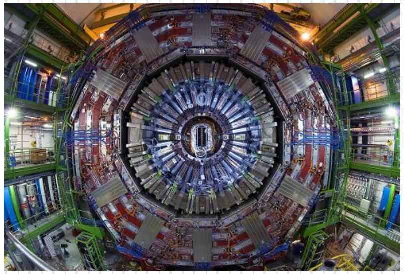
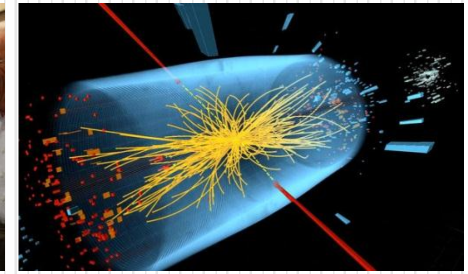
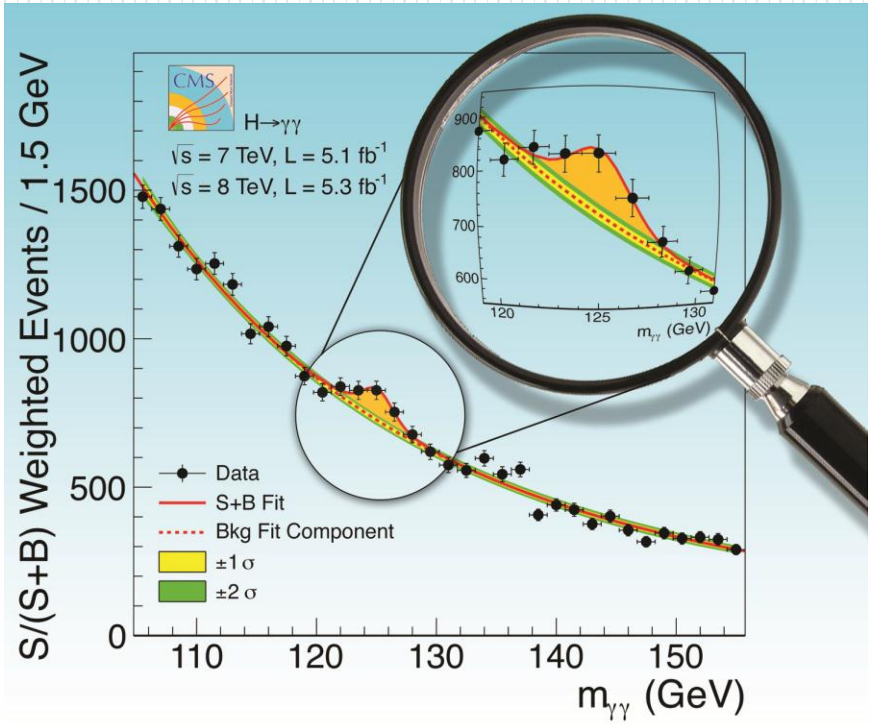
   

Does the Boson Decay to Fermions?



Search for H → ττ, bb @ CMS*

Jim Olsen

Princeton University

HEP Seminar, DESY – Hamburg

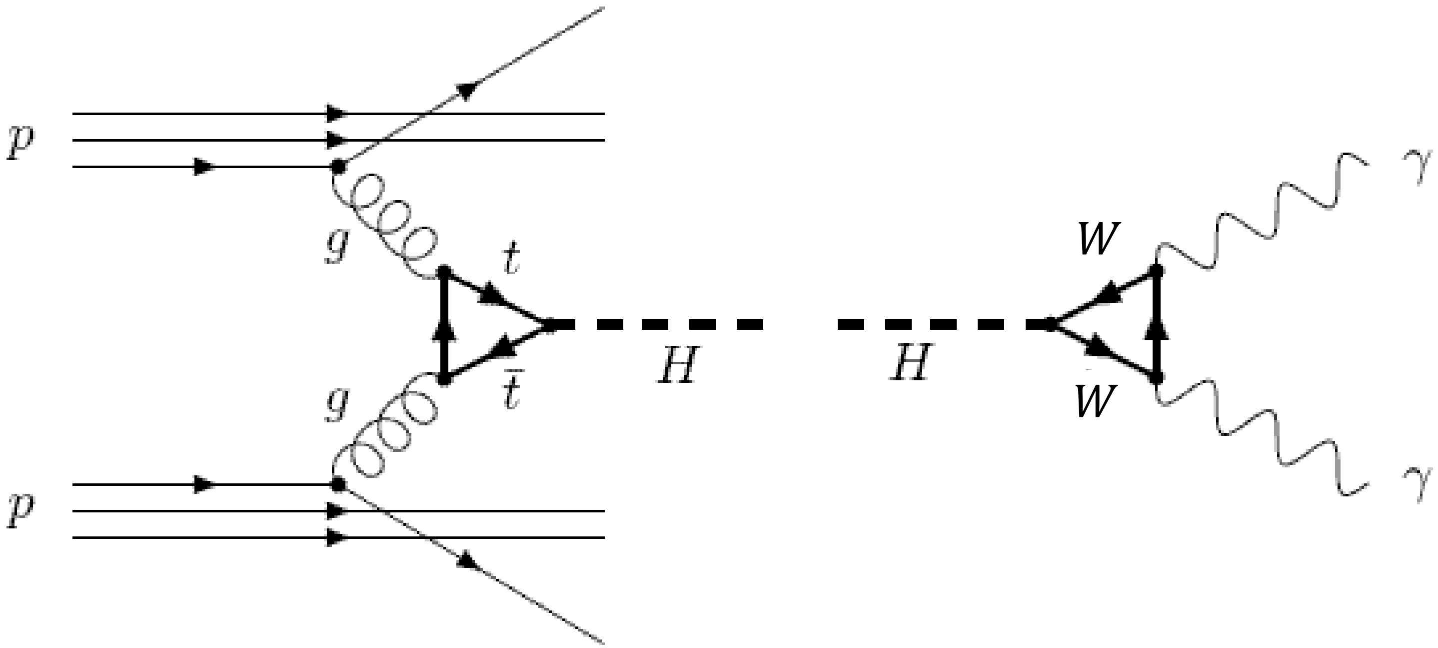
November 20, 2012

*Including MSSM, but excluding ttH(bb) and VH(ττ)

AP photo

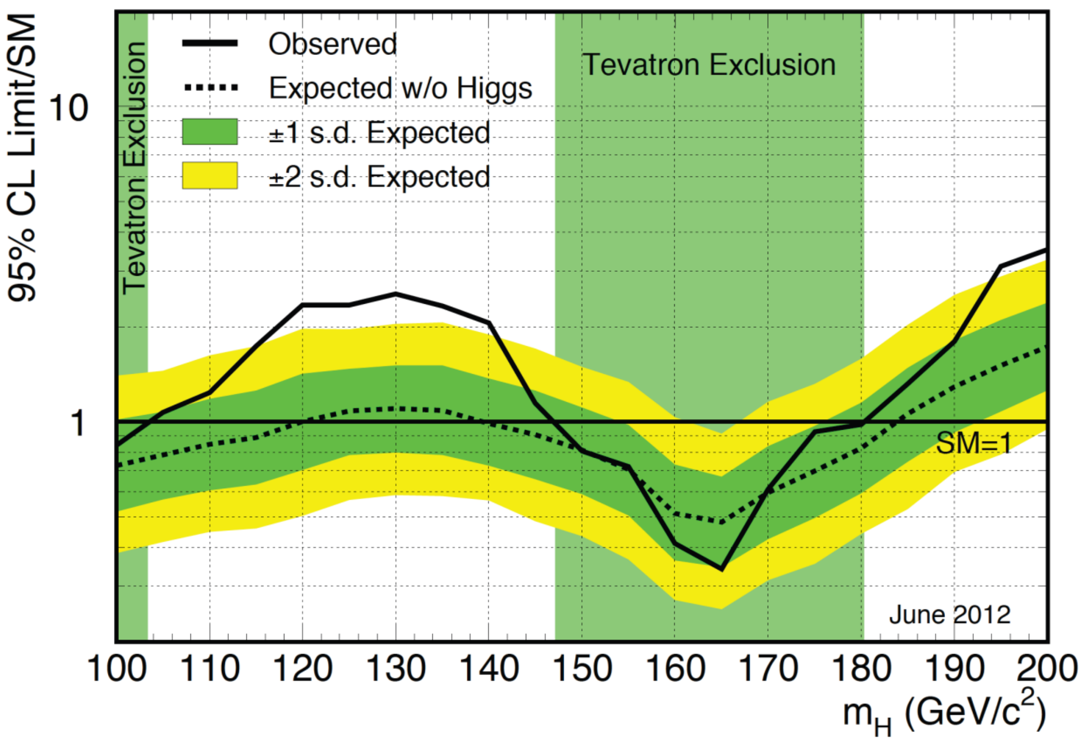
"As a layman, I think we have it. But as a scientist, I have to say, 'What do we have?'" – R. Heuer

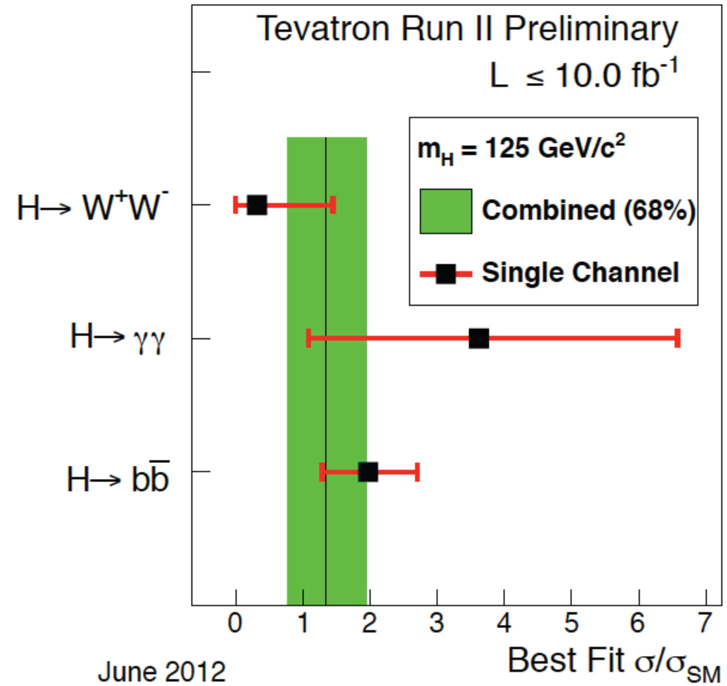
Does it **couple** to fermions?



In the context of the SM Higgs boson phenomenology, we already have strong **indirect** evidence for a coupling to the top quark via the loop in the dominant production mechanism.

Does it decay to fermions?



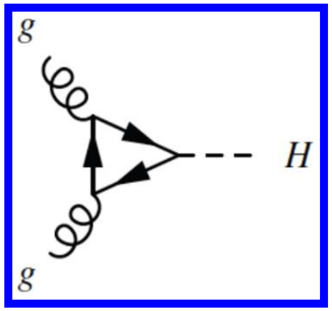


2.5σ (Global)
2.9σ (bb)

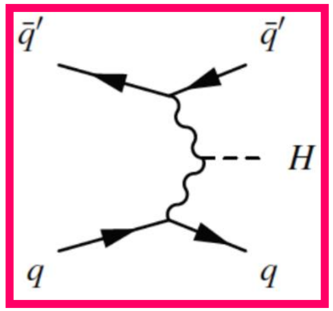
Is the Tevatron seeing H → bb?

Brief intro and update of LHC status and non-fermion results from CMS

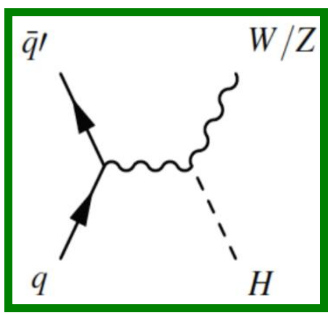
Higgs Production at the LHC



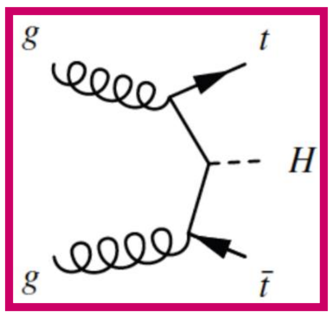
Gluon Fusion



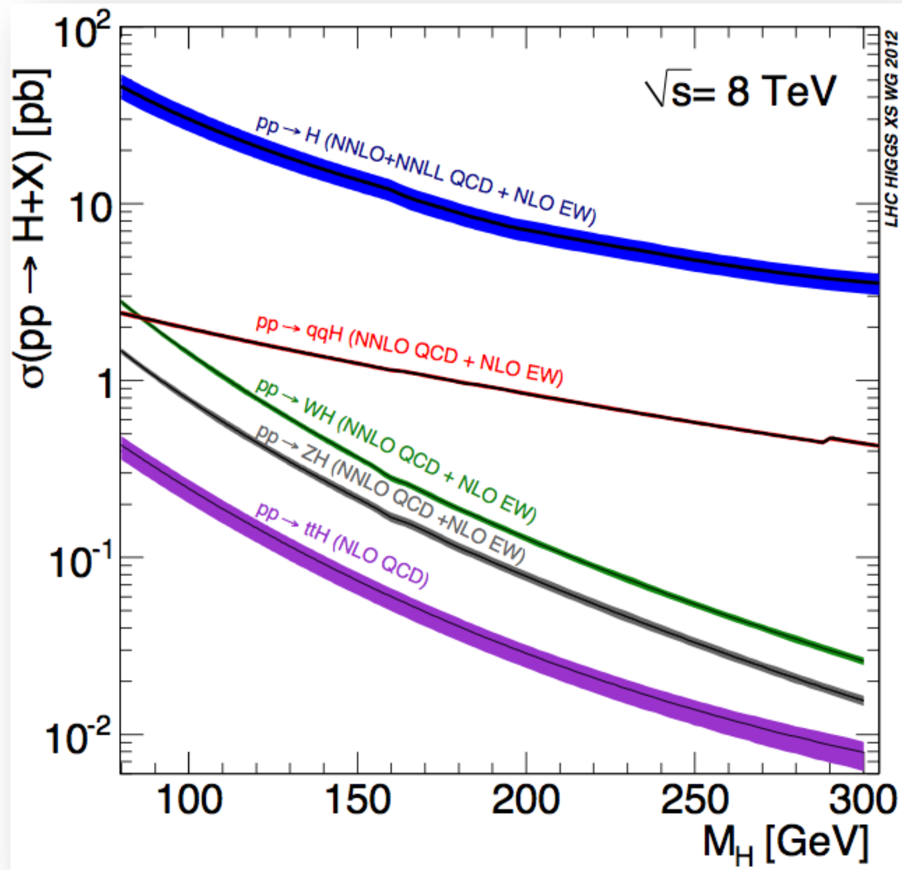
Vector-Boson Fusion



Higgs-strahlung

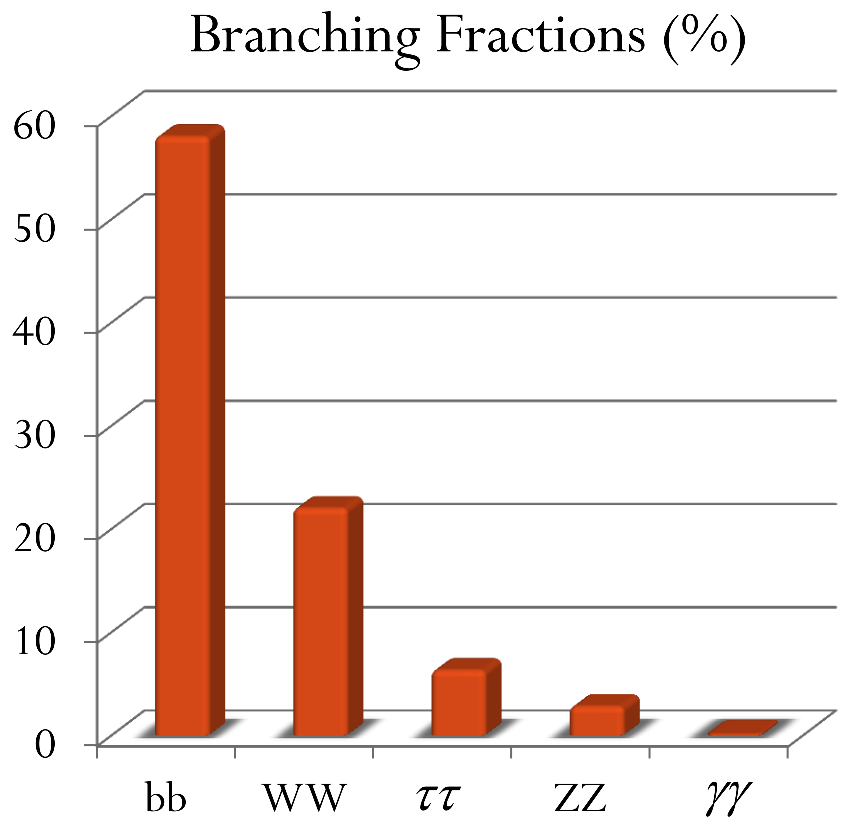


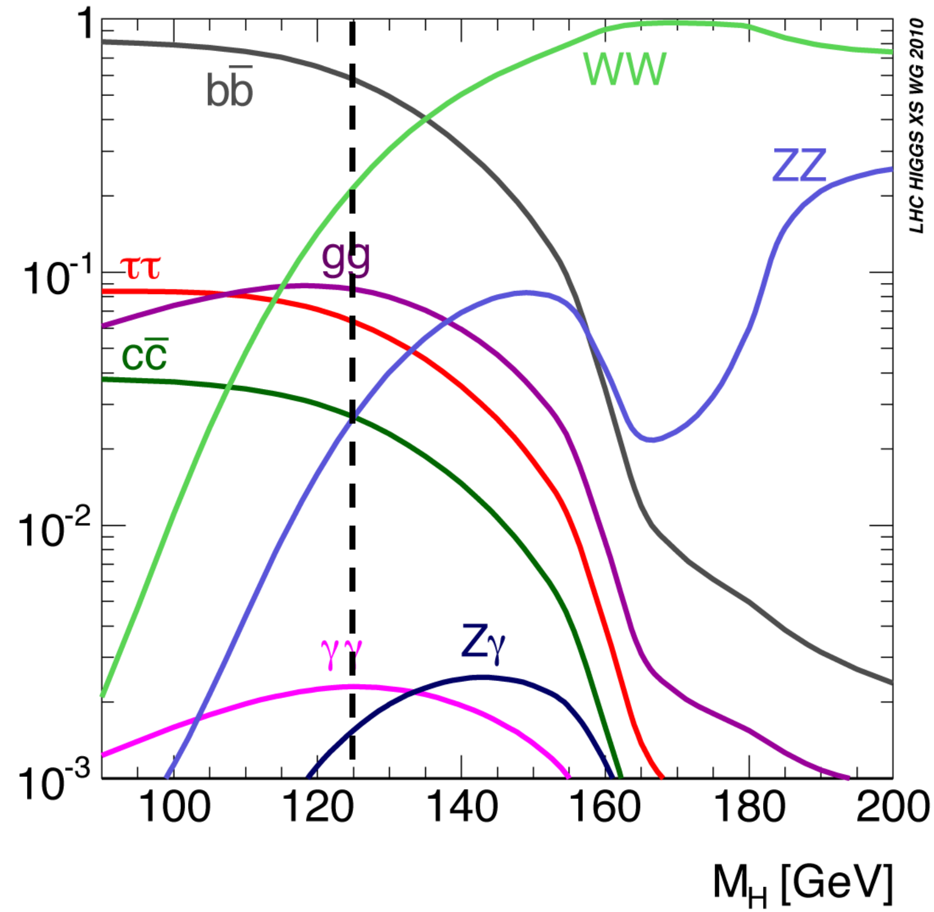
Top Fusion ($t\bar{t}H$)



LHC in 2012, at record luminosity (7 x 10^{33} $cm^{-2}s^{-1}$) and energy (8 TeV), is now producing SM Higgs bosons (M_H = 125 GeV) at a rate **~750/hr**

How does it Decay (m_H = 125 GeV) ?





Only region in m_H where →

- Cross sections are large
- Fermion decays (bb+ττ) are accessible
- Natural width is negligible

What does a Higgs boson look like?

