Study of Higgs Boson in Fermionic Decay Channels at CMS

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(DESY)

for the CMS collaboration

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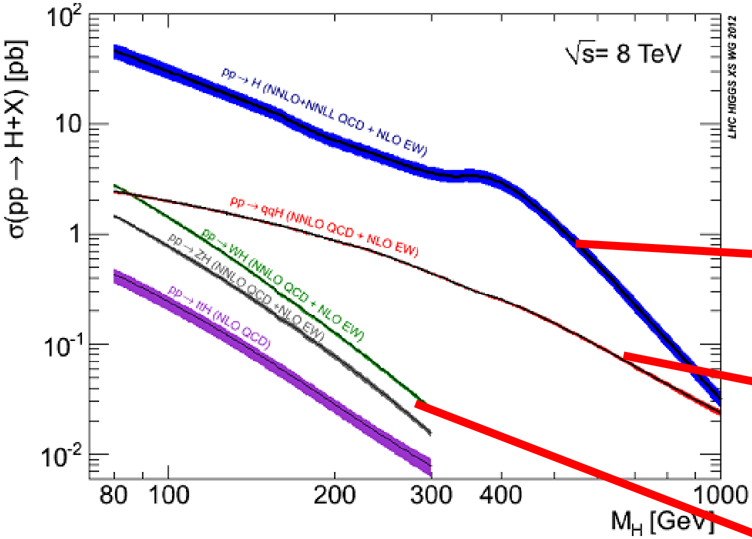
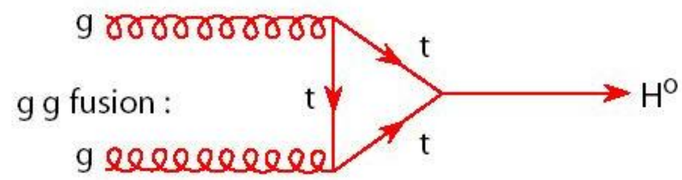
Outline

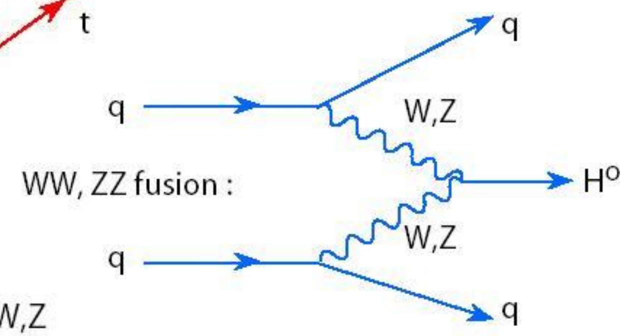
- Higgs Sector: SM & MSSM
- LHC & the CMS detector
- Physics Objects – τ and b jets
- Higgs to Tau Lepton Pairs
- Higgs to Bottom Quark Pairs
- Summary & Outlook

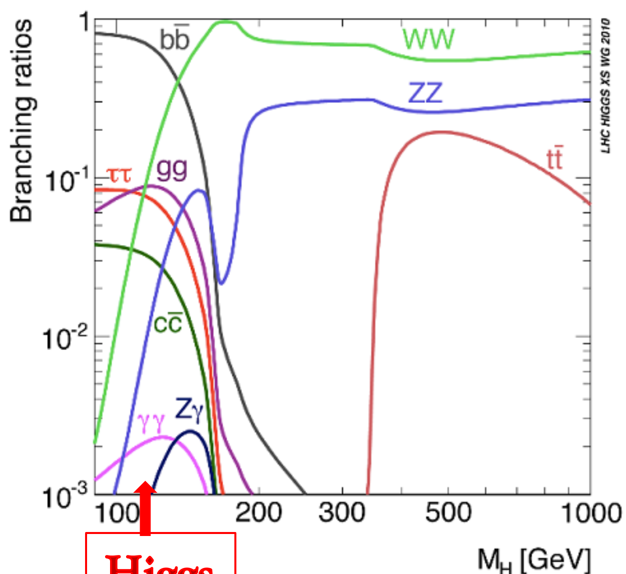
Standard Model Higgs Sector

The quest for over 40 years has ended
The Higgs has been finally pinned down!

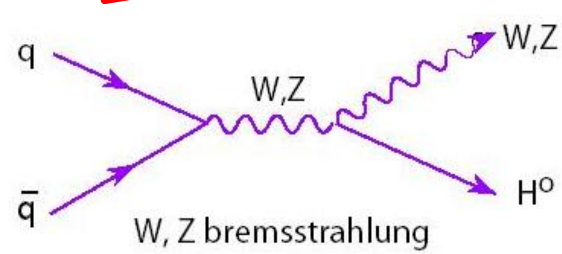








Higgs



- Access to coupling of Higgs field with fermions
- Proportionality between mass and coupling in fermion sector

MSSM Higgs Sector

Minimal Super- Symmetric Standard Model (MSSM)

Two isospin Higgs doublets

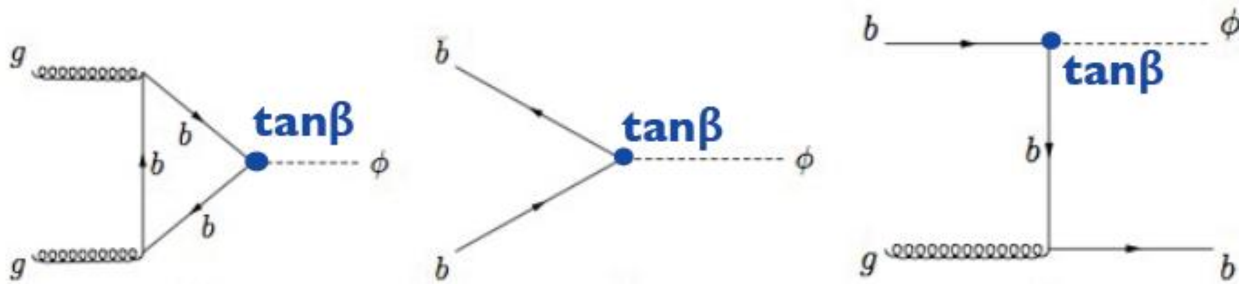
$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ and } H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

2 Higgs doublets each with 4 degrees of freedom

EW symmetry breaking: 5 physical Higgs bosons

Φ {
- h, H (scalar, CP-even)
- A (pseudo-scalar, CP-odd)
}
- $H^{\pm}$ (charged)

- ➢ Coupling bbA ~ tanβ at LO
- ➢ Production rate enhanced – high tanβ

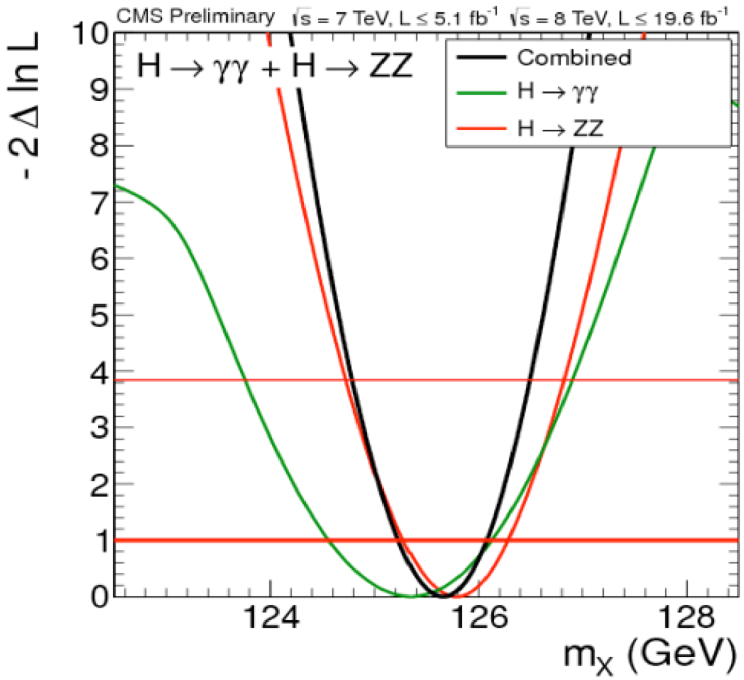


- ➢ Φ (h/H/A) decays to b-quark (~ 90%) and τ (~ 10%) pairs enhanced at all masses
- ➢ MSSM Higgs production and decays significantly affected by radiative corrections
- ➢ Dominant corrections are due to top/stop at the one-loop level

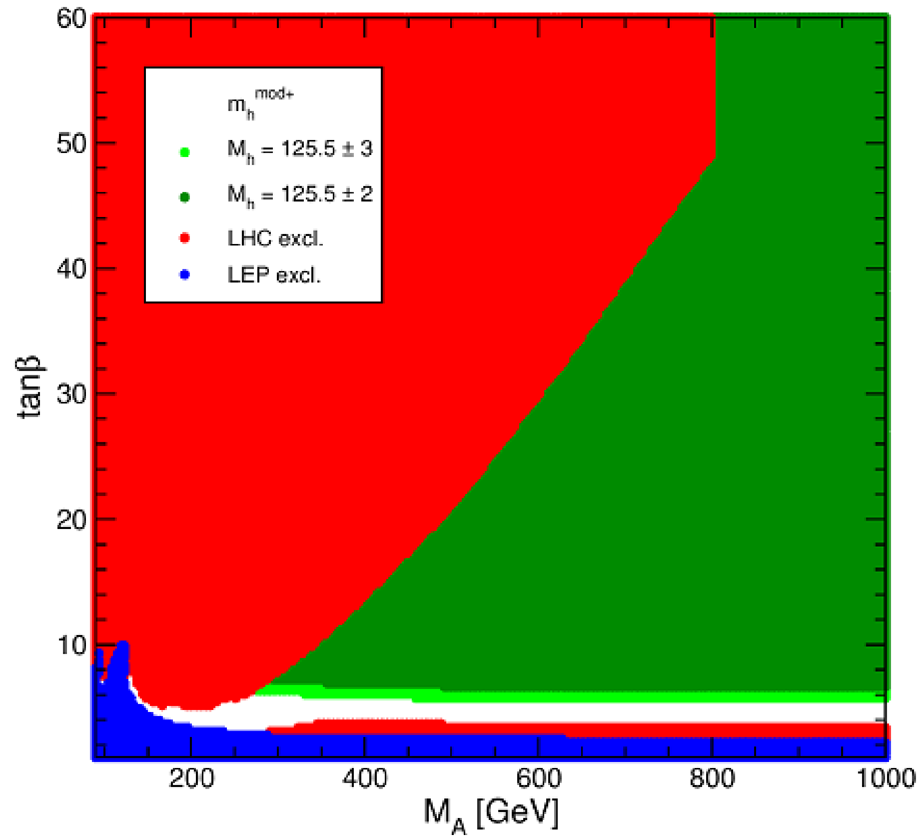
2 free parameters (M_A, tan β – ratio of the vev of two doublets)

MSSM predicts low mass Higgs $M_h \lesssim$ 135 GeV

125 GeV Higgs : Interpretation on MSSM



M. Carena et. al. , arXiv:1302.7033 [hep-ph]



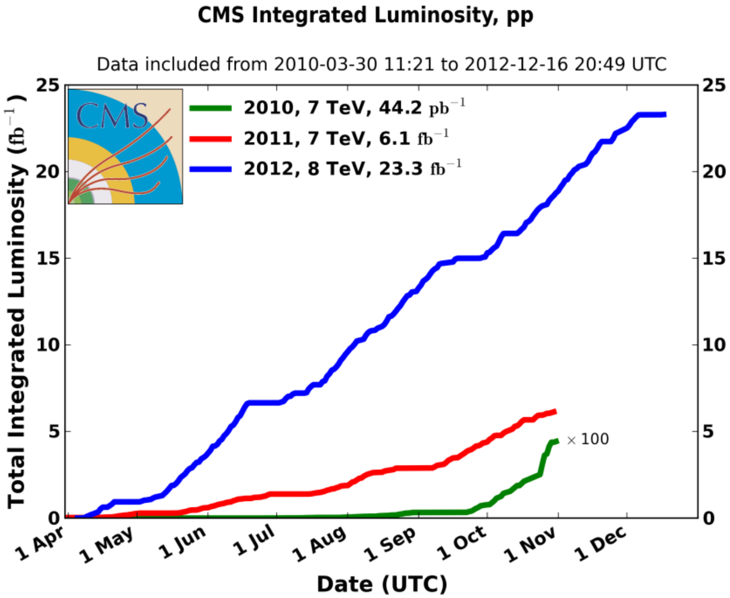
The mass value 125 GeV is rather large for the MSSM light h boson

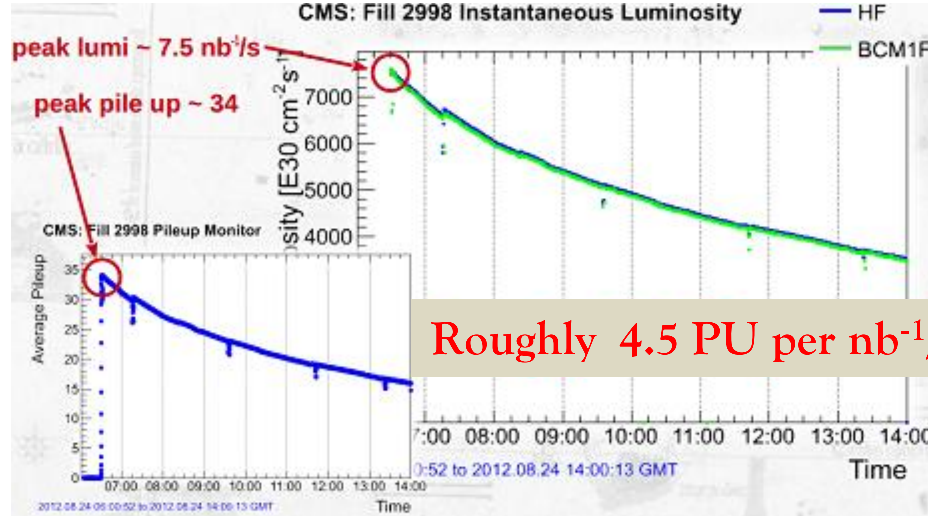
Maximizing M_h is maximizing the radiative corrections at 1-loop level

