Evidence for the decay of the SM Higgs Boson to Fermions

A presentation of Steffen Landgraf

Advised by Prof. Dr. M. Schumacher

University of Freiburg

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Talk outline

- Introduction
- The Higgs Boson production and decay modes
- The ATLAS search of the Higgs boson decaying to a pair of bottom quarks
- CMS results on H → b bbar
- The ATLAS search on the Higgs decay to a pair of Tau leptons
- CMS results on H → Tau+Tau-
- Summary

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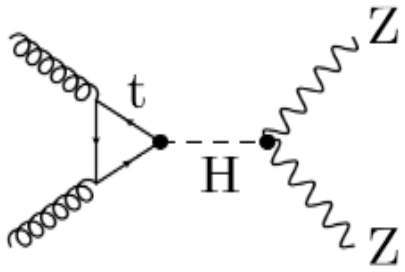
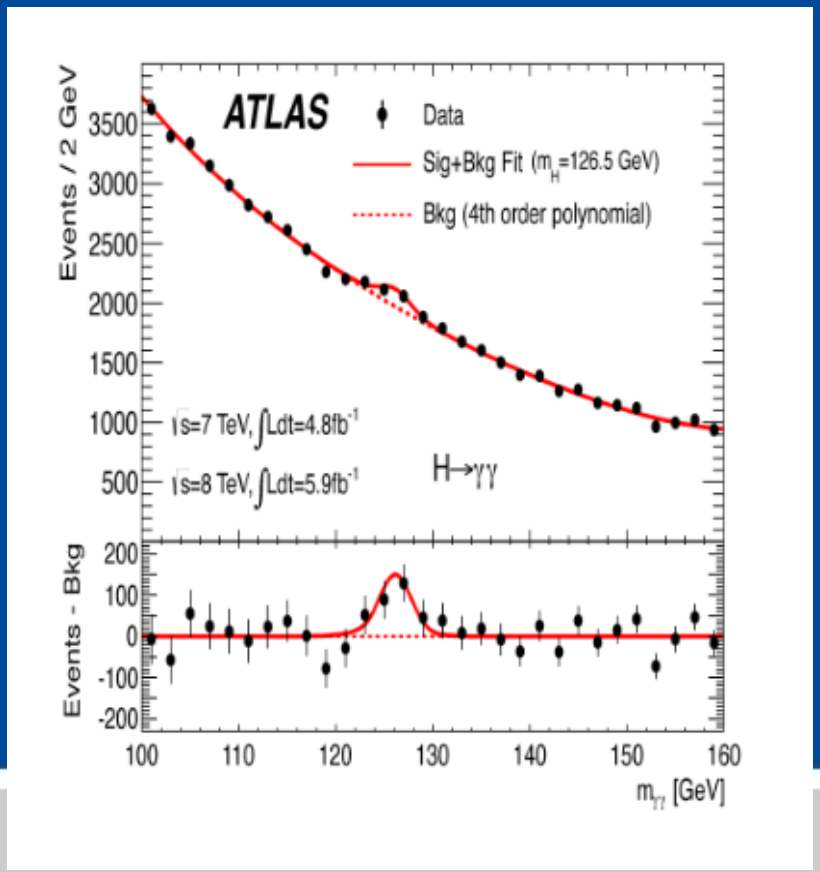
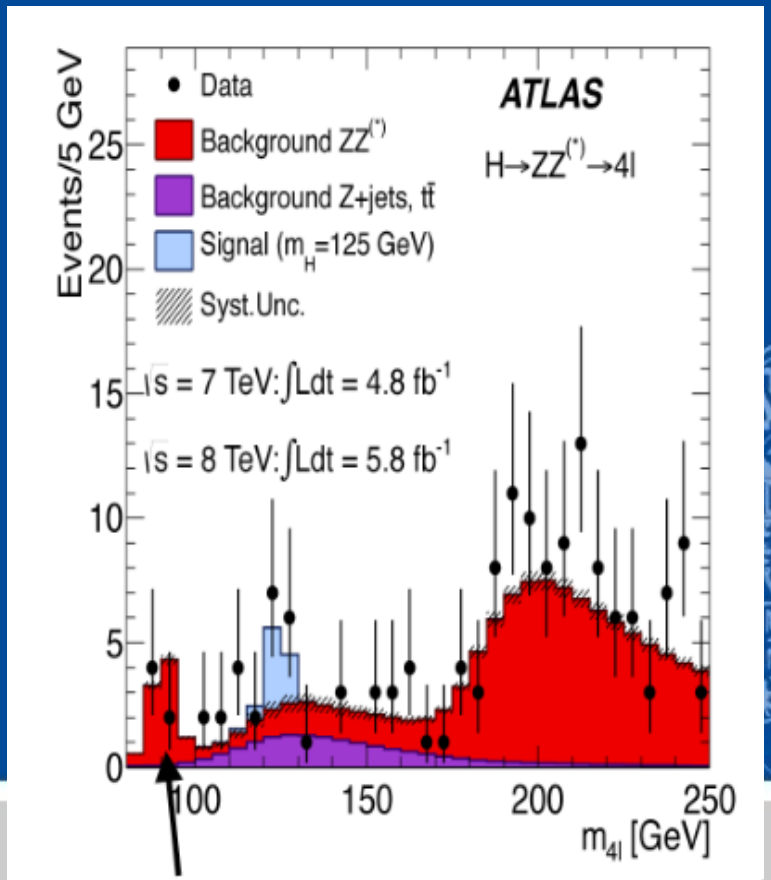
Introduction

Why search for the Fermionic decay of the Higgs boson?