@Low mass

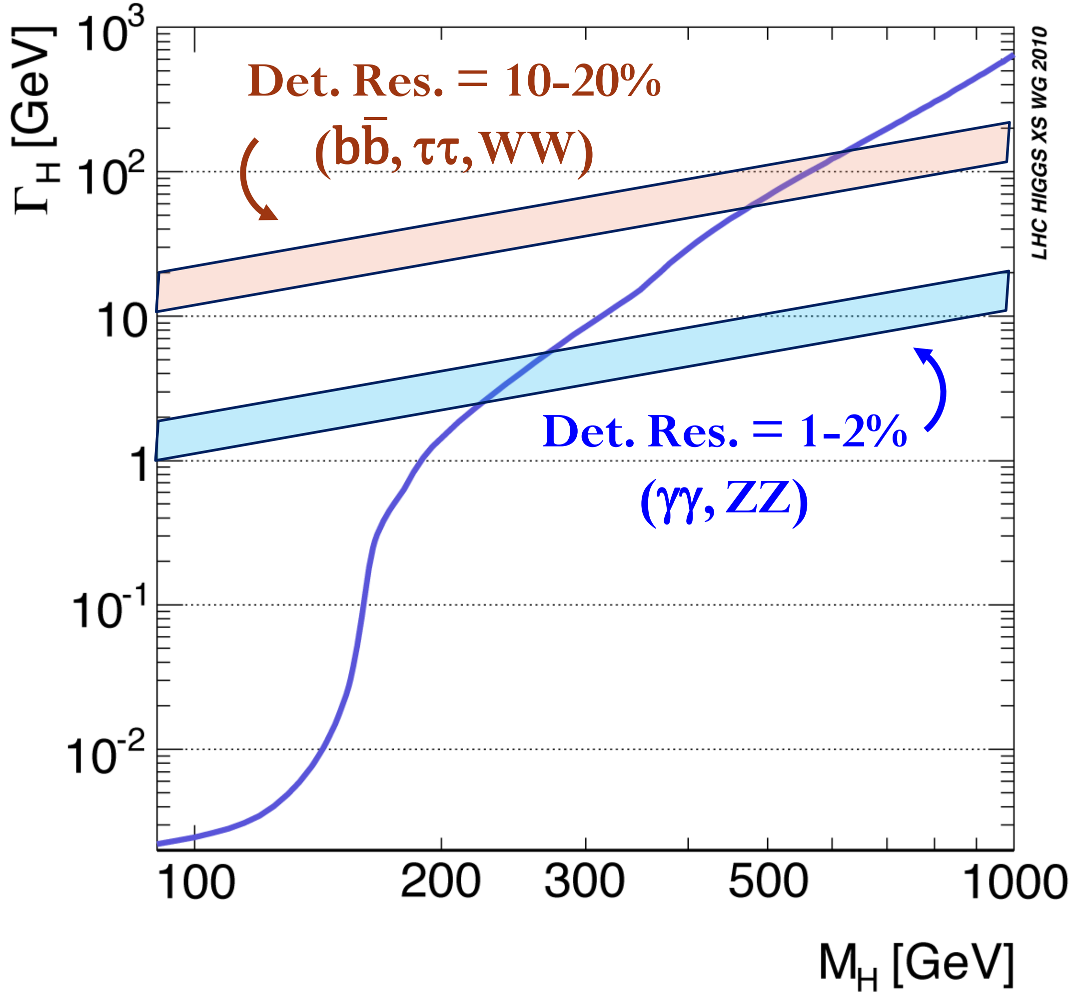
Narrow! $\Gamma_H / M_H \sim 10^{-5}$

Observed width dominated by ***detector resolution***

@High mass

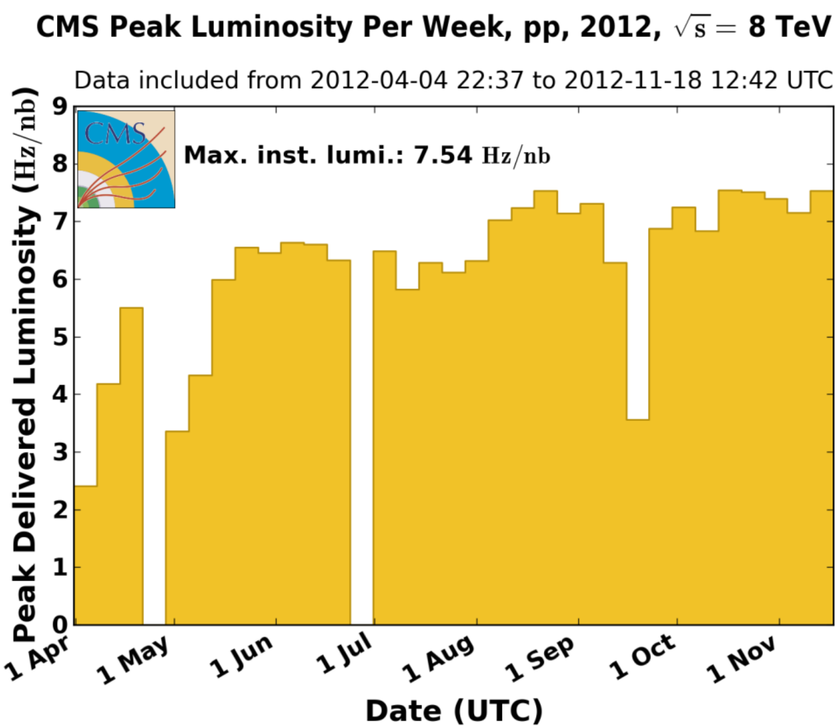
Higgs becomes a broad resonance dominated by ***natural width***

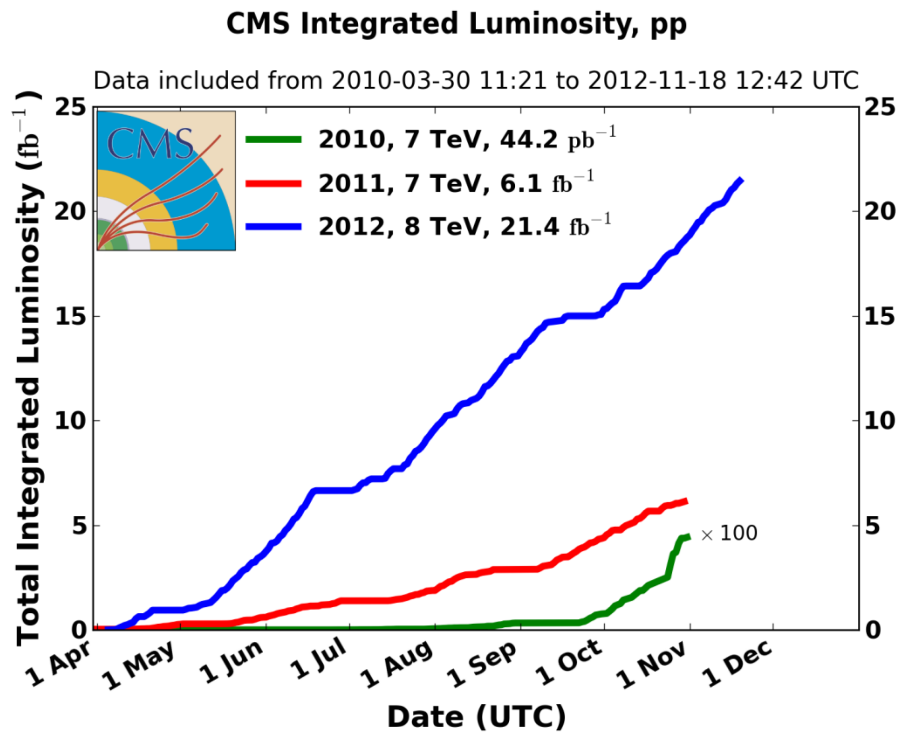
Theory input is critical



Latest LHC + CMS Performance

Higher energy (4 TeV per beam) and higher luminosity (> 7e33)





- Phenomenal performance:
  - Record luminosity (> 5 e 33) obtained soon after startup in 2012
  - Sustained data collection rate of > 1.0fb^{-1} /wk
  - Total delivered/recorded @ 8 TeV = 21.4 (20.7) fb^{-1} [>93% CMS efficiency]

Latest results for the SM Higgs:

Channel	m_H range [GeV/c^2]	data set [fb^{-1}]	Data used CMS [fb^{-1}]	m_H resolution
1) $H \to \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \to$ tau tau	110-145	5+12/fb	2011+12	15%
3) $H \to bb$	110-135	5+12/fb	2011+12	~~10%~~ 8-9%
4) $H \to WW \to l\nu l\nu$	110-600	5+12/fb	2011+12	20%
5) $H \to ZZ \to 4l$	110-1000	5+12/fb	2011+12	1-2%

Updates from ZZ, WW, $\tau\tau$, and bb presented at HCP last week

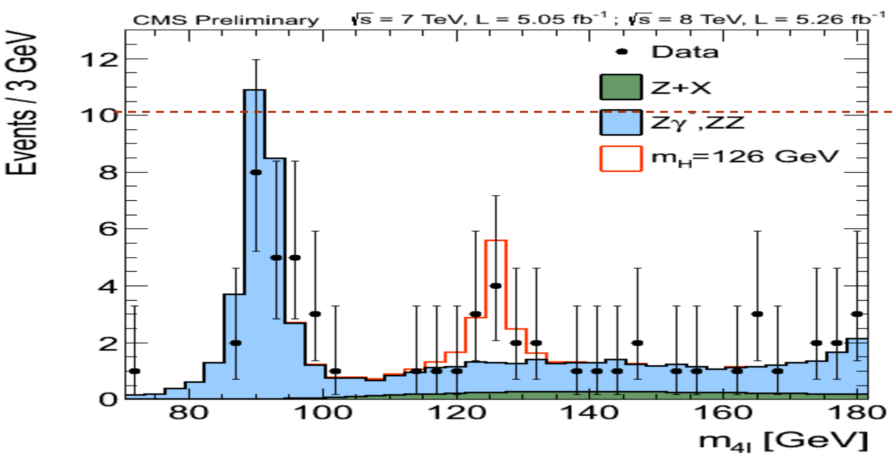
Updated results for $H \to ZZ^* \to 4\ell$

July

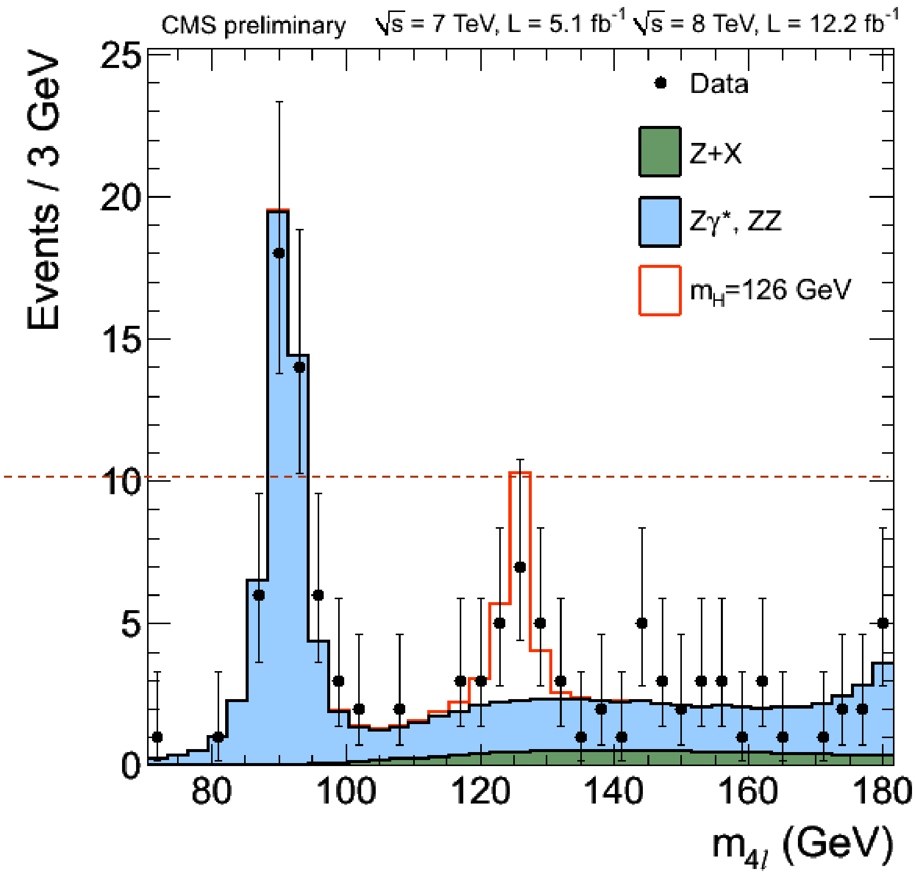
Expected significance = 3.8σ

Observed significance = 3.2σ

Backgrounds well modeled, including peak from $Z \to 4\ell$



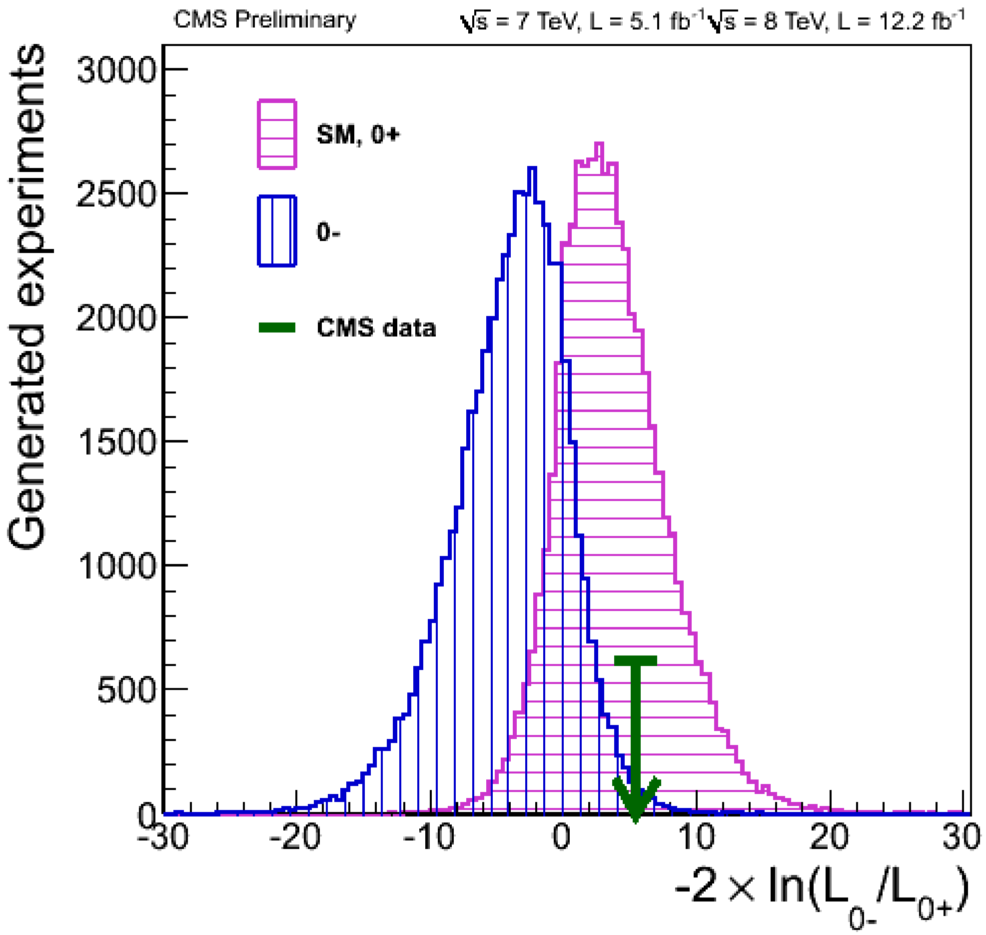
November



With 1.7x more data, the peak near 125 GeV grows according to SM expectation: max observed significance @ 125.9 GeV = 4.5σ

Best-fit mass (with signal strength varying) = 126.2 ±0.6 (stat) ± 0.2 (syst)

Parity of the new boson from ZZ*



From angular analysis (MELA) of the four-lepton final state, can separate scalar from pseudoscalar: exp ~ 2σ

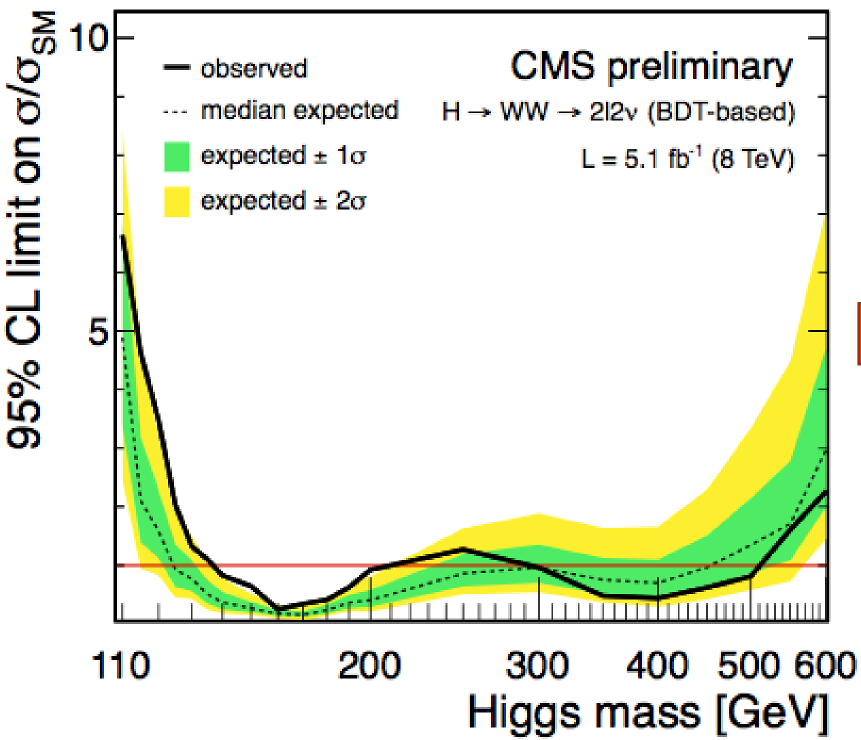
Data consistency with 0^+ = 0.5σ

Data consistency with 0^- = 2.4σ

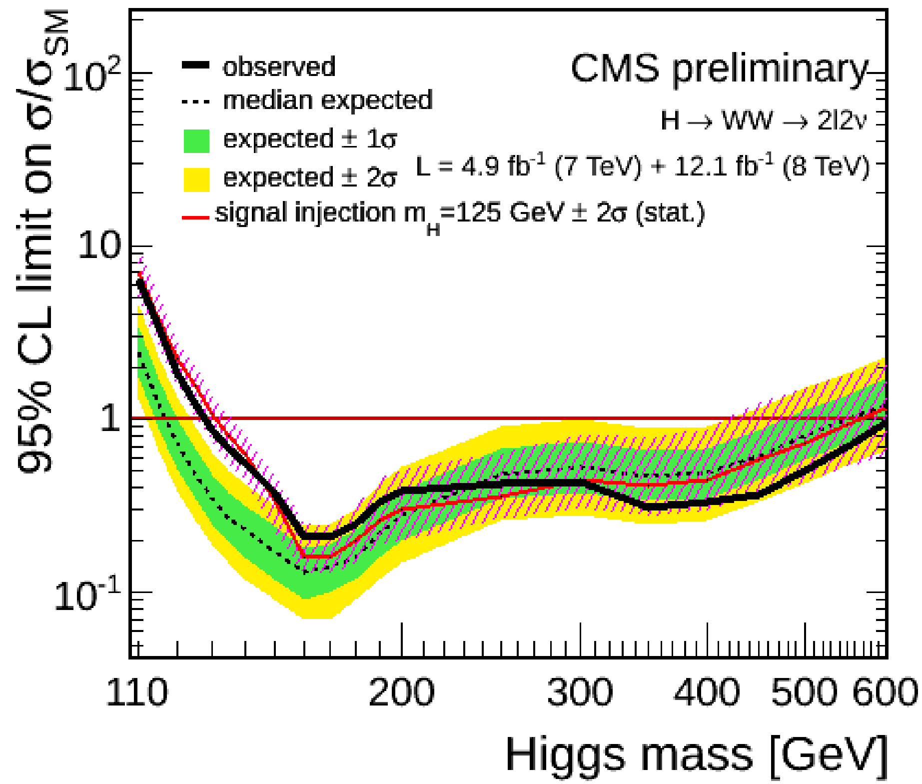
Current data favors SM hypothesis comparing against pseudoscalar alternative

Update on $H \rightarrow WW^* \rightarrow 2\ell 2\nu$

July

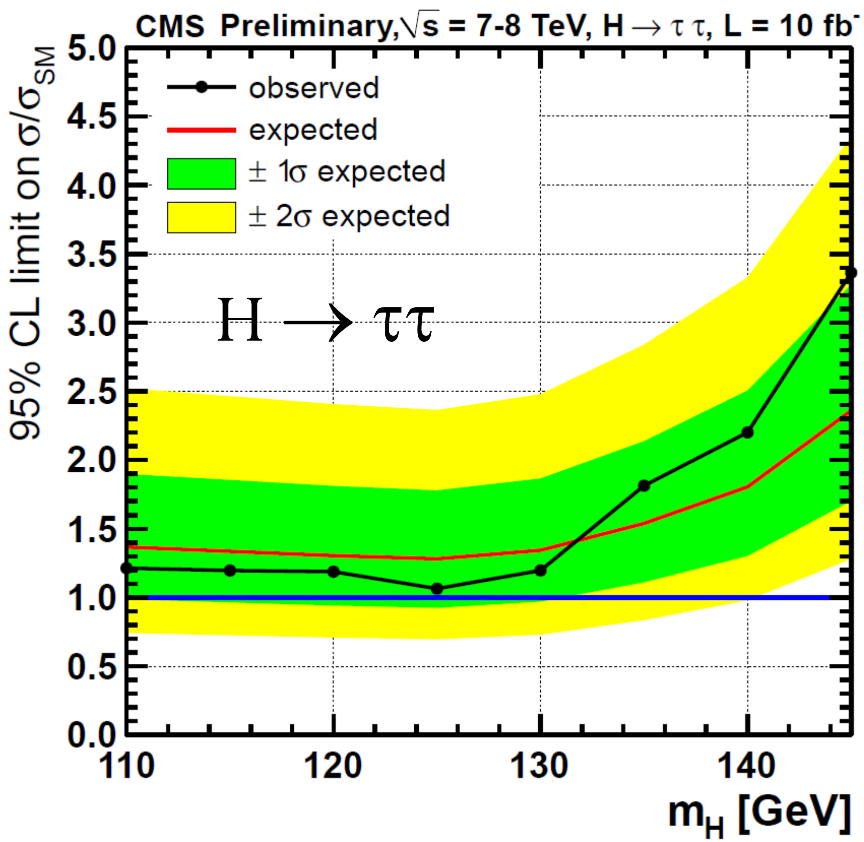


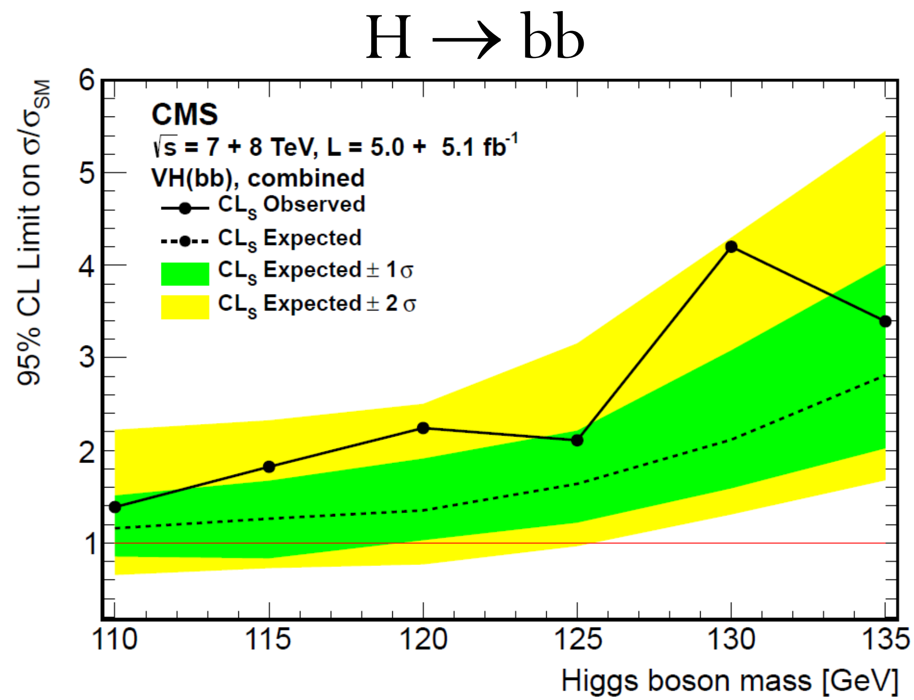
November



Adding 1.7x more data increases the observed significance @ 125 GeV from ~2σ to > 3σ

The boson decays are certainly looking more and more SM every day, what about the fermions?





