# Search for Fermionic Higgs Boson Decays in *pp* Collisions at ATLAS and CMS

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on behalf of ATLAS and CMS collaboration

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**Physics In Collision Conference – Beijing, China**

4th of September 2013

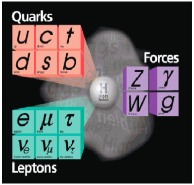
# The Higgs boson in a nutshell

**Fundamental interest :**

The Higgs boson is the relic particle of the Electroweak symmetry breaking :

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{\text{em}}$$

(Lagrangian symmetry) (Vacuum symmetry)



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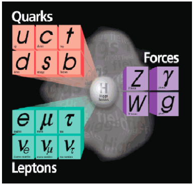


**Status of couplings between the Higgs boson and other fields ?**

- Direct observation of bosonic decays
- Direct evidence of fermionic decays
- Indirect observation of coupling to fermion (loop-induced production)

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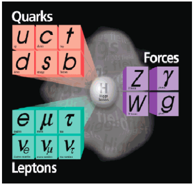


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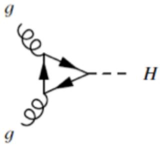
**Key role of direct fermionic coupling :**

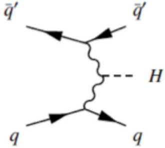
- Reduce experimental uncertainties on coupling & branching ratios
- Disantangle potential new physics from SM coupling in loops

## 1. Production of $H(125)$

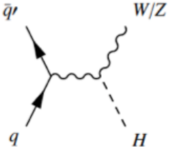
$\sigma_{tot}(H) = 22.1$ pb  $\sigma_{tot}(Z) \sim 10^4$ pb



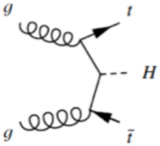

**GGF (88%)**
high rate but loops,
no specific topology




**VBF (6.6%)**
low rate but tree level,
**specific jet topology**




**VH (5%)**
low rate but **clean**
**final state** (leptons)




**ttH (0.4%)**
extremely low rate and
**busy final state**

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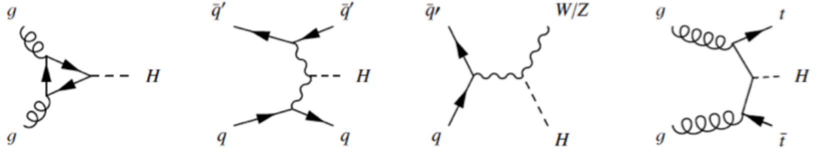


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low rate but **clean final state** (leptons)

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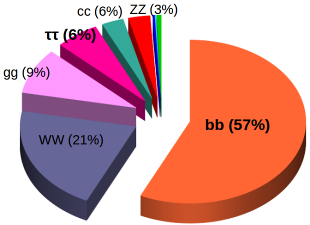
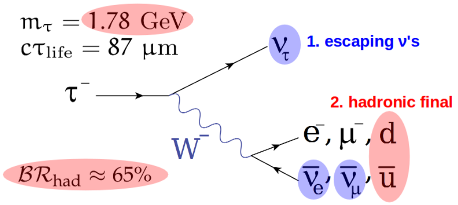
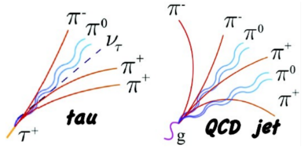
## 2. Decays of $H(125)$ (emphasis on fermionic decay)




- ***bb* decay** : largest BR, benefits from additional lepton to reduce $pp \to b\bar{b} + X$.
- **$\tau\tau$ decay** : lower BR, cleaner signature
- ***cc* decay** : impossible in hadron collider
- **$\mu\mu$ decay :** extremely low BR (0.02%), good mass resolution

# Key particles identification (1/2)

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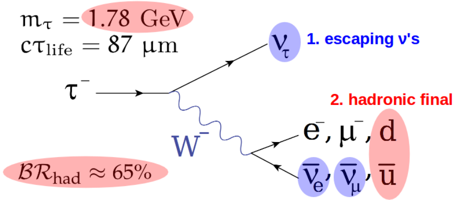


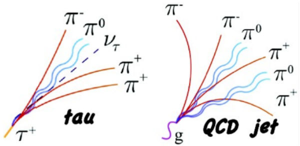


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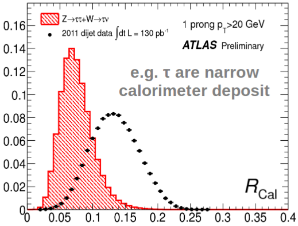
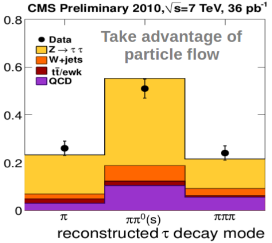
**ATLAS : ~7 observables combined in a BDT**




**CMS : based on hadronic substructure**

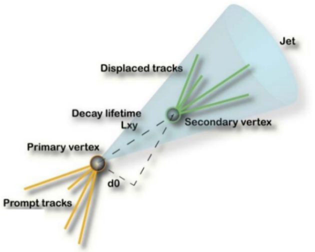



ATLAS & CMS

$\varepsilon_\tau \sim 50\%$

$\varepsilon_{jets} \sim 1\%$

# Key particles identification (2/2)




**Based on *b*-hadron properties :**

- $c\tau \sim$ few mm, higher mass
- Displaced vertex of high mass
- Semi-leptonic decay

Background : *c*-hadrons

**Algorithm :** multivariate techniques to exploit all these properties and their correlations ($\sim$ 5 input variables).

