# Higgs boson measurements and extended scalar sector searches in fermionic final states at the CMS experiment


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DESY

(on behalf of the CMS Collaboration)


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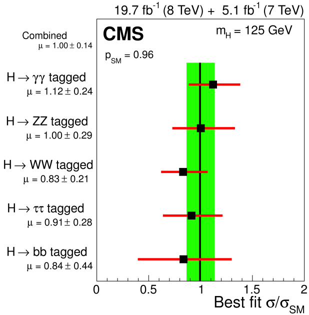
# Introduction to Standard Model Higgs measurements

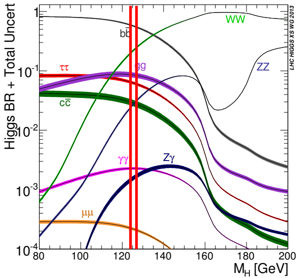
Standard Model Higgs results from Run-I:

- Higgs discovered or evident at 8TeV in
  - $H \to \gamma\gamma$
  - $H \to WW$
  - $H \to ZZ$
  - $H \to \tau\tau$




- All measurements agree with SM predictions

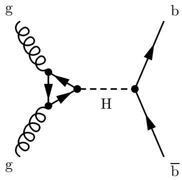
- But $H \to b\overline{b}$ still open for discovery



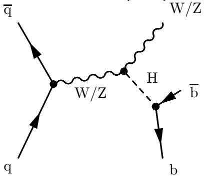
# $H \to b\bar{b}$: Search strategy

Possible to search for this process in different production channels:

*Gluon fusion*




*Vector boson associated production (VH)*

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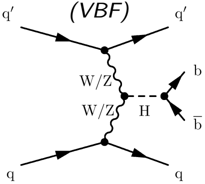
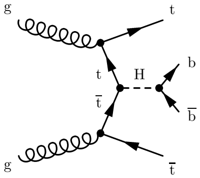



*$t\bar{t}$ associated production*



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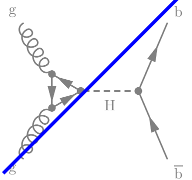


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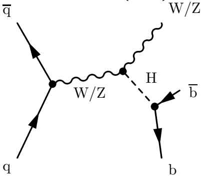


- gg-channel: overwhelmed by QCD-multijet background

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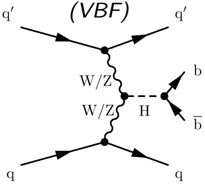


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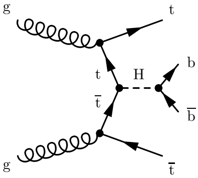

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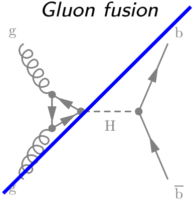


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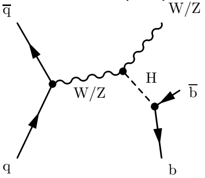


- gg-channel: overwhelmed by QCD-multijet background
- See talk by Georgios Krintira for $t\bar{t}H$

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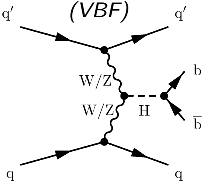


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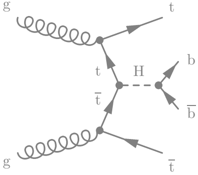

# $H \rightarrow b\bar{b}$: Search strategy

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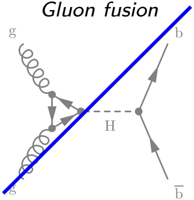


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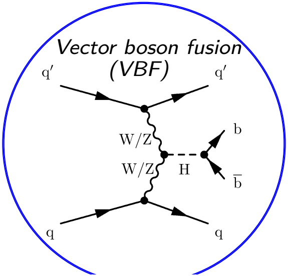
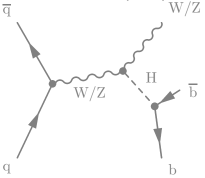



- gg-channel: overwhelmed by QCD-multijet background
- See talk by Georgios Krintira for $t\bar{t}H$
- VH on-going analysis at 13 TeV → **Today**: VBF channel

*Vector boson associated production (VH)*

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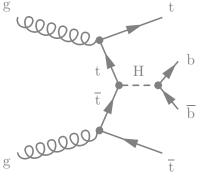
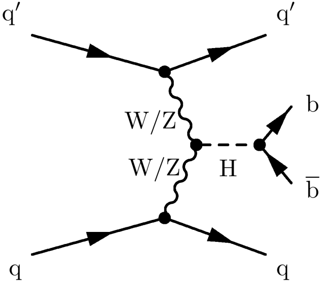