→ already high evidence in γγ or ZZ→4l channels







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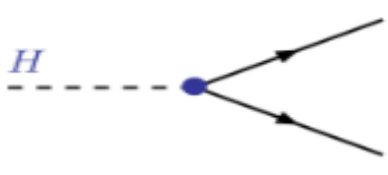
Introduction

- Higgs field interaction Lagrangian with fermions:

$$\mathcal{L}_{\text{Fermion}}(\phi, \psi) = G_\psi \overline{\psi} \phi \psi$$

- → Higgs mechanism produces mass



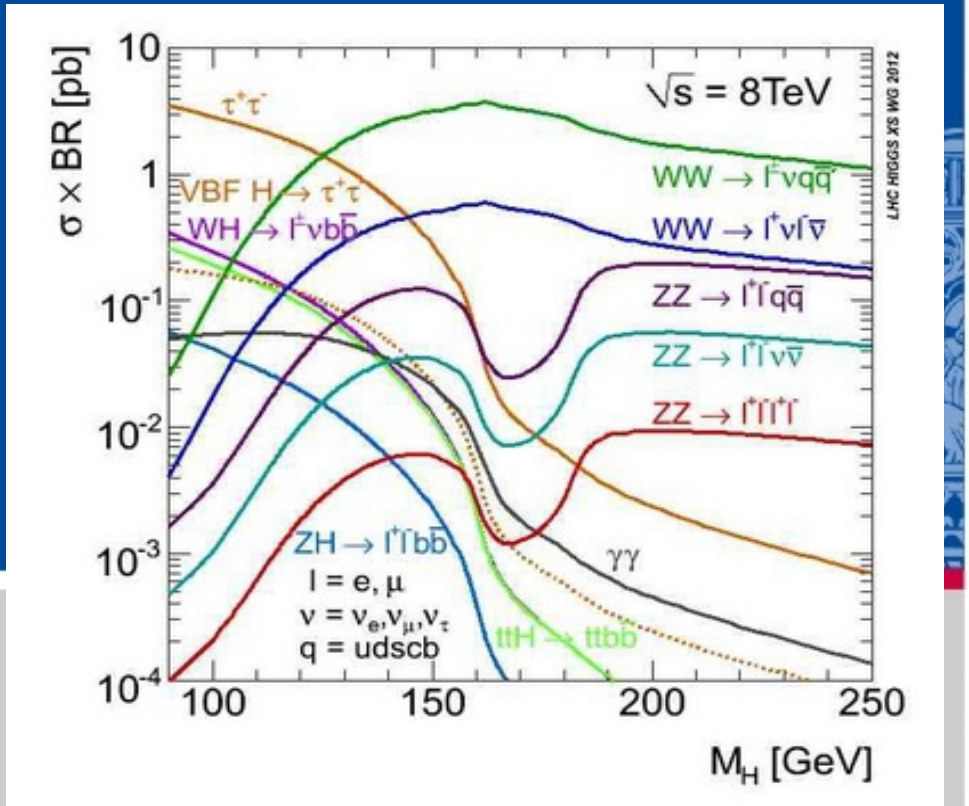
$$g_{Hff} = m_f / v$$

Introduction

- Scale factors for couplings: κ_V, κ_F

$$\sigma(ZH) * \mathrm{BR}(H \to b\bar{b}) \sim \frac{\kappa_Z^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, \kappa_Z)},$$

- → test of the standard model



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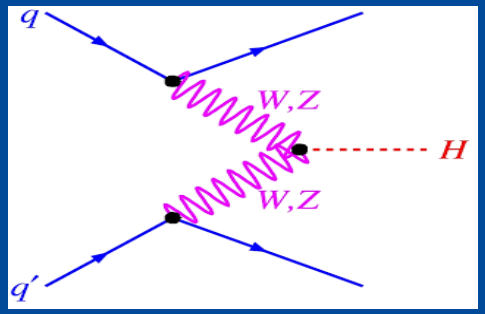
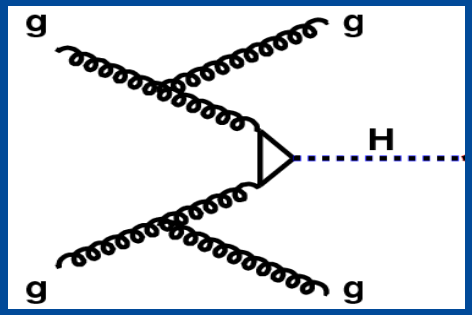
SM Higgs Boson production mechanism and decay modes

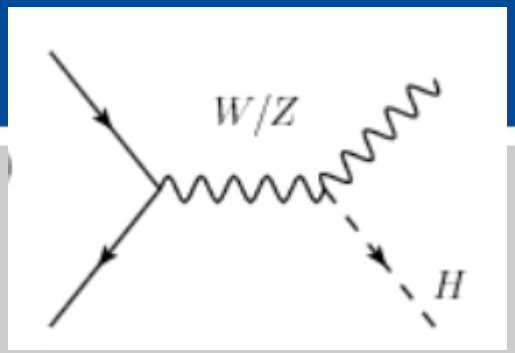
- VBF:



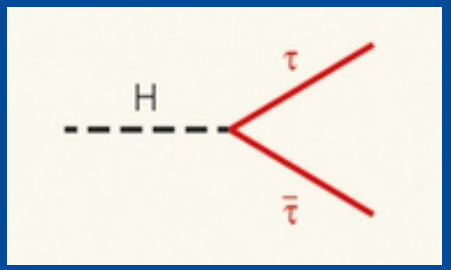
- ggF:



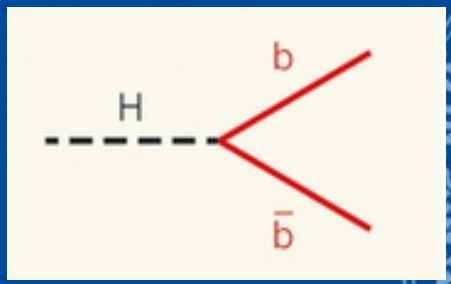
- VB associated:



- decay to tau leptons

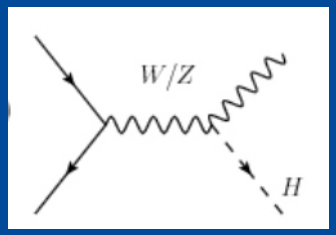


- decay to bottom quarks:

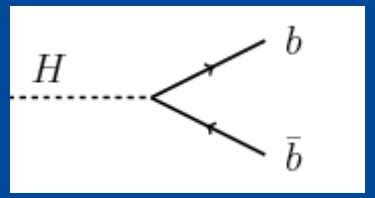


The ATLAS search: VH production and decay to $b\bar{b}$

- Measure the associated vector boson
  → leptonic decay into: ll, lv, vv
  → use of lepton triggers



- Higgs boson decay into a pair of b quarks
  → b-jets

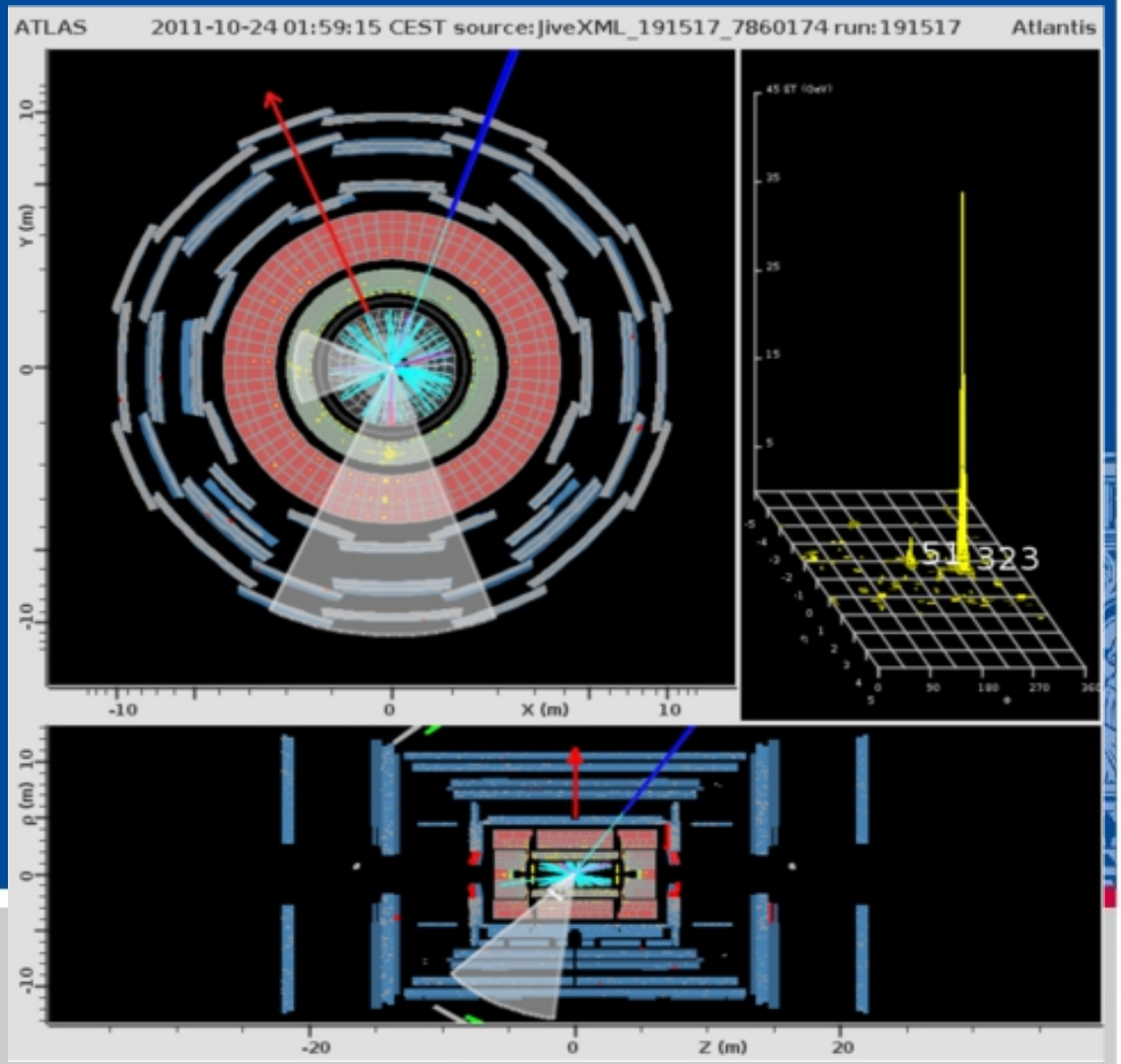


Challenges:

- B quark identification and energy measurement
- Identification of the leptonic decay of the vector boson
- Control of the background produced by decays of Vector Bosons

The ATLAS search: VH production and decay to bb: Event display

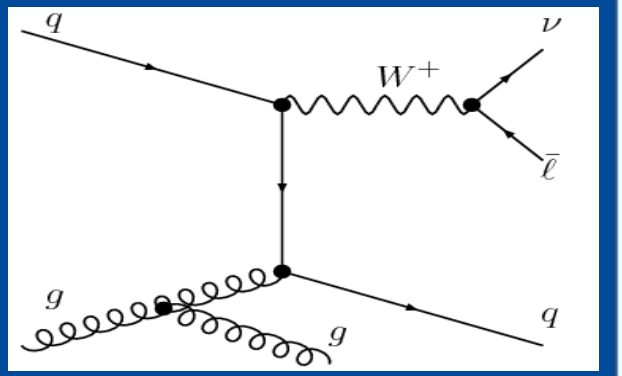
- Example : $WH \rightarrow l\nu\, b\, \bar{b}$

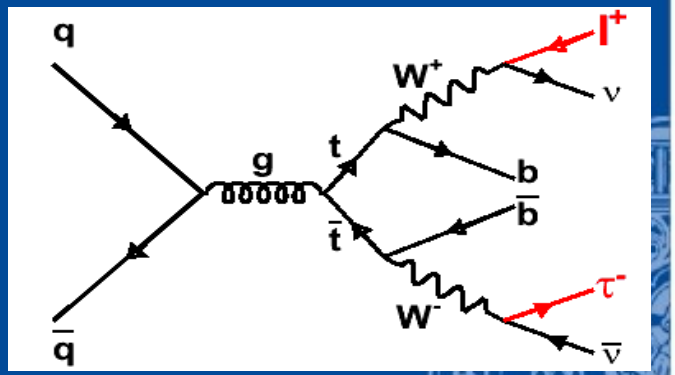


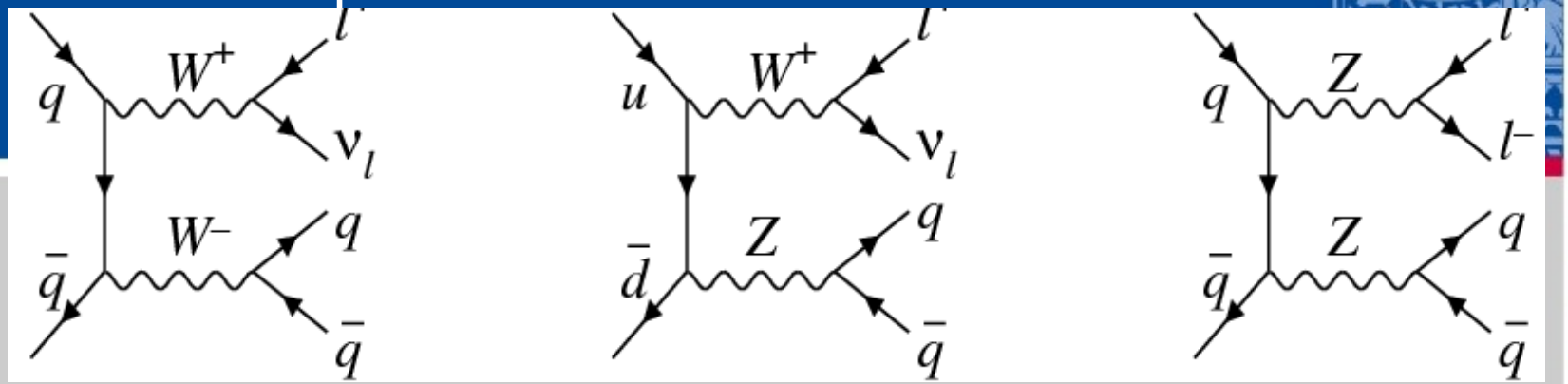
The ATLAS search: Summay of background processes

The main background sources:

- → W + jets
- → Multijet
- → top pair / single top
- → diboson processes







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The ATLAS search: VH production and decay to $b\bar{b}$

Table 1: The basic event selection for the three channels.