The stop mass scale M_{SUSY} ~ 1 TeV

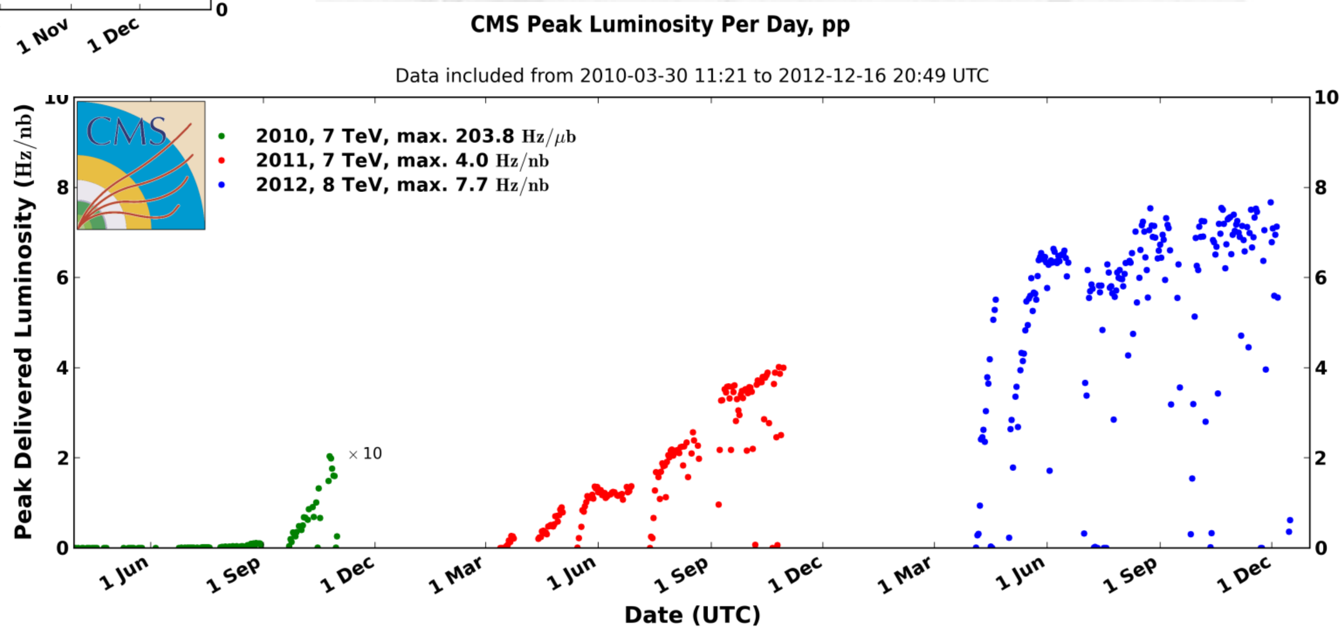
Dependence of m_h on stop scale ~ log

Mixing parameter X_t > stop mass





Roughly 4.5 PU per nb^{-1}/s



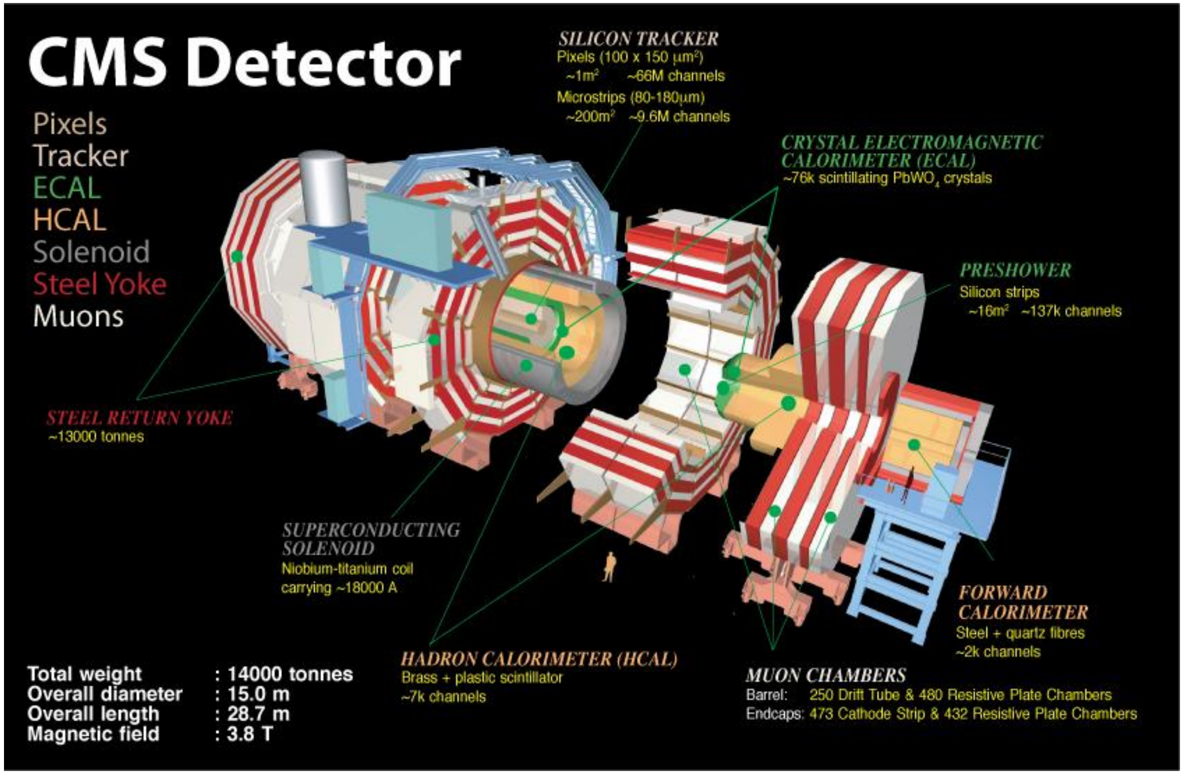
Overall data taking efficiency ~ 91%

3.8 T superconducting solenoid envelop:

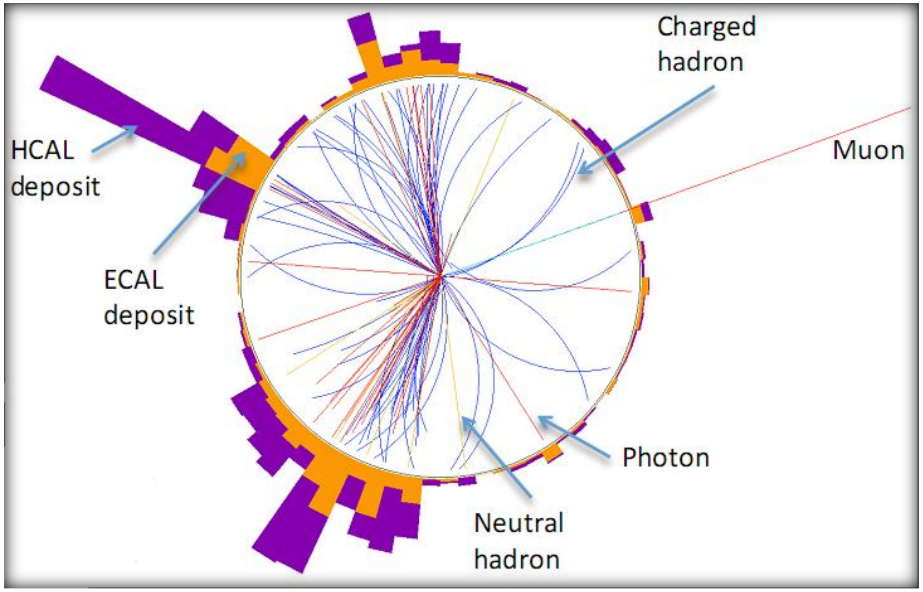
- Tracker (silicon pixel and strip detectors) $|\eta| < 2.5$
- ECAL ($PbWO_4$ crystals)
- HCAL (brass/scintillator samplers)

Barrel $|\eta| < 1.48$
Endcap $1.48 < |\eta| < 3.0$

- Muon Chambers – gas ionization detectors embedded in steel return yoke outside the solenoid, $|\eta| < 2.4$
Drift Tubes, Cathode Strips and Resistive Plate Chambers



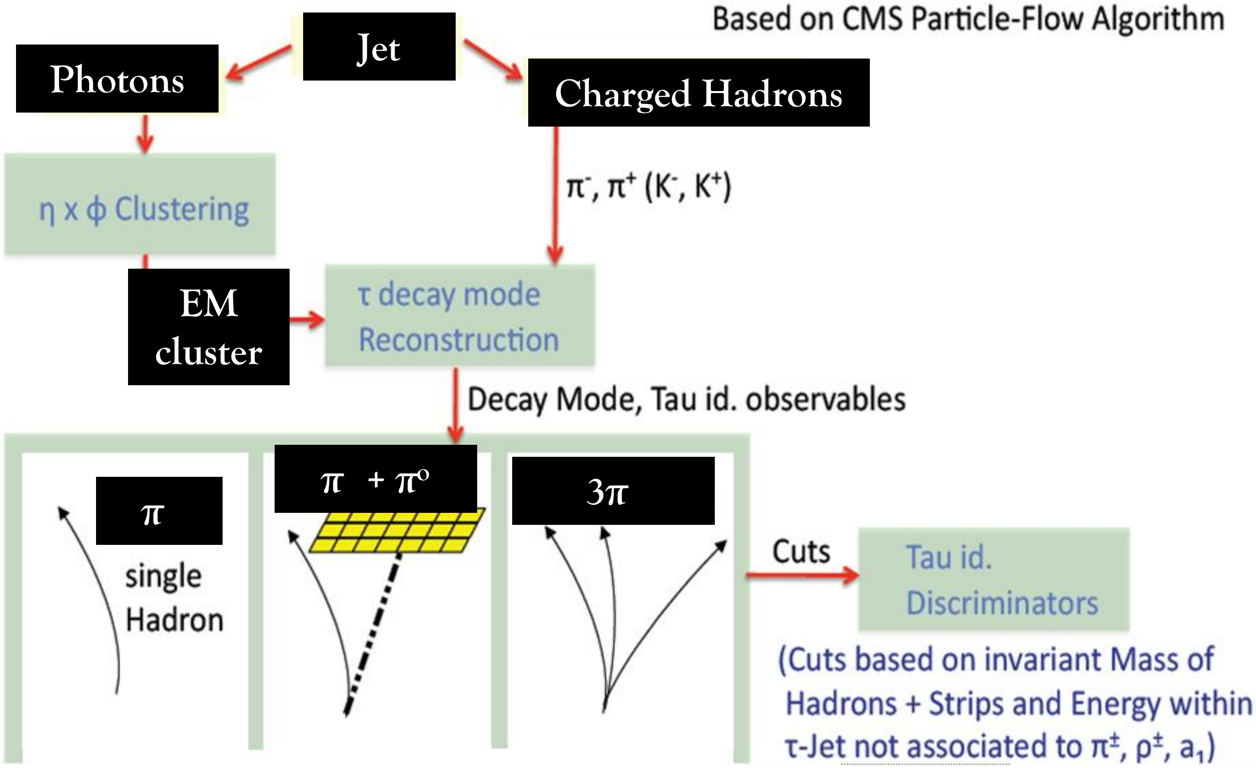
⇒ Event description in form of mutually exclusive particles

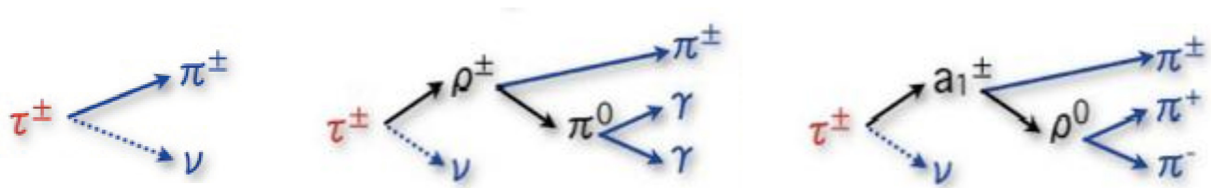


⇒ identification of all stable particles
produced in the event

⇒ combining capabilities of each sub-detector
most precise measurement
of the energy and direction for each particle

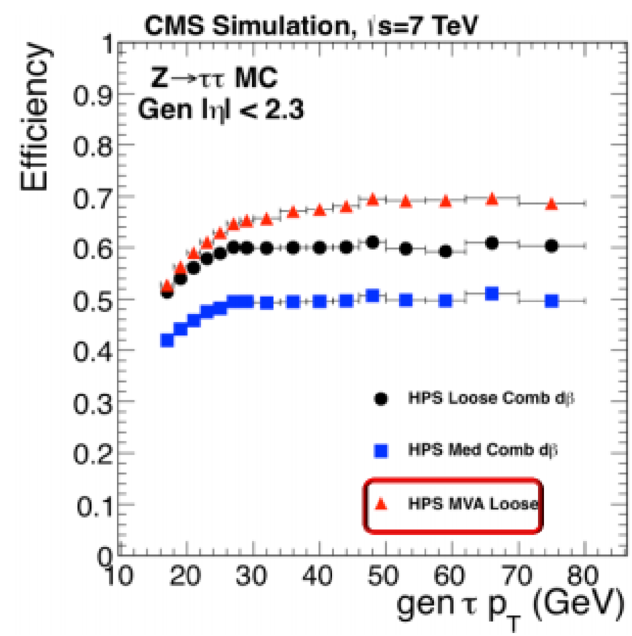
⇒ individual measurements combined
by a geometrical linking algorithm,
e.g. extrapolating a charged-particle track into ECAL and HCAL
particle ID on blocks of linked elements



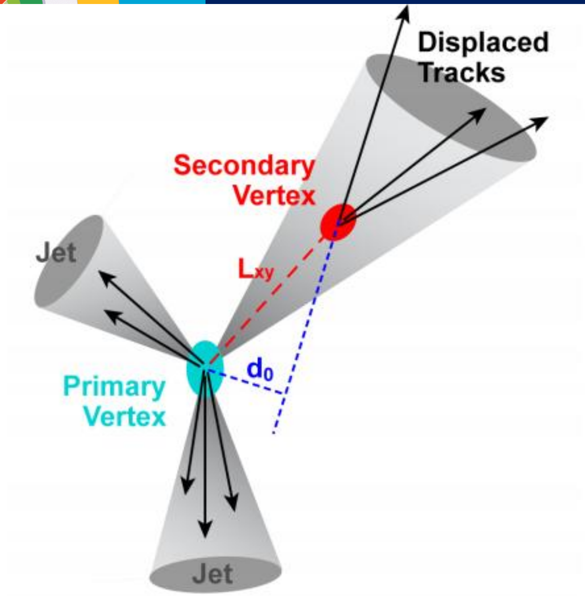


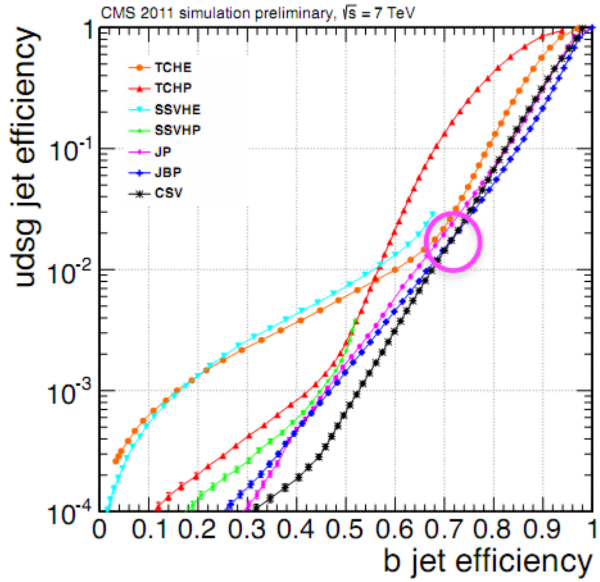
MVA based hadronic tau isolation in concentric rings
Based on relative p_T of PF candidates in isolation rings