# VBF $H \to b\bar{b}$: Characteristics and challenges 13 TeV

CMS-PAS-HIG-16-003

**Special characteristics of this process:**

- Four energetic jets in the final state
- Two b-tagged jets
- Two forward jets (VBF topology)
- Electroweak process $\to$ no color connection between jets




**Challenges of this search:**

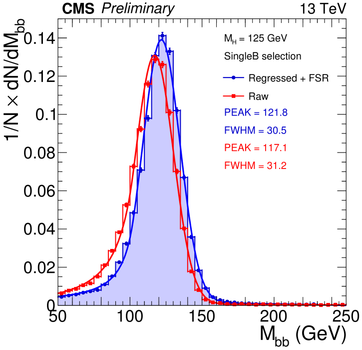
- Separation from QCD-multijet background
- Mass reconstruction from two b-tagged jets

# VBF $H \to b\bar{b}$: Higgs mass reconstruction 13 TeV

CMS-PAS-HIG-16-003

- Challenging because of neutrinos in semi-leptonic b-decays

- Improvements by:
  - B-jet specific jet energy corrections (multivariate regression techniques)
  - Recovering gluon radiation not clustered to the jet cone

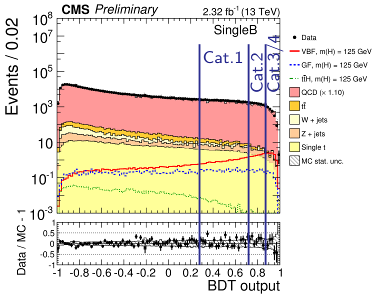


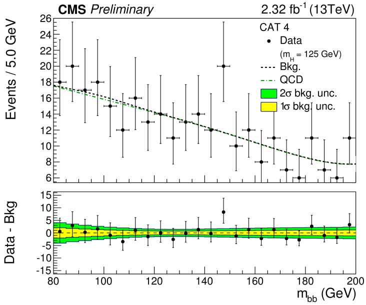

$\rightarrow$ Improvements of the mass resolution of 7% achieved

# VBF $H \to b\bar{b}$: Signal vs. background discrimination 13 TeV

CMS-PAS-HIG-16-003

- Multivariate techniques (**B**oosted **D**ecision **T**rees)
  - Kinematic variables of jets, b-jet discriminators, QCD gap activity, ...
- Categorization depends on BDT output



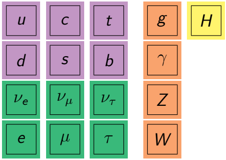




**Best-fit signal strength:**

**Run-II** at $\sqrt{s} = 13\,\text{TeV}$ with $\mathcal{L} = 2.3\,\text{fb}^{-1}$ : $\mu = \sigma/\sigma_{\text{SM}} = \mathbf{-3.7^{+2.4}_{-2.5}}$

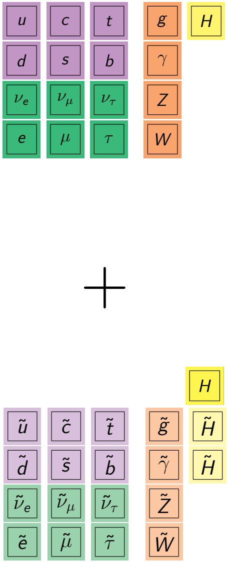
**Combined with Run-I** ($20\,\text{fb}^{-1}$ at 8TeV) : $\mu = \sigma/\sigma_{\text{SM}} = \mathbf{+1.3^{+1.2}_{-1.1}}$

# Beyond the SM - possible extensions of the Higgs sector




- The Standard Model is a very successful theory, but suffers from shortcomings ...
  - Hierachy problem
  - Dark Matter
  - ...
- Many possible extensions ...

# Beyond the SM - possible extensions of the Higgs sector




- The Standard Model is a very successful theory, but suffers from shortcomings ...
  - Hierachy problem
  - Dark Matter
  - ...
- Many possible extensions ...