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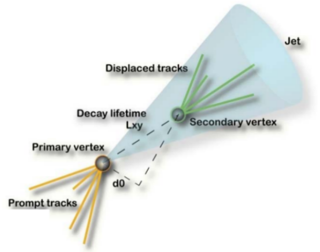


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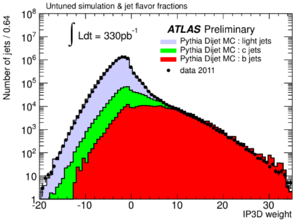
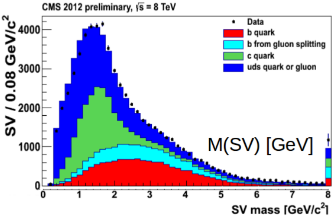
**e.g. IP related variable**




**e.g. secondary Vertex Mass**




ATLAS & CMS

$\varepsilon_{b\text{-quark}} \sim 70\%$

$\varepsilon_{c\text{-quark}} \sim 25\%$

$\varepsilon_{light} \sim 1\%$

# Overview

1. Search for $H \rightarrow bb$ decay
2. Search for $H \rightarrow \tau\tau$ decay
3. Search for $H \rightarrow \mu\mu$ decay
4. Dedicated searches for $ttH$ production

# ATLAS and CMS analyses overview

Analyzed integrated luminosity ($fb^{-1}$) of 7 and 8 TeV collisions

**$bb$ final state**

| | ATLAS | CMS |
|---|---|---|
| GGF | - | - |
| VBF | - | 19.0 |
| ***VH*** | 4.7+ 20.3 | 5.0 + 19.0 |
| ttH | 4.7 | 19.0 |

**$\tau\tau$ final state**

| | ATLAS | CMS |
|---|---|---|
| GGF, ***VBF*** | 4.9 + 13.0 | 4.9 + 19.4 |
| VH | - | 19.0 |
| ttH | - | 19.0 |

(***bold :*** most sensitive process, gray : impossible to extract from background)

+ inclusive search in the **$\mu\mu$ final state** in ATLAS (20.7)

## Documentation :

- ATLAS $H \to \tau\tau$ : GGF+VBF
- ATLAS $H \to bb$ : VH, ttH
- ATLAS $H \to \mu\mu$ : inclusive
- CMS $H \to \tau\tau$ : GGF+VBF, VH
- CMS $H \to bb$ : VH, VBF
- CMS ttH : $\tau\tau$ and $bb$

# Overview

1. **Search for $H \to bb$ decay**
2. Search for $H \to \tau\tau$ decay
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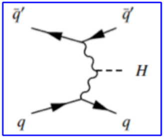
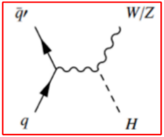
# Search for $H \rightarrow bb$

**Which production mode for $bb$ final state ?**

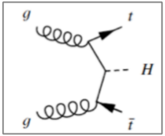
All but gluon fusion
$\sigma_{\text{tot}}(b\bar{b}) \sim 10^7$ pb




*qqbb* final state
**high bkg rate**




W/Z signature
**most sensitive**




dedicated search, **see later**

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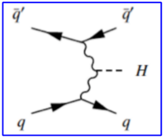


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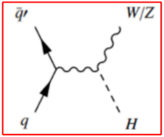


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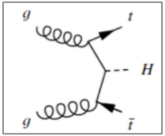


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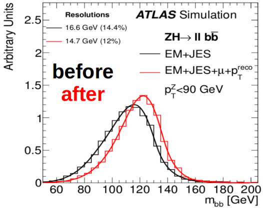
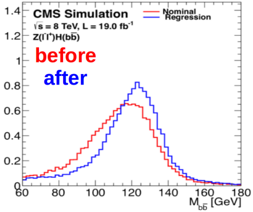
**Relevant observable : $m_{bb}$**

*ATLAS : method based on Jet level correction*




*CMS : method based on Multivariate Regression*




Refined energy scale and resolution for $b$-jets

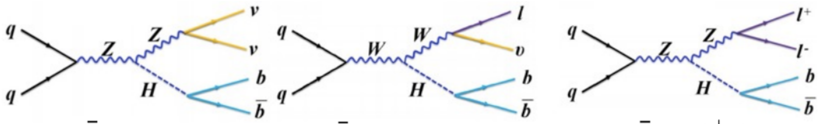
- jet kinematics
- soft lepton properties
- ...

Improvement : $\sim 10 - 15\%$

References : ATLAS-CONF-2013-079, CMS PAS HIG-13-012, CMS PAS HIG-13-011

# VH production

**1. Analysis strategy :** number of leptons $\equiv$ vector boson decay




$b\bar{b} + \not{E}_T$ $\quad$ $b\bar{b} + \ell + \not{E}_T$ $\quad$ $b\bar{b} + \ell^+\ell^-$

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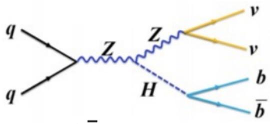


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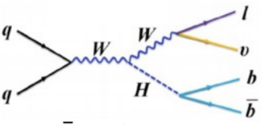


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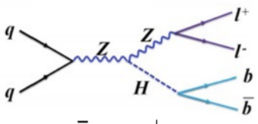


$b\bar{b} + \ell^+\ell^-$

**2. Standard Model backgrounds :**

- top quark production
- $W/Z + bb$ production - same final state as signal
- $W/Z + u/d/s/c$ (fake $b$-jet)
- Multijets production (fake/non isolated lepton and $b$-jet)

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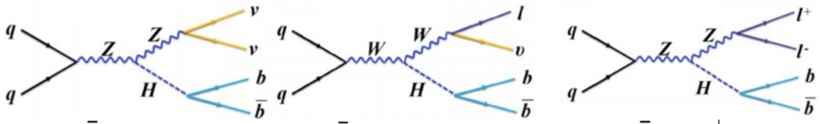


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**3. Main kinematic handles :**

- $m_{bb}$ reconstruction (look for a bump in $m_{bb}$ distribution)
- Transverse momentum of vector boson (higher $S/\sqrt{B}$ at high $p_T^V$)

# Controlling the background

**General approach :** global fit of data over several categories of different background composition ($n_\ell$, $p_T^V$, $n_{\mathrm{b}-jets}$)

- background normalization & shape
- account for signal contamination
- include systematics uncertainties (b-tagging, Jet Energy Scale, ...)