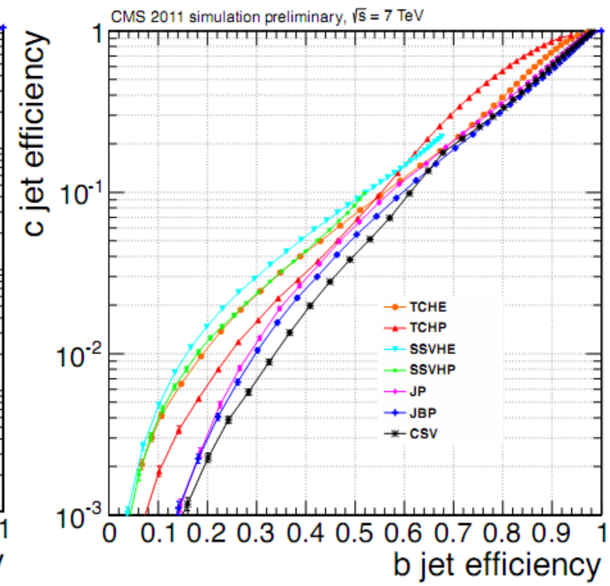
Fake Rate of jets→τ ~ 2%

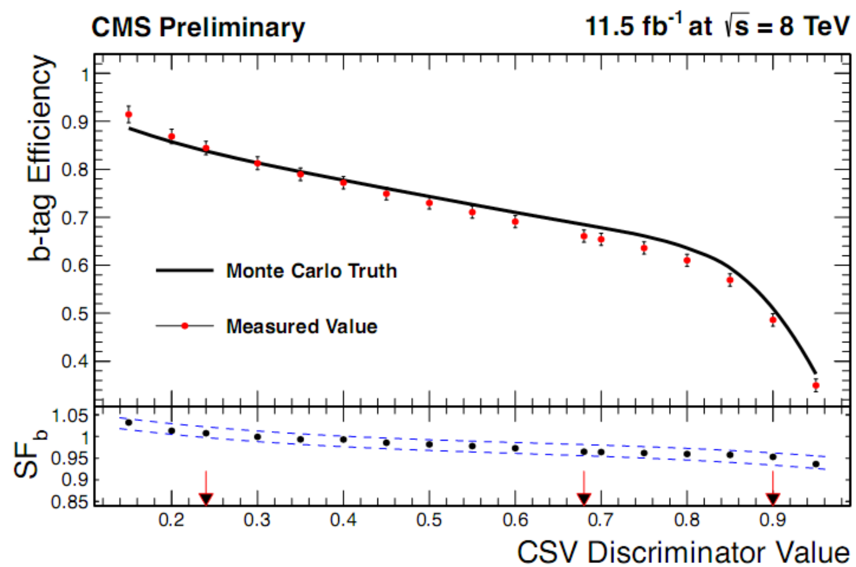


b – jet Identification







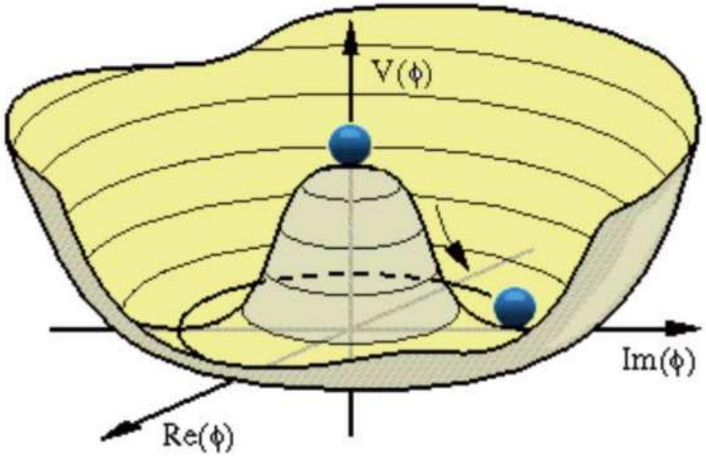


Separation from udsg and c jets

- Combined Secondary Vertex : track impact parameters and secondary vertex properties within jets in a likelihood discriminant
- Efficiency and fake-rate from top pair and muon + jets sample

Efficiency of ~70% for a fake-rate of ~ 2%

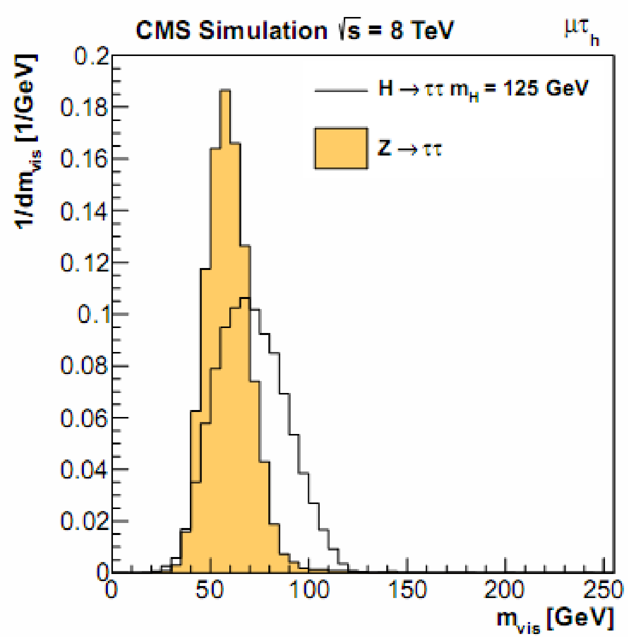
$H \rightarrow \tau\tau$

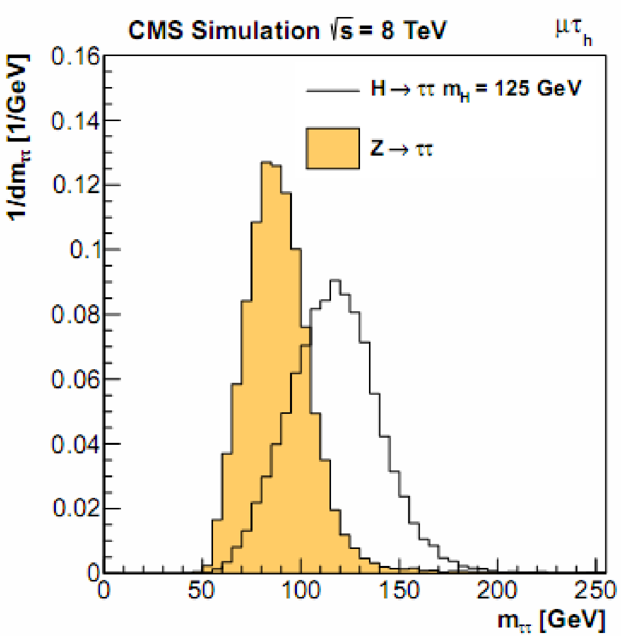


Mass of τ lepton pair reconstructed via a **Likelihood technique**, based on:

- **τ decay kinematics**
- **Compatibility of reconstructed E_T^{miss} with neutrino hypotheses**

$m_{\tau\tau}$ - Obvious observable to discriminate Z boson from the Higgs signal





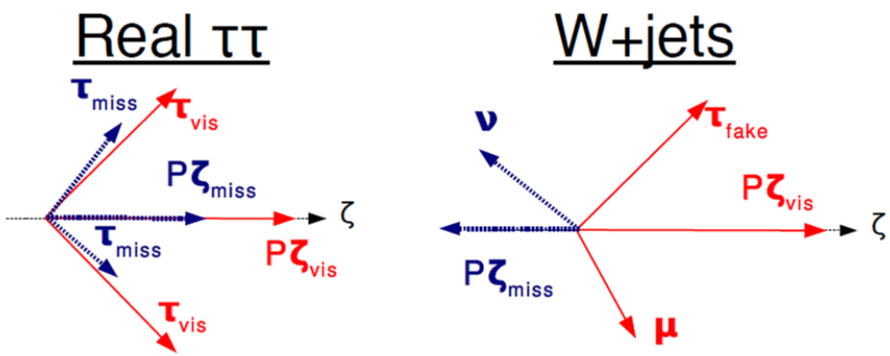
Selection Strategy

Decay final states : $\mu + \tau_h$, $e + \tau_h$, $\mu + e$, $\mu\mu$, $\tau_h\tau_h$

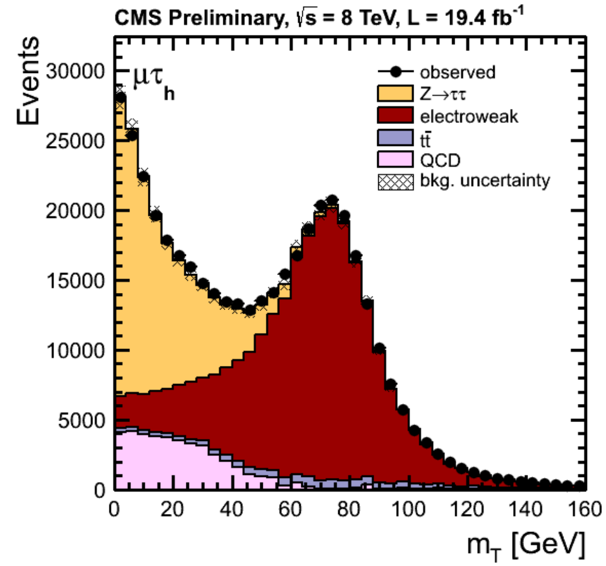
- Select isolated, well-identified leptons, τ_h
- Trigger

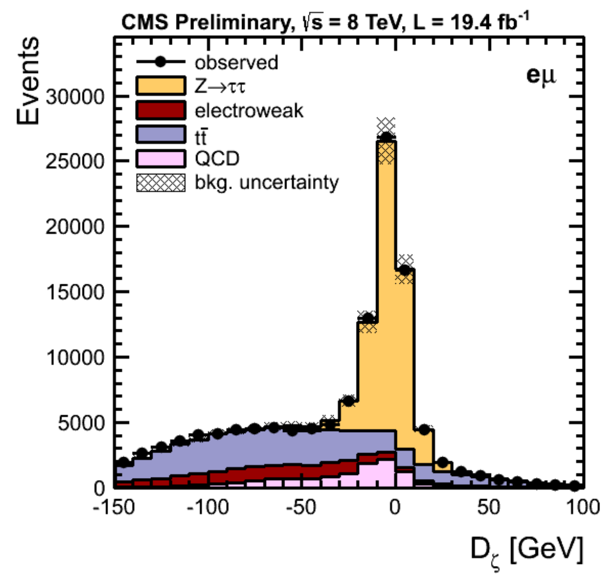
  $l + \tau_h$ cross-trigger or lepton trigger or tau/jet trigger
- Lepton / τ_h Selection (p_T, η, isolation)
- Opposite Charge Lepton Pair
- Veto Events with additional isolated Leptons
- Topological cuts (based on angular info)

$$M_T = \sqrt{2 p_T^{\ell} E_T (1 - \cos\Delta\phi)}$$



$$P_\zeta^{vis} = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta$$
$$P_\zeta = P_\zeta^{vis} + E_T^{miss} \cdot \zeta$$



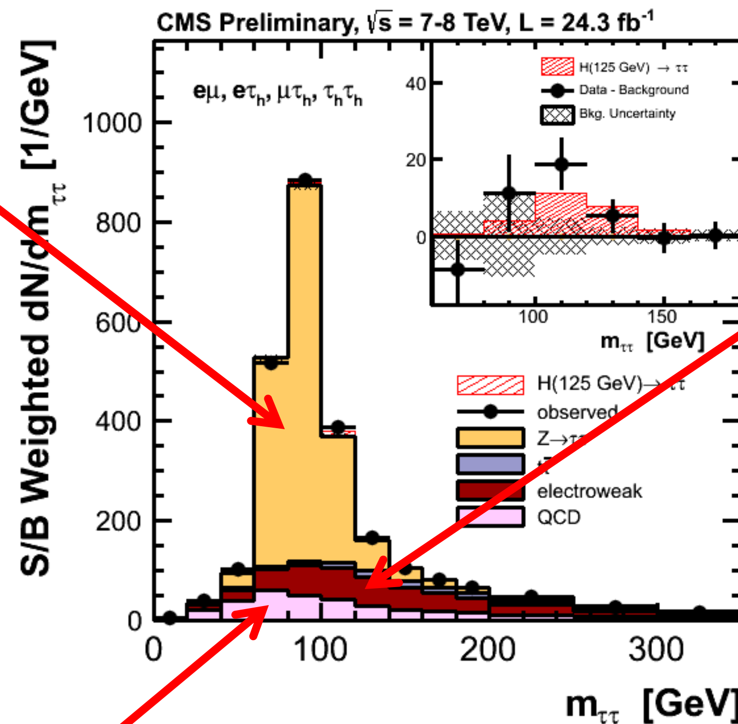


Background Estimation

$Z \to \tau\tau$: observed $Z \to \mu\mu$ sample and replace μ by simulated τ (embedding)

W + jets : Shape from simulation, normalization from m_T/P_ζ sideband

Z + jets : OS/SS ratio and lepton / jet faking hadronic τ with shape from simulation



QCD : From OS/SS data and mass shape from SS data in relaxed lepton isolation

Top pair and **Di-boson**

SM Event Categorization

number of jets

$e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$

τ p_T

0-jet, low p_T
- High background, constrains nuisance parameters
- No fit for signal