The **M**inimal **S**upersymmetric **S**tandard **M**odel

- Hierarchy problem solved: $m_H^2 \propto \ln(\Lambda_{UV})$
- R-parity conserved → Lightest sparticle stable → DM candidate

# The Higgs sector of the MSSM

- Two Higgs doublets needed because of
  - Supersymmetry condition (holomorphic superpotential)
  - Anomaly cancellation (fermion triangle anomalies)

After spontaneous symmetry breaking (5 degrees of freedom):

$h$ $H$ $A$ $H^{\pm}$

- Relevant parameters in the Higgs sector: $\tan\beta$, $m_A$
- Lightest Higgs ($h$) usually associated with h(125 GeV) state

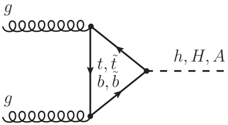
Search for $H$, $A$ and $H^{\pm}$

(would be an unambiguous proof of new physics)

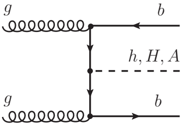
**Why in the ditau final state?**

CMS-PAS-HIG-16-037

- Higgs couplings proportional to mass ($\to$ *t*, *b*, $\tau$)
- Large tan $\beta \to$ enhanced couplings to down-type fermions ($\to \tau$, *b*)
- Good discrimination against SM processes ($\to \tau$)




no b-tagged jets




$\geq$ 1 b-tagged jets

$\to$ Search for events with two tau leptons

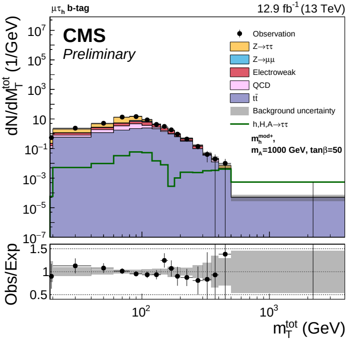
$\to$ For 2 tau leptons $\to$ 4 of 6 possible final states used:

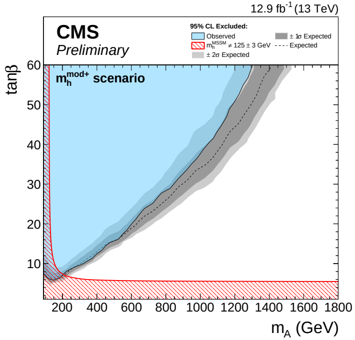
$\tau_h\tau_h$, $\tau_h\tau_e$, $\tau_h\tau_\mu$, $\tau_e\tau_\mu$

$\to$ Generally differ in background composition $\to$ optimized separately

## Final observable: The total transverse mass

$$m_T^{tot} = \sqrt{m_T\left(\not{E}_T, \tau_1^{vis}\right)^2 + m_T\left(\not{E}_T, \tau_2^{vis}\right)^2 + m_T\left(\tau_1^{vis}, \tau_2^{vis}\right)^2}$$



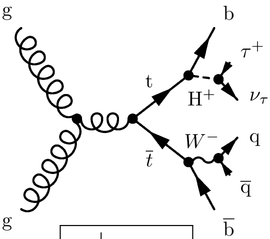




$\rightarrow$ First exclusions that extend beyond $m_A > 1\,\text{TeV}$ at CMS

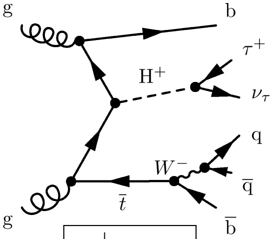
# Search for a charged MSSM Higgs boson $\rightarrow \tau\nu$ 13 TeV

CMS-PAS-HIG-16-031

- Production mechanisms depend on Higgs mass




$m_H^{\pm} < m_t$



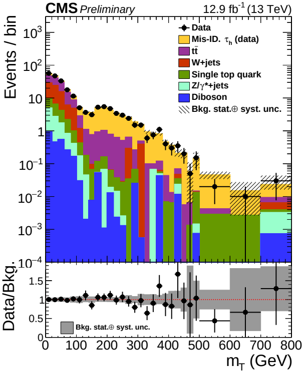

$m_H^{\pm} > m_t$

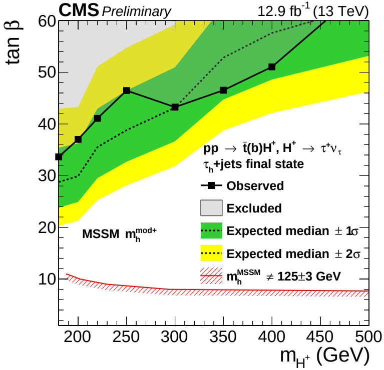
**Select events with**

- One tau lepton ($p_\mathrm{T} > 50\,\mathrm{GeV}$)
- Missing transverse energy ($\not{E}_\mathrm{T} > 90\,\mathrm{GeV}$)
- At least three jets (in tracker-covered region: one b-tagged jet)
- No back-to-back topology between MET and tau lepton