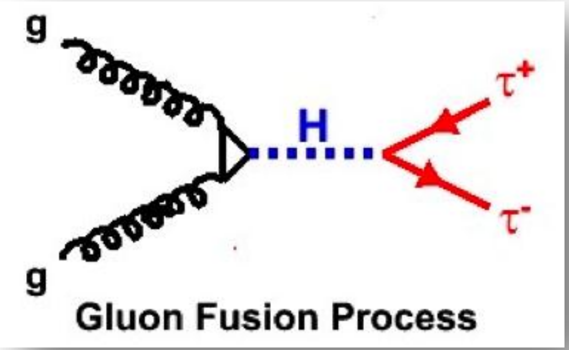
Situation in July (ICHEP): slight deficit in ττ, slight excess in bb

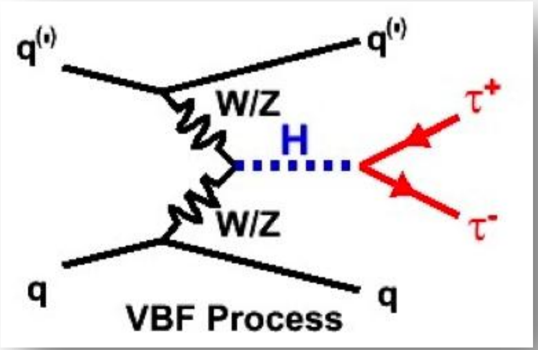
Search for H $\rightarrow$ $\tau\tau$ @ CMS

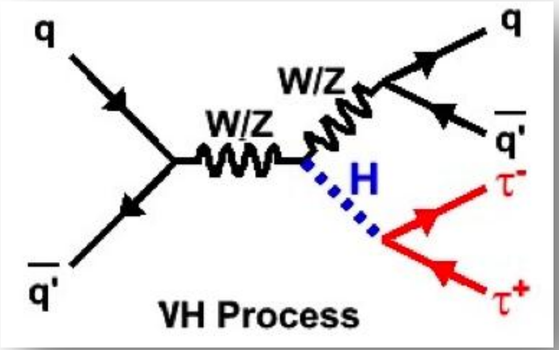
Overview

- **Importance of $H \to \tau\tau$:**
  - Only currently active probe of lepton coupling
  - Complementarity with $H \to bb$ in down-type fermion couplings
  - Largest σ x Br for SM mH < 130 GeV
  - Sensitivity to BSM models
- **Broad-based search**
  - Currently use all production channels except ttH (only discussing GGF and VBF here)

Decay Channel	Luminosity
HIG-12-043	
$\mu\tau_h$	17 fb^{-1}
$e\tau_h$	17 fb^{-1}
$e\mu$	17 fb^{-1}
$\mu\mu$	17 fb^{-1}
$\tau_h\tau_h$	12 fb^{-1} (2012)



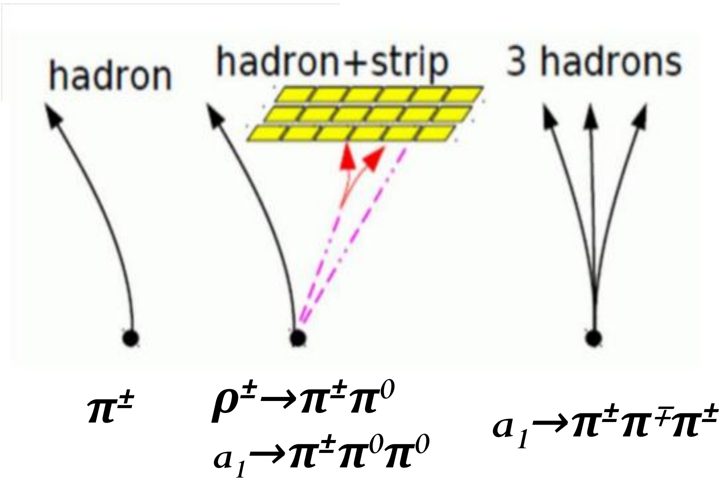


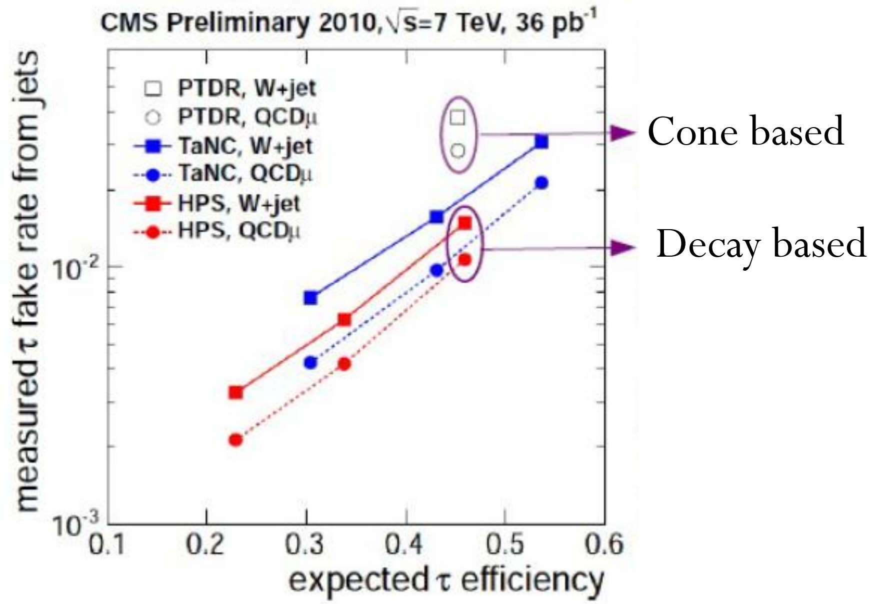


Search Strategy

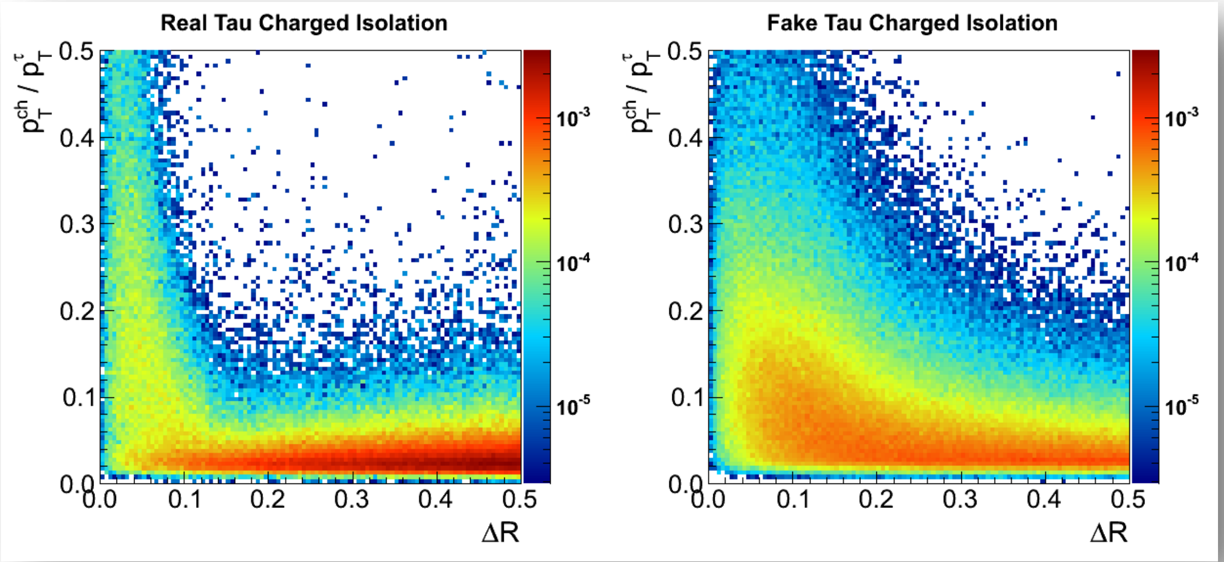
- **Dominant background: $Z \rightarrow \tau\tau$**
- **Analysis strategy depends on tau decays**
  - Hadronic decays dominant, but reco/ID challenging
  - Search in e/μ, e/h, μ/h, μ/μ, [and h/h]
- **Hadronic tau reconstruction**
  - Identify 1-prong and 3-prong decays
- **Mass reconstruction**
  - Multiple neutrinos, dedicated MVA algorithm
  - Final signal estimate from $m_{\tau\tau}$ shape
- **Event categorization**
  - Inclusive, VBF, [and VH production]
  - Boosted categories to improve mass resolution and bkg rejection

Tau Reconstruction and ID



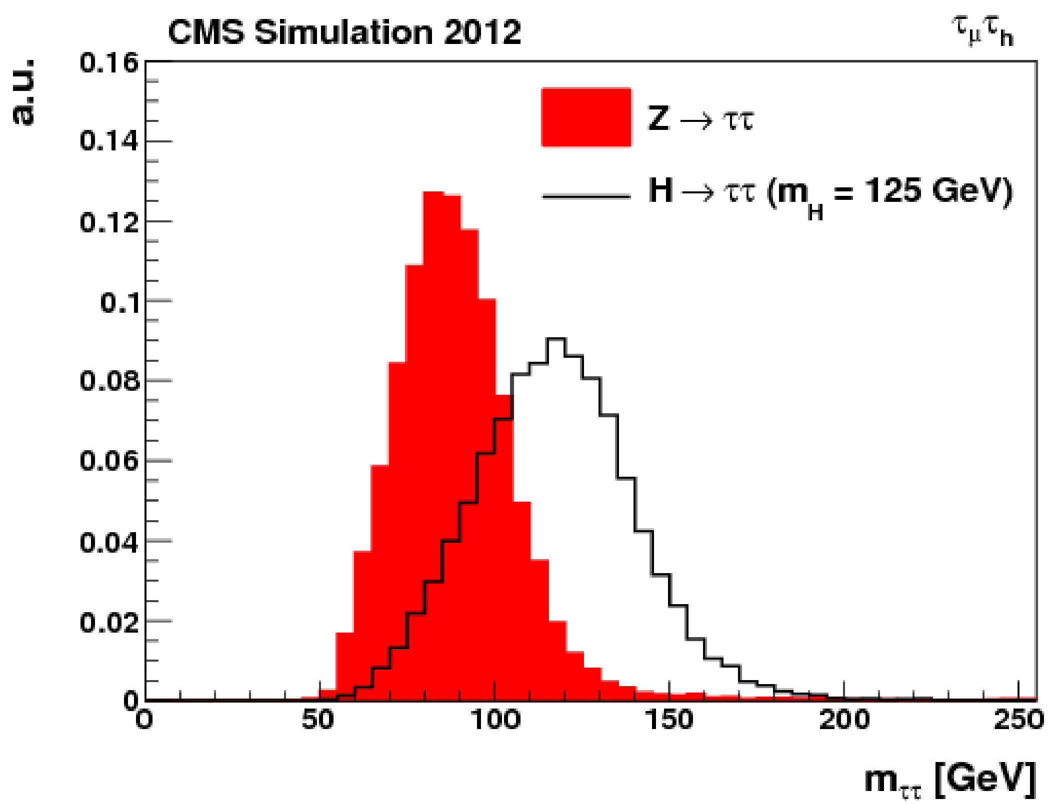


MVA ID based on relative pT(chg) in rings around tau dir.

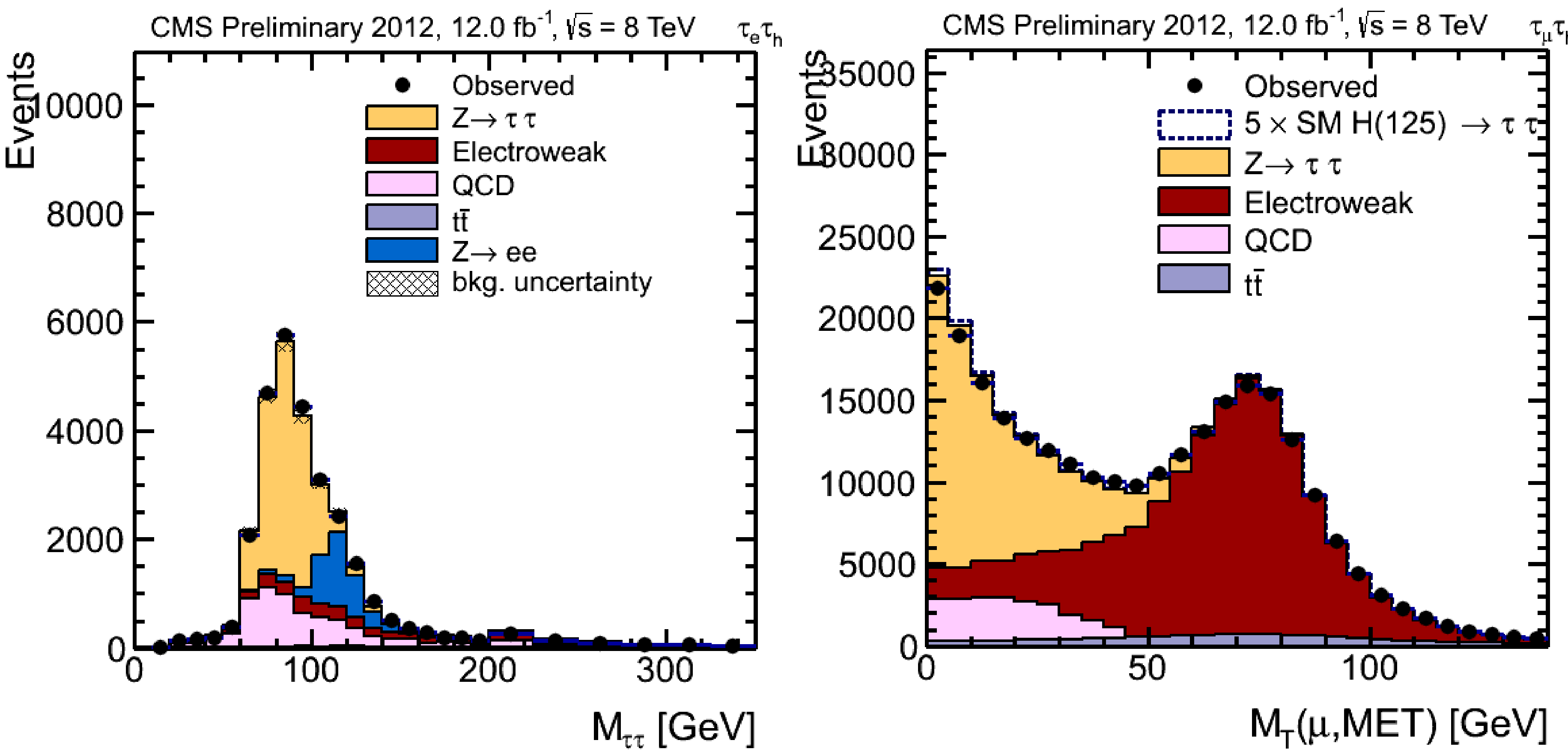


Mass Reconstruction(I)

- Attempt to separate $H \to \tau\tau$ from $Z \to \tau\tau$
  - Use kinematics of visible decay products (particle flow objects) and MET to build and event-by-event likelihood
- Inputs
  - 4-vectors of tau dtrs
  - MET
  - ME for $\tau \to \ell\nu\nu$
  - Phase space for $\tau \to \pi$
- $m_{\tau\tau}$ resolution ~15-20%



Backgrounds



Non-Z backgrounds: EWK (W+jet), obtained from data control regions, ttbar normalized to CMS measurement and checked in control regions

Event Categorization: GGF and VBF

Number of jets

τ_h or μ p_T

0 Jet, Low p_T
High background

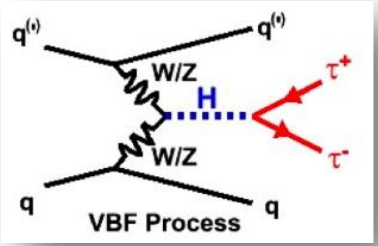
1 Jet, Low p_T
Improved bkg rej from jet req, veto b jets

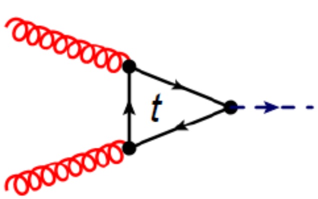
0 Jet, High pT
Lepton p_T spectrum harder from H

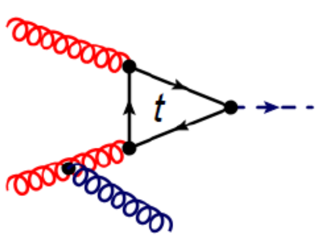
1 Jet, High p_T
Improved $m_{\tau\tau}$ resolution from p_T, veto b jets