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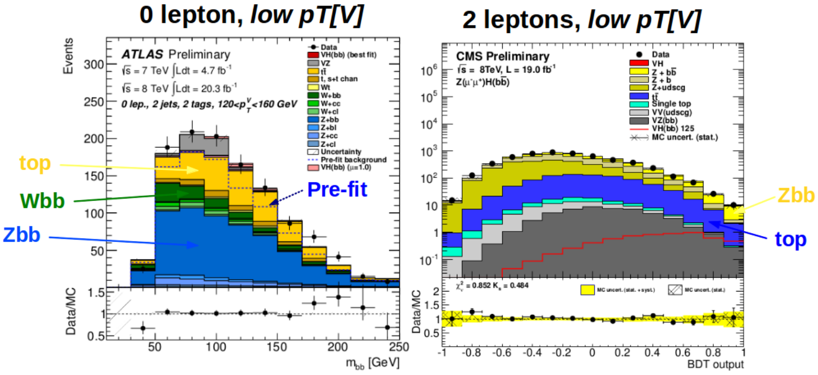

# Signal extraction

**Strategy :** exploit topology differences between signal and background

- Properties of $(b, \bar{b})$ system (mass, angle, color connection, ...)
- Direction of $\not{E}_T$ relative to $(b, \bar{b})$ system
- Consistency of $(\not{E}_T, \ell)$ system as coming from $W$ decay
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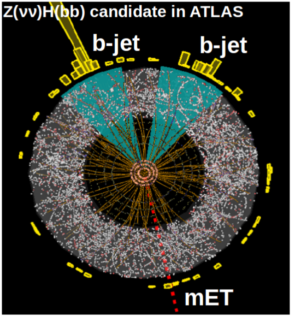
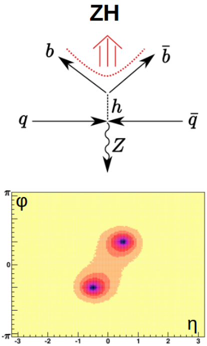
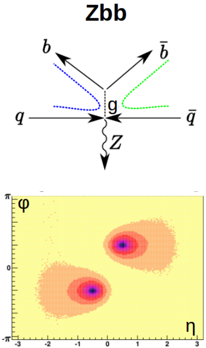
$\Delta\phi(\not{E}_{\mathrm{T}}, bb) \sim \pi$



# Method validation

All these technics can be applied to extract $VZ(\to bb)$ production (very similar signature), as a validation of the experimental method.

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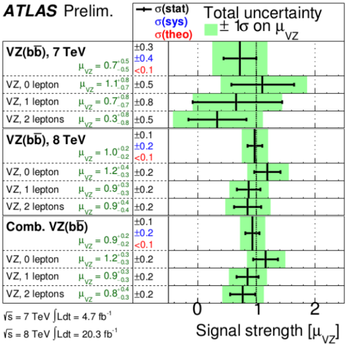
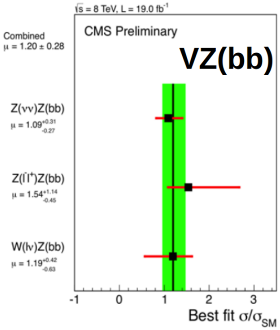
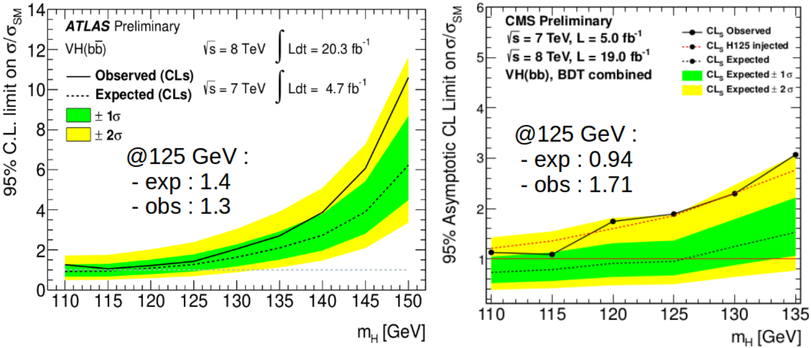


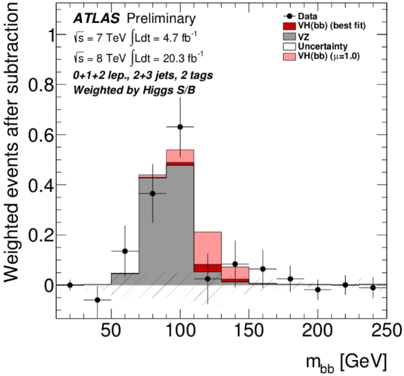



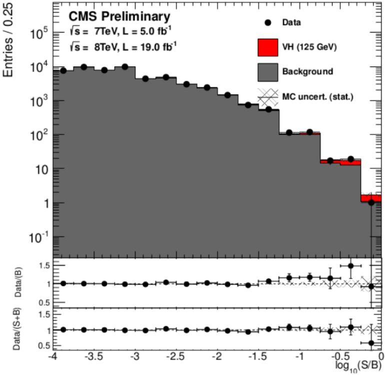

Both experiments **measure VZ(bb) at the expected rate**

# Results of $VH(bb)$ search (1/3)

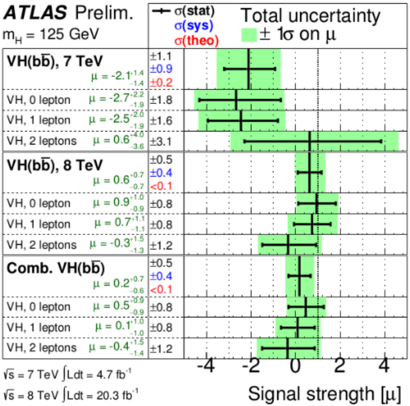


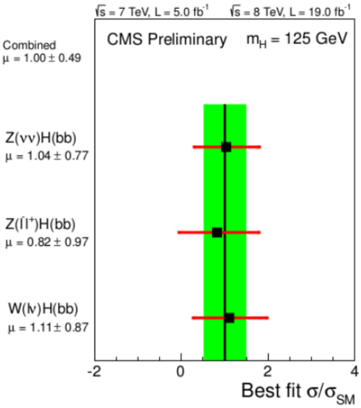
# Results of $VH(bb)$ search (2/3)



# Results of $VH(bb)$ search (3/3)



# Vector boson fusion production

**1. Analysis strategy :** look at *qqbb* final state

- Dedicated 4jets triggers exploiting VBF topology (high $\Delta\eta_{jj}$)
- Select 2 forward jets with high $m_{jj}$ also specific to the VBF production
- Apply b-tagging criteria for the non forward jets
- Discrimination of quark/gluon jets (different fragmenation)