1-jet, low p_T
- Enhancement from jet requirement

2-jet (VBF)
- ≥2 jets, no jet in rapidity gap
- $m(jj) > 500$ GeV, $|\Delta\eta(jj)| > 3.5$

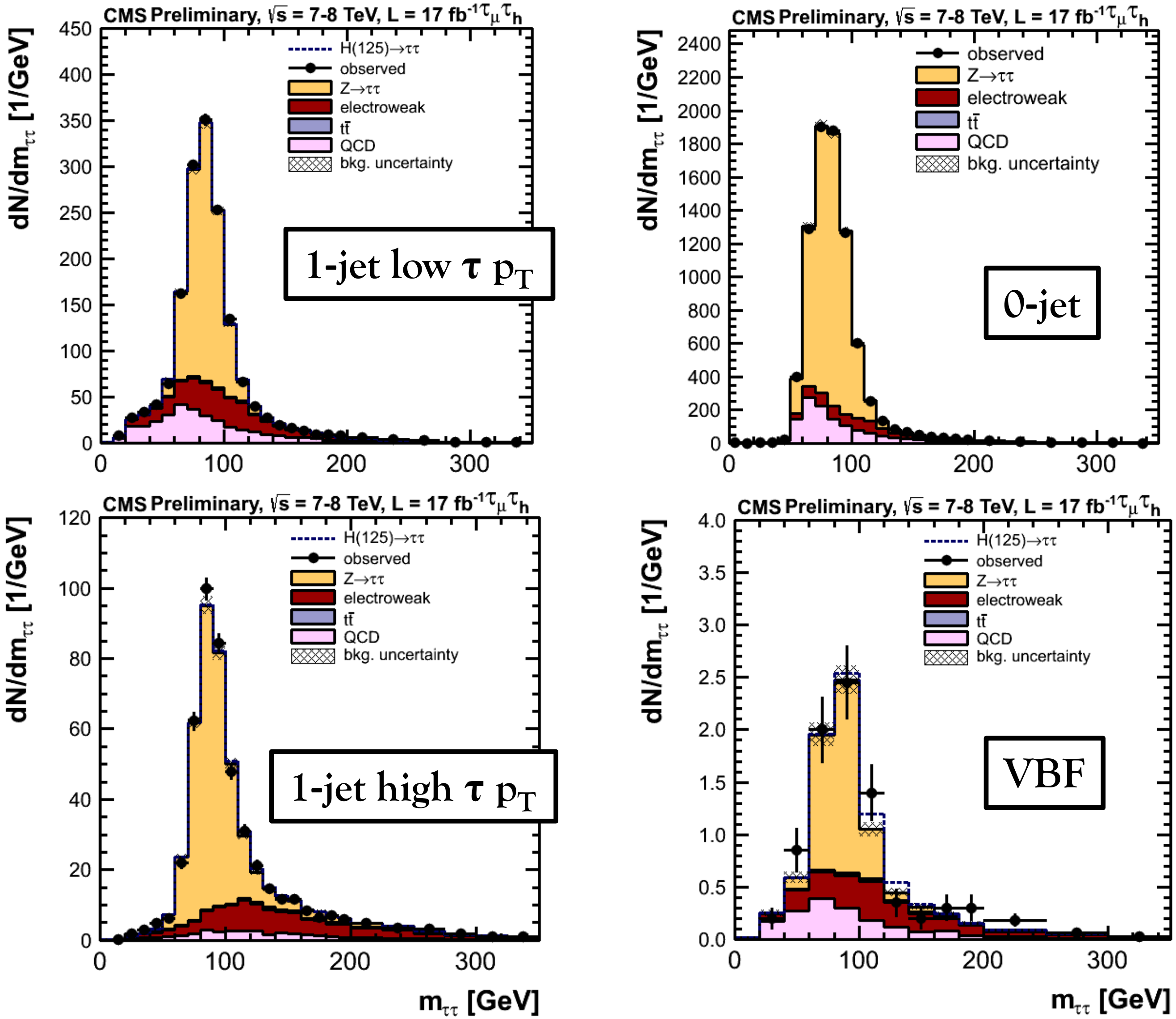
0-jet, high p_T
- High background, constrains nuisance parameters
- No fit for signal

1-jet, high p_T
- Enhancement from jet and p_T requirement

$\tau_h\tau_h$ 1-jet
1 jet, high $p_T(H)$ requirement

$\tau_h\tau_h$ 2-jet (VBF)
2 jets, high $p_T(H)$ requirement, $m(jj) > 250$ GeV, $|\Delta\eta(jj)| > 2.5$

SM Event Categories

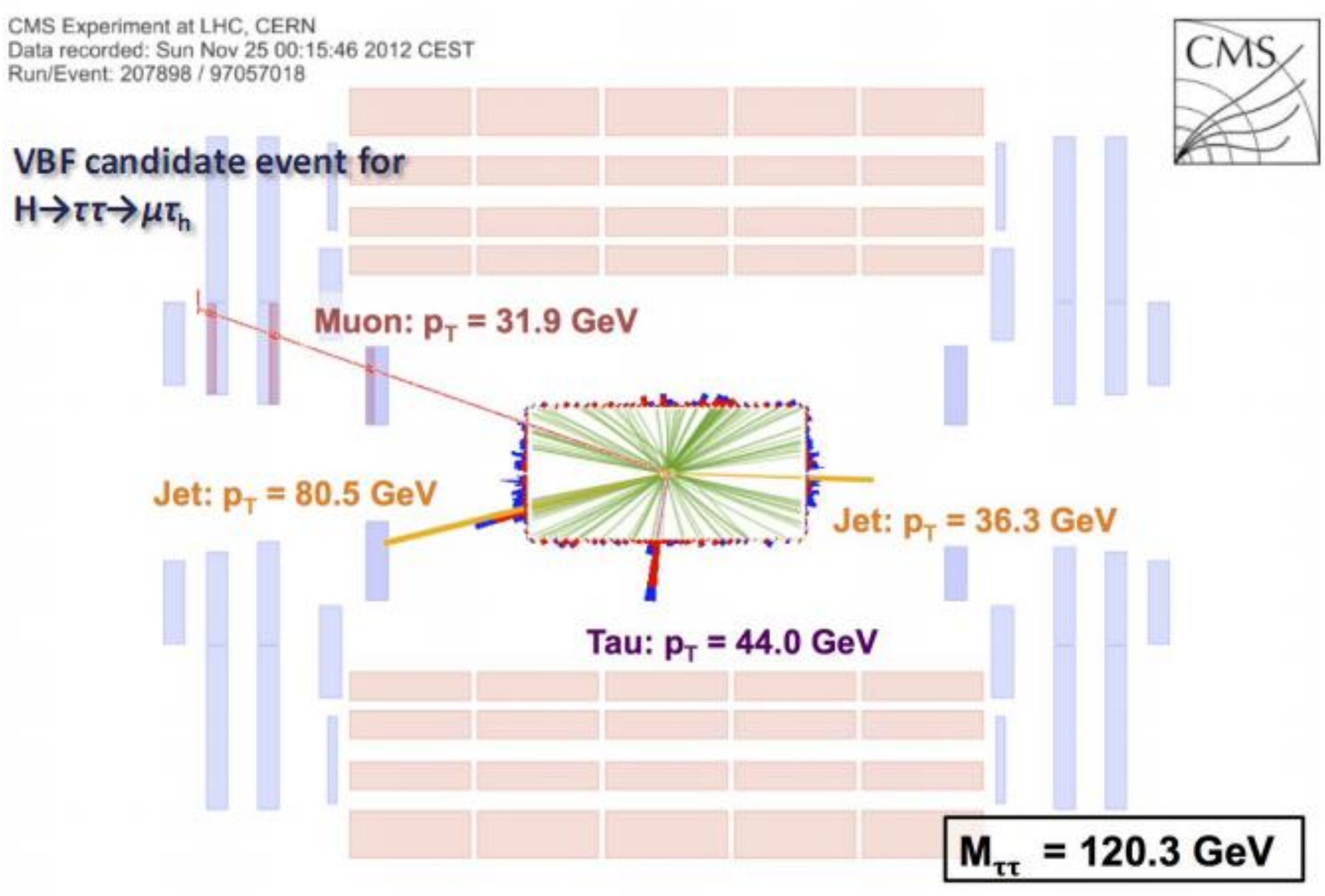


0 – jet category : constrains background, id efficiencies, energy scales

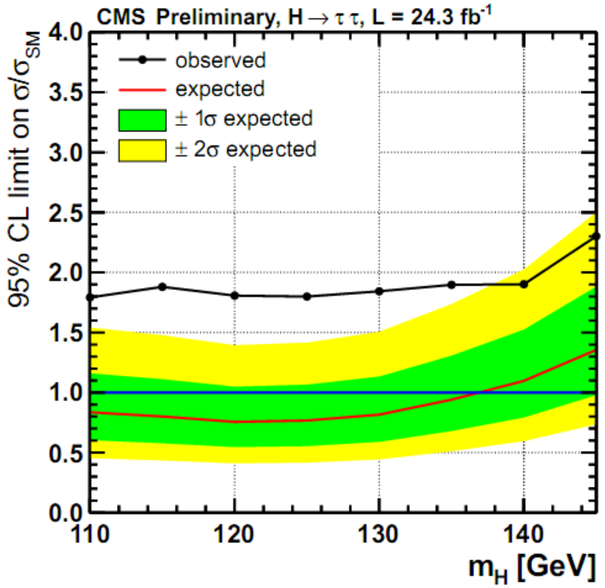
1 – jet category : improves resolution of Higgs mass

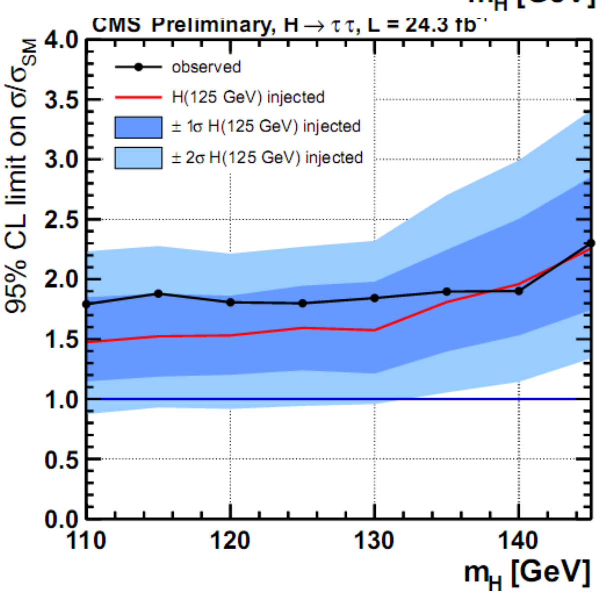
2 – jet category : VBF process - high S/B ratio

Event Display



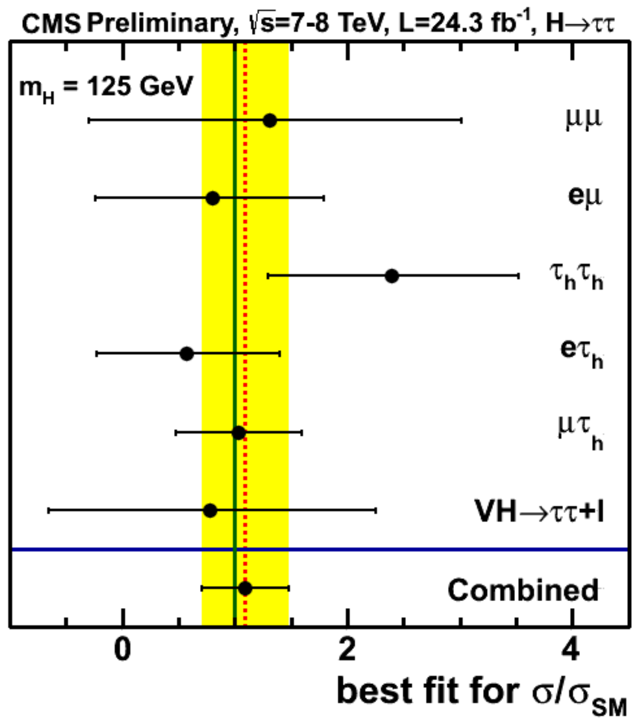
Results @ 7 + 8 TeV





CMS PAS HIG-13-004

- Broad excess observed over range of m_H
- Max local significance 2.93**σ** at 120 GeV compatible with 125GeV SM scalar boson
- Observed (expected) Signf 2.85**σ** (2.62**σ**) for m_H = 125 GeV
- Strong affirmation on Higgs-Fermion coupling, 1st Indication to Leptons



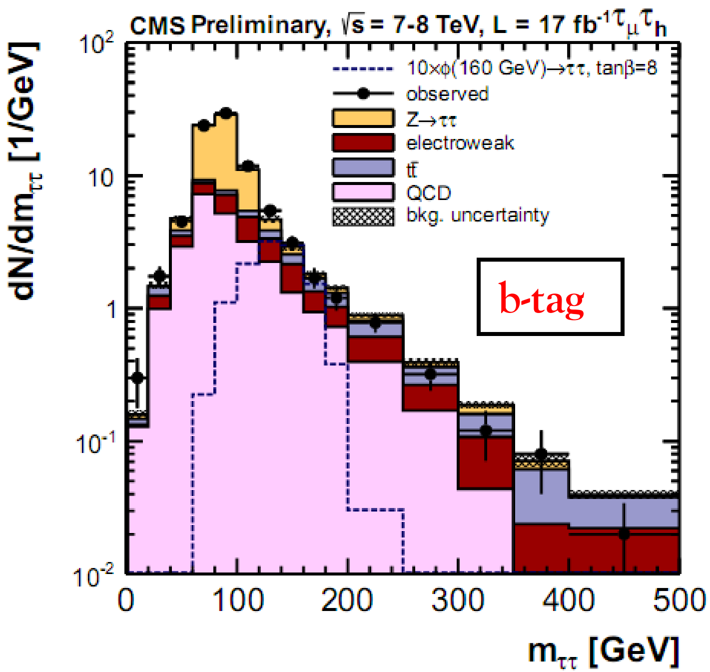
CMS PAS HIG-12-050

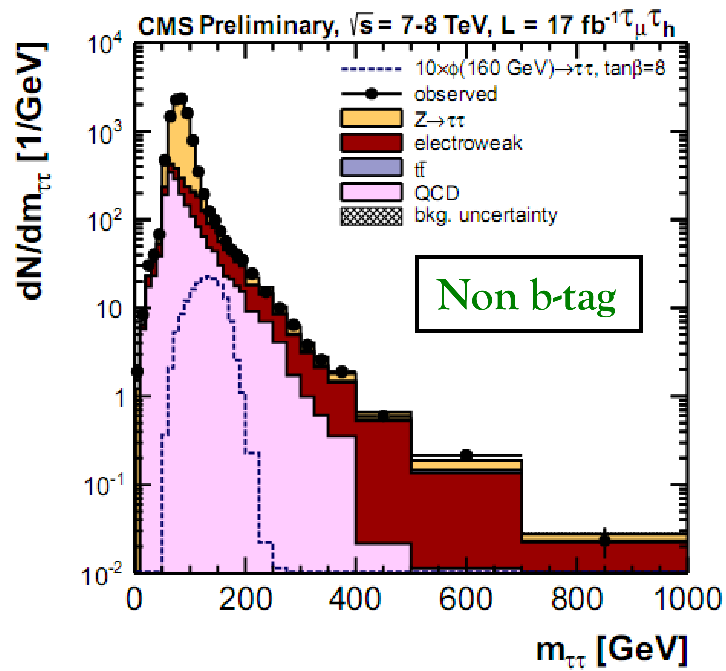
Decay final states : $\mu + \tau_h$, $e + \tau_h$, $\mu + e$, $\mu\mu$