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_{\mathrm{T}}^{\mathrm{jet_1}} > 45$ GeV $p_{\mathrm{T}}^{\mathrm{jet_2}} > 20$ GeV + ≤ 1 extra jets		
Missing E_T	$E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, b\bar{b}) > 2.8$	$E_{\mathrm{T}}^{\mathrm{miss}} > 25$ Gev	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_{\mathrm{T}}^{W} < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV
	$Z \rightarrow \nu\nu$	**$W \rightarrow l\nu$**	**$Z \rightarrow ll$**

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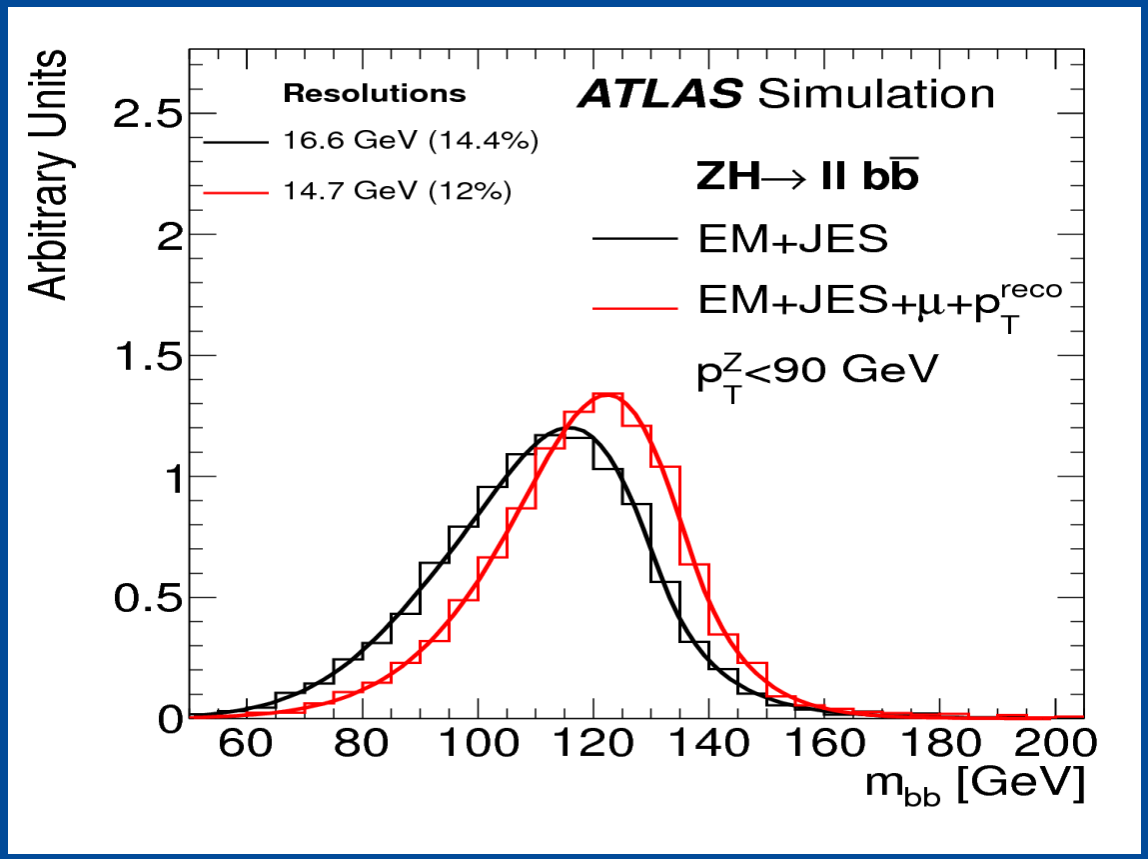
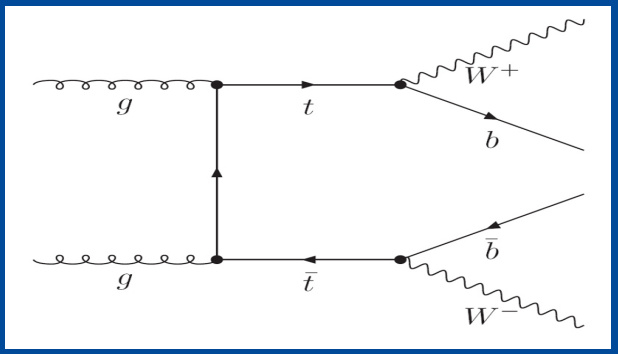
The ATLAS search: VH production and decay to $b\bar{b}$

Jet-energy reconstruction validation

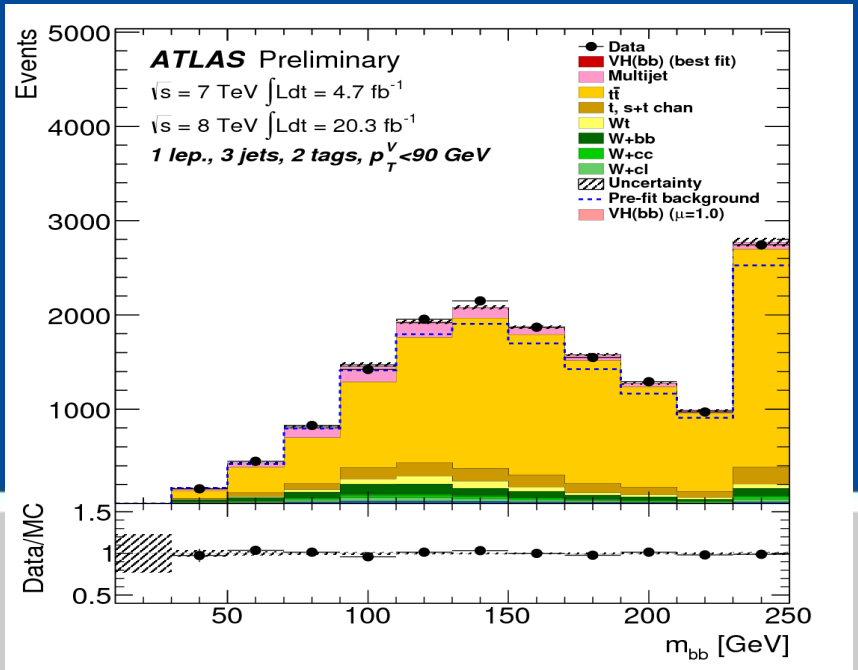


The ATLAS search: VH production and decay to $b\bar{b}$: background normalization example $t\bar{t}$:

- 1) MC generator:
  - → simulation of specific background processes



- 2) normalization of the simulation in control regions



3) scale factors:

Process	Scale factor
$t\bar{t}$	1.13 ± 0.05
Wb	0.89 ± 0.15
Wcl	1.05 ± 0.14
Zb	1.30 ± 0.07
Zcl	0.89 ± 0.48

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The ATLAS search: VH production and decay to $b\bar{b}$ Observed events

2-jet, 2-tag sample														
	0-lepton			1-lepton					2-lepton					
Process	E_T^{miss} [GeV]			p_T^W [GeV]					p_T^Z [GeV]					
	120-160	160-200	>200	0-90	90-120	120-160	160-200	> 200	0-90	90-120	120-160	160-200	>200
$Z \to \nu\nu$	1.6	0.9	1.0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$Z \to \ell\ell$	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	2.1	0.5	0.4	0.2	0.2
$W \to \ell\nu$	0.4	0.2	0.2	7.6	1.7	1.2	1.0	1.1	<0.1	<0.1	<0.1	<0.1	<0.1
VH total	2.0	1.1	1.1	7.8	1.8	1.2	1.1	1.1	2.1	0.5	0.4	0.2	0.2
VH expected	11	5.8	6.1	42	9.5	6.6	5.6	6.1	11	2.7	2.2	1.1	1.2
Top	159	33	8	2763	729	359	113	40	166	32	8.0	0.5	<0.1
W+c, light	21	5.3	2.7	616	65	27	12	7.8	<0.1	<0.1	<0.1	<0.1	<0.1
W+b	30	10	6.1	909	106	49	25	19	<0.1	<0.1	<0.1	<0.1	<0.1
Z+c, light	23	8.1	5.2	22	2.1	0.5	0.3	0.1	91	12	5.6	1.6	1.0
Z+b	226	71	39	97	13	3.9	1.8	0.5	938	146	64	14	8.3
WW	0.5	0.1	0.1	11	1.0	0.7	0.3	0.2	<0.1	<0.1	<0.1	<0.1	<0.1
VZ	26	11	10	145	20	12	7.6	6.5	60	8.6	4.5	2.2	2.1
Multijet	4.8	1.1	0.7	1306	45.6	8.7	4.8	0.4	<0.1	<0.1	<0.1	<0.1	<0.1
Total Bkg.	491 ± 10	141 ± 3	72 ± 2	5869 ± 64	981 ± 16	460 ± 9	165 ± 4	74 ± 3	1255 ± 24	199 ± 4	82 ± 2	18 ± 1	11.4 ± 0.5
Data	502	143	90	5916	990	458	162	79	1282	204	70	22	6
S/B	0.004	0.008	0.02	0.001	0.002	0.003	0.006	0.02	0.002	0.003	0.005	0.01	0.02