CMS-PAS-HIG-16-031

**Final observable: Transverse mass between $\not{E}_T$ and tau lepton**



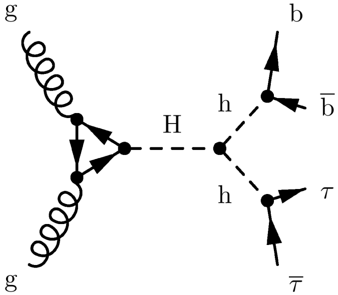




→ Exclusions up to $m_{H^\pm} \approx 450\,\text{GeV}$ in the $m_h^{\text{mod}+}$ scenario

→ Model independent limits on $\sigma \cdot BR$ up to $\approx 2\,\text{pb}$ for $m_{H^\pm} = 180\,\text{GeV}$

# Search for resonant Higgs pair production $\rightarrow \tau\tau bb$ 13 TeV

CMS-PAS-HIG-17-002




- Resonant pair production of SM Higgs bosons possible in many BSM models (including MSSM)
- Many possible final states (today: $H \rightarrow hh \rightarrow \tau\overline{\tau}b\overline{b}$)

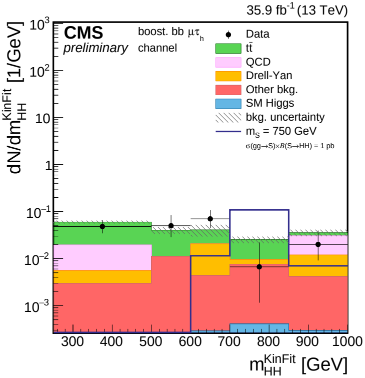
**Peculiarities:**

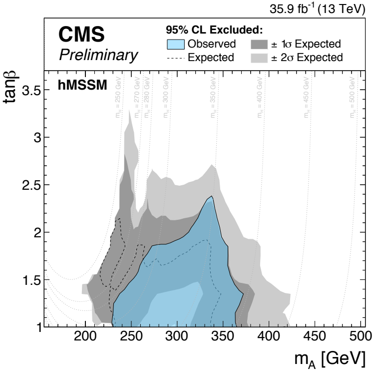
- For $m_H > 700$ GeV the two b-jets overlap
  - $\rightarrow$ Reconstructed as one large-cone jet + 2 small-cone jets
  - $\rightarrow$ Clear separation from $t\overline{t}$ events possible
  - $\rightarrow$ "Boosted" category
- Mass reconstruction of $m_{\tau\overline{\tau}}$, $m_{b\overline{b}}$ and $m_{hh}$

# Search for resonant Higgs pair production $\rightarrow \tau\tau bb$ 13 TeV

CMS-PAS-HIG-17-002

- Mass reconstruction of $m_{hh}$ with kinematic fit




$\rightarrow$ Exclusions between $m_A \approx 230\,\text{GeV} - 370\,\text{GeV}$ in the hMSSM

$\rightarrow$ Model independent limits on $\sigma \cdot BR$ up to 600 fb for $m_H \approx 270\,\text{GeV}$

# Conclusion

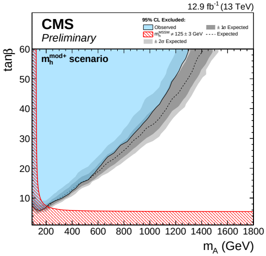
## SM:

- First VBF $H \to b\bar{b}$ search at 13 TeV at CMS
- Together with 8 TeV search compatible with SM expectations
- $VH \to b\bar{b}$ result will follow

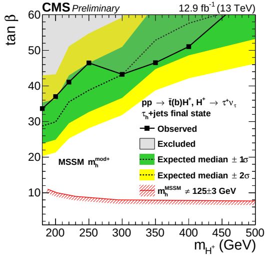
## Beyond the SM:

- No discovery of new particles
- Significant sensitivity increases in the $m_A - \tan\beta$ plane