Selected Events analyzed in 2 Categories: b-Tag and non-b-Tag
(to enhance sensitivity of bbΦ coupling)
B-tagging : based on secondary vertex + track-based life-time info

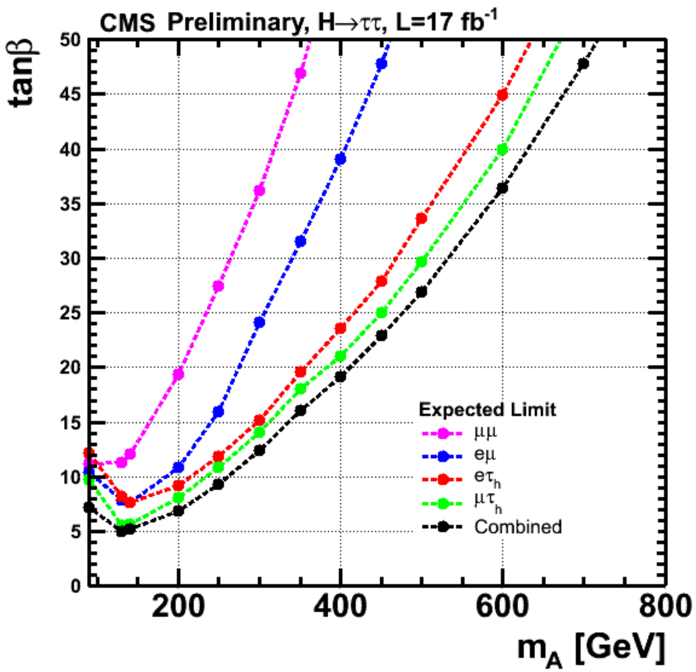
- **b-tag :**
  ≤ 1 light q jet with p_T > 30 GeV,
  ≥ 1 b-tagged jet with p_T > 20 GeV

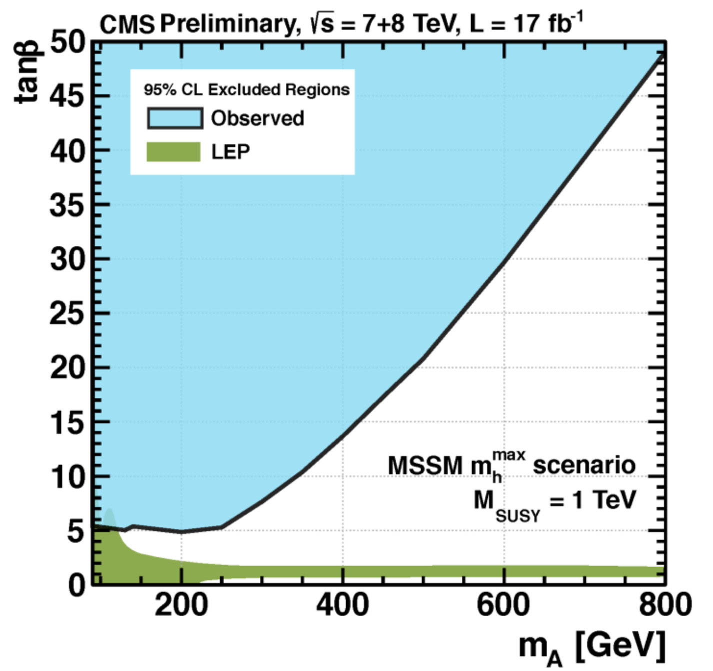
- **Non b-tag :**
  ≤ 1 light q jet with p_T > 30 GeV,
  No b-tagged jet with p_T > 20 GeV





MSSM results @ 7 + 8 TeV



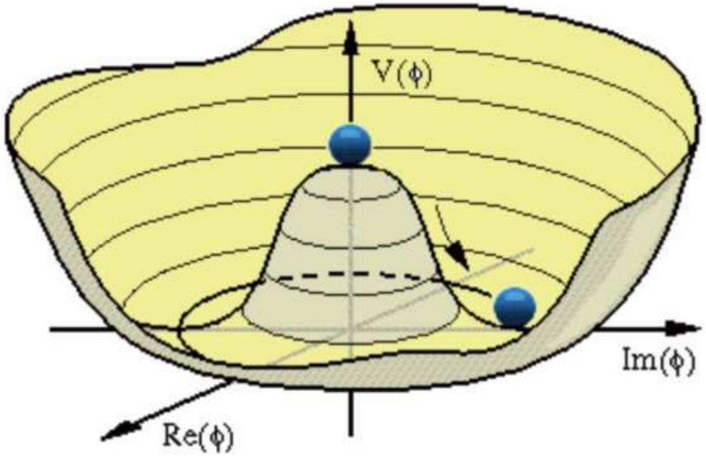


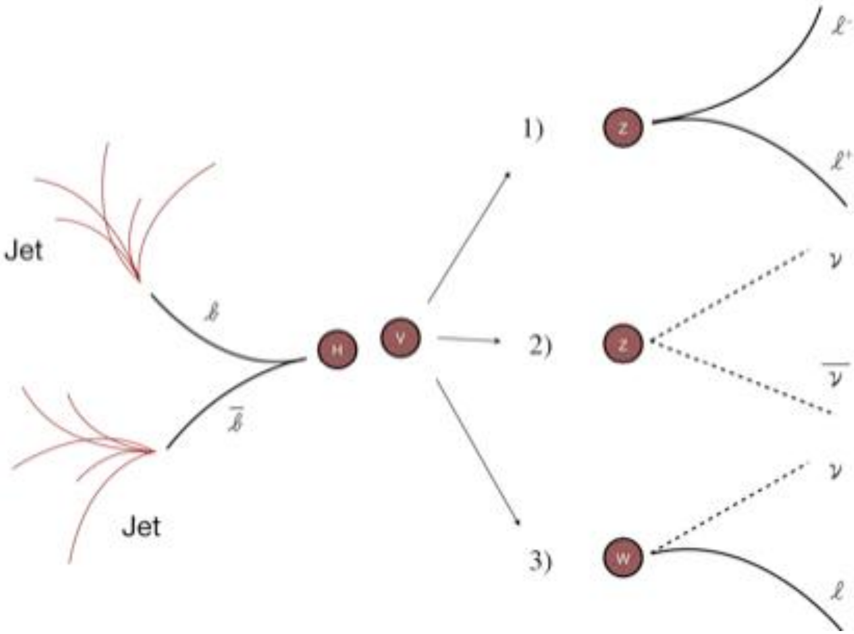
95% CL upper bound on cross-section x $\mathscr{B}$r ($\Phi \to \tau\tau$) – based on mass shape of $m_{\tau\tau}$ distribution
mapped to m_A – tanβ plane (4FS + 5FS)

Uncertainties –
- Theory
- Normalization (Lumi, Efficiencies)
- Shape (Energy scale)

This excludes previously unexplored region:
now reaching as low as tan β ~ 4 at m_A = 200 GeV

$H \to b\bar{b}$





Boosted Decision Tree – Multivariate technique
- Trained with MC simulation to discriminate bkg events

Most powerful discriminant – dijet invariant mass M(jj)

– Combine M(jj) and other discriminating variables into one single discriminant
- p_T of the jets and the di-jet system
- CSV of the jets
- Angular information

– Correlations between variables also encapsulated
- Such as M(jj) and ΔR(jj)

$H \rightarrow b\bar{b}$ association with vector bosons		
W(μν)H	W(eν)H	
Z(μμ)H	Z(ee)H	Z(νν)H

Backgrounds

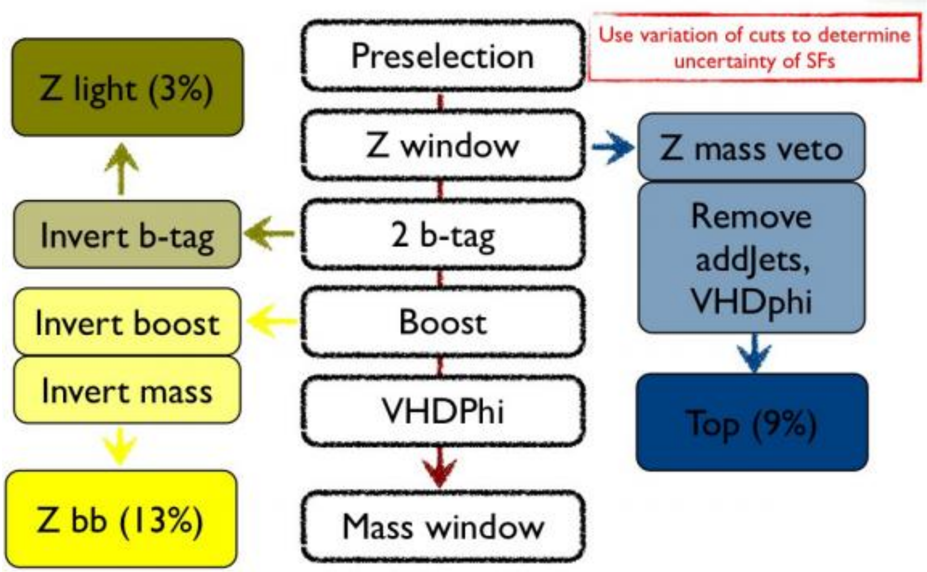
- V + jets
  - High cross section, non-resonant background
  - V + heavy flavor jets largest bkg after b-tagging (irreducible)

- V + light flavor jets - reducible
  - Falls more rapidly than signal when high boost is required

- top pair, single top

- VV
  - Smaller cross section, but very similar to VH (irreducible)
  - Best discriminated by the invariant mass

- Other reducible background:
  - QCD fake leptons or jet energy mis-measurement



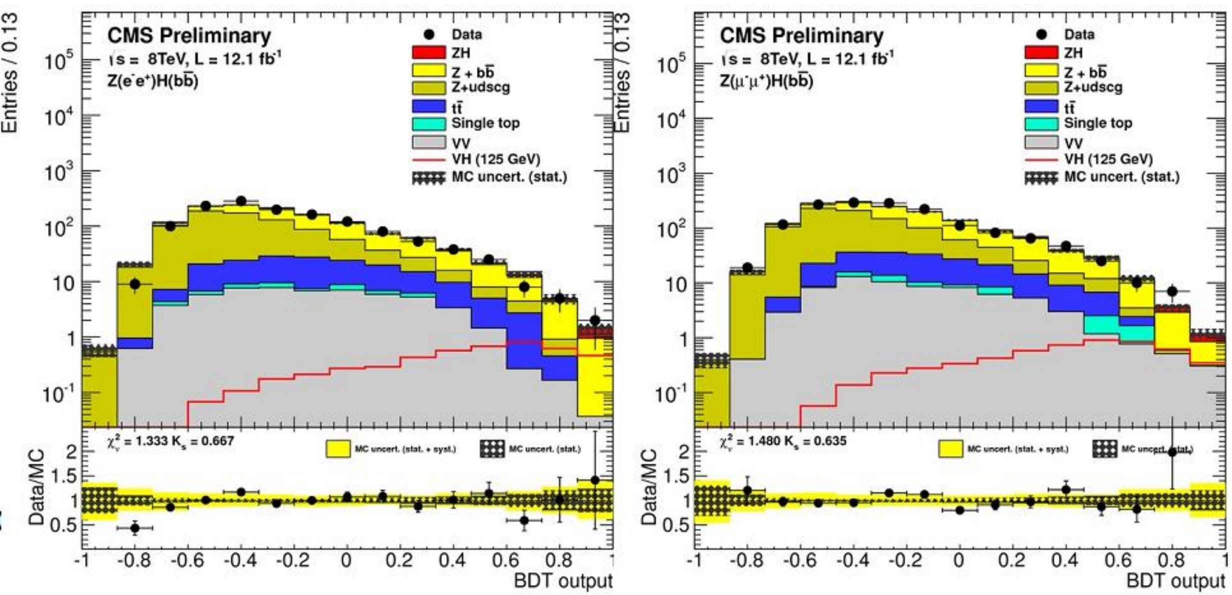
b-jet identification substantially reduces multi-jet background

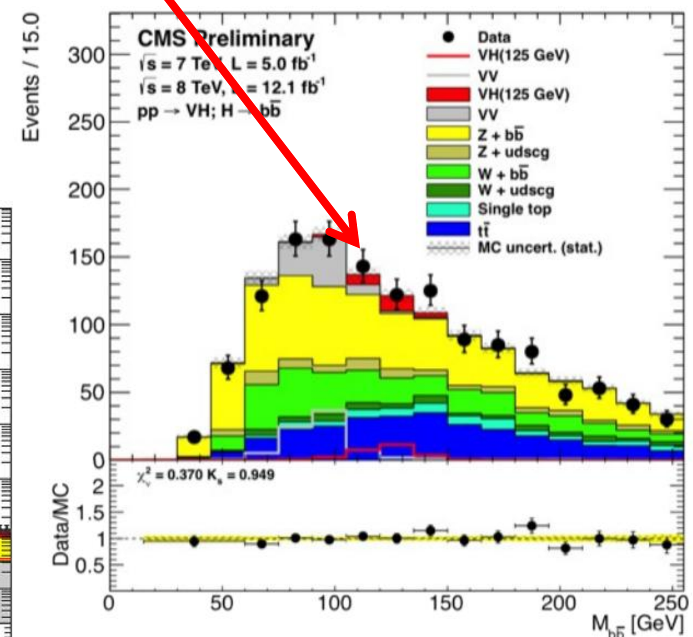
Requires higher boost and VH back-to-back topology to enhance S/B
– Signal decreases more slowly than bkg