0-jet bin used to fit bkg

VBF
2 jets, no jets in rapidity gap
MVA based selection

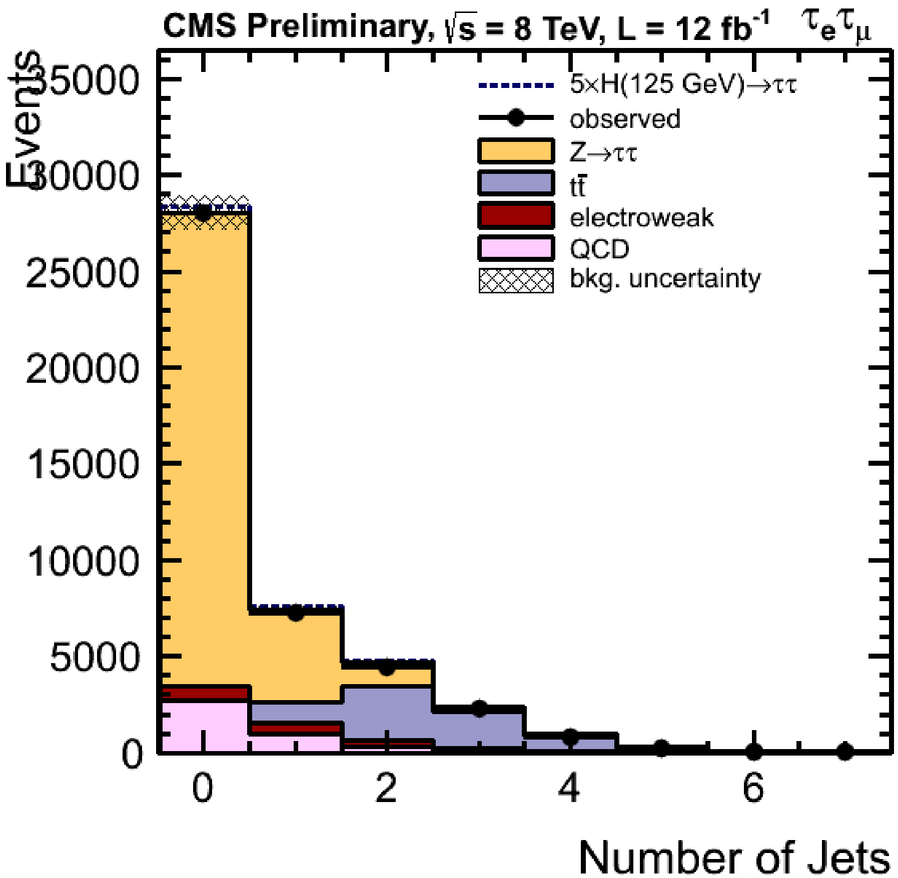


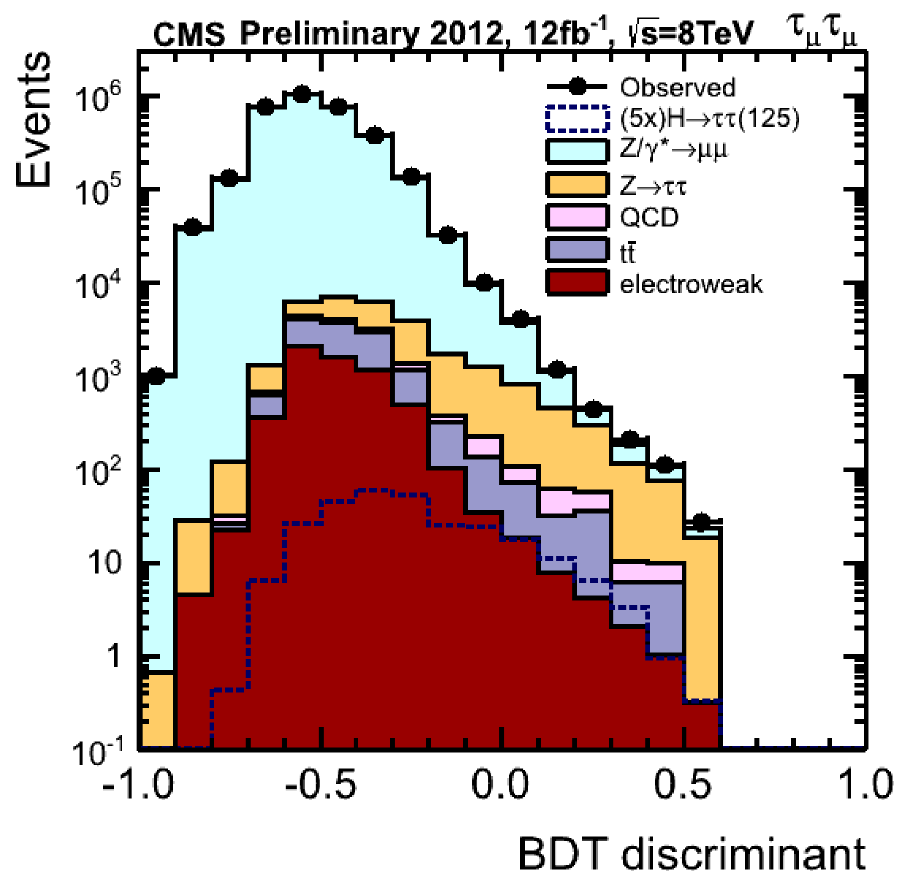




Use topology and kinematics to isolate production processes and suppress backgrounds

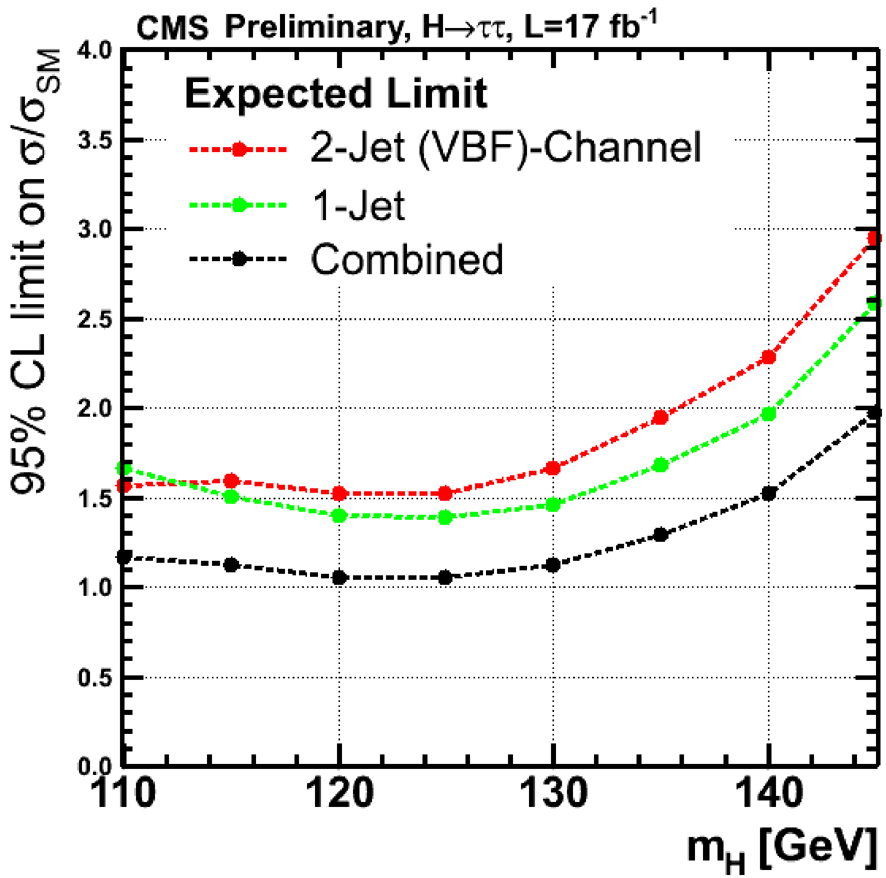
Data/MC: Njet and BDT(μμ)



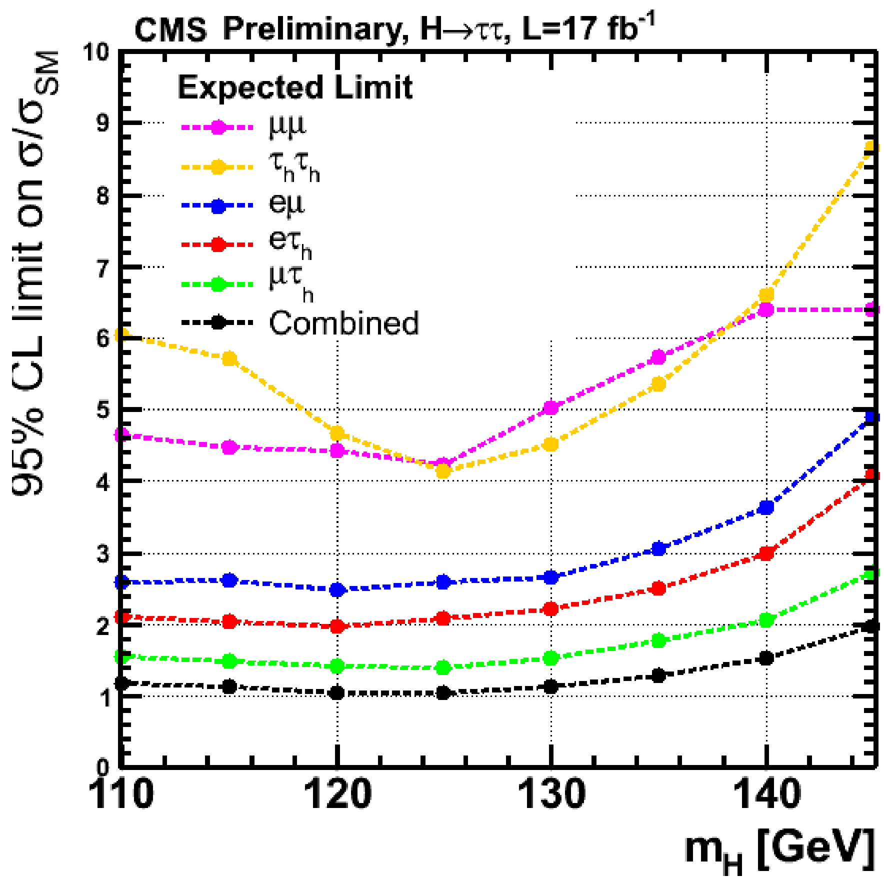


Expected Sensitivity (17/fb)

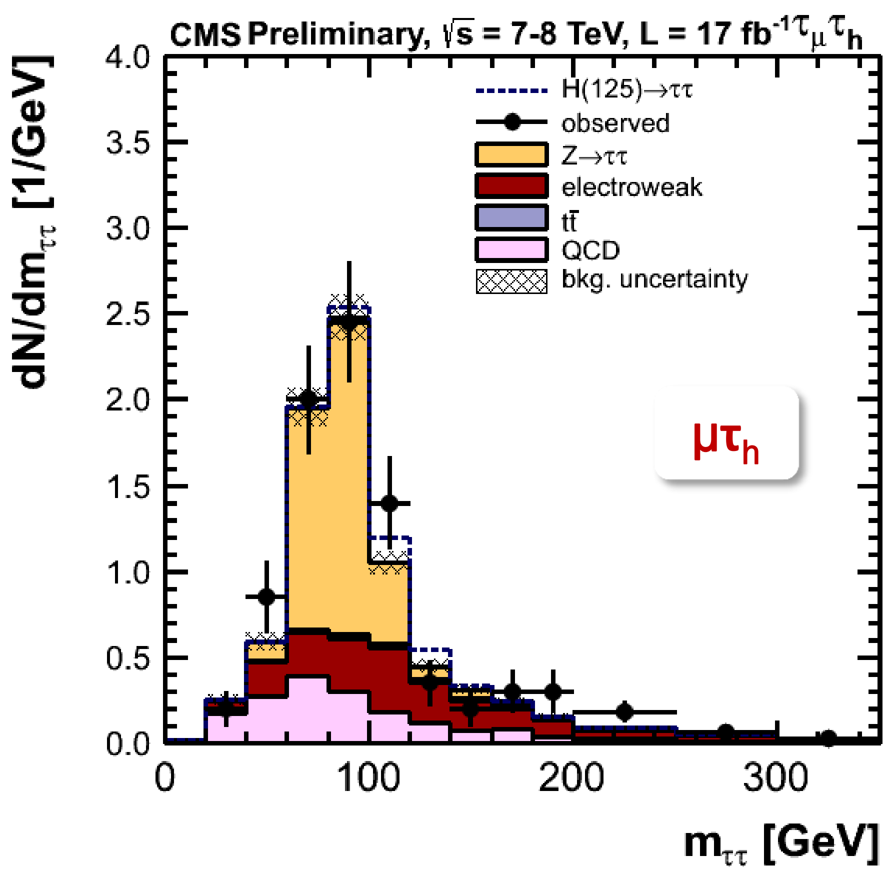
By category

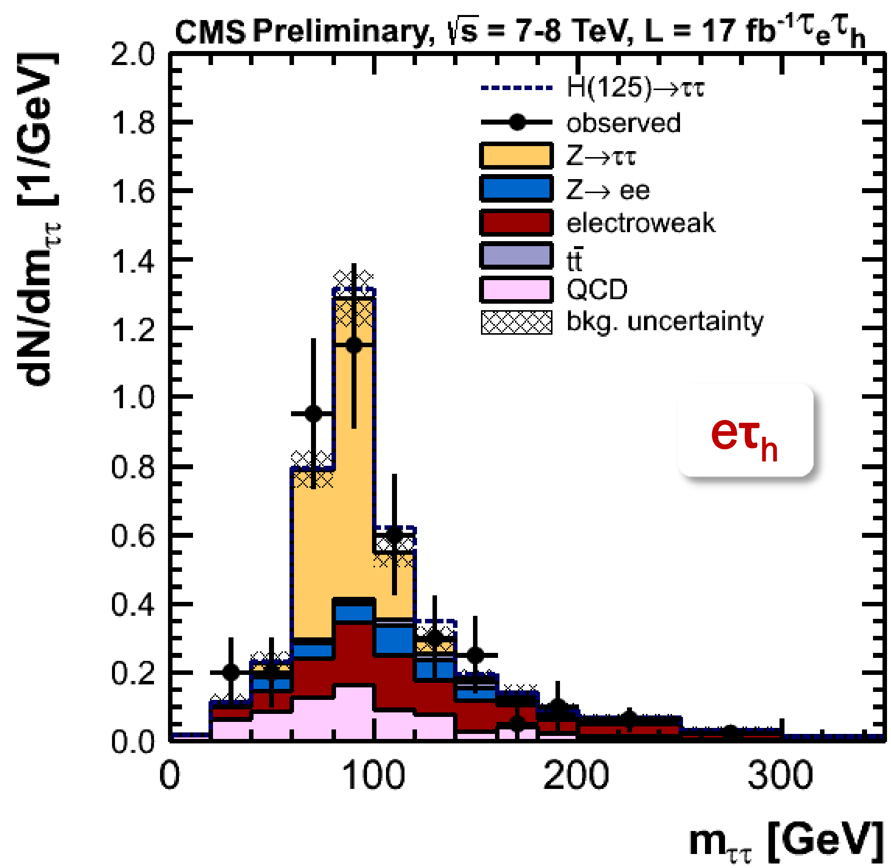


By channel

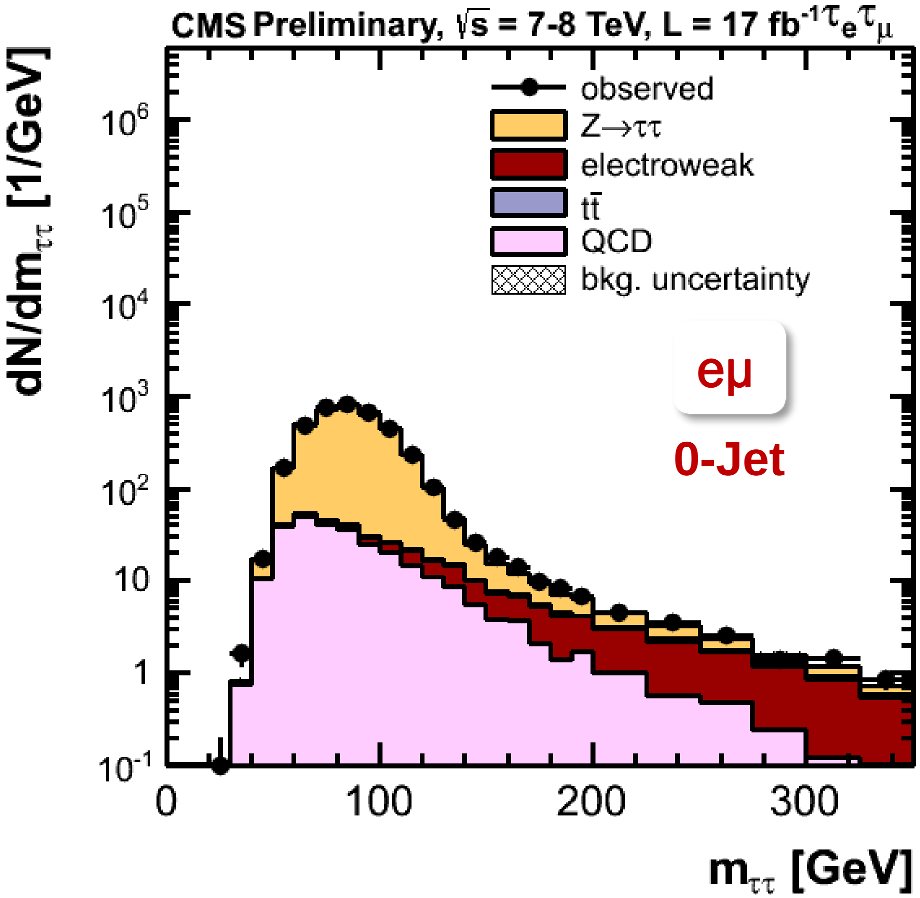


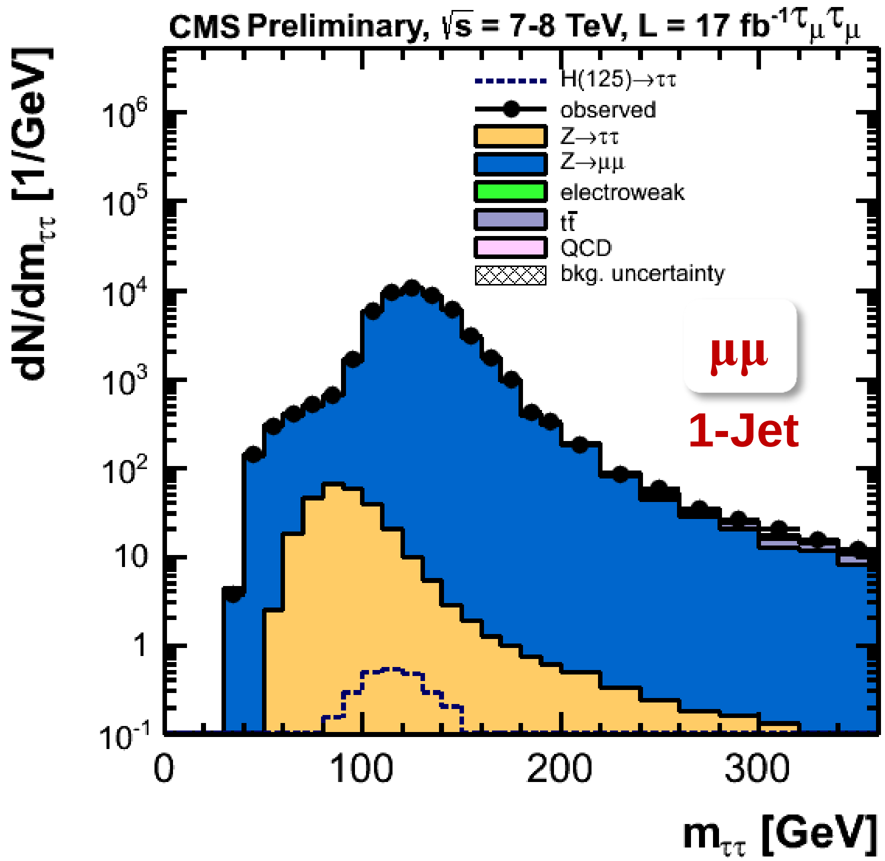
Example Distributions: VBF





Example Distributions: 0-jet, 1-jet





Most Important Systematic Uncertainties

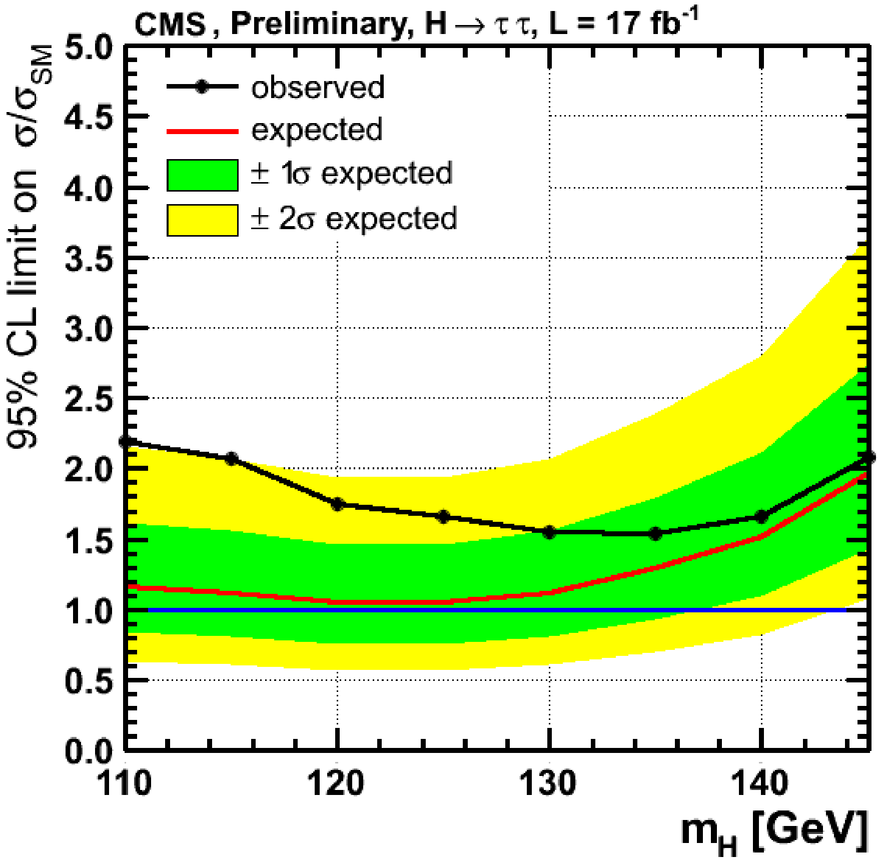
Experimental Uncertainties		Propagation into Limit Calculation		
Uncertainty	Uncert.	*0-Jet*	*Boost*	*VBF*
Electron ID & Trigger (*)	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
Muon ID & Trigger (*)	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
Tau ID & Trigger (*)	$\pm 7\%$	$\pm 7\%$	$\pm 7\%$	$\pm 7\%$
JES (Norm.) (*)	$\pm 2.5 - 5\%$	$\mp 1\%$	$\pm 5\%$	$\pm 10\%$
b-Tag Efficiency (*)	$\pm 10\%$	$\mp 1\%$	$\mp 2\%$	$\mp 2\%$
Mis-Tagging (*)	$\pm 30\%$	$\mp 1\%$	$\mp 1\%$	$\mp 1\%$
Norm. $Z \to \tau\tau$	$\pm 3\%$	$\pm 3\%$	$\pm 5\%$	$\pm 13\%$
Norm. $t\bar{t}$ (*)	$\pm 10 - 30\%$	$\pm 10\%$	$\pm 12\%$	$\pm 30\%$
Norm *EWK*	$\pm 30\%$	$\pm 30\%$	$\pm 15 - 30\%$	$\pm 30 - 100\%$
Norm Fakes	$\pm 10 - 30\%$	$\pm 10\%$	$\pm 10\%$	$\pm 30\%$
Lumi (Signal & EWK)	$\pm 2.2(5)\%$	$\pm 2.2(5)\%$	$\pm 2.2(5)\%$	$\pm 2.2(5)\%$
Norm. $W + jets$	$\pm 10 - 30\%$	$\pm 10\%$	$\pm 10 - 30\%$	$\pm 30\%$
Norm. Z: l fakes τ_h	$\pm 20 - 100\%$	$\pm 20 - 30\%$	$\pm 20 - 100\%$	$\pm 30\%$
Norm. Z: jet fakes τ_h	$\pm 20\%$	$\pm 20\%$	$\pm 20\%$	$\pm 30\%$