**2. Main background :** QCD production of 4 jets events

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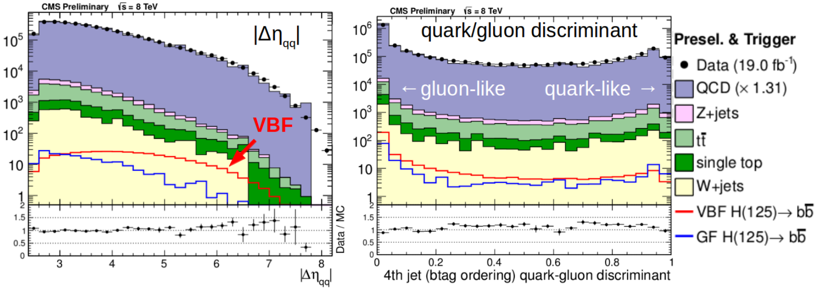
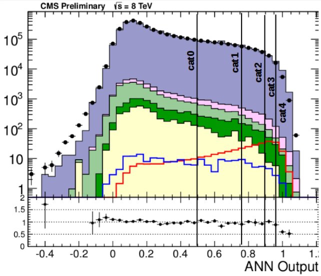


**Signal extraction :**

Categories based in BDT (VBF tagging jets, b-tagging)
Then look at $m_{bb}$ distribution.
Combine categories.



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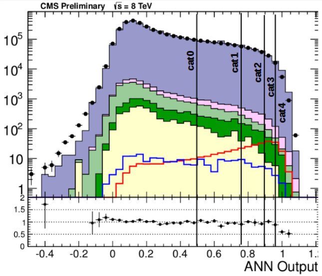
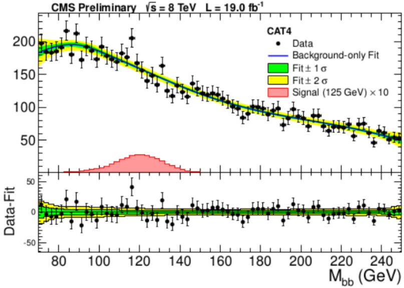
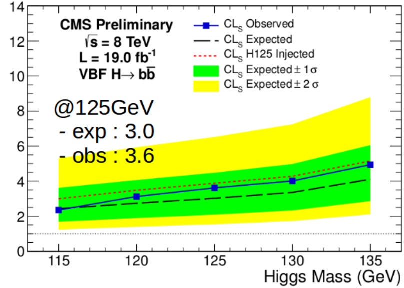



## $m_{bb}$ distribution and result :



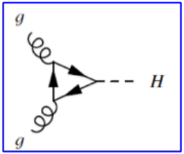



# Overview

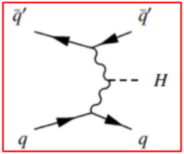
1. Search for $H \to bb$ decay
2. **Search for $H \to \tau\tau$ decay**
3. Search for $H \to \mu\mu$ decay
4. Dedicated searches for $ttH$ production

# Search for $H \to \tau\tau$

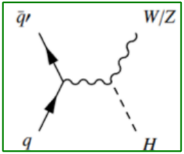
**Which production mode ?** All of them are exploited



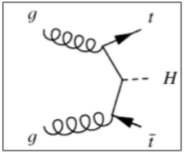

mostly sensitive for
**high $p_T(\tau,\tau)$**




tagging jets
**most sensitive**



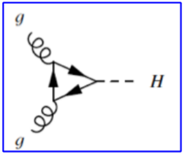

lower rate, **less sensitive**




dedicated search, **see later**

# Search for $H \to \tau\tau$

**Which production mode ?** All of them are exploited

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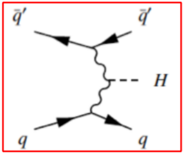


tagging jets
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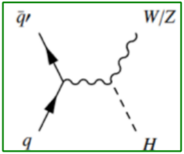


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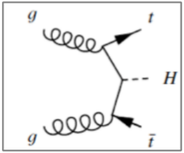
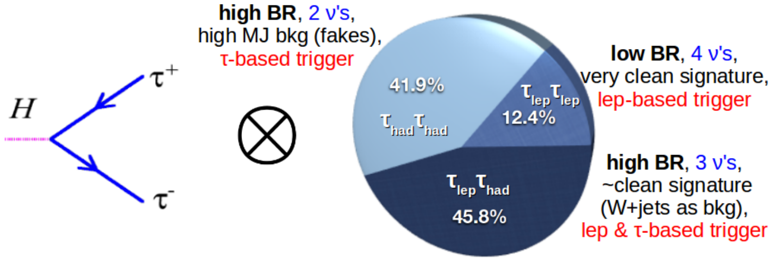


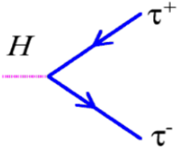

dedicated search, **see later**

**Experimental challenges for $H \to \tau\tau$ :**

- Decay of $\tau$ pair into stable particles leads to 3 different final states
- Reconstruction of $(\tau, \tau)$ invariant mass (escaping neutrinos)
- Energy scale determination of hadronic $\tau$ decays (and its uncertainty)

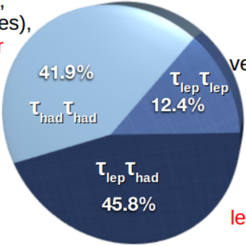
**References :** ATLAS-CONF-2012-160
CMS PAS HIG-13-004, CMS PAS HIG-12-053


H
τ+
τ-
high BR, 2 ν's,
high MJ bkg (fakes),
τ-based trigger
41.9%
τhad τhad
τlep τlep
12.4%
τlep τhad
45.8%
low BR, 4 ν's,
very clean signature,
lep-based trigger
high BR, 3 ν's,
~clean signature
(W+jets as bkg),
lep & τ-based trigger