CMS PAS HIG-12-044

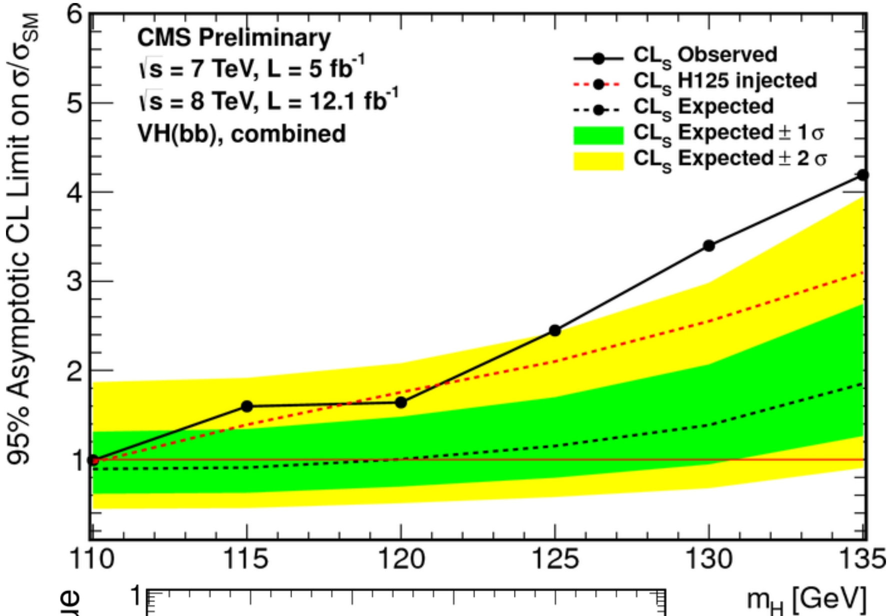
Excess around 125 GeV

BDT output for ZH
after applying all selections



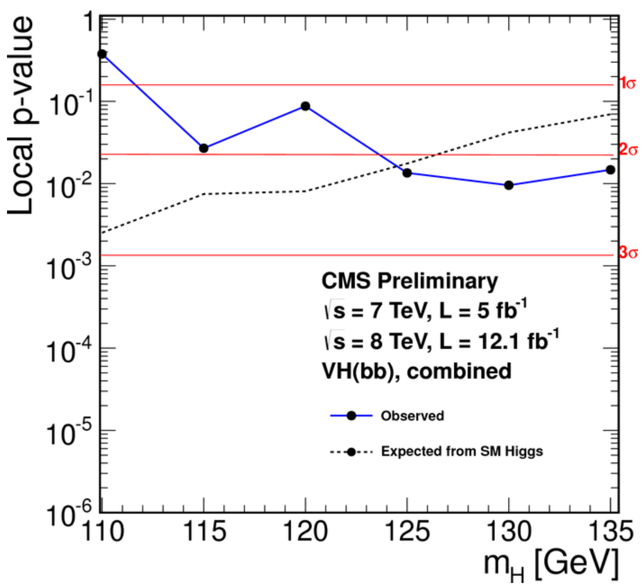


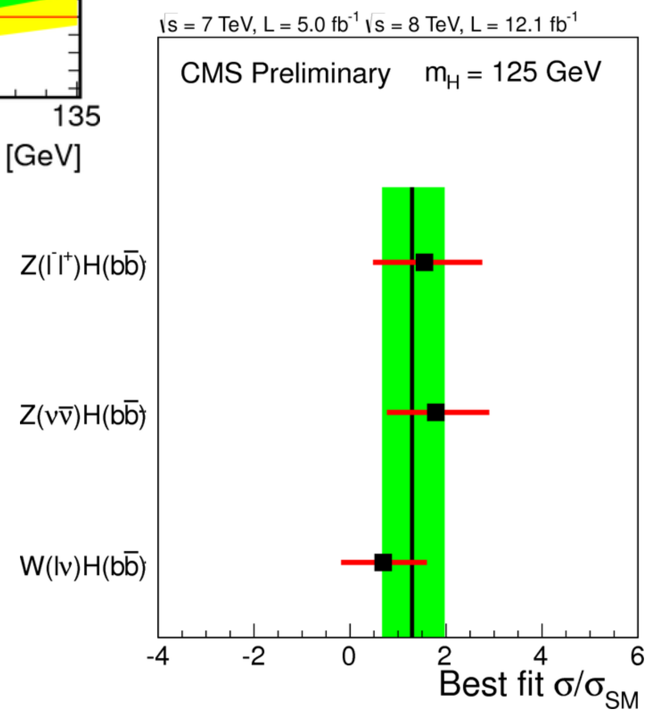
Di-jet Invariant Mass



Observed (expected) limit
2.5 (1.2) x SM at 125 GeV

Observed (expected) local signf
2.2σ (2.1σ) for m_H=125 GeV

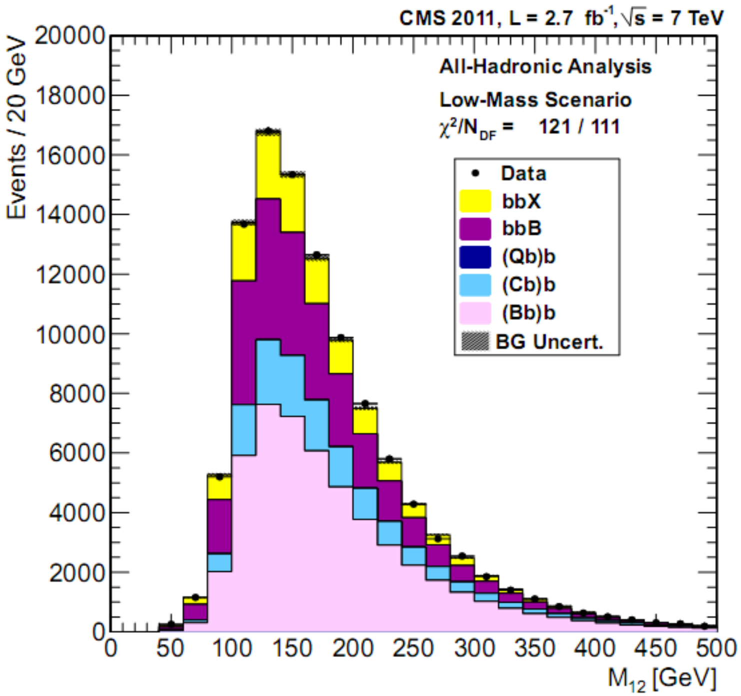


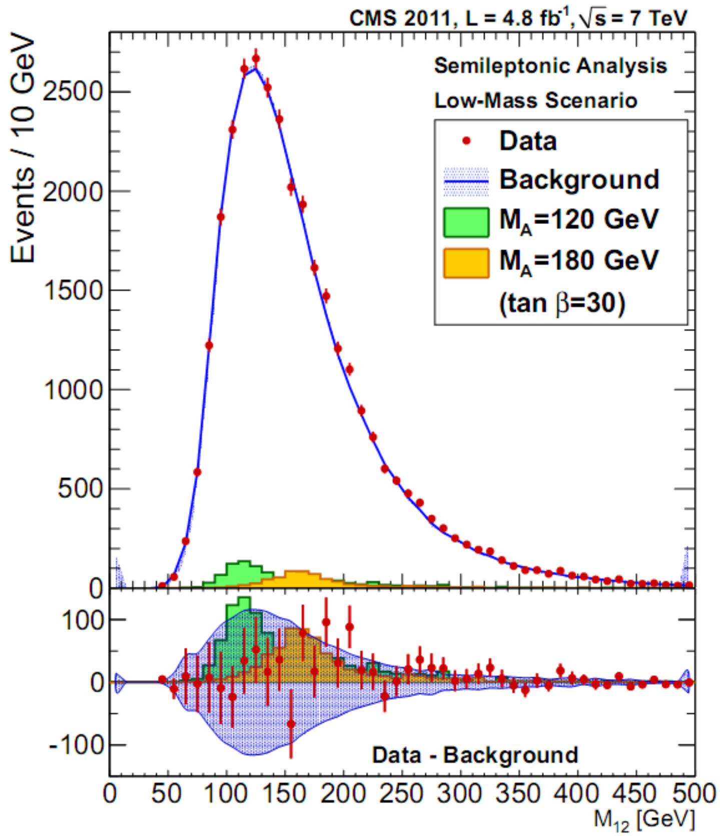


Combined best-fit
$\mu = 1.3^{+0.7}_{-0.6}$

MSSM selection strategy

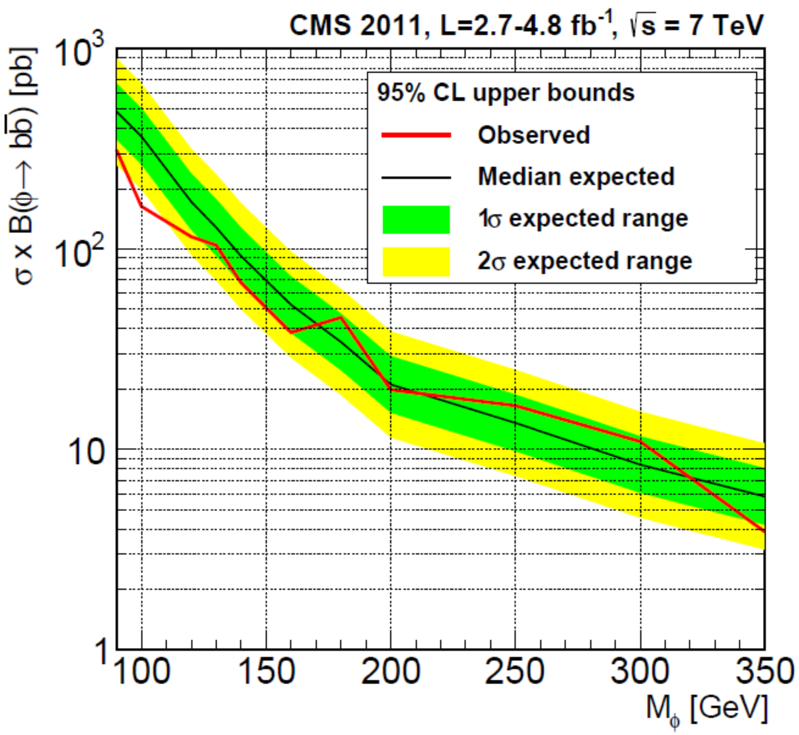
- sensitive to Higgs bosons in MSSM scenarios with large values of tanβ
- Higgs decaying to b quark pair in association with at least one additional b quark
- multijet final states with 3 b-tagged jets, one may include a non-isolated muon

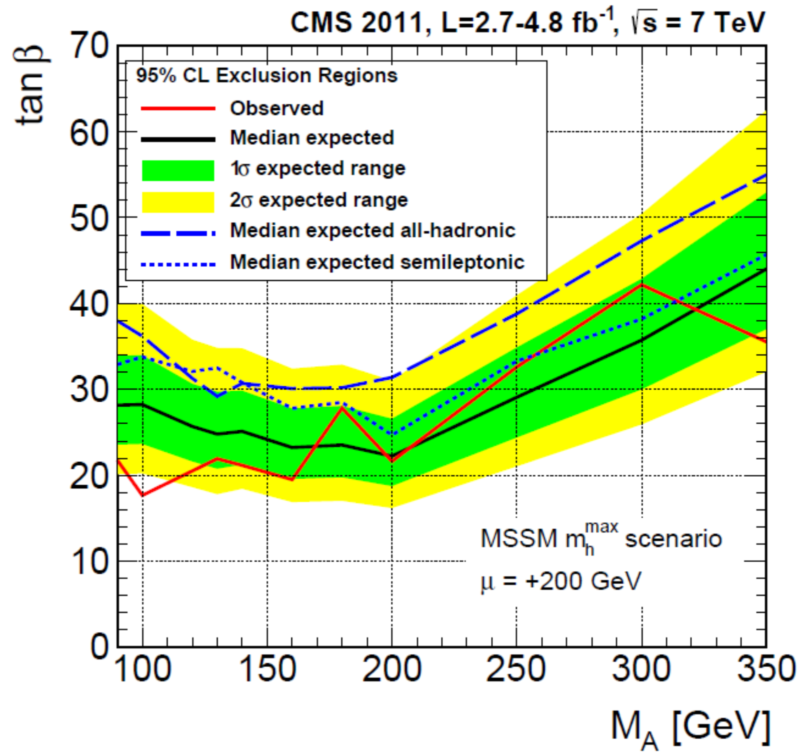




- Background: heavy flavour multi-jet, derived from the data
- Signal would appear as a peak in the di-jet mass distribution in triple b-tag sample

arXiv: 1302.2892 [hep-ex]





- combined all hadronic and semi-leptonic results
- upper bound on x-section mapped to MSSM plane - 5 FS scheme employed
- reaching as low as tan β ~ 18 at m_A = 100 GeV

- Time for celebration: Observation of a new boson around 125 GeV !
- SM Higgs analysis in ττ uses full 2011 and 2012 data set
- Broad excess observed in di-tau decay mode consistent with the new boson
- First Indication of Higgs coupling to Leptons
- Complete data set analysis underway with b-jet final states

- Exciting moment also for the MSSM Higgs
- Robust program of MSSM Higgs searches with the CMS detector
- MSSM Higgs parameters significantly constrained with $H\rightarrow\tau\tau$
- Efforts on update with full data set is ongoing!

