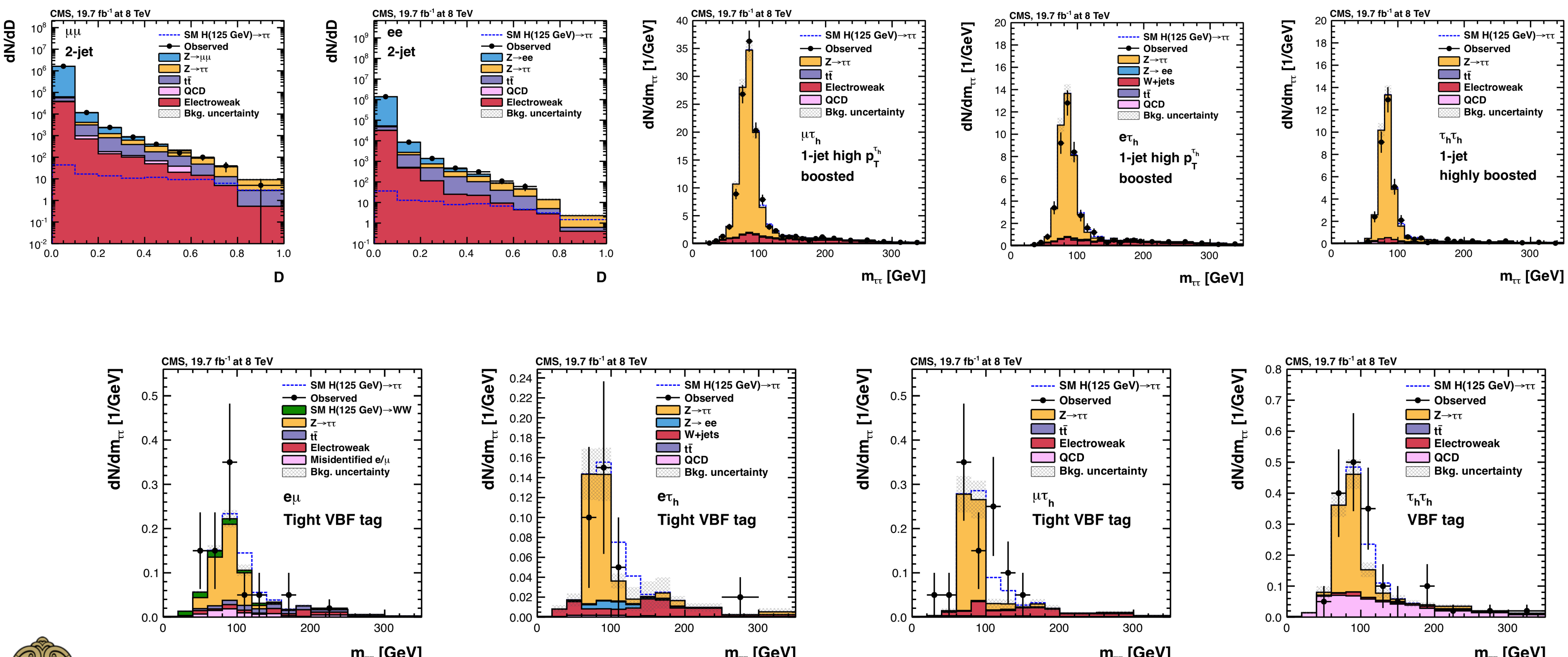


H->ττ: Non-VH

Showing selected Categories from each Channel

$\tau_e\tau_e$ and $\tau_\mu\tau_\mu$ use a BDT discriminant for signal extraction

Remaining categories use Secondary Vertex-Fit Mass



H->ττ: VH

All τ final states considered in the ZH and WH analyses except Z+$\tau_\mu\tau_\mu$ or Z+$\tau_e\tau_e$