$\otimes$

**high BR**, 2 ν's,
high MJ bkg (fakes),
τ-based trigger

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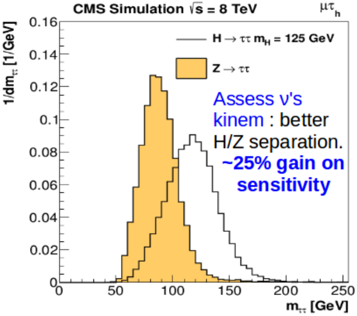
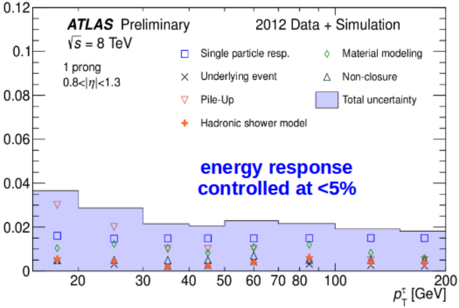
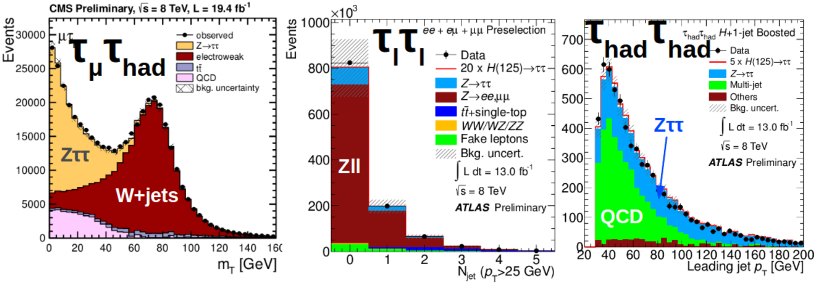
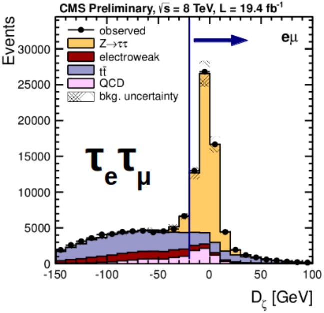


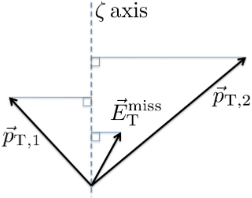






## Common strategy :

- Search for a bump in $m_{\tau\tau}$ on top of dominant background : $Z \to \tau\tau$
- Data-driven estimation of $Z \to \tau\tau$ : use $Z \to \mu\mu$ data events with $\mu$ pair replaced by simulated $\tau$ pair (non $\tau$ quantities are *data*).
- Exploit VBF via di-jet topology (high $\Delta\eta_{jj}$, high $m_{jj}$)
- Exploit GGF at high $(\tau, \tau)$ boost : better RMS($\not{E}_T$) $\to$ better RMS($m_{\tau\tau}$)
- Reduce and understand the fake $\tau$s (see next slide)

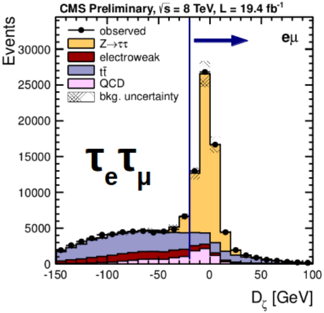


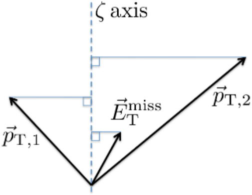




$$D_\zeta \equiv \not{p}_\zeta - 0.85 \cdot p_\zeta^{vis}$$

Reduces contribution from
* **Top** bkg (true leptons)
* **W+jets** bkg (fake lepton)
(used in CMS)

ATLAS uses same kinematic properties slightly differently

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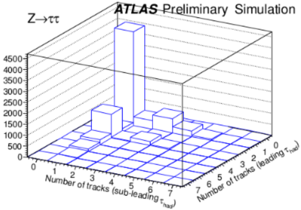
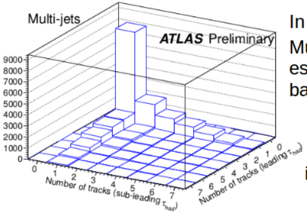
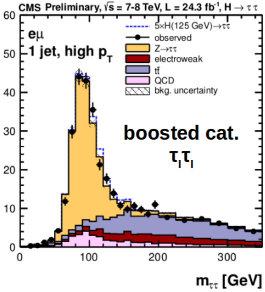


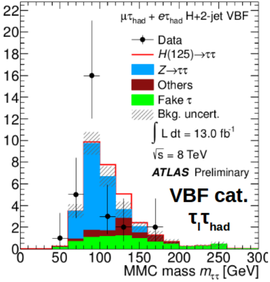



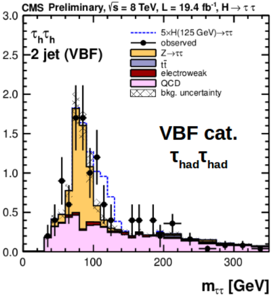

In $\tau_{had}\tau_{had}$ channel : Multi-jets contribution estimated via a fit on data based on 2D templates (used in ATLAS)