Back-up

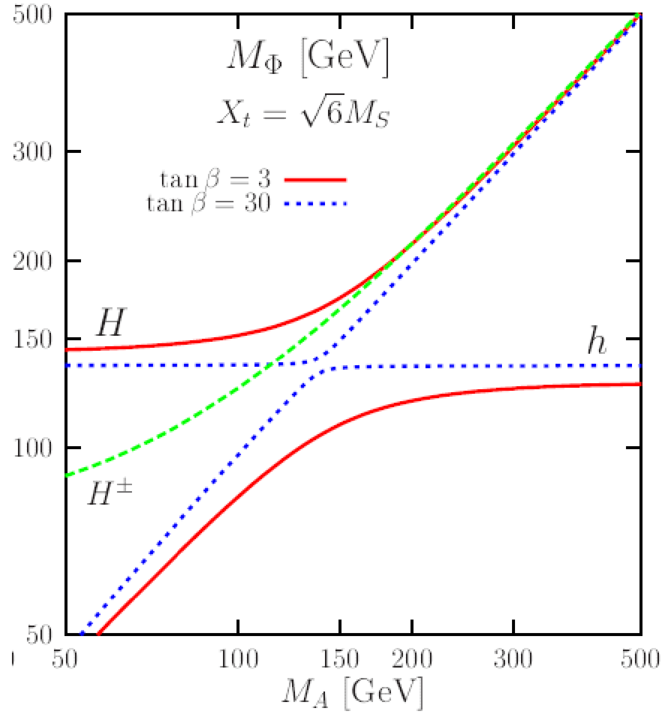
MSSM Higgs sector

Only two free parameters at the tree level : $\tan\beta$, M_A ; others are:

$$M^2_{h,H} = \frac{1}{2}\left[M^2_A + M^2_Z \mp \sqrt{(M^2_A + M^2_Z)^2 - 4M^2_A M^2_Z \cos^2 2\beta}\right]$$
$$M^2_{H^\pm} = M^2_A + M^2_W$$
$$\tan 2\alpha = \tan 2\beta\,(M^2_A + M^2_Z)/(M^2_A - M^2_Z)$$

$$M_h \le \min(M_A, M_Z)\cdot|\cos 2\beta| \le M_Z,$$
$$M_{H^\pm} > M_W,\, M_H > M_A$$

Phys. Rept. 459:1-241, 2008

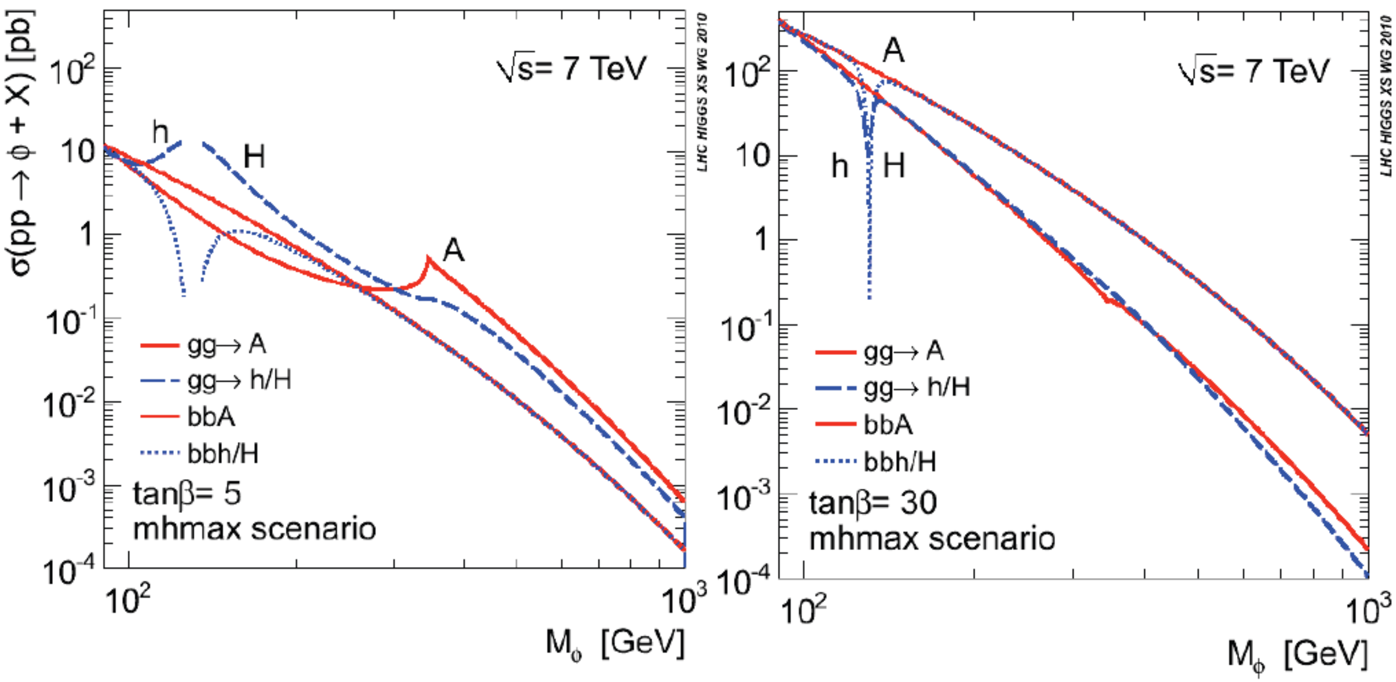


Radiative corrections very important in the MSSM Higgs sector

Dominant corrections are due to top/stop at the one-loop level

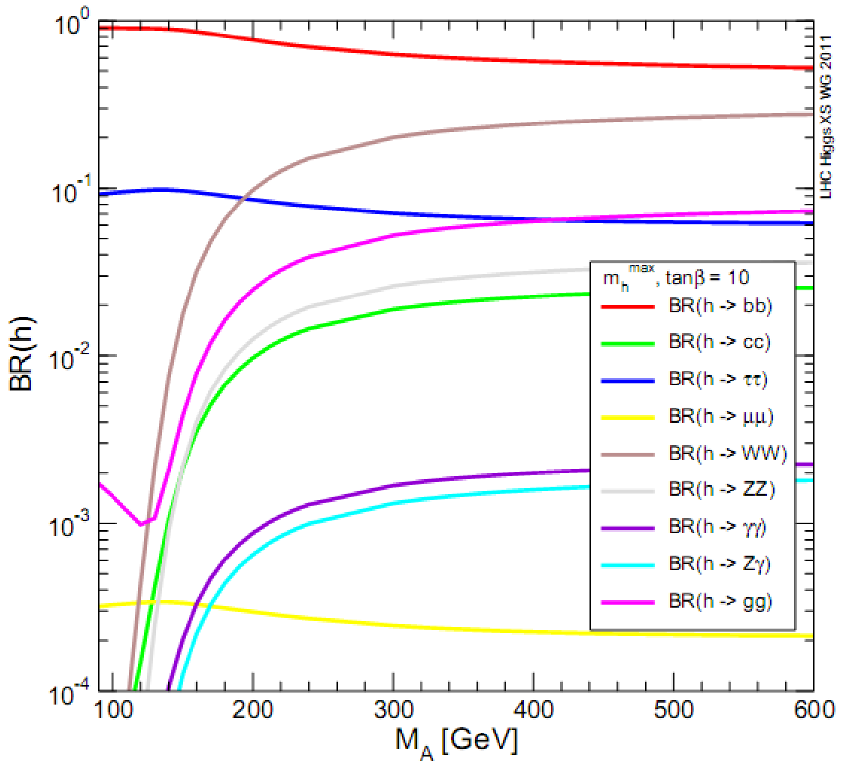
$$M_h \overset{M_A \gg M_Z}{\longrightarrow} M_Z|\cos 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

tanβ = 5 | mhmax scenario | tanβ = 30



bbφ from ggH@NNLO (5FS)
Scaled by $(g_b^{MSSM}/g_b^{SM})^2$ from FeynHiggs

arXiv:1101.0593 [hep-ph]



Φ (h/H/A) decays to
bb mode (~ 90%)
ττ mode (~ 10%)

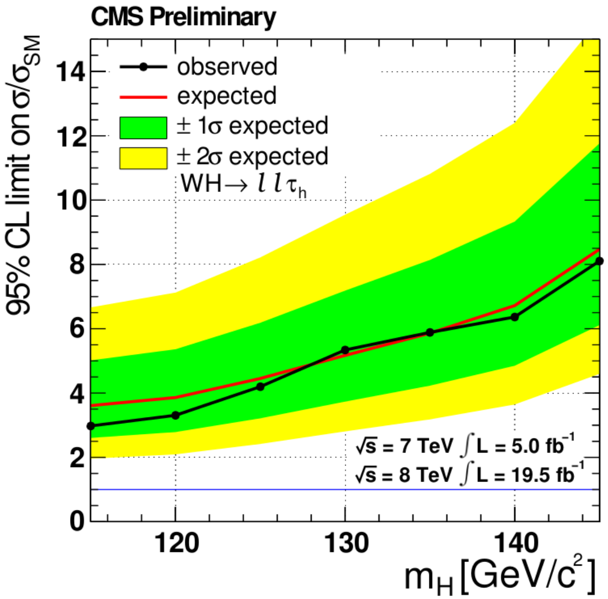
- MSSM Higgs production and decays can be significantly affected by radiative corrections
- The bb channel is more sensitive to these corrections (and therefore to the SUSY scenario), while the **ττ** channel is more robust

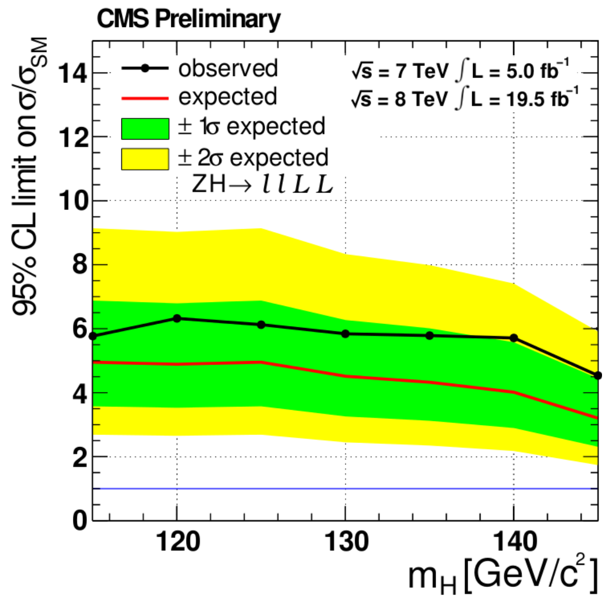
$$\sigma(b\bar{b} \to A) \times BR(A \to b\bar{b}) \cong \sigma(b\bar{b} \to A)_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

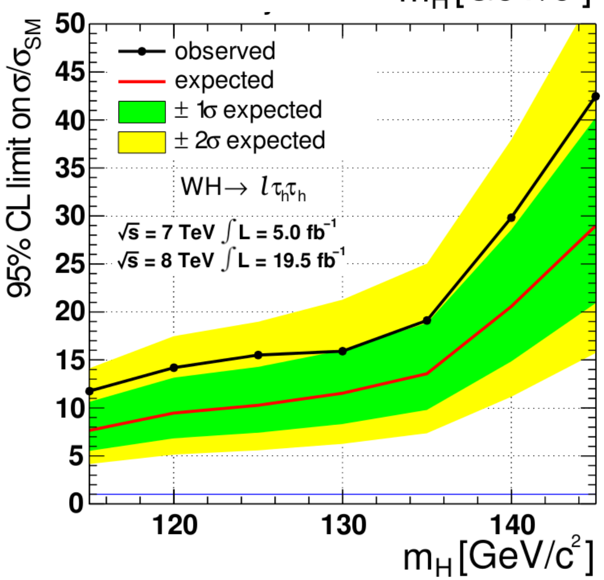
$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \cong \sigma(b\bar{b}, gg \to A)_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2 + 9}$$

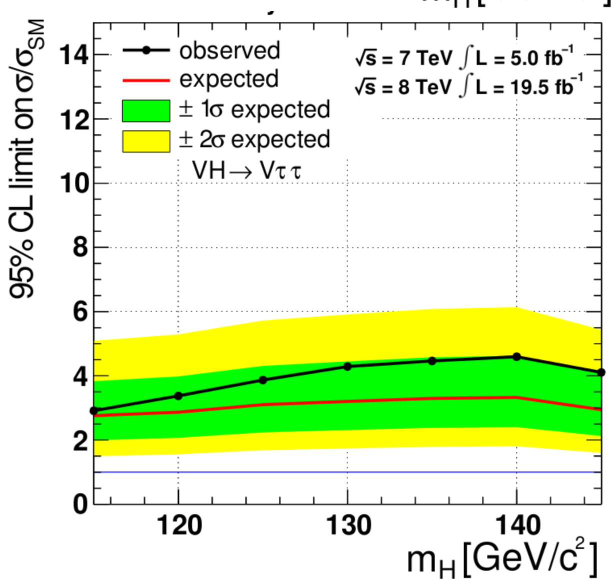
Δ_b is a function of SUSY parameters

VH with H→ττ



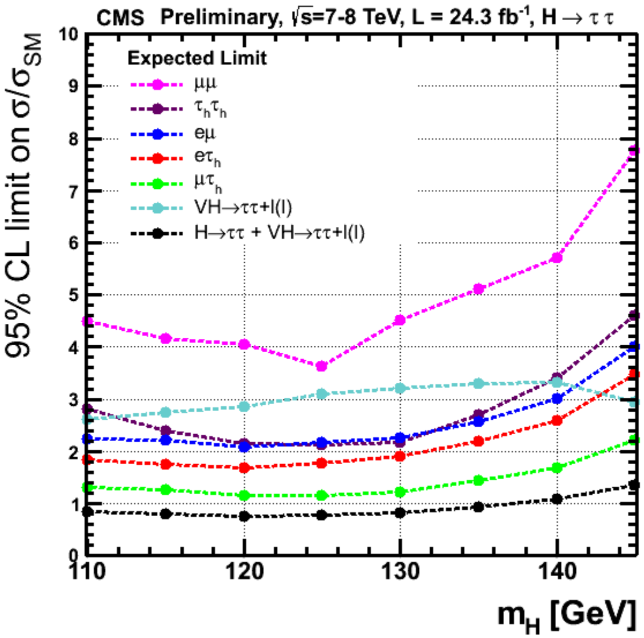


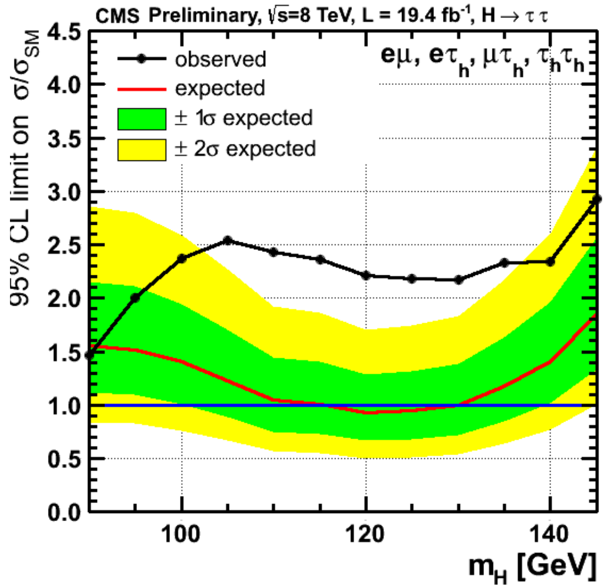




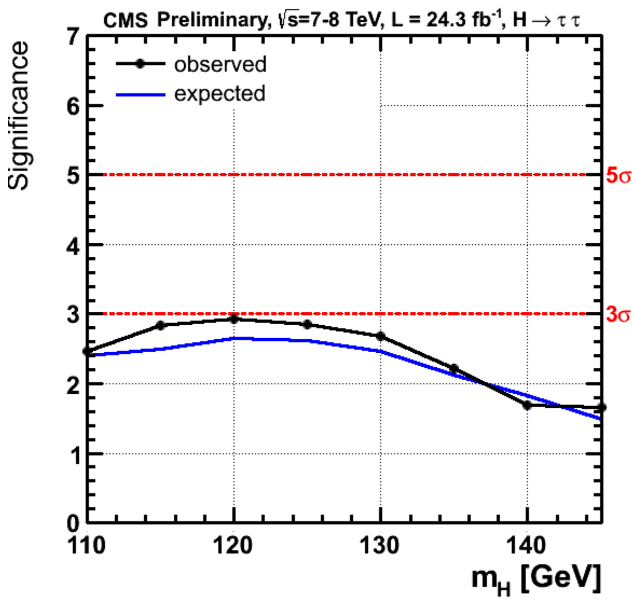
95% CL upper limits on SM Higgs production in VH channels and its combination