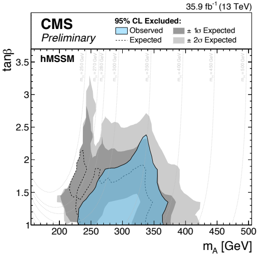
$H \to \tau\tau$




$H^{\pm} \to \tau\nu$




$H \to hh \to \tau\tau bb$



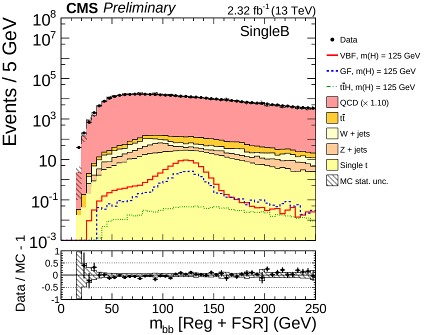
# Thank you

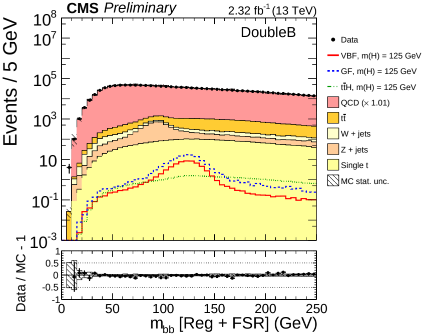
# Backup

# VBF $H \to b\bar{b}$: Event selection

| | SingleB | DoubleB |
|---|---|---|
| Trigger | one b-tagged jet | two b-tagged jets |
| jets $p_T$ | $p_T^{1,2,3,4} > 92, 76, 64, 30$ GeV | |
| jets $\|\eta\|$ | <4.7 | |
| b tag | no cut | two jets with CSV>0.5 |
| $\Delta\phi_{bb}$ | <1.6 radians | <2.4 radians |
| VBF topology | $m_{qq} > 460$ GeV<br>$\|\Delta\eta_{qq}\| > 4.1$ | $m_{qq} > 200$ GeV<br>$\|\Delta\eta_{qq}\| > 1.2$ |
| Veto | None | Events that belong to SingleB |

# VBF $H \to b\bar{b}$: Invariant mass of the two b-jets



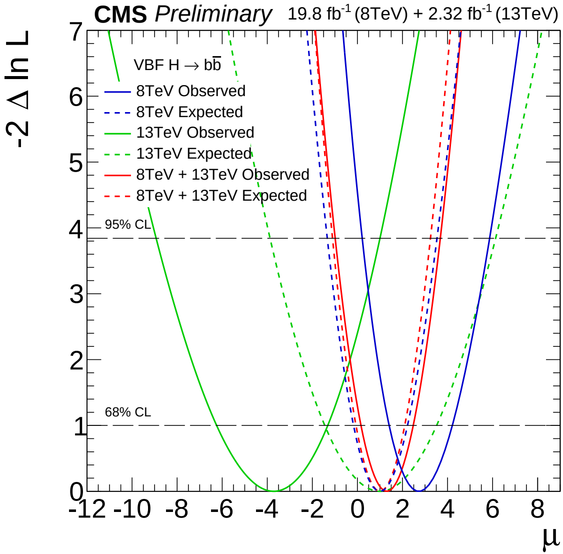
# VBF $H \to b\bar{b}$: Categories

| BDT boundary values | SingleB | | | | DoubleB | | |
|---|---|---|---|---|---|---|---|
| | Cat. 1 | Cat. 2 | Cat. 3 | Cat. 4 | Cat. 5 | Cat. 6 | Cat. 7 |
| | 0.28 – 0.72 | 0.72 – 0.87 | 0.87 – 0.93 | 0.93 – 1.0 | 0.36 – 0.76 | 0.76 – 0.89 | 0.89 – 1.0 |
| Data | 25298 | 5834 | 1281 | 302 | 69963 | 9831 | 1462 |
| Z +jets | 49± 4 | 12.5± 2.0 | 4.1± 1.1 | 1.7± 0.7 | 448± 11 | 50± 4 | 8.4± 1.7 |
| W +jets | 25.8± 3.5 | 1.6± 0.9 | 0.1± 0.1 | <0.1 | 74± 6 | 4.6± 1.3 | 0.9± 0.6 |
| $t\bar{t}$ | 53± 1 | 5.1± 0.2 | 0.7± 0.1 | 0.2± 0.04 | 534± 2 | 22.6± 0.4 | 1.1± 0.1 |
| Single t | 52± 1 | 9.7± 0.5 | 1.8± 0.2 | 0.4± 0.1 | 221± 3 | 23.2± 0.8 | 1.8± 0.2 |
| VBF $m_{\mathrm{H}}(125)$ | 19.5± 0.2 | 13.7± 0.1 | 7.2± 0.1 | 4.2± 0.1 | 21.7± 0.2 | 10.5± 0.1 | 3.8± 0.1 |
| GF $m_{\mathrm{H}}(125)$ | 5.5± 0.2 | 1.8± 0.1 | 0.6± 0.07 | 0.2± 0.04 | 18.7± 0.4 | 3.1± 0.1 | 0.6± 0.07 |