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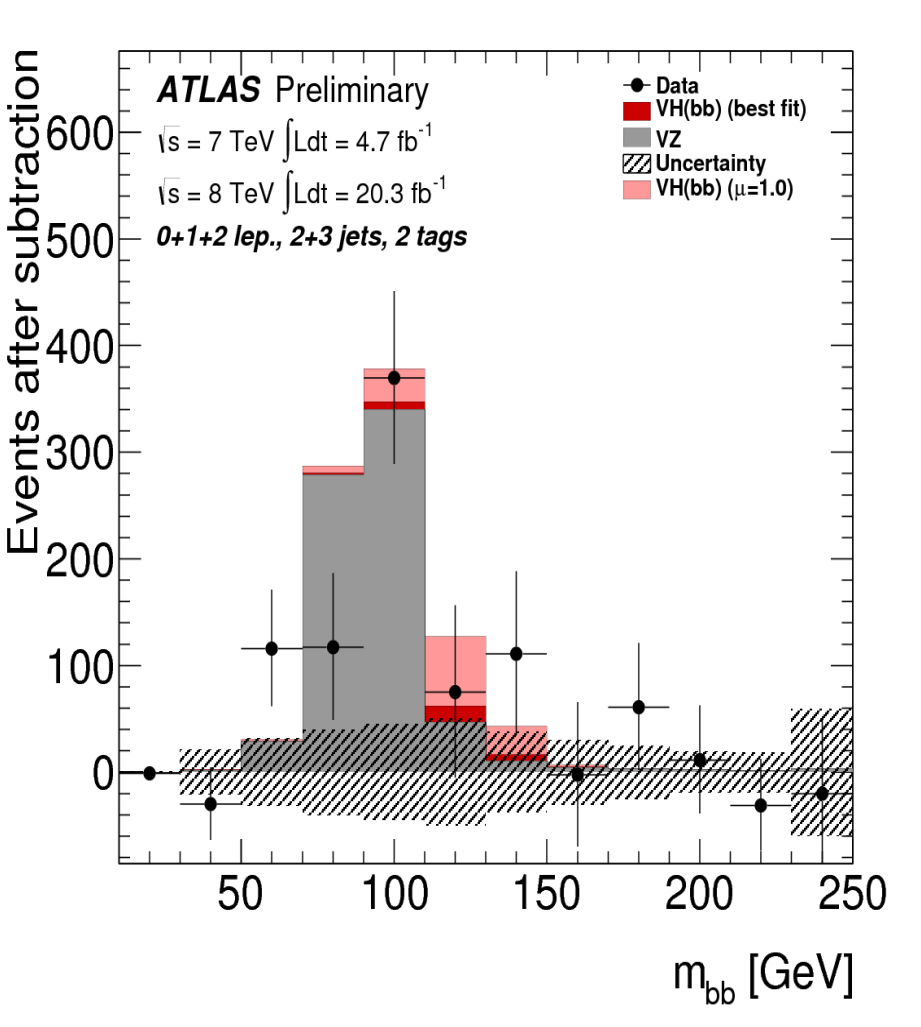
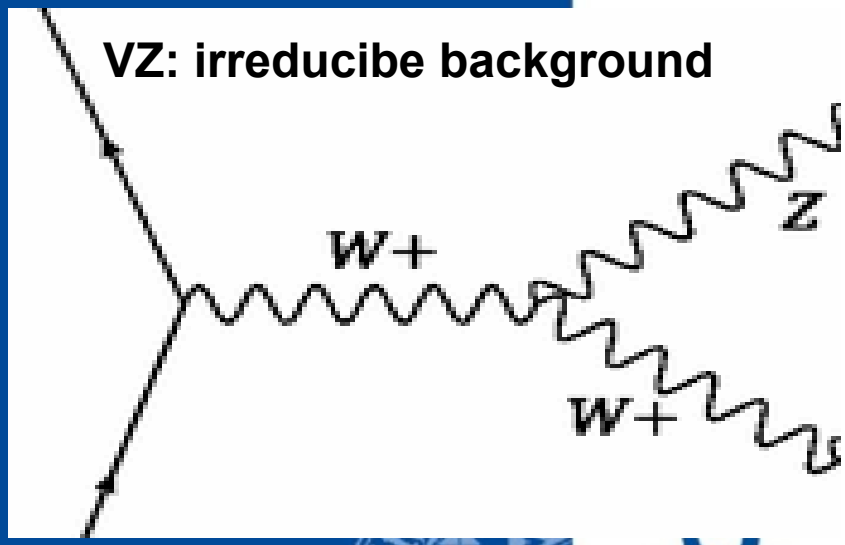
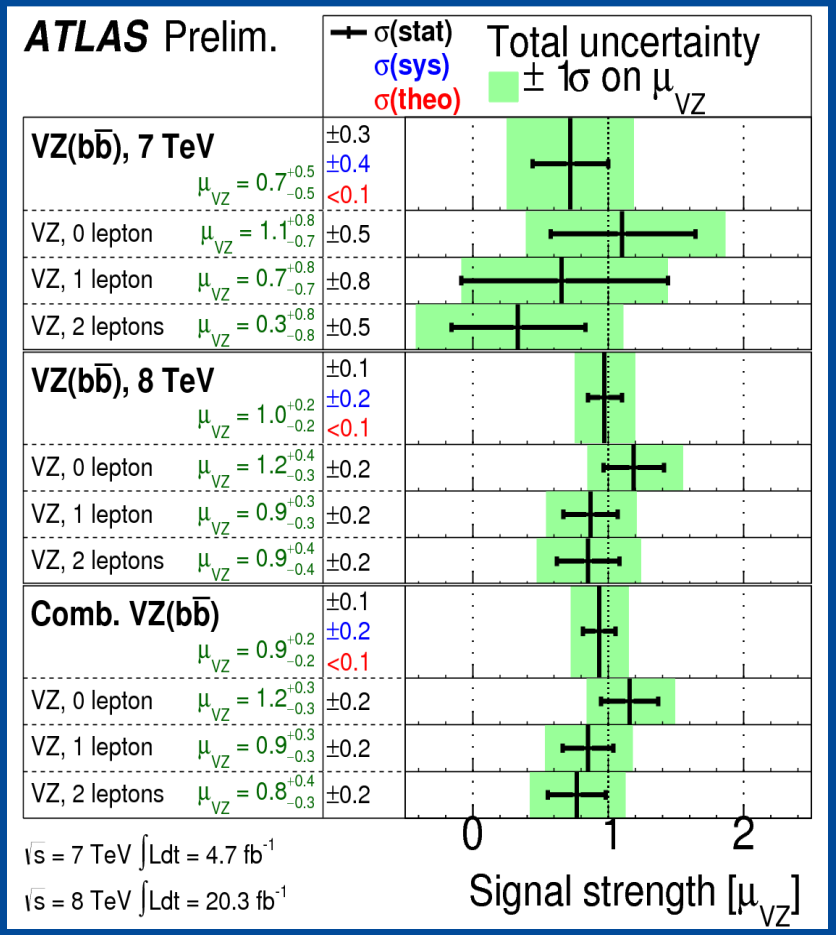
The ATLAS search: VH production and decay to $b\bar{b}$ Observed events