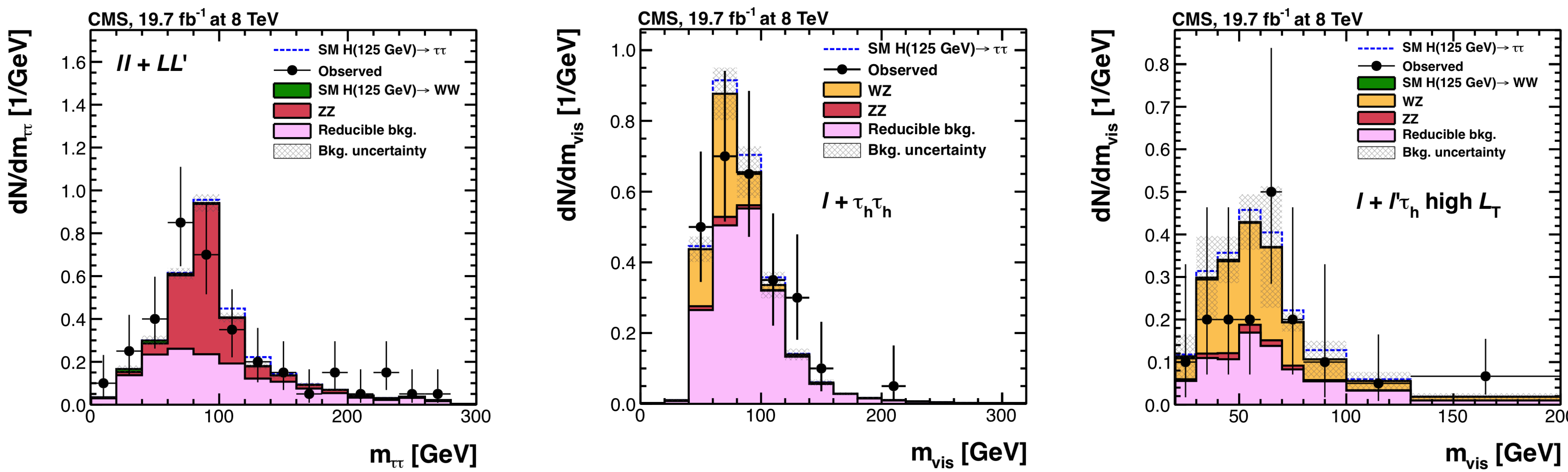
Possible to Lower p_T Thresholds of Selected Leptons due to di-lepton Trigger

Primary backgrounds:

Di-boson and Fake Leptons →

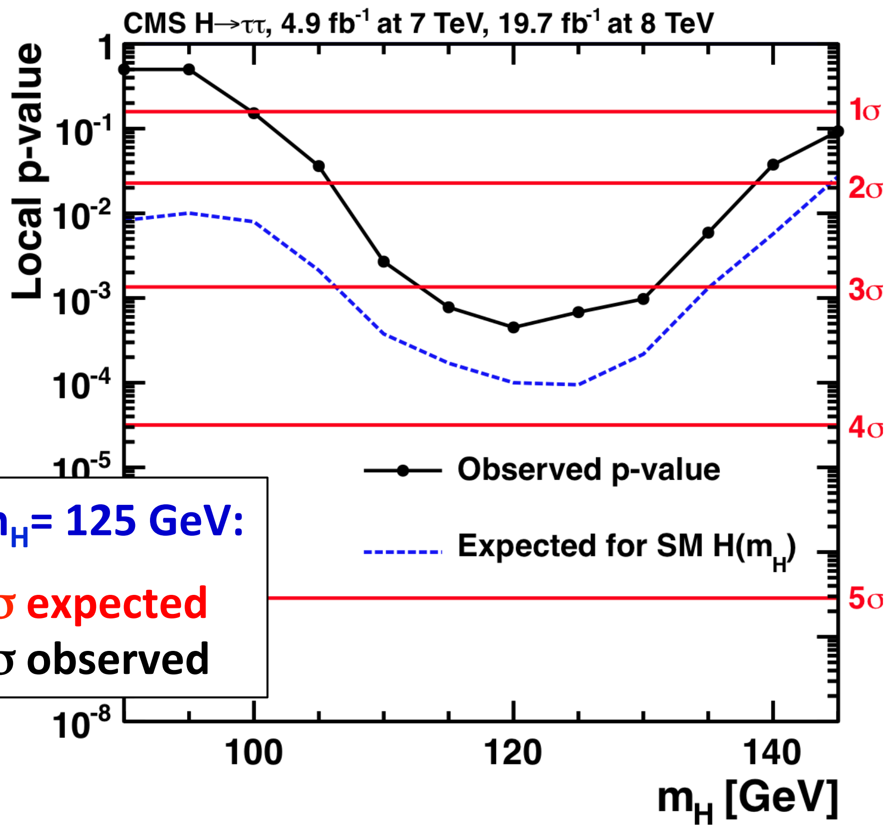
Lepton Fake Rate derived from data

Resonance	HLT requirement	Lepton selection		
$Z \to \mu\mu$	$\mu(17)$ & $\mu(8)$	$p_T^{\mu_1} > 20$ $p_T^{\mu_2} > 10$	$\lvert\eta^\mu\rvert < 2.4$	$R^\mu < 0.3$
$Z \to ee$	e(17) & e(8)	$p_T^{e_1} > 20$ $p_T^{e_2} > 10$	$\lvert\eta^e\rvert < 2.5$	$R^e < 0.3$
$H \to \mu\tau_h$		$p_T^\mu > 10$ $p_T^{\tau_h} > 15$	$\lvert\eta^\mu\rvert < 2.4$ $\lvert\eta^{\tau_h}\rvert < 2.3$	$R^\mu < 0.3$ $I^{\tau_h} < 2$
$H \to e\tau_h$		$p_T^e > 10$ $p_T^{\tau_h} > 15$	$\lvert\eta^e\rvert < 2.5$ $\lvert\eta^{\tau_h}\rvert < 2.3$	$R^e < 0.2$ $I^{\tau_h} < 2$
$H \to \tau_h\tau_h$		$p_T^{\tau_h} > 15$	$\lvert\eta^{\tau_h}\rvert < 2.3$	$I^{\tau_h} < 1$
$H \to e\mu$		$p_T^\ell > 10$	$\lvert\eta^e\rvert < 2.5$ $\lvert\eta^\mu\rvert < 2.4$	$R^\ell < 0.3$



Secondary Vertex-Fit Mass or Visible Mass for Signal Extraction

H->ττ: Results

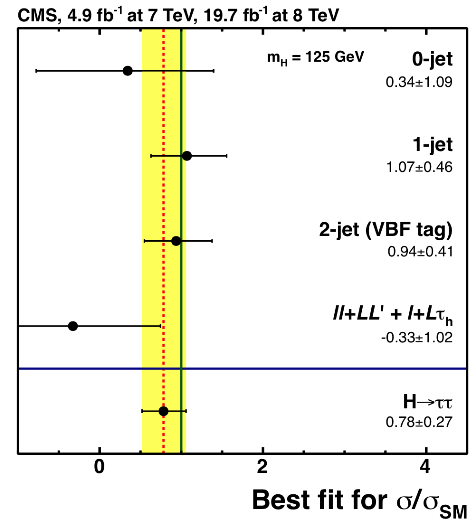


At m_H= 125 GeV:

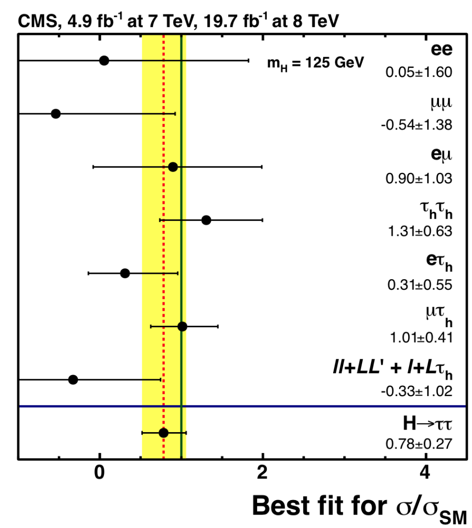
3.7 σ expected

3.2 σ observed

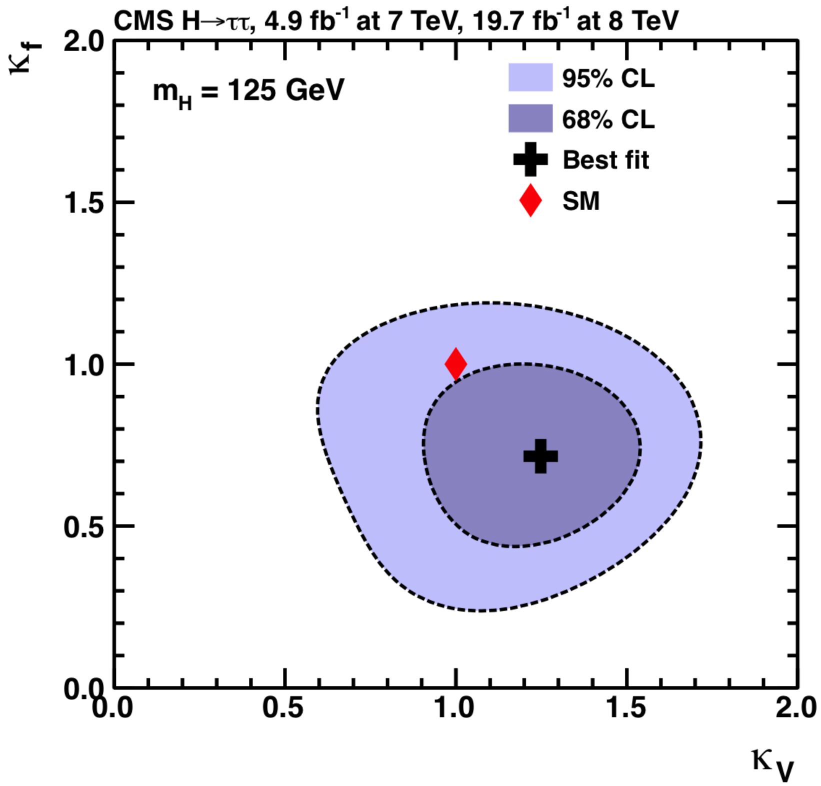
Split by category



Split by channel



H->ττ: Results



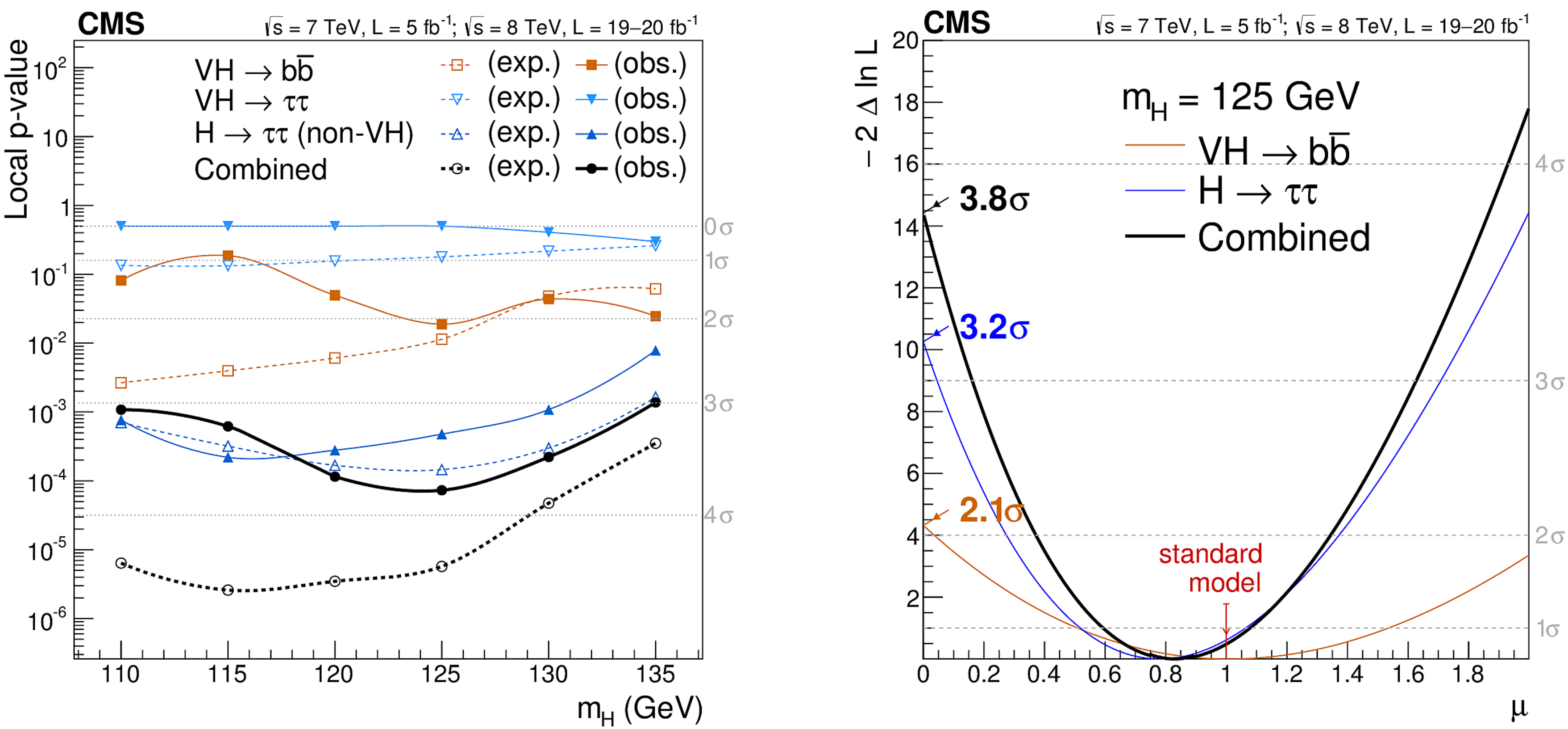
Vector and fermion couplings grouped

κ_V: κ_W=κ_Z κ_F: κ_t=κ_b= κ_τ=κ_g

Consistent with SM, where κ_V=κ_F=1

H-> Fermions Combination

VH->bb, VH→ττ, H->ττ included in the combination



Conclusions

Evidence for Higgs Couplings to Fermions Found!

Preparation for Data Collection and Analysis with CMS at 13 TeV well underway!

During Run II:

- Higgs couplings to Taus will be measured very well
- Looking forward to analyzing further ttH to see if the excess in the multi-lepton final state continues
- Higgs to bb Expected Limit will be improved with more statistics

Thank You!

ttH: H->bb with MEM

Matrix Element Method (used at D0/CDF)

Event differential probability density:

$$w_i(\mathbf{y}) = \frac{1}{\sigma_i} \sum_{perm} \int d\mathbf{x} \int dx_a dx_b \frac{2g(x_a;Q_i)g(x_b;Q_i)}{x_a x_b s} \times$$
$$\times\, \delta\{(x_a P_a + x_b P_b) - \sum_{k=1}^{8} p_k\} \mathcal{R}\left(\vec{\rho}_T | \vec{P}_T\right) \left|\mathcal{M}_i^{LO}(\mathbf{x})\right|^2 W(\mathbf{y}|\mathbf{x}),$$