# VBF $H \to b\bar{b}$: Systematic uncertainties

| Background uncertainties | | |
|---|---|---|
| QCD shape parameters | determined by the fit | |
| QCD bkg. normalization | determined by the fit | |
| Top quark bkg. normalization | 30% | |
| Z/W+jets bkg. normalization | 30% | |
| **Uncertainties affecting the signal** | **VBF signal** | **GF signal** |
| JES (signal shape) | 2% | |
| JER (signal shape) | 2% | |
| Integrated luminosity | 2.7% | |
| Branching fraction ($H \to b\bar{b}$) | 1.3% | |
| JES (acceptance) | 1–4% | 2–11% |
| JER (acceptance) | 1–2% | 1–3% |
| b-jet tagging | 3–9% | 2–10% |
| Trigger | 8–15% | 6–11% |
| **Theory uncertainties** | **VBF signal** | **GF signal** |
| UE & PS | 2–7% | 10–45% |
| Scale variation (global) | 0.4% | 8% |
| Scale variation (categories) | 1% | 15% |
| PDF (global) | 2% | 3% |
| PDF (categories) | 1–2% | 1–2% |

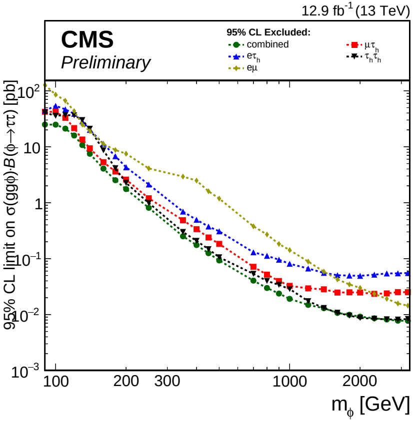
# VBF $H \to b\bar{b}$: Fitted signal strength



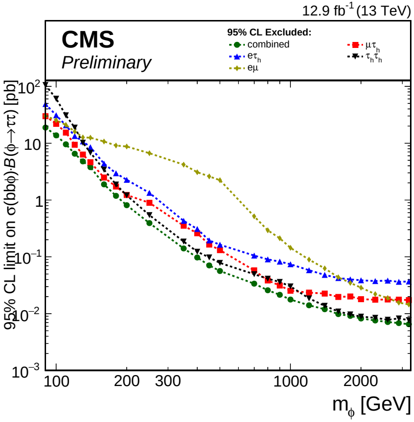
# Search for $H \to \tau\tau$: Lepton selections in the four channels