CMS uses an anti-isolated τ to estimated this background

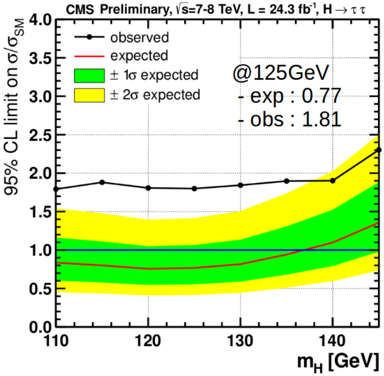
# $m_{\tau\tau}$ distribution

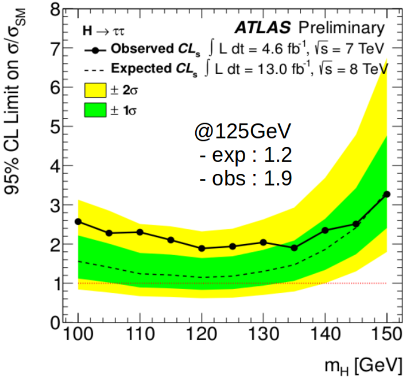


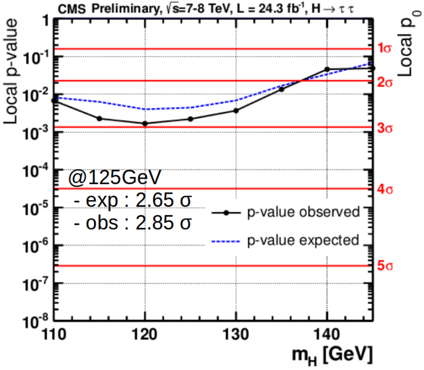



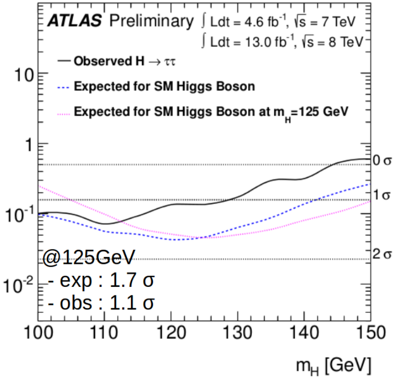
# Results : exclusion limit

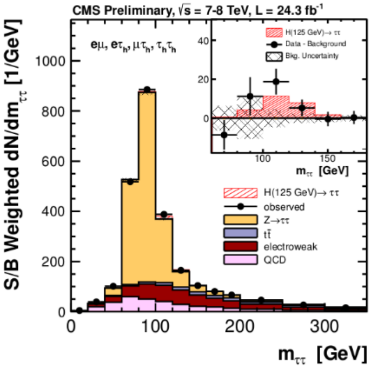


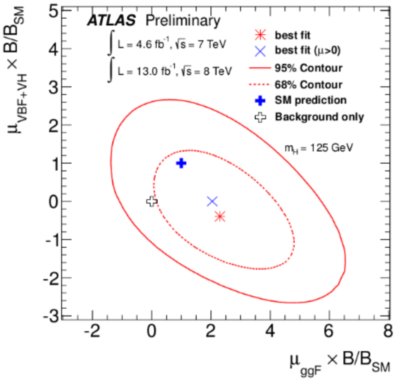



# Results : compatibility with background only



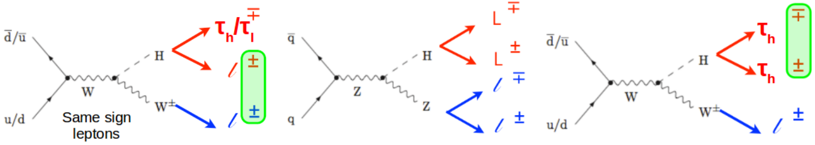


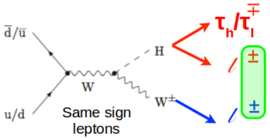

## Some highlights :

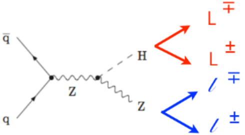
- 2.85 $\sigma$ excess for CMS, compatible with $H \to \tau\tau$ SM process
- ATLAS needs to add remaining 8 TeV data
- CMS $bb + \tau\tau$ combination leads to 3.4 $\sigma$ excess fermionic decay
- **Start to probe Higgs field properties in fermionic final state**

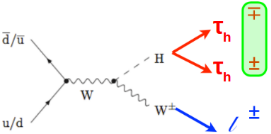
# Associated production *VH*

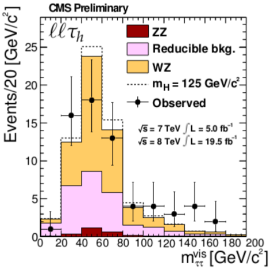


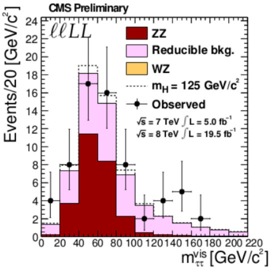
# Associated production *VH*

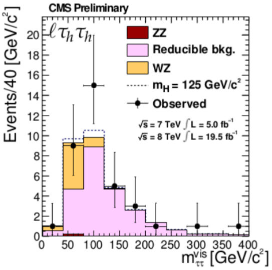


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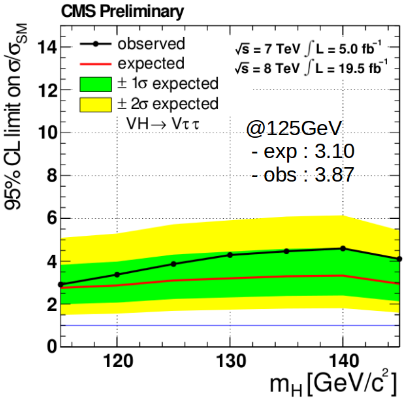


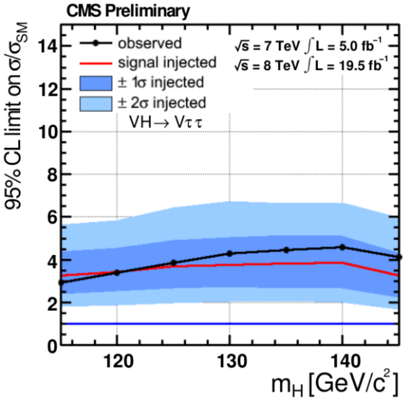

# Overview

# $H \rightarrow \mu\mu$ : motivations, challenges, strategy

### 1. Motivations :

- Directly sensitive to $g_{H\mu\mu}$,
- $\mathcal{BR}_{H\rightarrow\mu\mu} \sim 2.2 \,.\, 10^{-4}$ : small but enhanced in some BSM scenarios,
- Clear signature : bump in $M_{\mu\mu}$ distribution.

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**2. Challenges :**

- Important background : $Z \to \mu\mu$ with $s/\sqrt{b} \sim 0.26$ (for 20 fb$^{-1}$),
- Key instrumental feature : $M_{\mu\mu}$ resolution.