H→ττ

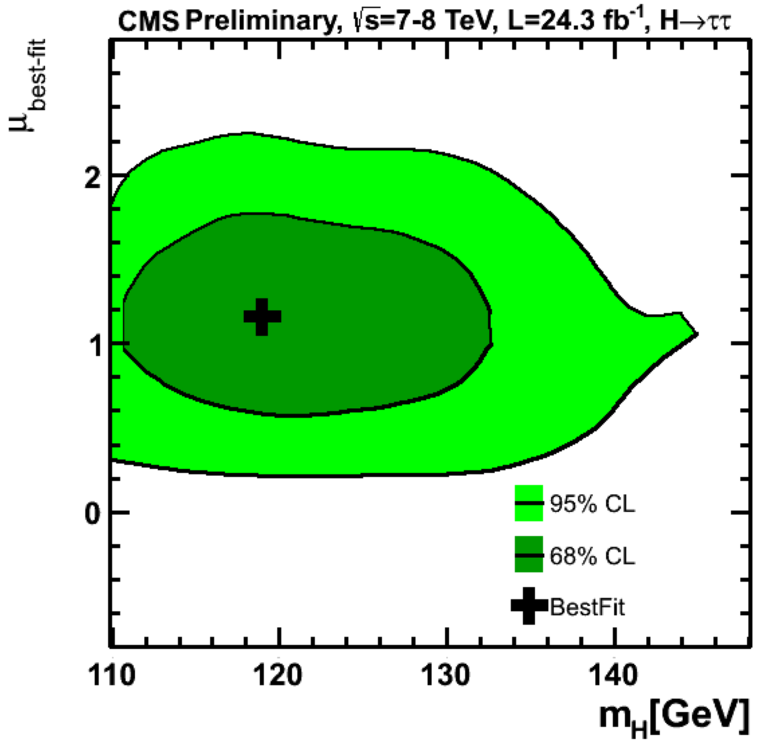


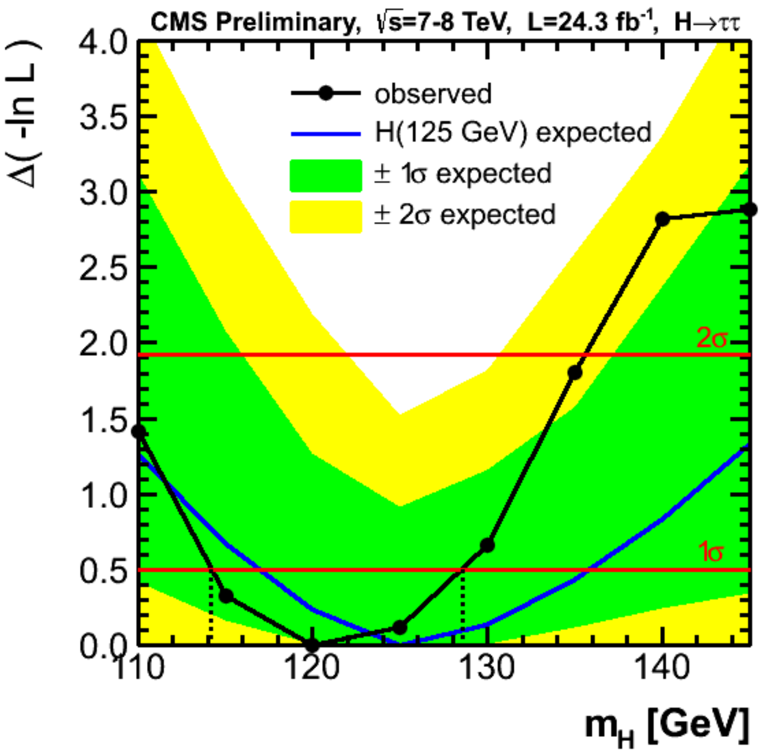


Significance of excess observed



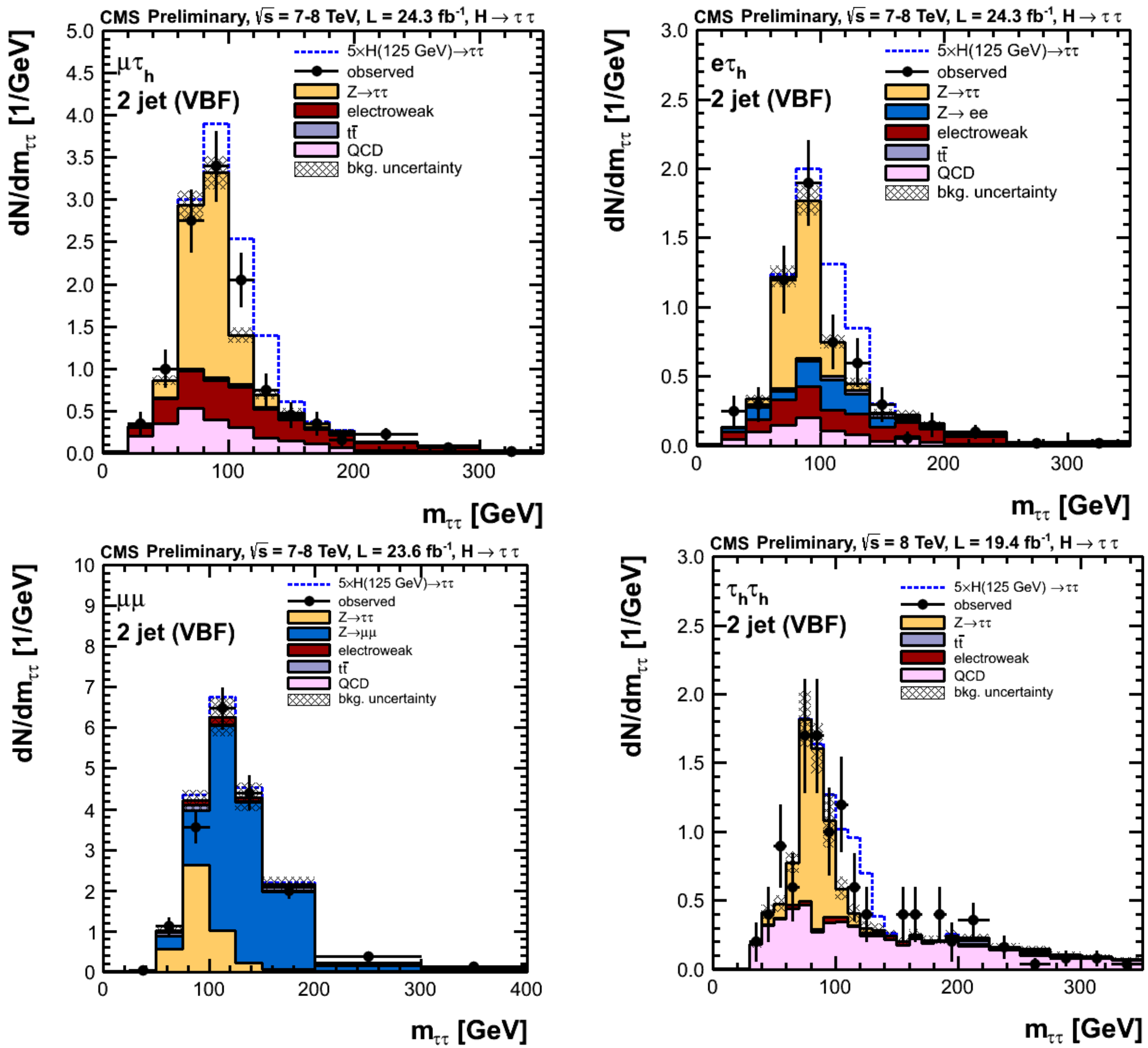
95% CL upper limits on SM Higgs production in different channels and its combination

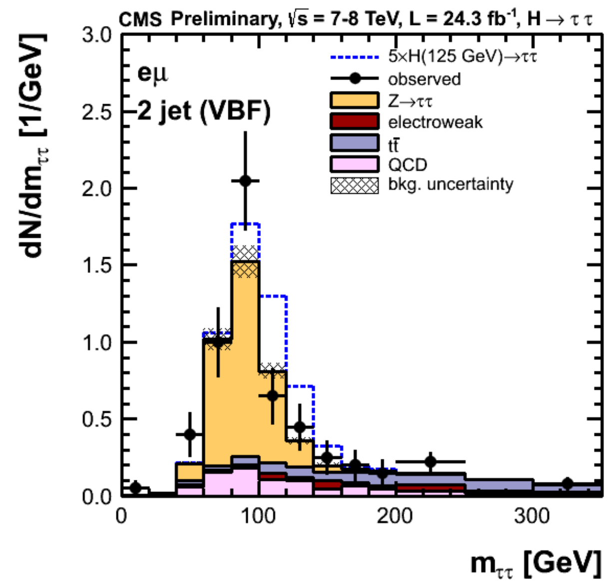




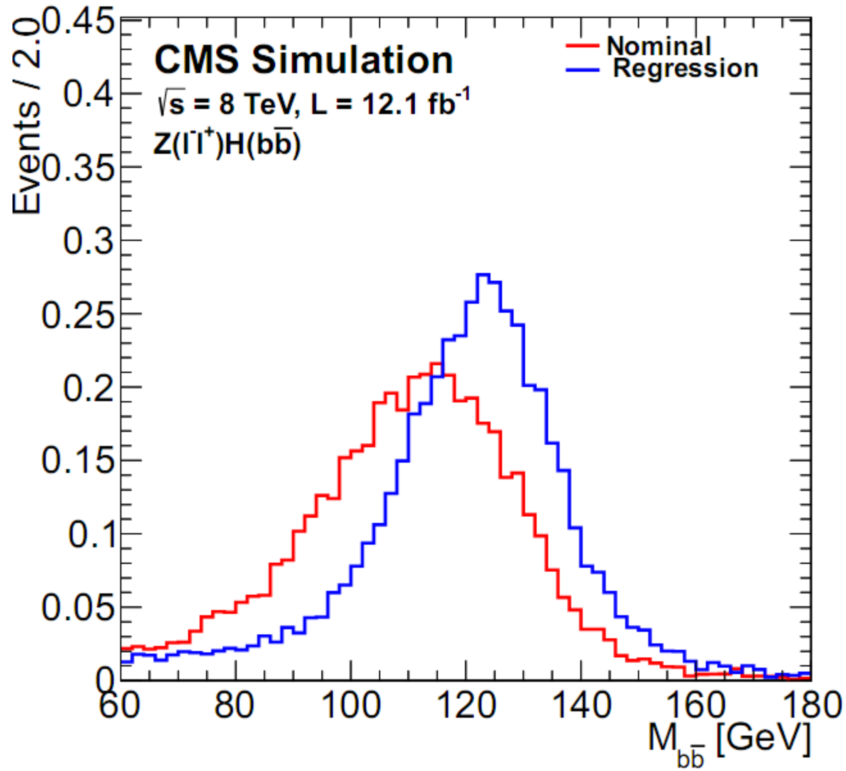
observed result gives a best fit
for the SM Higgs boson of
$m_H = 120\ ^{+9}_{-7}$ (stat + syst) GeV

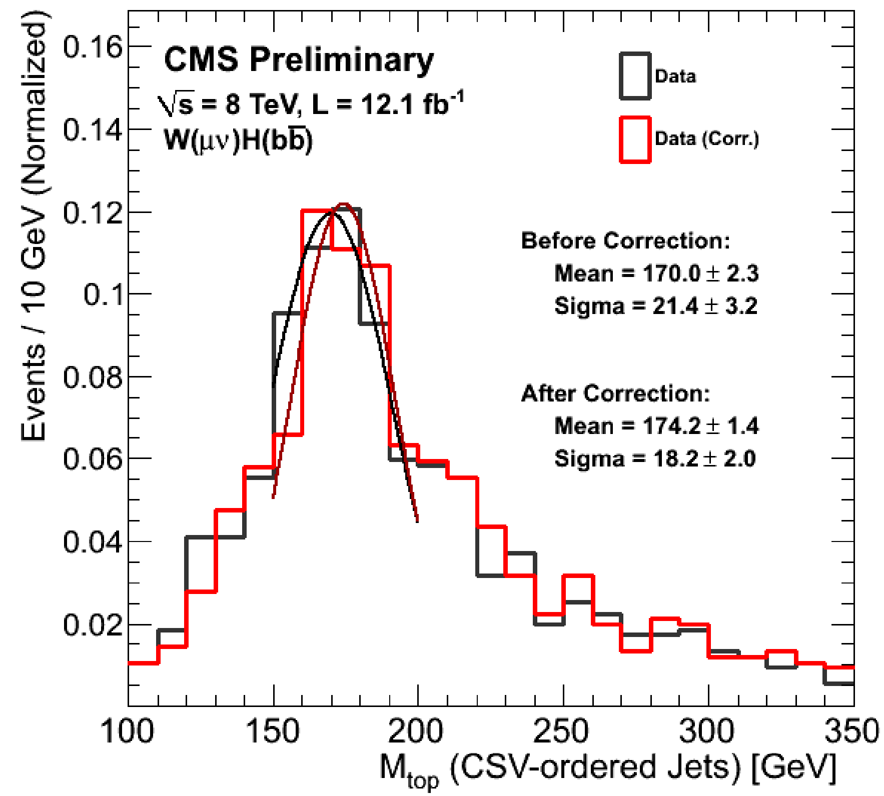
H→ττ





VBF category with S/B enhancement





M_{bb} resolution improves – applying regression