| | $\mu\tau_\mathrm{h}$ | $\mathrm{e}\tau_\mathrm{h}$ | $\tau_\mathrm{h}\tau_\mathrm{h}$ | $\mathrm{e}\mu$ |
|---|---|---|---|---|
| Trigger (threshold in GeV) | $\mu(22)$ | $\mathrm{e}(25)$ | $\tau_h(35)$ & $\tau_h(35)$ | $\mu(8)$ & $\mathrm{e}(23)$ or $\mu(23)$ & $\mathrm{e}(12)$ |
| Offline selection | $p_\mathrm{T}^\mu > 23$ GeV, $\lvert\eta^\mu\rvert < 2.1$ $p_\mathrm{T}^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$ | $p_\mathrm{T}^\mathrm{e} > 26$ GeV, $\lvert\eta^\mathrm{e}\rvert < 2.1$ $p_\mathrm{T}^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$ | $p_\mathrm{T}^{\tau_h} > 40$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.1$ $p_\mathrm{T}^{\tau_h} > 40$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.1$ | $p_\mathrm{T}^\mu > 10(24)$ GeV, $\lvert\eta^\mu\rvert < 2.4$ $p_\mathrm{T}^\mathrm{e} > 13(24)$ GeV, $\lvert\eta^\mathrm{e}\rvert < 2.5$ |
| Additional ID | Medium ID - | MVA ID 80% - | - - | Medium ID MVA ID 80% |
| Isolation | $I_\mu^{rel} < 0.15$ MVA Medium | $I_\mathrm{e}^{rel} < 0.1$ MVA Medium | MVA Tight MVA Tight | $I_\mu^{rel} < 0.2$ $I_\mathrm{e}^{rel} < 0.15$ |
| Impact parameter (cm) | $d_{xy}^\mu < 0.045$ $d_z^\mu < 0.2$ $d_z^{\tau_h} < 0.2$ | $d_{xy}^\mathrm{e} < 0.045$ $d_z^\mathrm{e} < 0.2$ $d_z^{\tau_h} < 0.2$ | $d_z^{\tau_h} < 0.2$ $d_z^{\tau_h} < 0.2$ | $d_{xy}^{\mu/\mathrm{e}} < 0.045$ $d_z^{\mu/\mathrm{e}} < 0.2$ |
| Lepton vetoes | No loose $\mu^+\mu^-$ pair with $p_\mathrm{T}^\mu > 15$ GeV | No loose $\mathrm{e}^+\mathrm{e}^-$ pair with $p_\mathrm{T}^\mathrm{e} > 15$ GeV | | - |
| | No additional loose e with $p_\mathrm{T} > 10$ GeV and $\lvert\eta\rvert < 2.5$ No additional loose $\mu$ with $p_\mathrm{T} > 10$ GeV and $\lvert\eta\rvert < 2.4$ | | | |

# Search for $H \rightarrow \tau\tau$: Seperate limits for the four channels

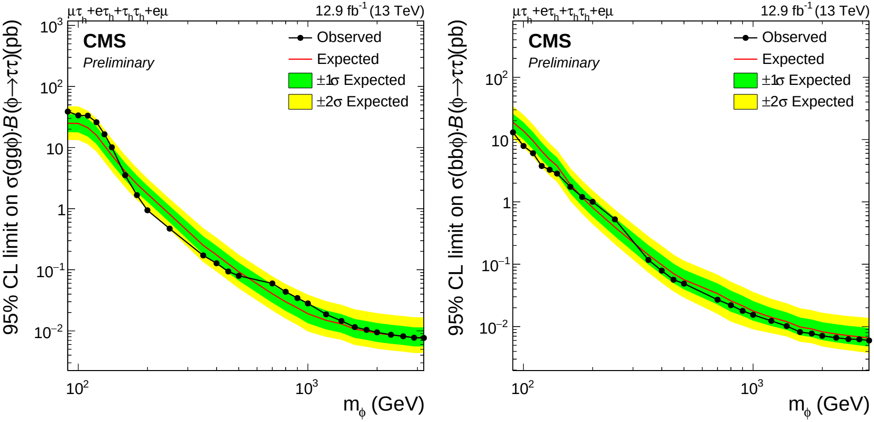



(a)



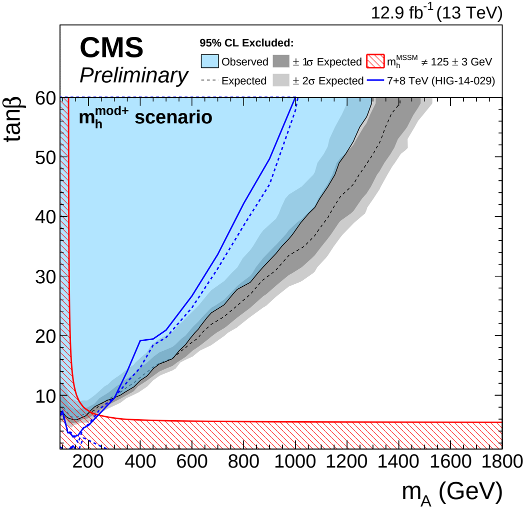

(b)

# Search for $H \to \tau\tau$: Limits in the two categories

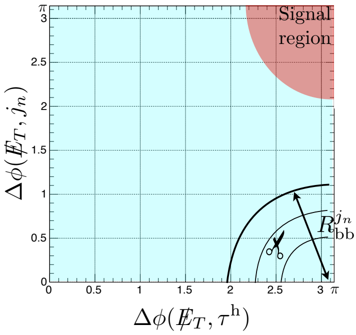


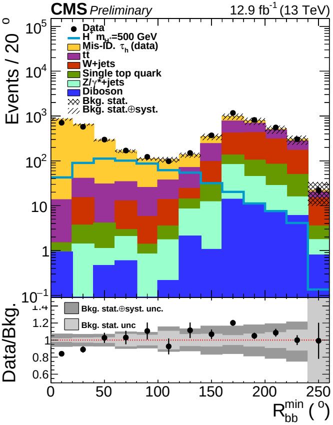

(a) (b)