$$\mathcal{L}_{bbbb}(\xi_1, \ldots, \xi_6) \equiv \sum_{\{i_1,\ldots,i_6\}} f_b(\xi_{i_1}) \cdot f_b(\xi_{i_2}) \cdot f_b(\xi_{i_3}) \cdot f_b(\xi_{i_4}) \cdot f_u(\xi_{i_5}) \cdot f_u(\xi_{i_6})$$

- f_b (f_u) b-tag probability density for heavy (light) flavored jets
- Sum over all u/b labeling of the jets

Three extended likelihoods are defined:

(Event Probability include b-tagging likelihood)

$$\mathcal{P}_S(\mathbf{y},\boldsymbol{\xi}) \equiv w_S(\mathbf{y})\, \mathcal{L}_{bbbb}(\boldsymbol{\xi})$$
$$\mathcal{P}_{B_1}(\mathbf{y},\boldsymbol{\xi}) \equiv w_B(\mathbf{y})\, \mathcal{L}_{bbbb}(\boldsymbol{\xi})$$
$$\mathcal{P}_{B_2}(\mathbf{y},\boldsymbol{\xi}) \equiv w_B(\mathbf{y})\, \mathcal{L}_{bbjj}(\boldsymbol{\xi})$$

$$\longrightarrow P_{b/j} = \frac{\mathcal{P}_{B_1}}{\mathcal{P}_{B_1} + \mathcal{P}_{B_2}}.$$

Final Discriminant:

$$P_{s/b} = \frac{\mathcal{P}_S}{\mathcal{P}_S + \lambda_{b/j}\mathcal{P}_{B_1} + (1-\lambda_{b/j})\mathcal{P}_{B_2}},$$

Where $\lambda_{b/j}$ sets the relative ratio of ttbb to ttjj, as determined by MC

ttH: H->bb with MEM

Utilizes kinematical and topological information from the event

→Each event is assigned a differential probability density wi(**y**) of measuring a set of observables **y** under either the signal or background hypothesis