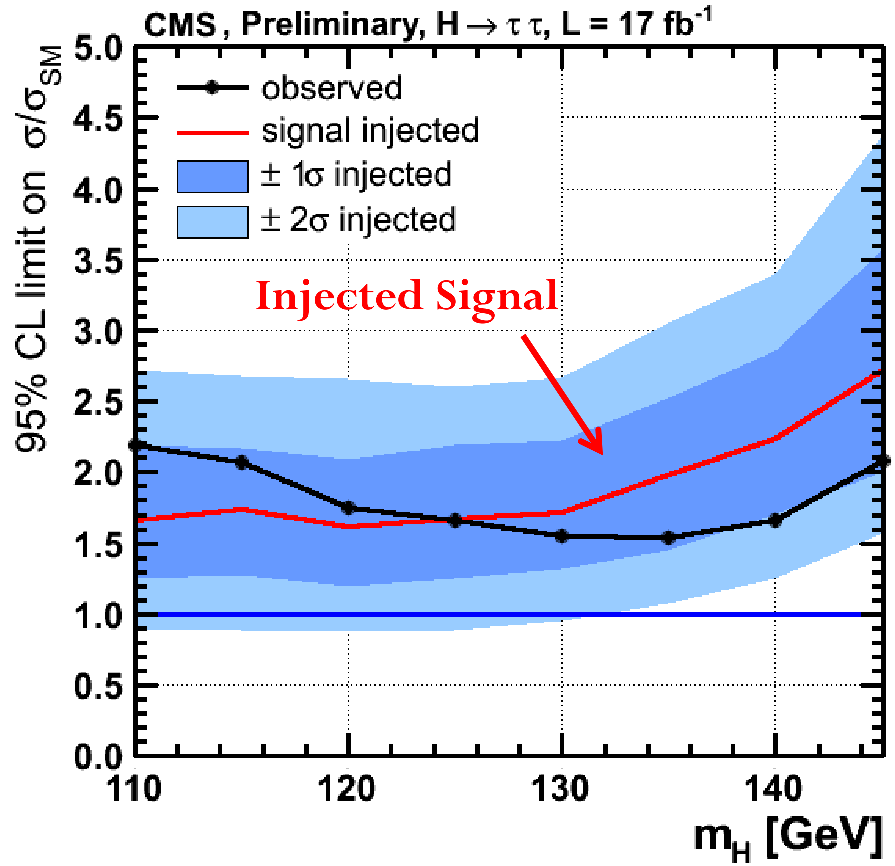
R. Wolf (@HCP)

+ shape uncertainties on τ/e energy scale.

+ theory uncertainties (O(5-10%)).

Results: 7 + 8 TeV (17/fb)



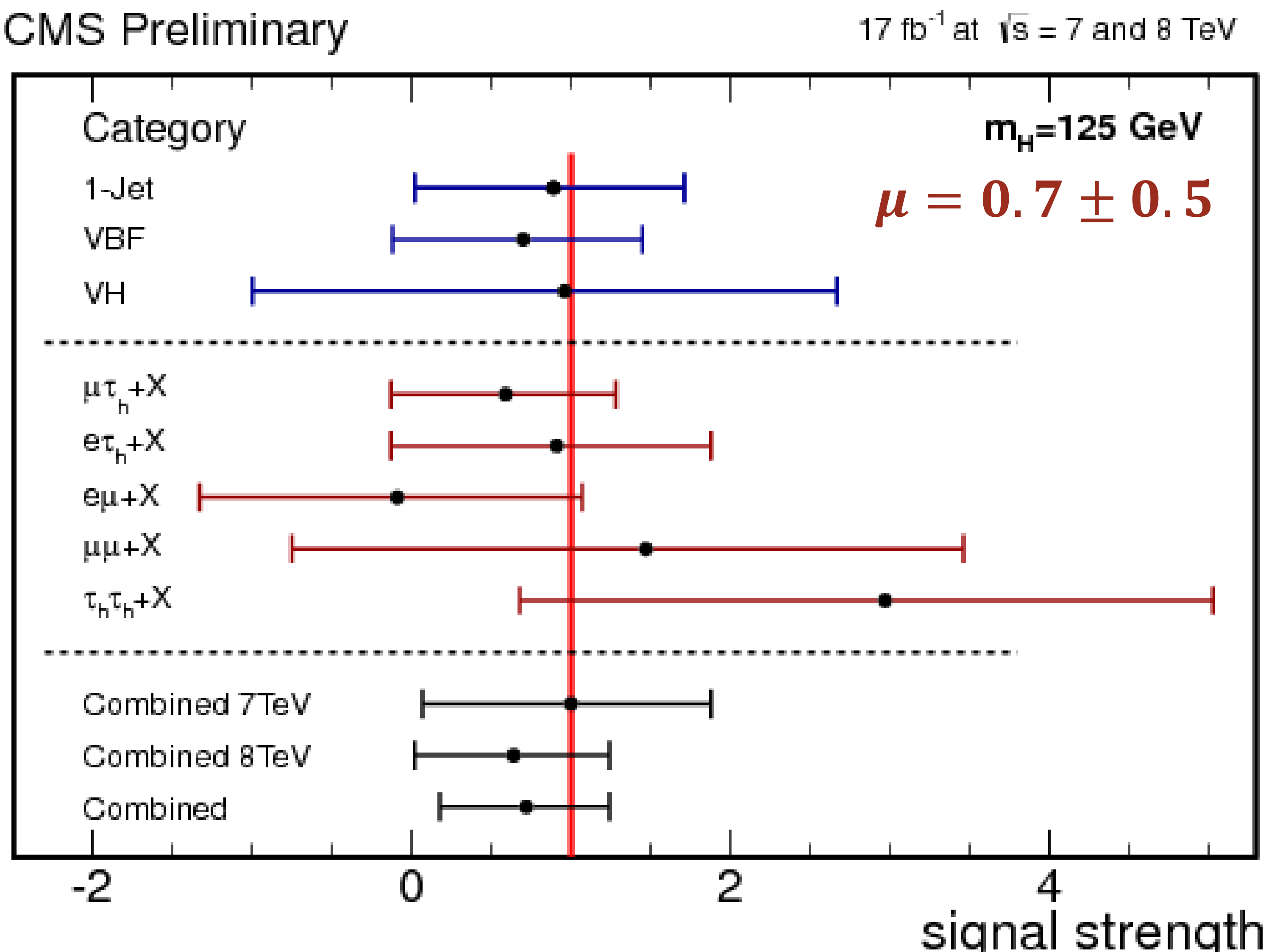


@125 GeV:

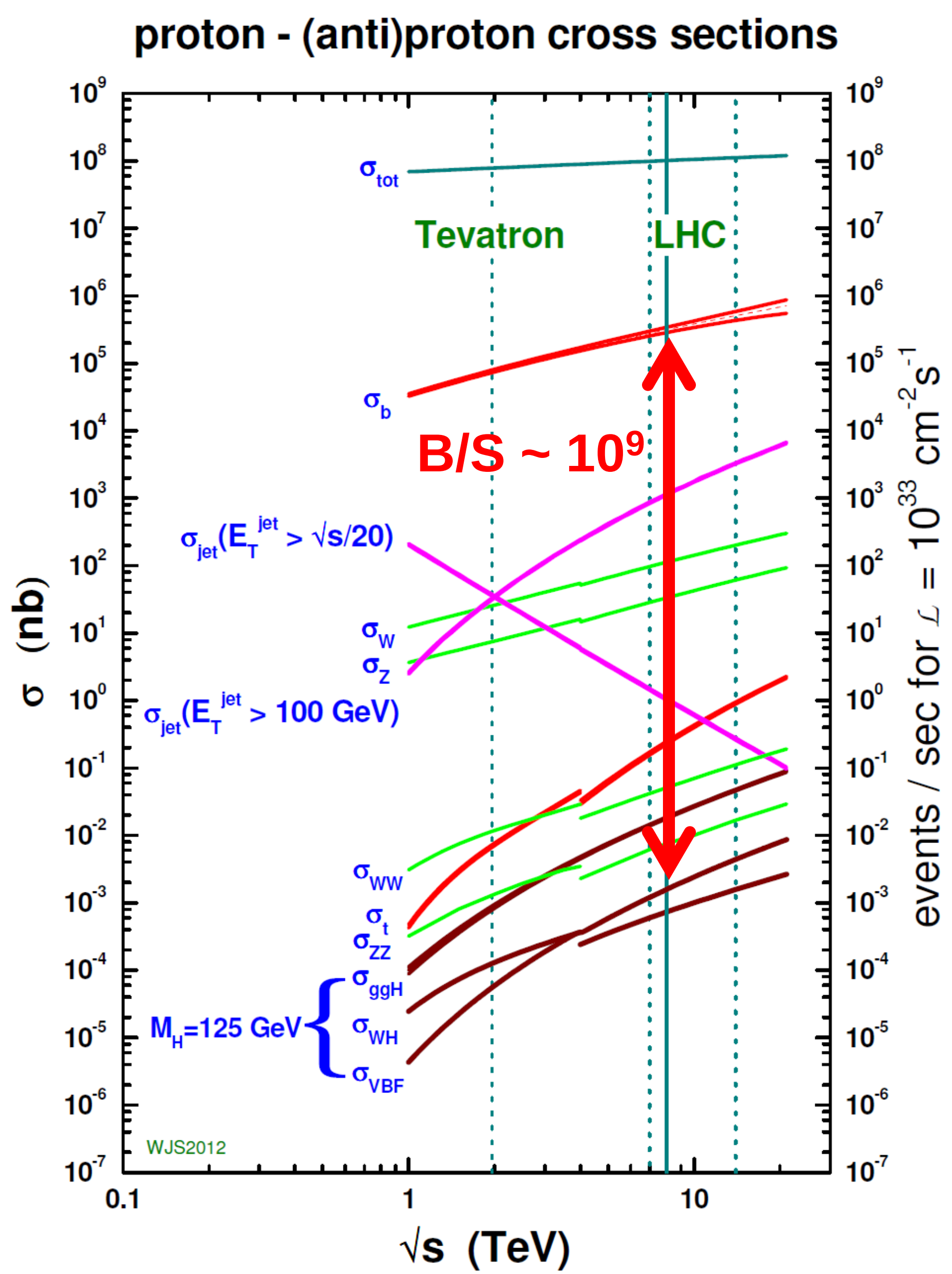
exp (obs) limit = 1.05 (1.66) x SM

exp (obs) significance = 2.45 (1.50) σ

Signal Strength



Search for $H \rightarrow bb$ @ CMS



Inclusive H → bb?

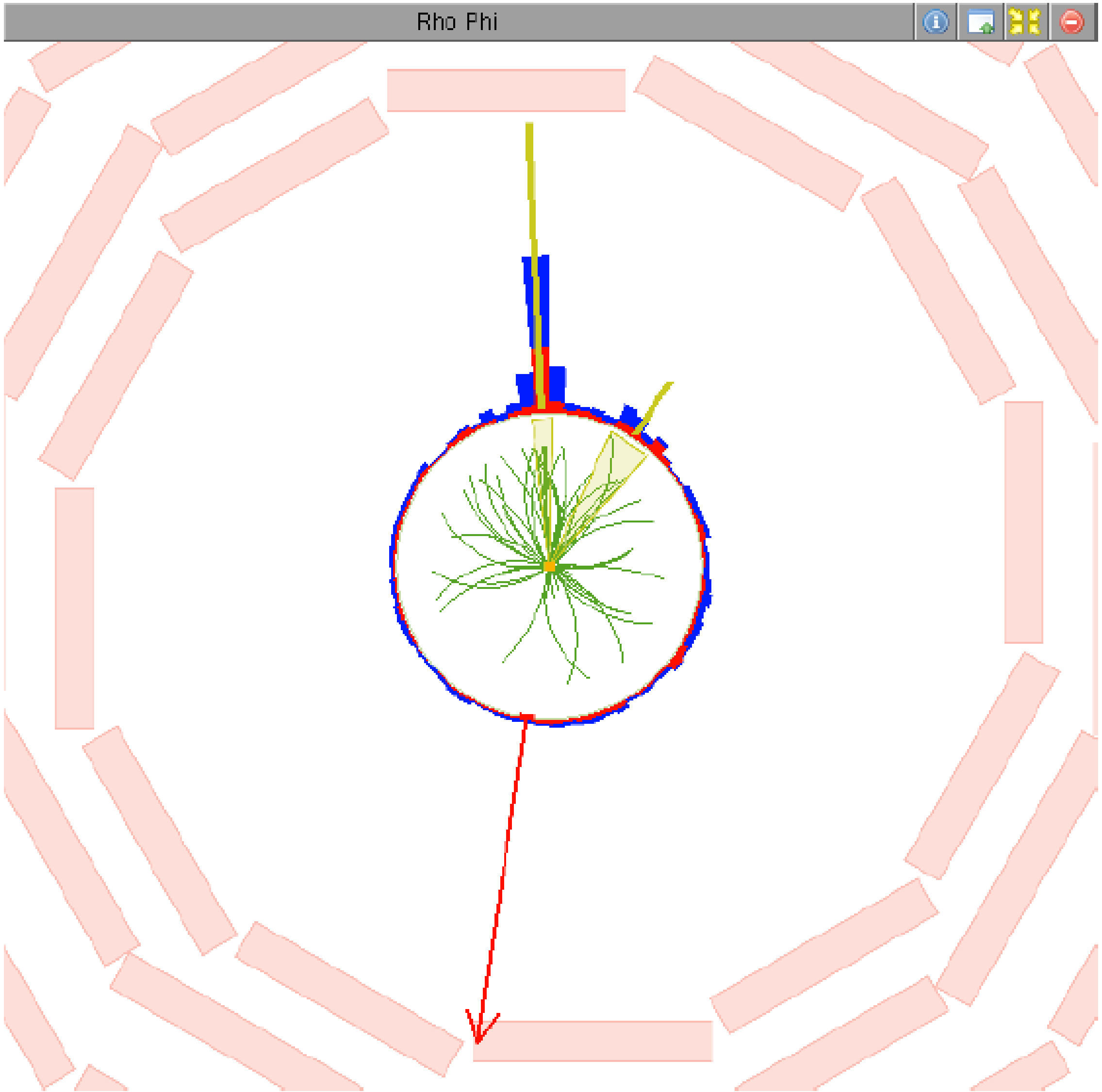
Overwhelmed by QCD production of bottom-quark jets (B/S ~ 10^9)

Need to find another haystack!
Boosted VH, H→bb

Analysis strategy

- **Five separate channels:** $Z(\ell\ell)$, $Z(\nu\nu)$, $W(\ell\nu)$; $\ell = e,\mu$
- **Triggers (8 TeV):**
  - Incl μ (24-40 GeV), iso elec (27 GeV), double elec (17/8 GeV)
  - MET (80 GeV) + 2 jets (60/25 GeV) + ($\Delta\phi$ or MHT)
- **Jet reco and b-tagging:**
  - Two AK5 jets, b-tagged (discriminator input to BDT)
    - **No need for substructure techniques (at least at 8 TeV)**
  - Jet energy regression for improved M(jj) resolution
- **Boost and topology discriminants**
  - pT(V), pT(H) optimized separately for each channel
  - Topology: $\Delta\phi$(V,H), ΔR(jj), $\Delta\eta$(jj), N_{jet}, color flow
- **Shape analysis on BDT output**
  - Analysis performed in two bins of pT(V)

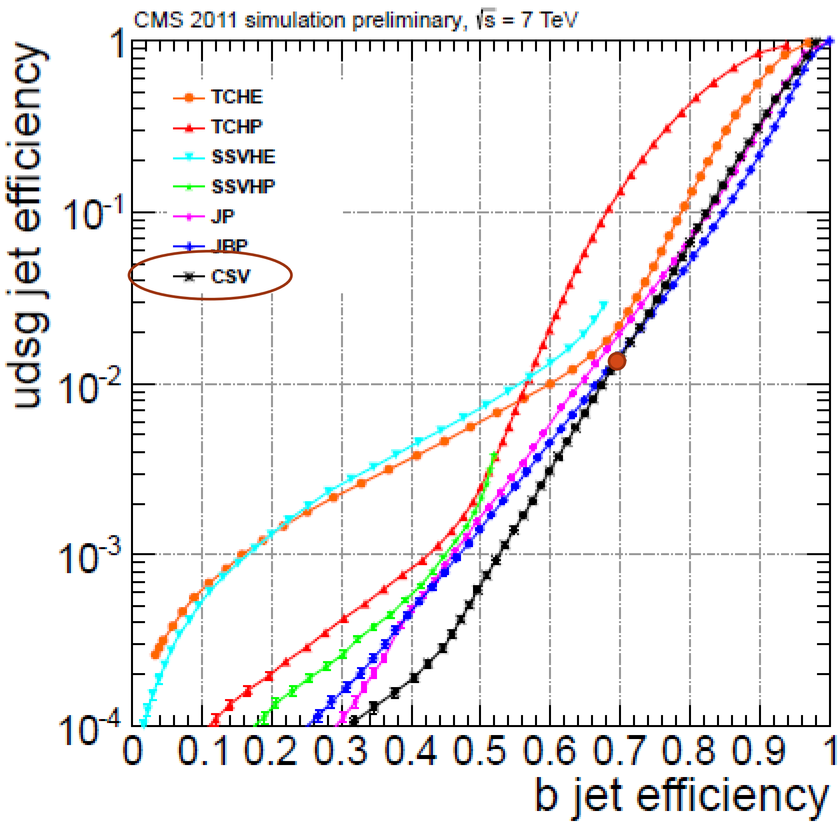
$Z(\nu\bar{\nu})H(b\bar{b})$ candidate



PD: /MET/Run2011B
Run: 177183
Lumi: 183
Event: 305295270

- M(jj) = 120.0 GeV
- p_T(jj) = 248.4 GeV
- Jets:
  - p_T = 209.5 GeV, CSV = 0.889
  - p_T = 46.2 GeV, CSV = 0.957
- MET:
  - 243.2 GeV

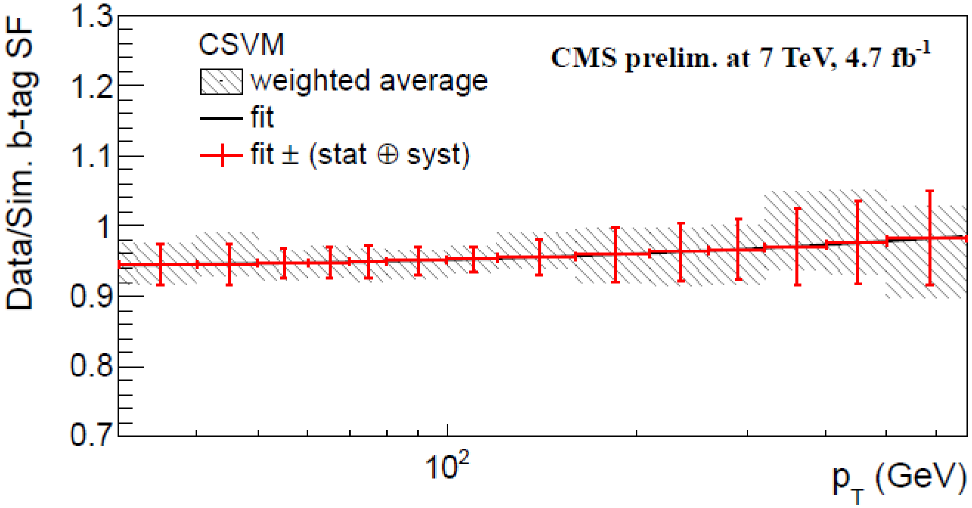
B-tagging: Performance and Validation

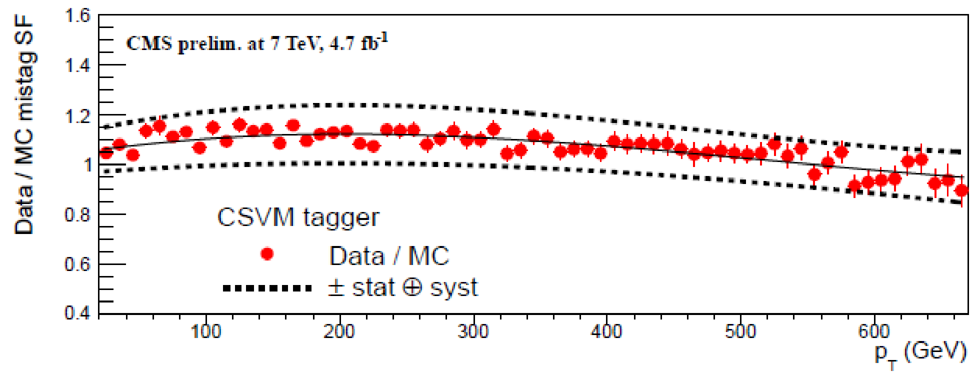


Typical working point:

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

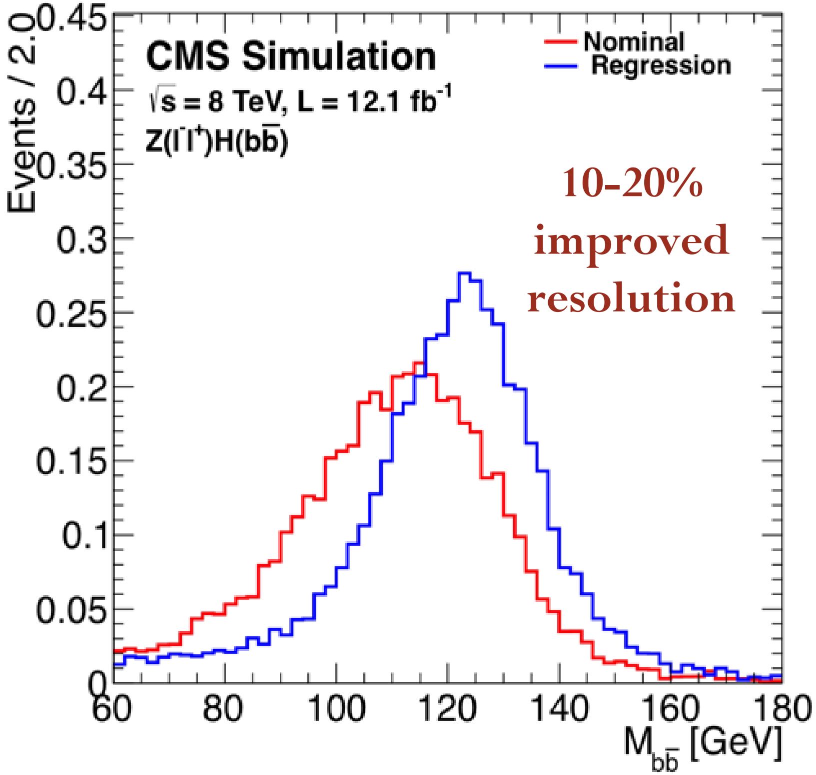
Calibrated on ttbar data up to pT(j) > 600 GeV

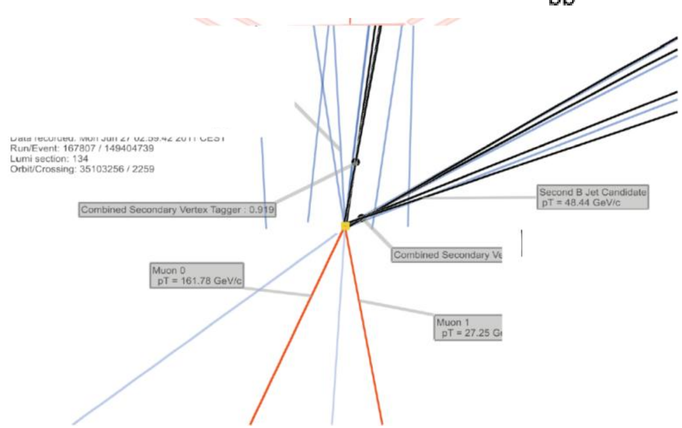




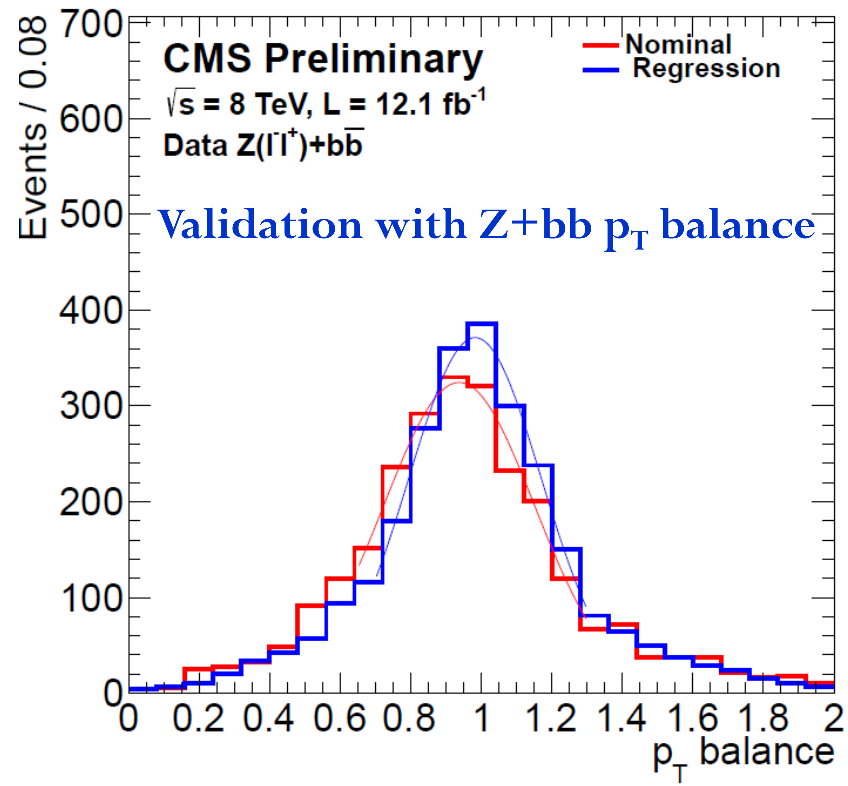
Corrected shapes used as input to BDT

B-jet Energy Regression



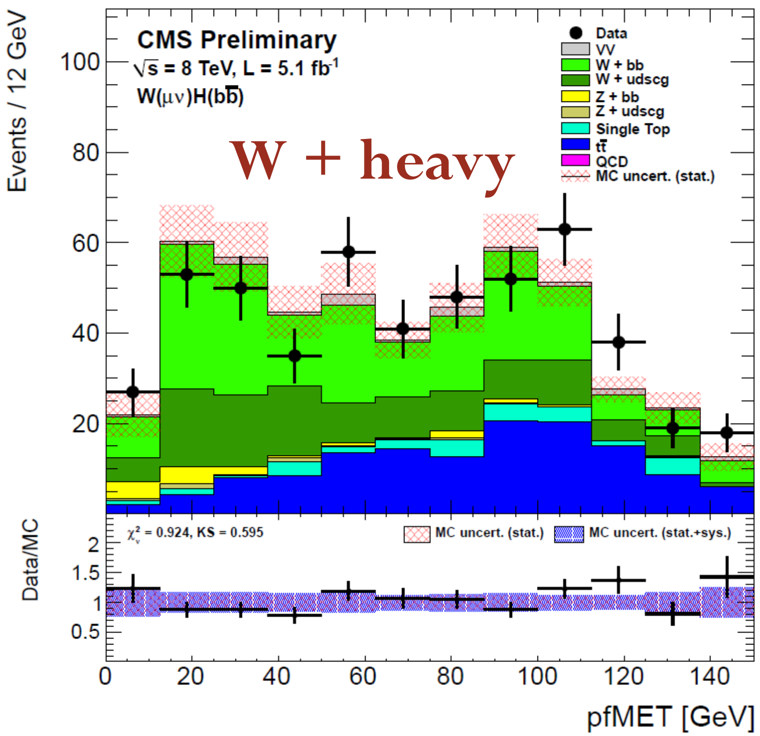


Use information about the jet energy and b-jet characteristics in a BDT regression to improve energy resolution (a la CDF)

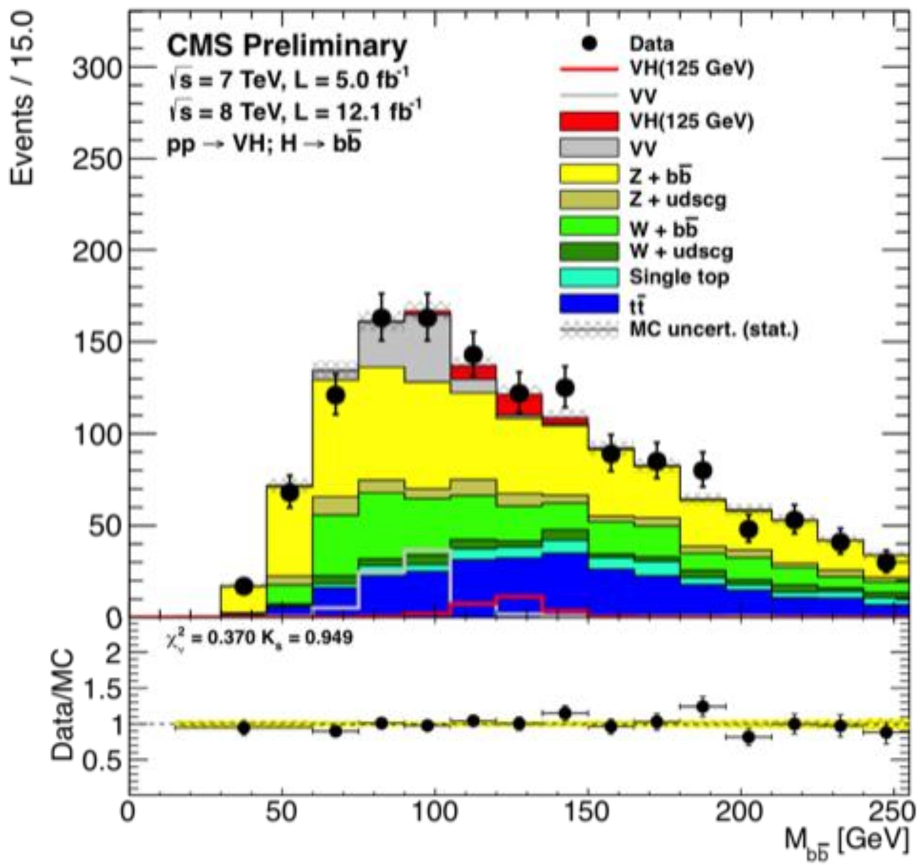


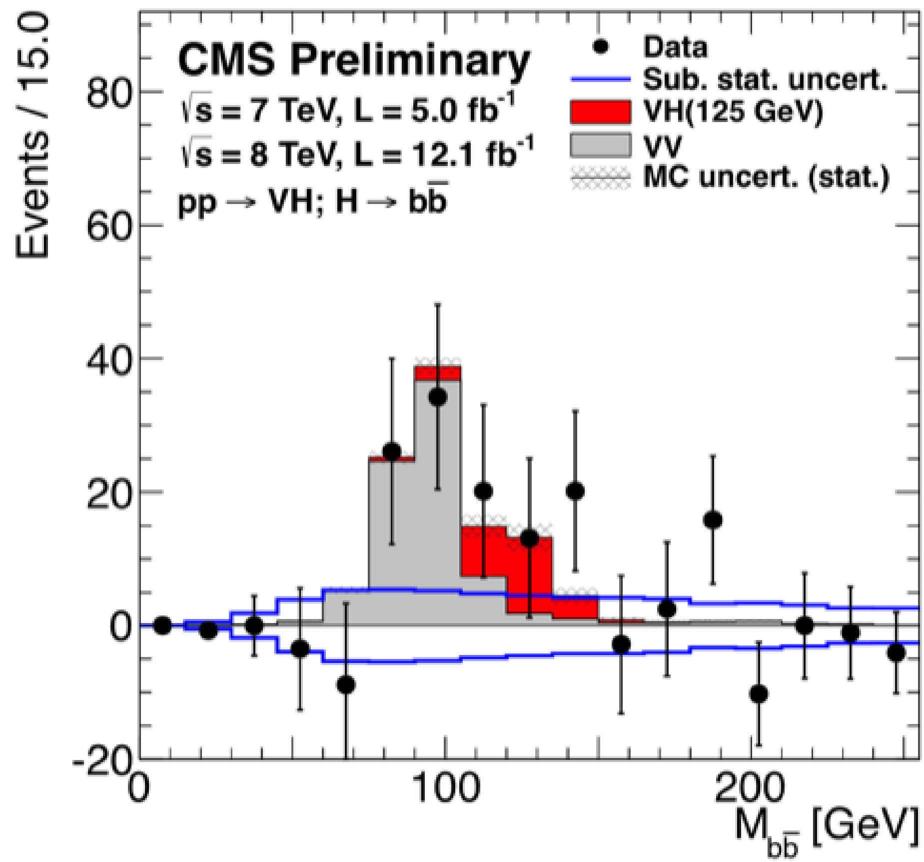
Backgrounds and Control Regions

- **Dominant backgrounds**
  - V+bb, V+udscg, ttbar, single top, VV
- **Control regions**
  - Enhance particular backgrounds
  - As close as possible to the signal region
  - "V+heavy", "V+light", "Top"
- **Extrapolation to signal region**
  - Scale factors obtained from control regions
  - Shape analysis floats the scale factors



Dijet Invariant Mass: all channels

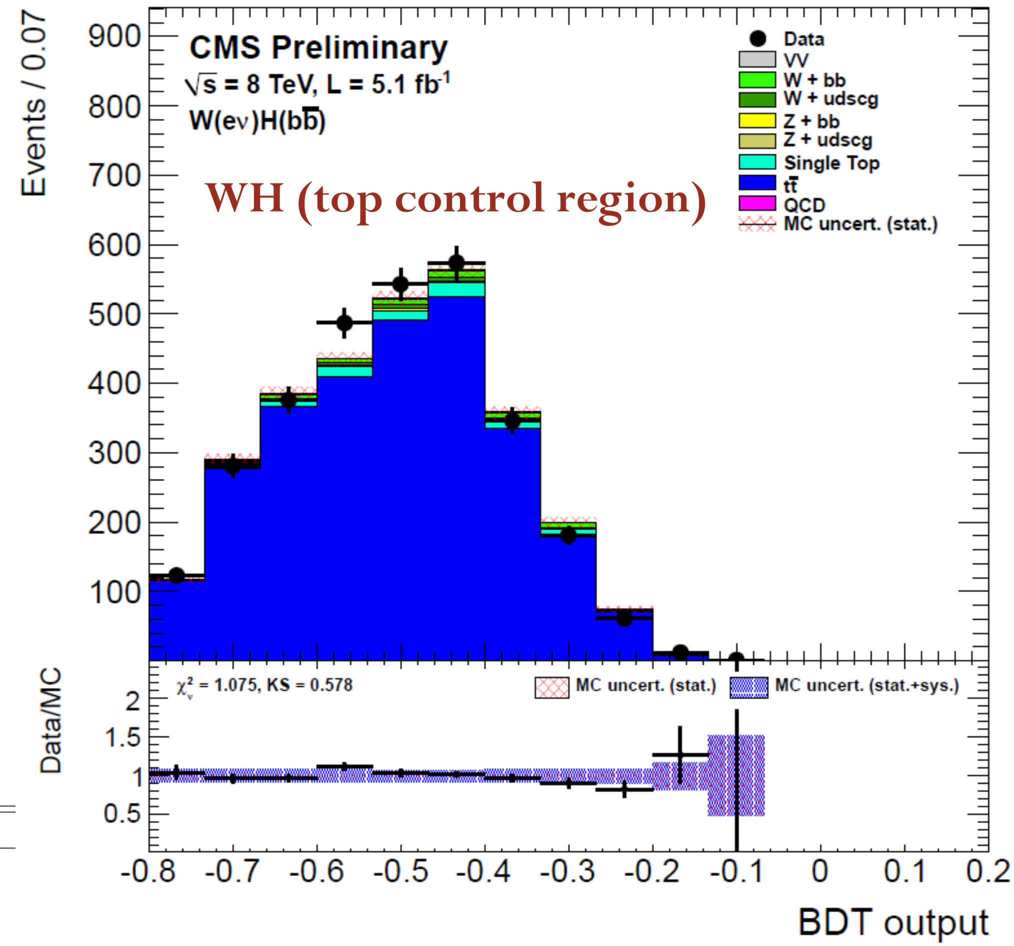




Already from non-optimized Mjj plot: a clear VV(+VH) peak above SM backgrounds

BDT discriminant

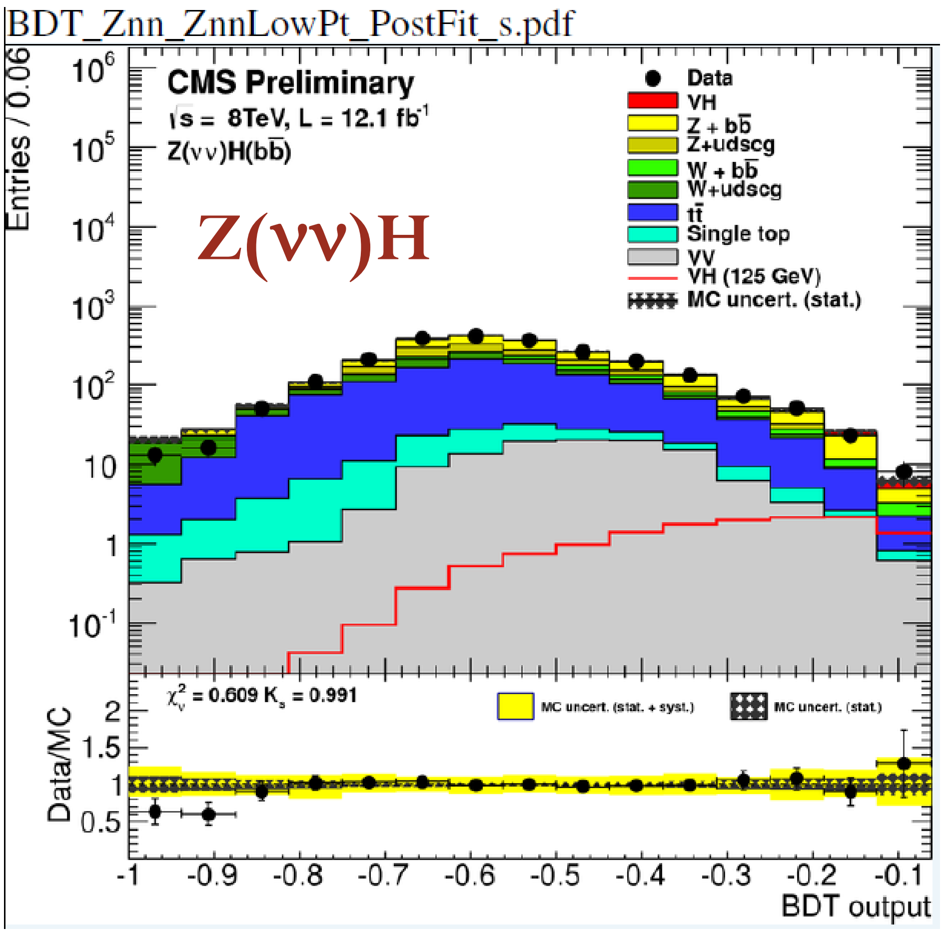
Combine kinematic, topoligical, b-tagging, and color flow variables into BDT, separately for high and low pT bins

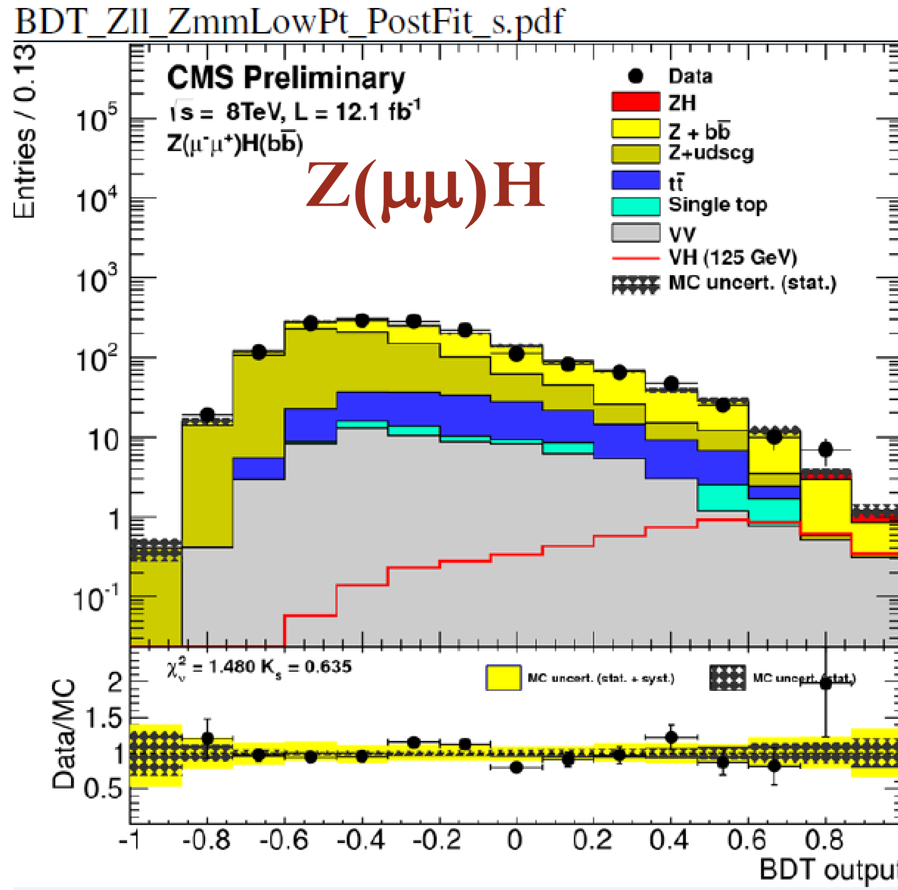


Variable
p_{Tj}: transverse momentum of each Higgs daughter
$m(\mathrm{jj})$: dijet invariant mass
$p_T(\mathrm{jj})$: dijet transverse momentum
$p_T(\mathrm{V})$: vector boson transverse momentum (or pfMET)
$\mathrm{CSV}_{\mathrm{max}}$: value of CSV for the b-tagged jet with largest CSV value
$\mathrm{CSV}_{\mathrm{min}}$: value of CSV for the b-tagged jet with second largest CSV value
$\Delta\phi(\mathrm{V,H})$: azimuthal angle between V (or E_T^{miss}) and dijet
$\lvert\Delta\eta(\mathrm{jj})\rvert$; difference in η between Higgs daughters
$\Delta R(\mathrm{j1,j2})$; distance in η–ϕ between Higgs daughters (not for $\mathrm{Z}(\ell\ell)\mathrm{H}$)
N_{aj}: number of additional jets ($p_T > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.5$)
$\Delta\phi(\mathrm{E_T^{miss}},\mathrm{jet})$: azimuthal angle between E_T^{miss} and the closest jet (only for $\mathrm{Z}(\nu\nu)\mathrm{H}$)
$\Delta\theta_{\mathrm{pull}}$: color pull angle [62] (not for $\mathrm{Z}(\ell\ell)\mathrm{H}$)