# $H \to \mu\mu$ : motivations, challenges, strategy

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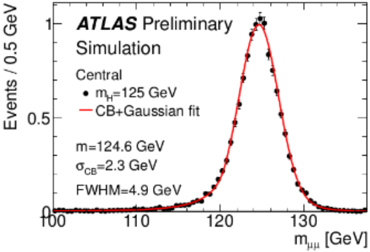
## 2. Challenges :

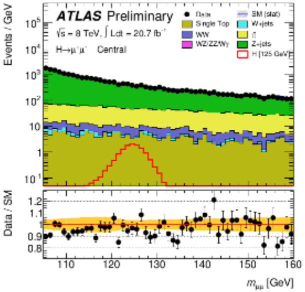
- Important background : $Z \to \mu\mu$ with $s/\sqrt{b} \sim 0.26$ (for 20 $\text{fb}^{-1}$),
- Key instrumental feature : $M_{\mu\mu}$ resolution.

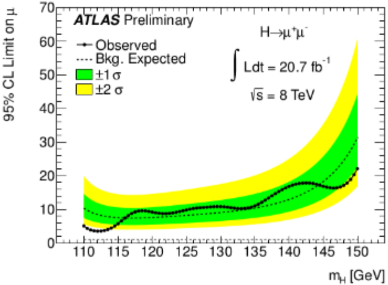
## 3. Strategy :

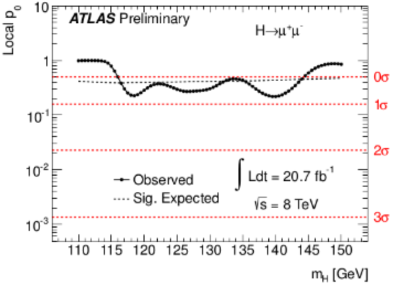
- Look for a bump between $110 - 150$ GeV $M_{\mu\mu}$
- Split events in 2 categories based on $M_{\mu\mu}$ resolution,
- Bkg/signal modelling : analytical shapes (fit in MC), unbinned fit

**References :** ATLAS-CONF-2013-010


ATLAS Preliminary
Simulation
Central
m_H=125 GeV
CB+Gaussian fit
m=124.6 GeV
σ_CB=2.3 GeV
FWHM=4.9 GeV
Events / 0.5 GeV
m_μμ [GeV]


ATLAS Preliminary
H→μ⁺μ⁻ Central
Single Top
WW
Z+jets
Events / GeV
Data / SM
m_μμ [GeV]


ATLAS Preliminary
Observed
Bkg. Expected
±1 σ
±2 σ
H→μ⁺μ⁻
∫ Ldt = 20.7 fb⁻¹
√s = 8 TeV
95% CL Limit on μ
m_H [GeV]


ATLAS Preliminary
H→μ⁺μ⁻
Observed
Sig. Expected
∫ Ldt = 20.7 fb⁻¹
√s = 8 TeV
0σ
1σ
2σ
3σ
Local p₀
m_H [GeV]

# Overview

1. Search for $H \to bb$ decay
2. Search for $H \to \tau\tau$ decay
3. Search for $H \to \mu\mu$ decay
4. **Dedicated searches for *ttH* production**

**Direct access to couplings between Higgs and top quark field :**

- Test proportionality between mass and couplings
- Higgs field properties at higher mass scale - new physics might appear
- Constrain potential new physics appearing in loops

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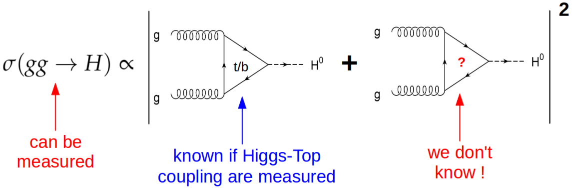

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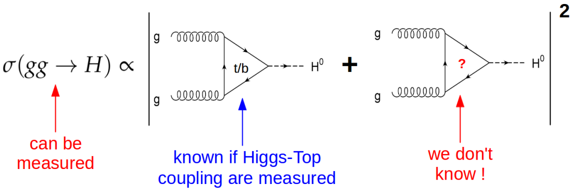
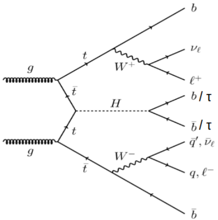



## Extremely challenging :

- Low production rate : 0.4% of $\sigma_{\text{tot}}(H)$.
- Complex final state : leptons, 4 $b$-jets (combinatorics), $\not{E}_T$, potentially $\tau$s
- Large background systematics ($t\bar{t}$ + $b$-jets, $t\bar{t} + V$).




**References :** ATLAS-CONF-2012-135, CMS PAS HIG-13-019

**Strategy adopted by ATLAS :**

- Focus on $H \to bb$ decay and $t\bar{t}$ semi-leptonic decay
- *Not presented* : $ttH(\to \gamma\gamma)$
- Kinematic reconstruction and $b$-jets pairing : global fit event-by-event

**Common to ATLAS & CMS :** fit data in several categories to reduce systematics on $t\bar{t} + b$-jets / $t\bar{t} + V$ backgrounds

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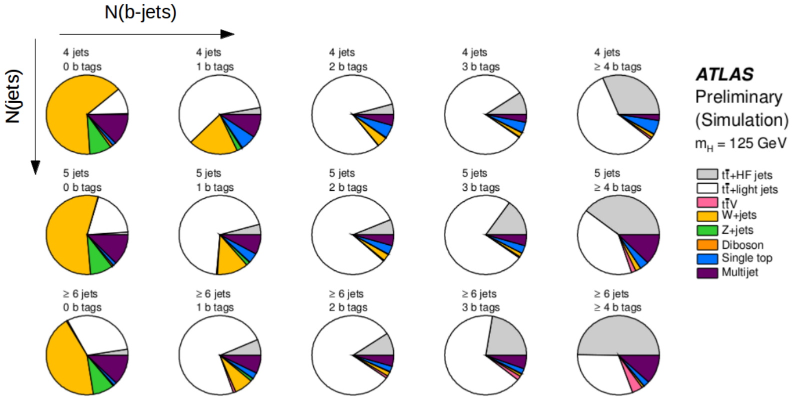
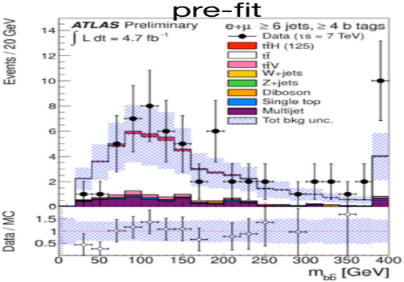
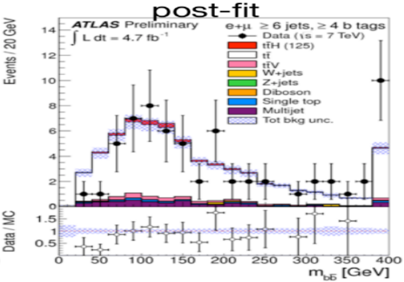
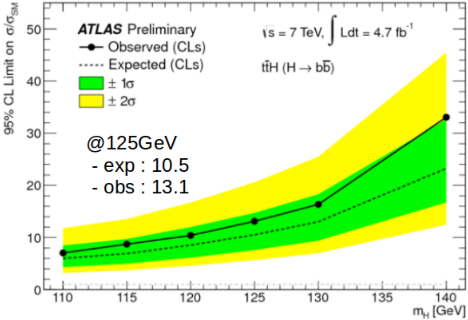