# Search for $H \to \tau\tau$: Comparison to 8 TeV limit



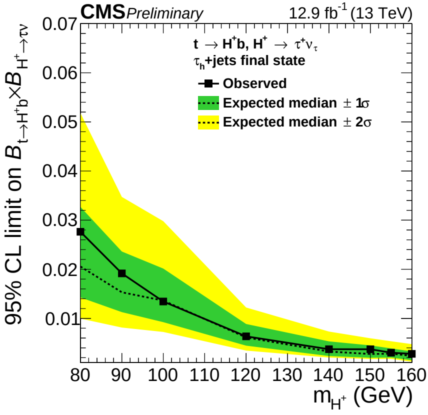
# Search for $H^{\pm} \to \tau\nu$: The angular variable $R_{bb}^{\min}$

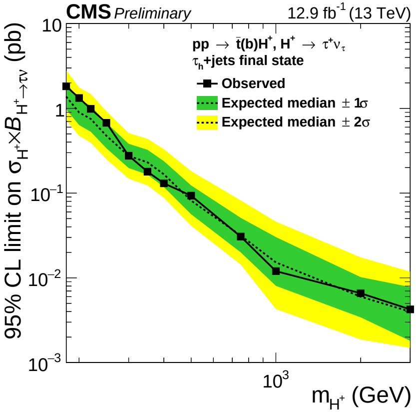


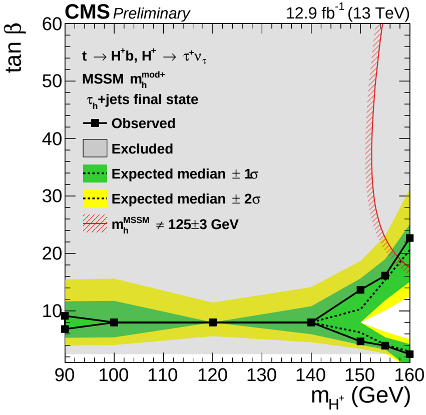

- $R_{bb}^{\min} = \min\sqrt{\Delta\phi\left(\not{E}_{\mathrm{T}}, j\right)^2 + \left(\pi - \Delta\phi\left(\tau^h, \not{E}_{\mathrm{T}}\right)\right)^2}$ for $j \in j_1..j_3$
- $R_{bb}^{\min} > 40^{\circ}$

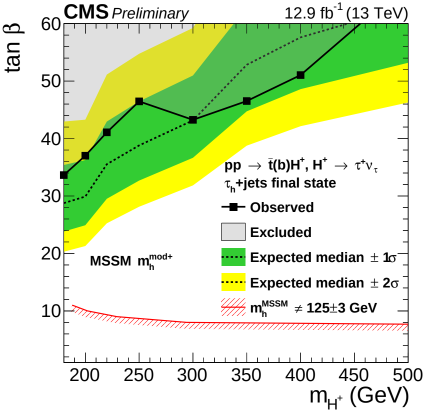
# Search for $H^\pm \to \tau\nu$: Limits on cross-section · BR



# Search for $H^{\pm} \to \tau\nu$: Exclusion limits



# Search for $H \to hh \to \tau\tau bb$: Systematic uncertainties

| Systematic | value | processes |
|---|---|---|
| Luminosity | 2.6% | all but multijet, $Z/\gamma^* \to \ell\ell$ |
| Lepton trigger and reconstruction | 2-6% | all but multijet |
| $\tau$ energy scale | 3-10% | all |
| Jet energy scale | 2-4% | all |
| b-tag efficiency | 2-6% | all |
| MC cross-section | 1-10% | all but multijet, $Z/\gamma^* \to \ell\ell$ |
| $Z/\gamma^* \to \ell\ell$ SF uncertainty | 0.1-2.5% | $Z/\gamma^* \to \ell\ell$ |
| multijet normalization | 5-30% | multijet |
| scale unc. | $+4/-6\%$ | signals |
| PDF variation | 3% | signals |

# Search for $H \to hh \to \tau\tau bb$: Limit on cross-section · BR