Shapes validated in background control regions, simulation (with shape uncertainties) used for final fit

Example BDT shapes in signal region



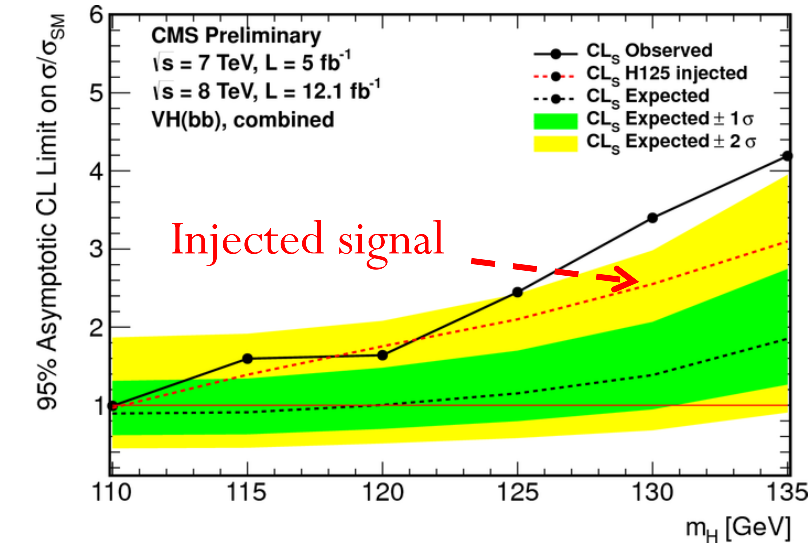


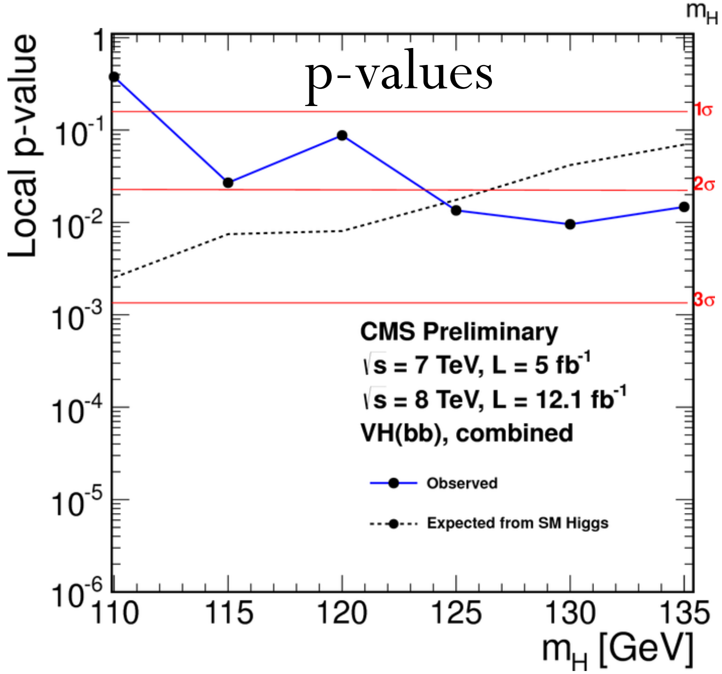
All shape comparisons look good, data consistent with background-only hypothesis

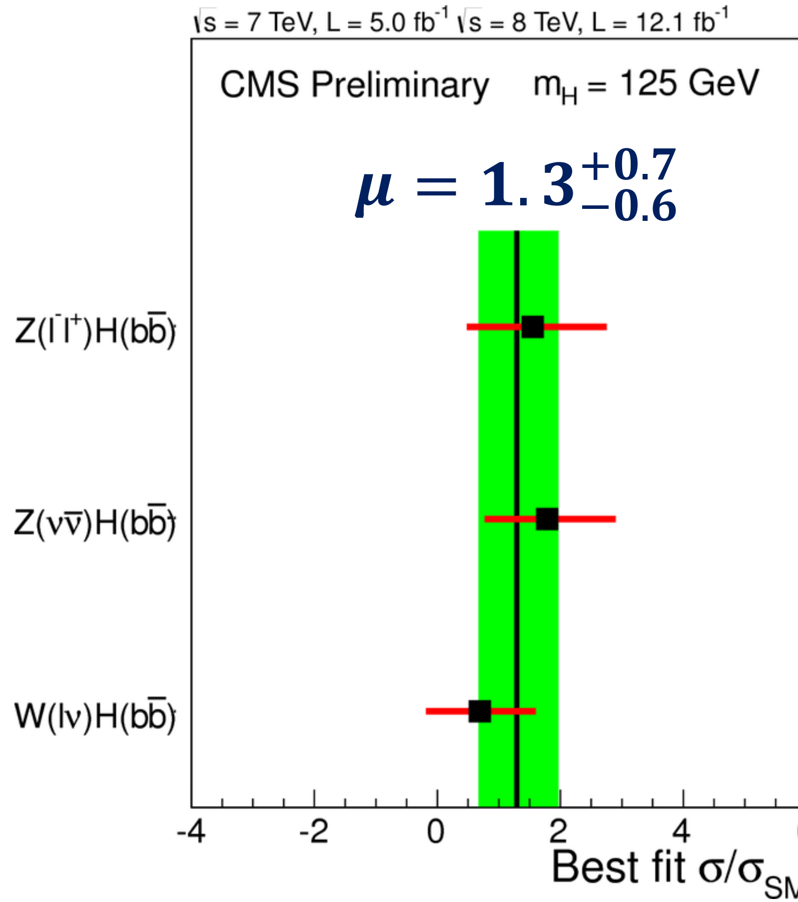
Systematic Uncertainties

Source	Range
Luminosity	2.2-4.4%
Lepton efficiency and trigger (per lepton)	3%
$Z(\nu\nu)H$ triggers	3%
Jet energy scale	2–3%
Jet energy resolution	3–6%
Missing transverse energy	3%
b-tagging	3–15%
Signal cross section (scale and PDF)	4%
Signal cross section (p_T boost, EWK/QCD)	5–10% / 10%
Signal Monte Carlo statistics	1-5%
Backgrounds (data estimate)	$\approx$ 10%
Single-top (simulation estimate)	15–30%
Dibosons (simulation estimate)	30%

Results: 7 + 8 TeV (17/fb)







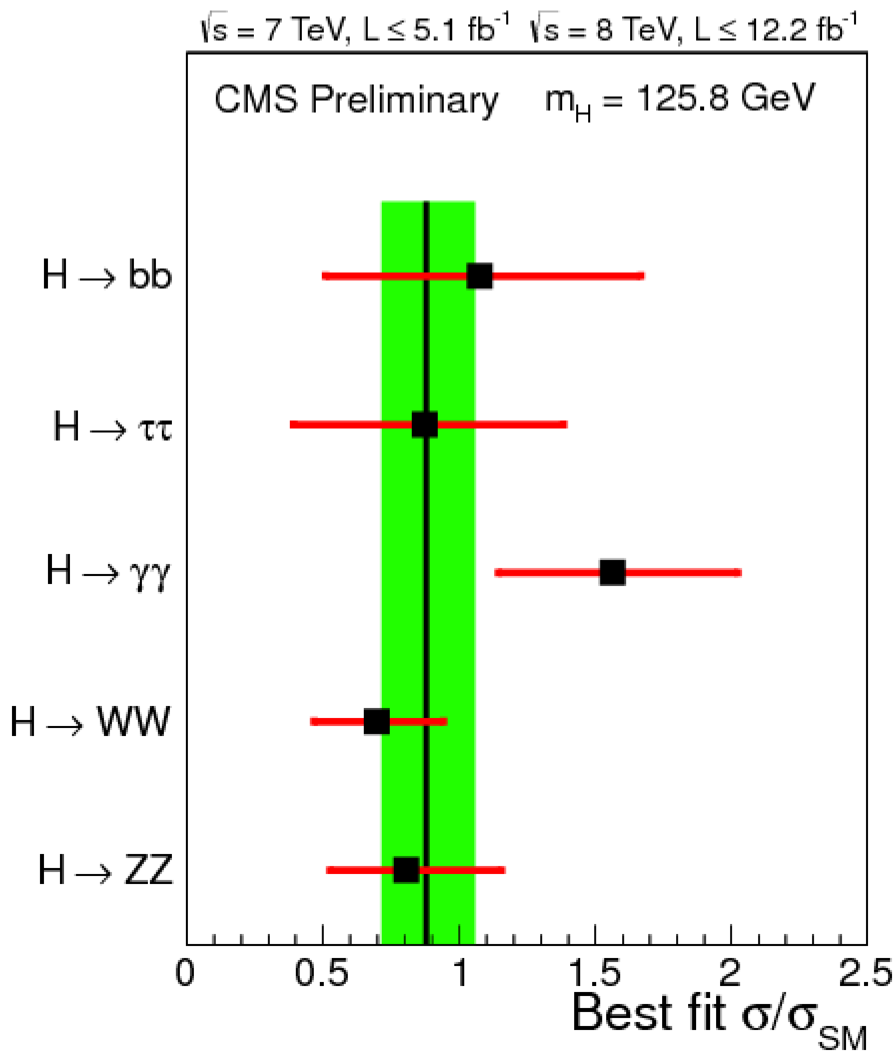
@125 GeV:

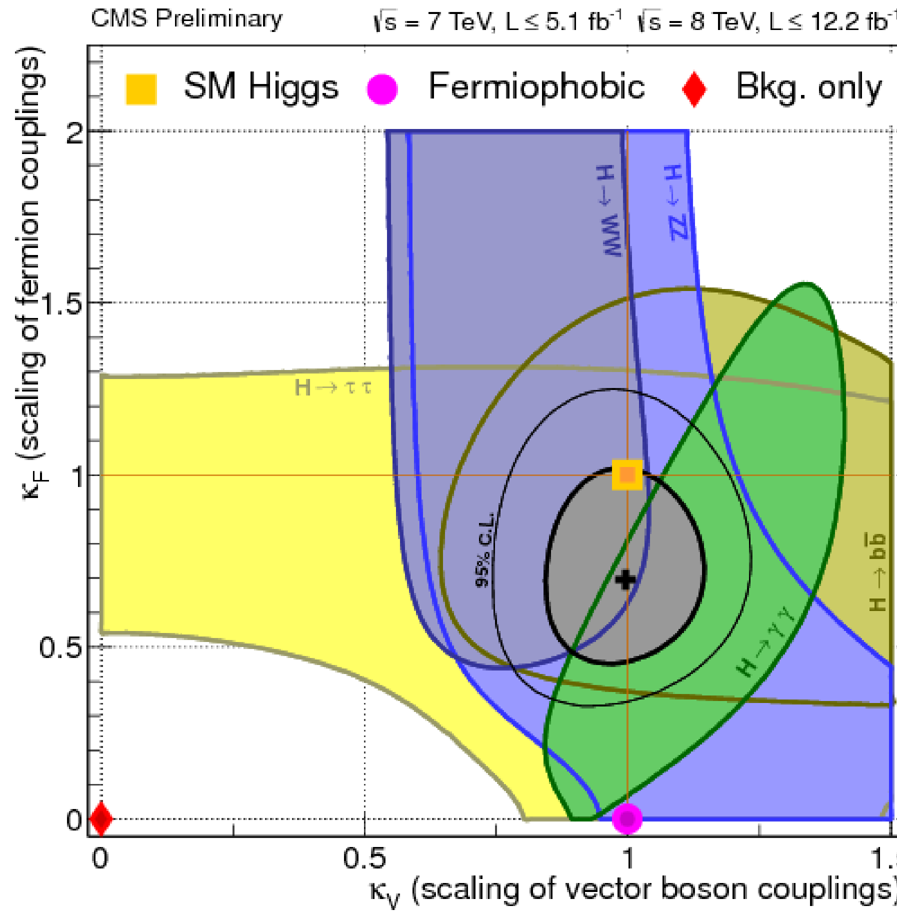
exp (obs) limit = 1.2 (2.2) x SM

exp (obs) significance = 2.1 (2.2) σ

Updated CMS Combination

Signal Strength and Couplings





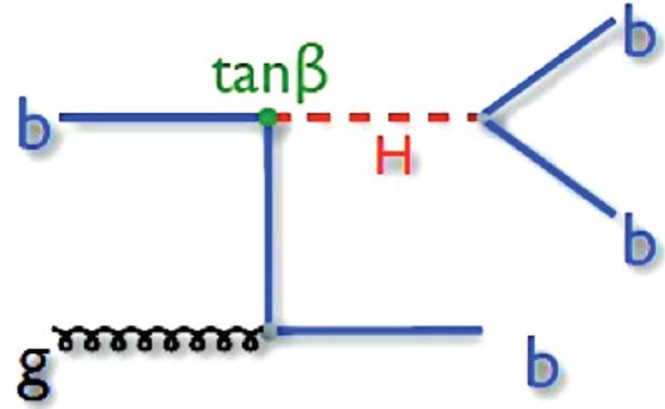
$\mu = 0.88 \pm 0.21$

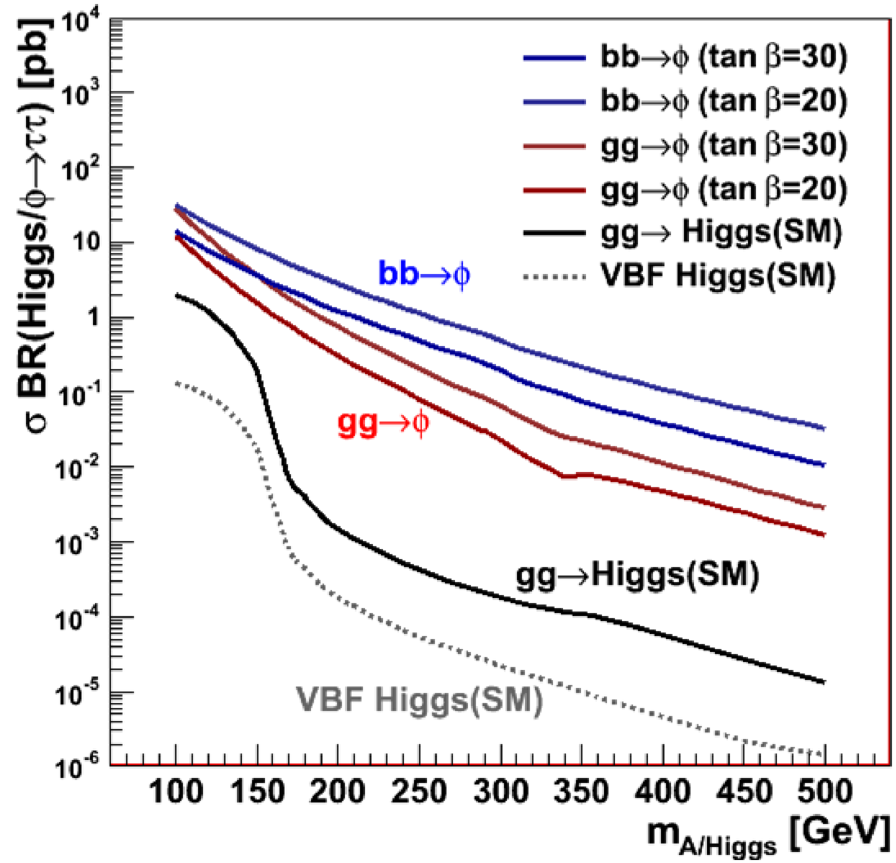
Couplings consistent with SM

One step beyond: Search for MSSM Higgs decaying to $\tau\tau$ and bb

MSSM Higgs

- Two Higgs doublets
  - Five Higgs particles
    - Three neutral (h, H, A)
    - Two charged ($H^{\pm}$)
  - Two free parameters
    - Mass
    - tanβ – ratio of vevs for up and down
- Searches @ CMS
  - Neutral: ττ and bb
  - Charged: look in top decays



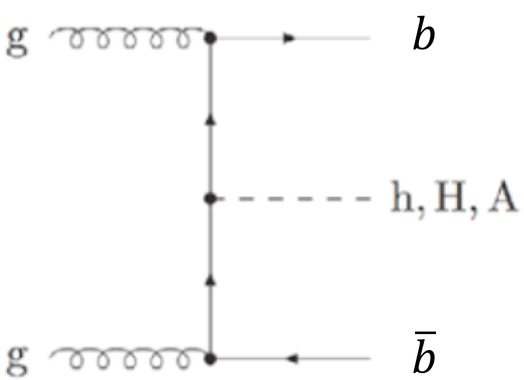


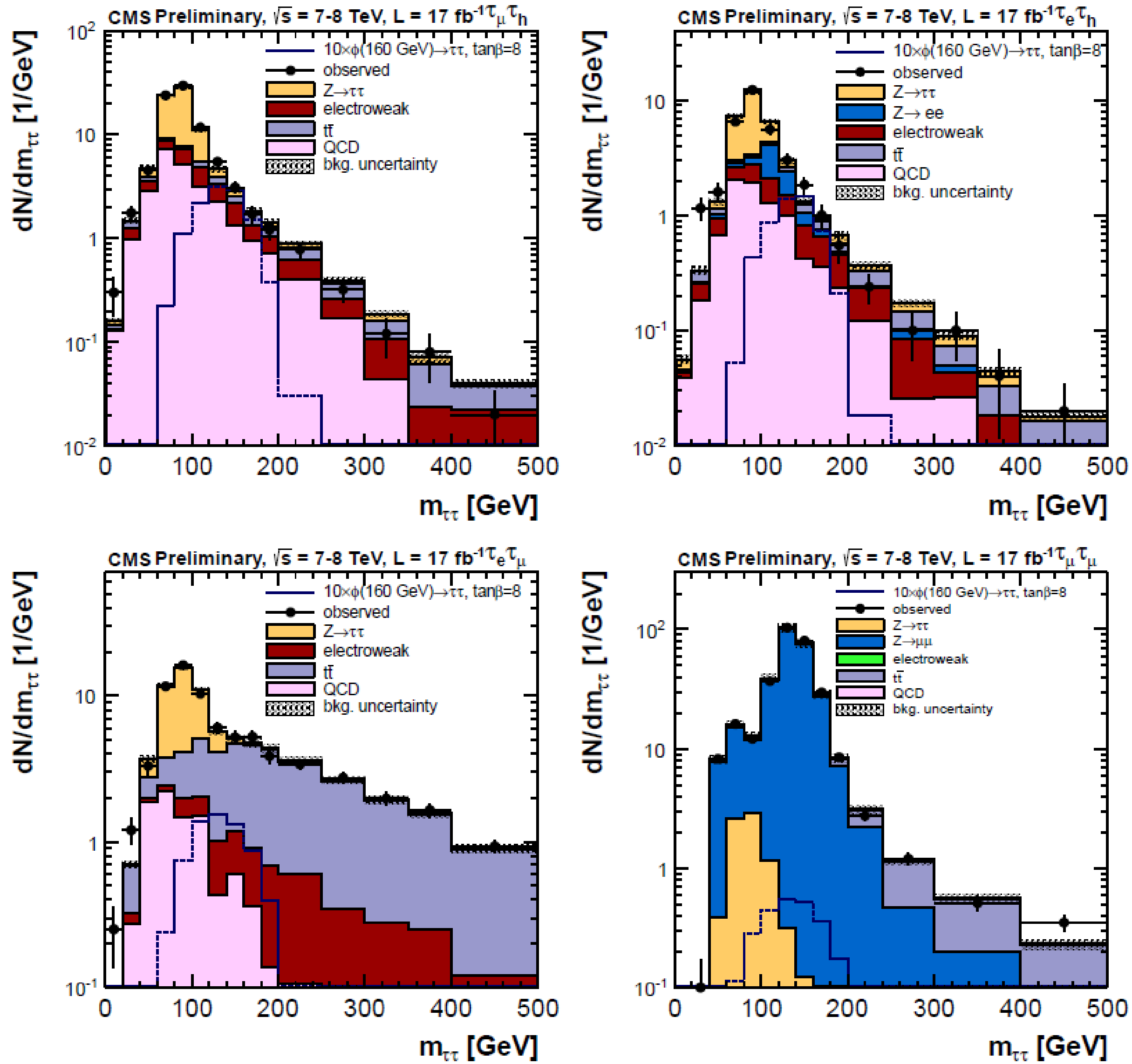
Search for MSSM $\phi(h, H, A) \rightarrow \tau\tau$

Even Categories:

- Events are split into two categories based on the presence (or not) of b-tagged jets