Only the ttbb matrix element is considered as the prototype to model background processes (some separation power with respect to the other backgrounds)

Signal and background probability densities are constructed at leading order assuming that in both cases the processes are initiated by a gluon pair

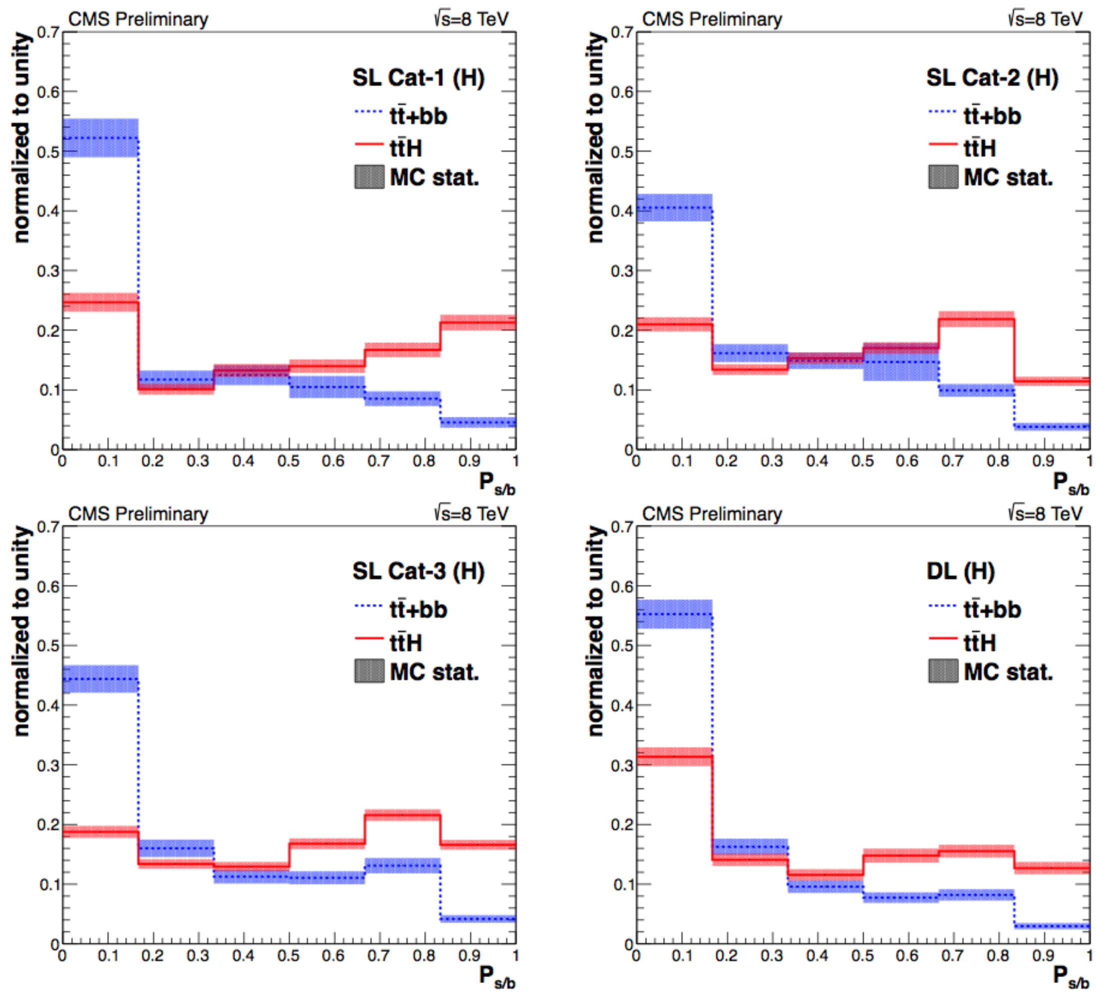
ttH: H->bb with MEM

Shape comparisons for the High Purity channel in the Single and Di-lepton Categories

High Purity and Low Purity Categories are split by bLR discriminant

$$b_{\rm LR} \equiv \frac{\mathcal{L}_{\rm bbbb}}{\mathcal{L}_{\rm bbbb} + \mathcal{L}_{\rm bbjj}}.$$