pre-fit
ATLAS Preliminary
∫ L dt = 4.7 fb⁻¹
e+μ ≥ 6 jets, ≥ 4 b tags
Data (√s = 7 TeV)
tt̄H (125)
tt̄
tt̄V
W+jets
Z+jets
Diboson
Single top
Multijet
Tot bkg unc.
Events / 20 GeV
Data / MC
m_bb̄ [GeV]


post-fit
ATLAS Preliminary
∫ L dt = 4.7 fb⁻¹
e+μ ≥ 6 jets, ≥ 4 b tags
Data (√s = 7 TeV)
tt̄H (125)
tt̄
tt̄V
W+jets
Z+jets
Diboson
Single top
Multijet
Tot bkg unc.
Events / 20 GeV
Data / MC
m_bb̄ [GeV]

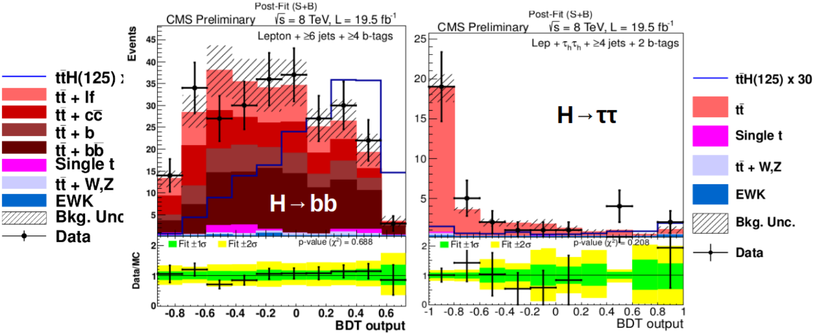

ATLAS Preliminary
Observed (CLs)
Expected (CLs)
± 1σ
± 2σ
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
tt̄H (H → bb̄)
@125GeV
- exp : 10.5
- obs : 13.1
95% CL Limit on σ/σ_SM
m_H [GeV]

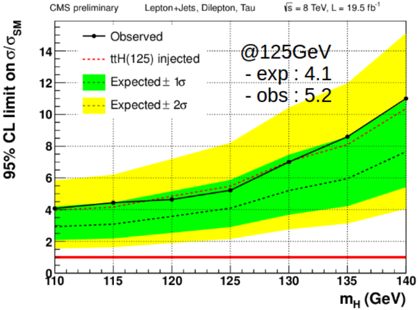
## Strategy adopted by CMS :

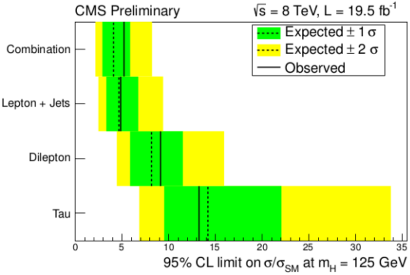
- Exploit $H \to bb$ and $H \to \tau\tau$ decays. Not presented : $ttH(\to \gamma\gamma)$.
- Make advantage of semi-leptonic and di-leptonic decays of $t\bar{t}$ system
- Combine b-tagging, $\tau$ID, $b$-jet pairing in a BDT for bkg/sig separation
- *Not presented* : $ttH(\to \gamma\gamma)$ and its full combination with $ttH(\to bb/\tau\tau)$

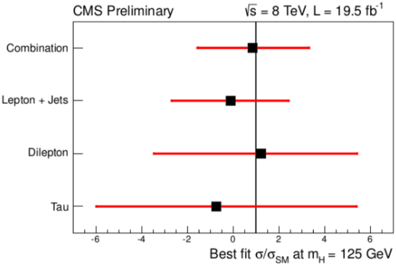
## Strategy adopted by CMS :

- Exploit $H \to bb$ and $H \to \tau\tau$ decays. Not presented : $ttH(\to \gamma\gamma)$.
- Make advantage of semi-leptonic and di-leptonic decays of $t\bar{t}$ system
- Combine b-tagging, $\tau$ID, $b$-jet pairing in a BDT for bkg/sig separation
- *Not presented* : $ttH(\to \gamma\gamma)$ and its full combination with $ttH(\to bb/\tau\tau)$




CMS preliminary
Lepton+Jets, Dilepton, Tau
√s = 8 TeV, L = 19.5 fb-1
Observed
ttH(125) injected
Expected ± 1σ
Expected ± 2σ
@125GeV
- exp : 4.1
- obs : 5.2
95% CL limit on σ/σSM
mH (GeV)


CMS Preliminary
√s = 8 TeV, L = 19.5 fb-1
Expected ± 1 σ
Expected ± 2 σ
Observed
Combination
Lepton + Jets
Dilepton
Tau
95% CL limit on σ/σSM at mH = 125 GeV


CMS Preliminary
√s = 8 TeV, L = 19.5 fb-1
Combination
Lepton + Jets
Dilepton
Tau
Best fit σ/σSM at mH = 125 GeV

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- Golden channels : VH($\rightarrow bb$) & GGF/VBF H$\rightarrow \tau\tau$
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**Essential step torward new physics discovery :**

- *ttH* and GGF offer a unique way of probing new physics in Higgs sector
- Sensitivty to $\mathcal{BR}(H \rightarrow \text{inv})$ is dominated by $\Gamma(H \rightarrow bb)$ uncertainty