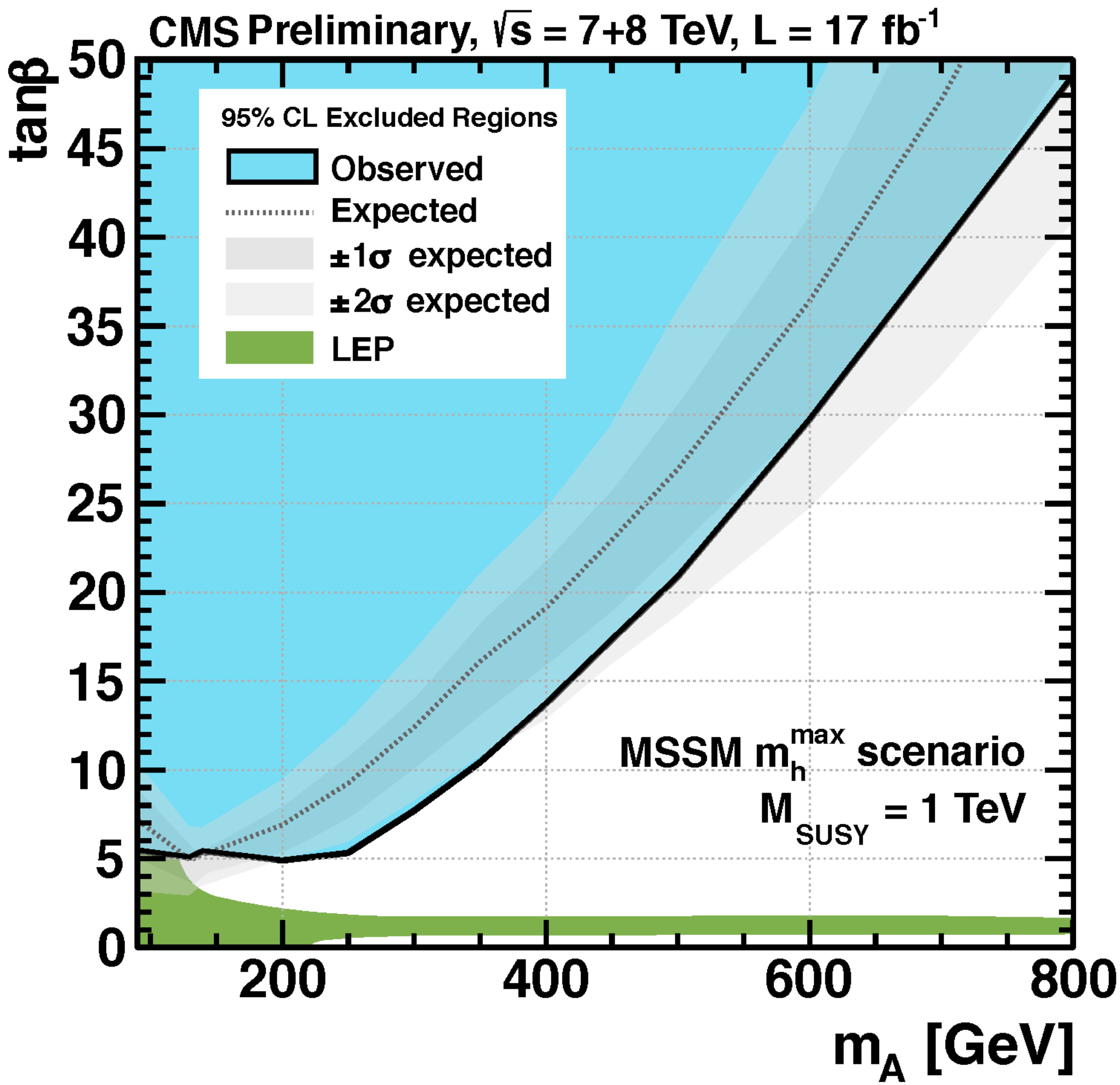
Enhances associated prod.



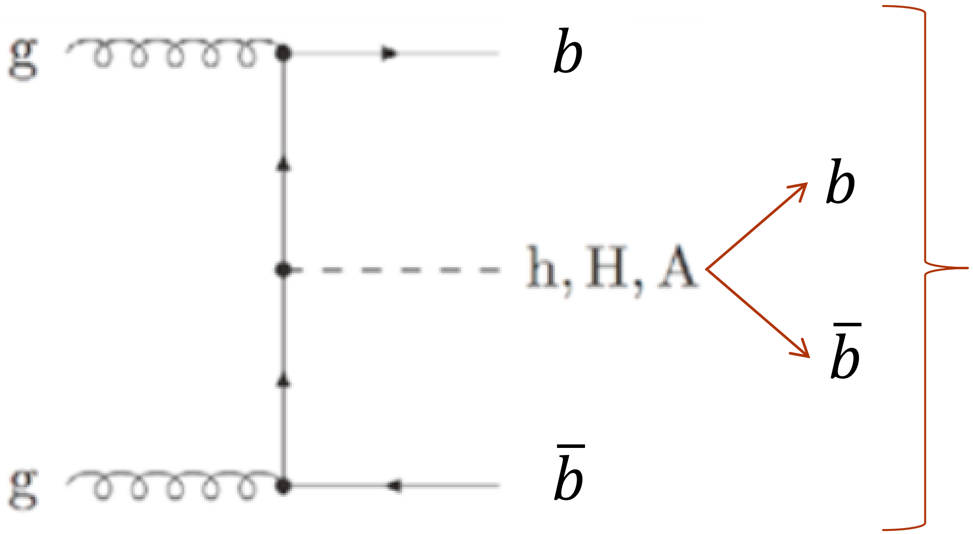


Events in b-tag category

Results: MSSM $\phi(h, H, A) \rightarrow \tau\tau$



Search for MSSM $\phi(h, H, A) \rightarrow bb$

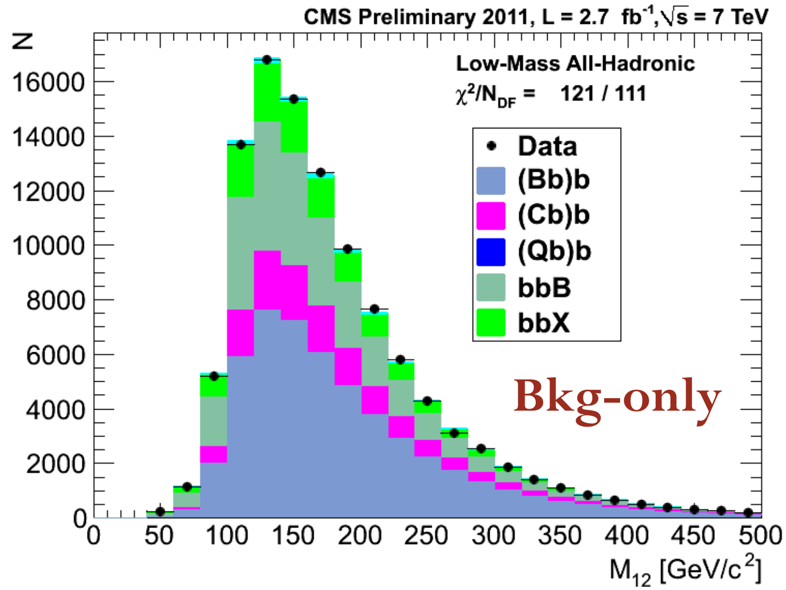


Only b-jets (and radiation) in the final state, trigger is one of the most challenging at LHC

Two complementary approaches:

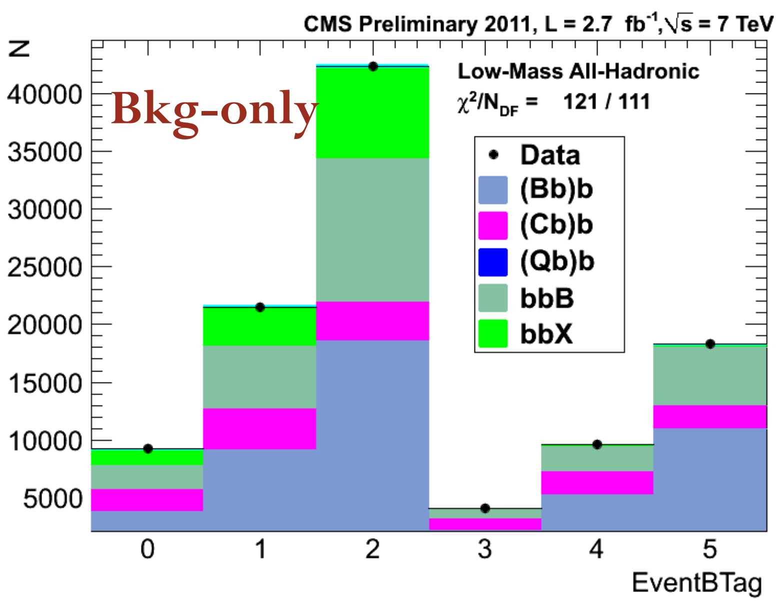
- <u>All-hadronic</u> trigger requiring up to three jets and at least two b-tagged jets (three offline)
- <u>Semileptonic</u> trigger requiring up to three jets, two b-tagged jets (three offline), and one muon from b-hadron decay
- **Essentially independent samples (2-3% overlap)**

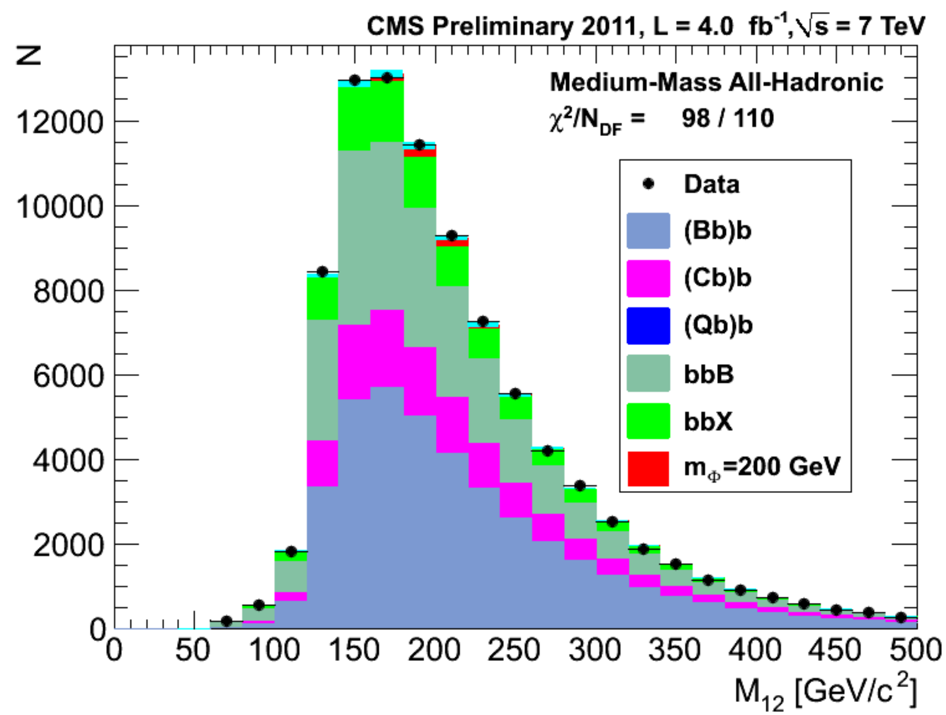
Results: All-hadronic analysis



Background shapes obtained from double-tag sample give excellent agreement when applied to triple-tag sample.

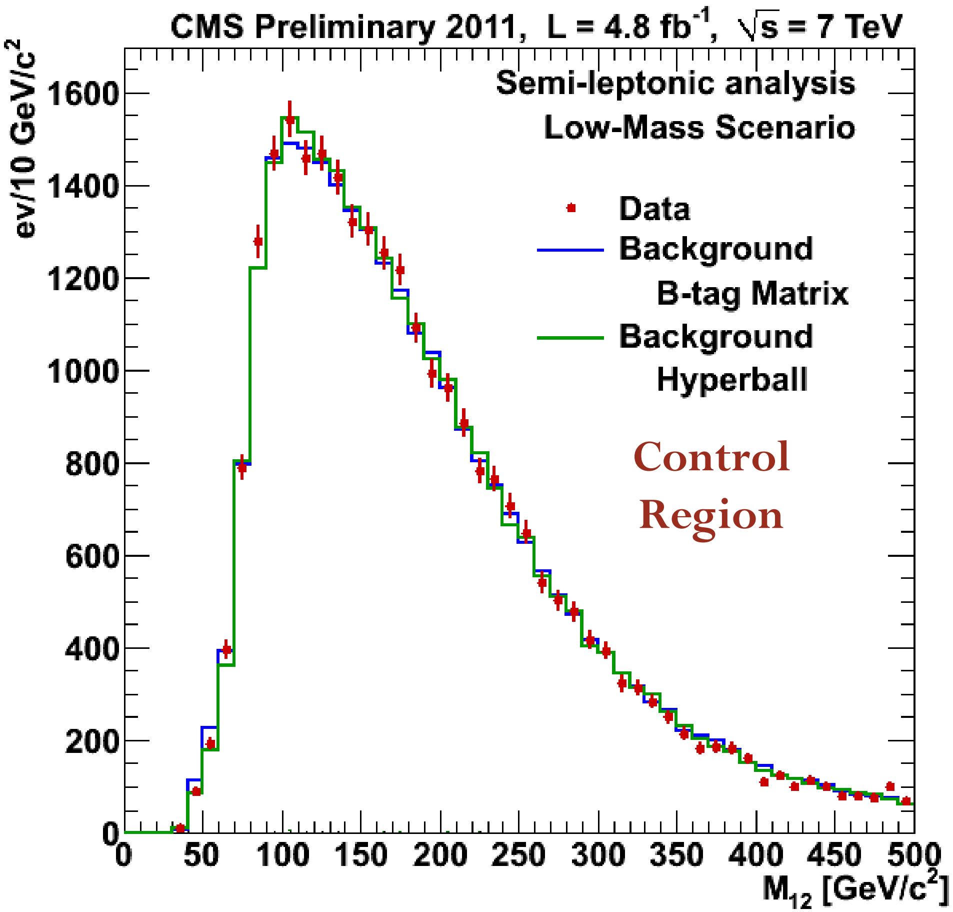
Signal fits scan in mass from 90 to 350 GeV, no significant signal is observed at any mass.

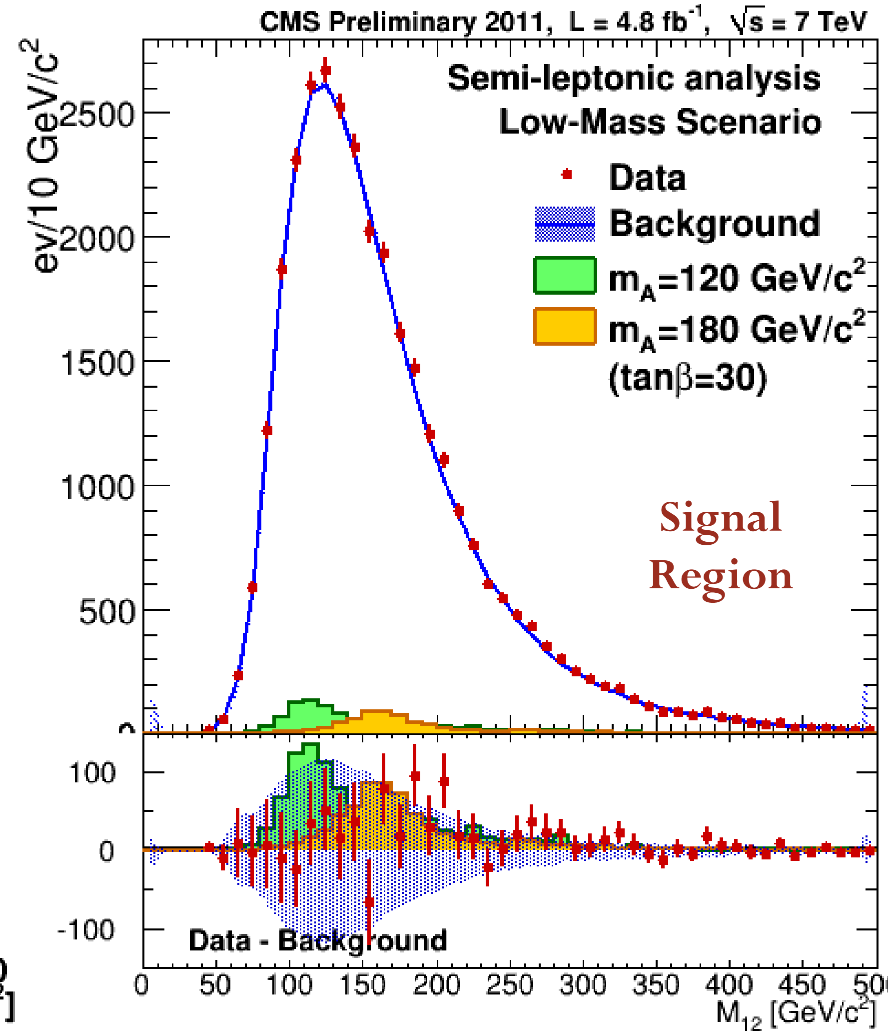




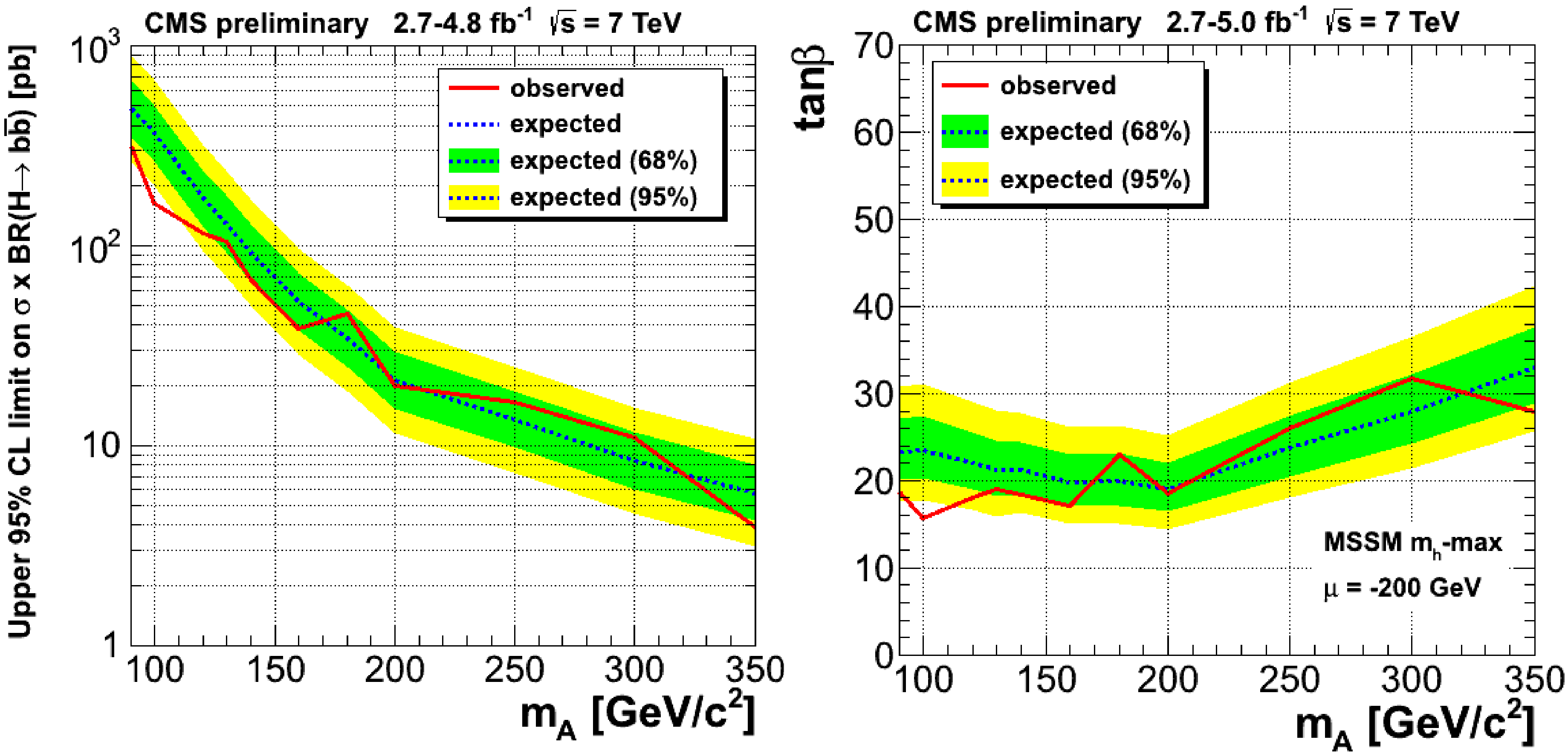
Results: Semileptonic analysis

Background shape determined from two independent methods applied to 2- and 1-tag samples





Limits on MSSM $\phi(h, H, A) \rightarrow bb$



No evidence for CDF 2σ excess at low mass

Conclusions

- The new particle @ "125 GeV" is observed to decay to all gauge bosons, mostly in the right proportion ($\gamma\gamma$ a little hot)
- Angular distribution in ZZ disfavors pseudoscalar hypothesis
- New results from CMS not yet conclusive, but moving to SM
  - $H \rightarrow \tau\tau$ observed significance = 1.5 σ
  - $H \rightarrow bb$ observed significance (VH) = 2.2 σ
- New CMS combination shows signal strength and couplings consistent with the SM expectation
- No sign of (any of) the MSSM Higgs bosons

If it is not "Weinberg's Higgs boson" it certainly is a good actor! Much more data is needed to be certain.