Value of b_{LR} optimized per category



VH->bb BDT Input Variables

Variable
$p_{\mathrm{T}}(\mathrm{j}_1), p_{\mathrm{T}}(\mathrm{j}_2)$: transverse momentum of each Higgs boson daughter
$m(\mathrm{jj})$: dijet invariant mass
$p_{\mathrm{T}}(\mathrm{jj})$: dijet transverse momentum
$p_{\mathrm{T}}(\mathrm{V})$: vector boson transverse momentum (or $E_{\mathrm{T}}^{\mathrm{miss}}$)
N_{aj}: number of additional jets (see caption)
$\mathrm{CSV}_{\mathrm{max}}$: value of CSV for the Higgs boson daughter with largest CSV value
$\mathrm{CSV}_{\mathrm{min}}$: value of CSV for the Higgs boson daughter with second largest CSV value
$\Delta\phi(\mathrm{V},\mathrm{H})$: azimuthal angle between V (or $E_{\mathrm{T}}^{\mathrm{miss}}$) and dijet
$\lvert\Delta\eta(\mathrm{jj})\rvert$: difference in η between Higgs boson daughters
$\Delta R(\mathrm{jj})$: distance in η–ϕ between Higgs boson daughters
$\Delta\theta_{\mathrm{pull}}$: color pull angle [45]
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\mathrm{jet})$: azimuthal angle between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest jet (only for $\mathrm{Z}(\nu\nu)\mathrm{H}$)
$\mathrm{maxCSV}_{\mathrm{aj}}$: maximum CSV of the additional jets in an event (only for $\mathrm{Z}(\nu\nu)\mathrm{H}$ and $\mathrm{W}(\ell\nu)\mathrm{H}$)
$\mathrm{min}\Delta R(\mathrm{H},\mathrm{aj})$: minimum distance between an additional jet and the Higgs boson candidate (only for $\mathrm{Z}(\nu\nu)\mathrm{H}$ and $\mathrm{W}(\ell\nu)\mathrm{H}$)
Invariant mass of the VH system (only for $\mathrm{Z}(\ell\ell)\mathrm{H}$)
Cosine of the angle between the direction of the V boson in the rest frame of the VH system and the direction of the VH system in the laboratory frame (only for $\mathrm{Z}(\ell\ell)\mathrm{H}$)
Cosine of the angle between the direction of one of the leptons in the rest frame of the Z boson and the direction of the Z boson in the laboratory frame (only for $\mathrm{Z}(\ell\ell)\mathrm{H}$)
Cosine of the angle between the direction of one of the jets in the rest frame of the reconstructed Higgs boson and the direction of the reconstructed Higgs boson in the laboratory frame (only for $\mathrm{Z}(\ell\ell)\mathrm{H}$)

VH->bb Category Selections

Table 3: Selection criteria for the samples used in the m(jj) analysis in each channel. Entries marked with "–" indicate that the variable is not used in the given channel. If different, the entries in square brackets indicate the selection for the different boost regions as defined in the first row of the table. The p_T thresholds for the highest and second highest p_T jets are $p_T(j_1)$ and $p_T(j_2)$, respectively. The transverse momentum of the leading tau track is p_T(track). The values listed for kinematic variables are in units of GeV, and for angles in units of radians.

Variable	W($\ell\nu$)H	W($\tau\nu$)H	Z($\ell\ell$)H	Z($\nu\nu$)H
p_T(V)	[100–150] [>150] (e) [100–130] [130–180] [>180] (μ)	[<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	>20	[> 60][> 60][> 80]
$p_T(j_2)$	>30	>30	>20	>30
p_T(jj)	>100	>120	–	[> 110][> 140][> 190]
N_{aj}	=0	=0	–	=0
$N_{a\ell}$	=0	=0	–	=0
E_T^{miss}	>45	>80	< 60	–
$p_T(\tau)$	–	>40	–	–
p_T(track)	–	>20	–	–
CSV_{max}	0.898	0.898	0.679	0.898
CSV_{min}	>0.5	>0.4	>0.5	>0.5
$\Delta\phi$(V,H)	>2.95	>2.95	–	>2.95
ΔR(jj)	–	–	[–][–][< 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
$\Delta\phi(E_T^{miss}, \ell)$	$< \pi/2$	–	–	–