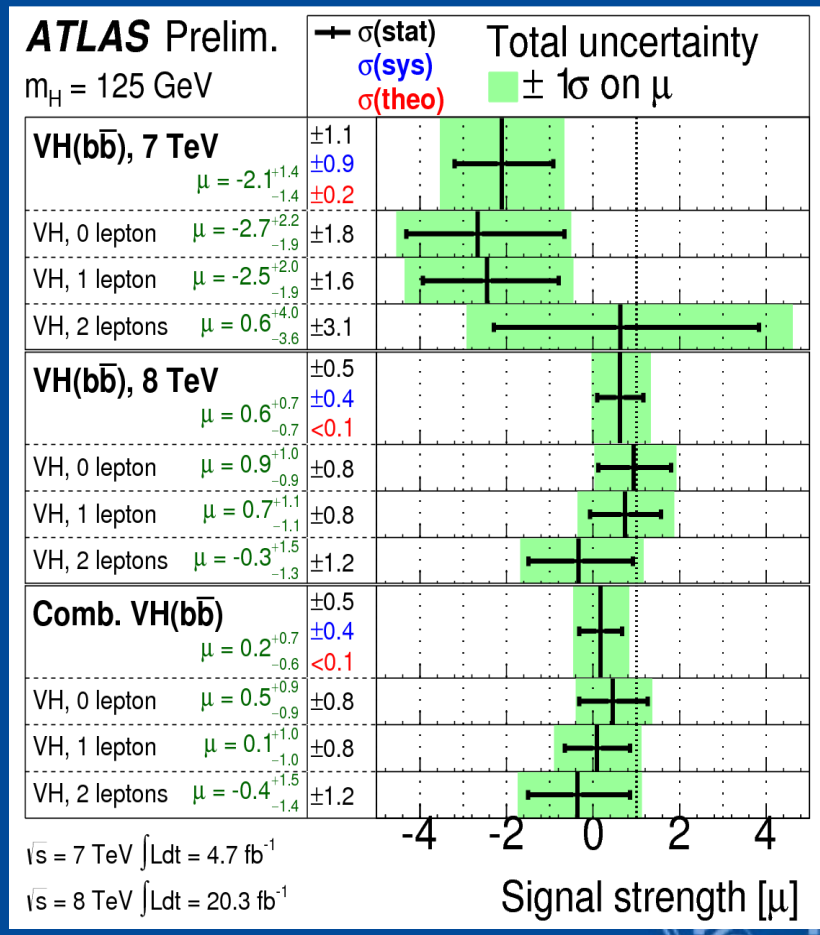


VZ: irreducibe background



The ATLAS search: VH production and decay to $b\bar{b}$ Results for SM expectations





→ **No significance for the 125 GeV Higgs decay to a pair of bottom quarks**

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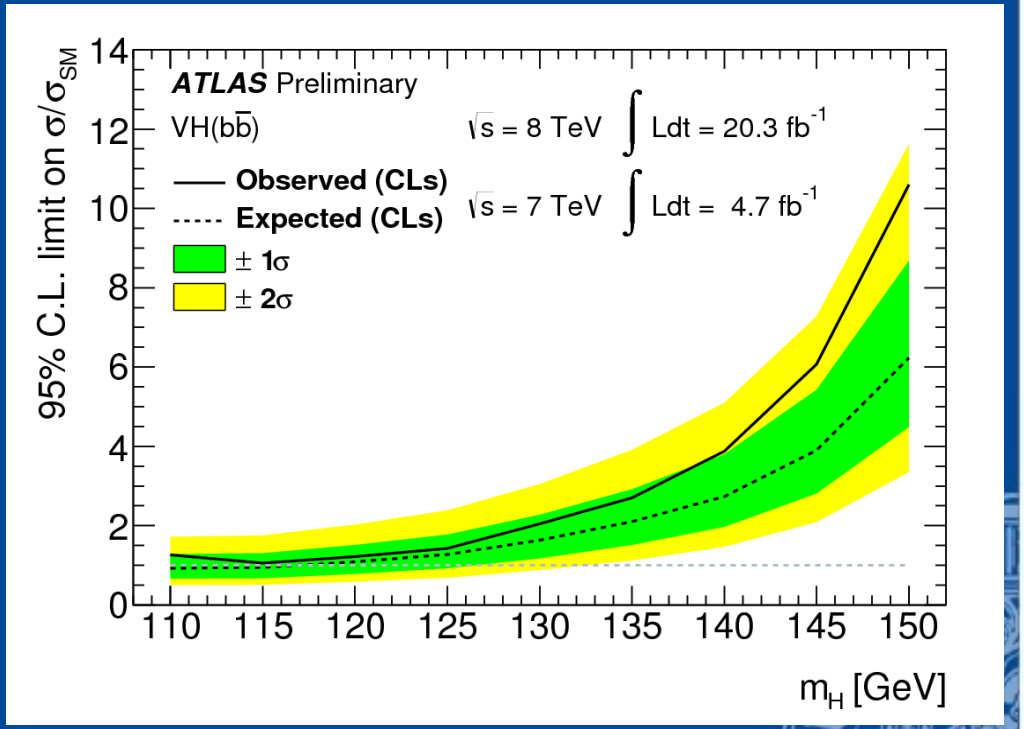
The ATLAS search: VH production and decay to $b\bar{b}$ Results for SM expectations

For m(H) = 125 GeV:
→ No significance

95% C.L. Upper limit for SM expectation:

→ expected: 1.3
(for absence of signal)
→ measured: 1.4



→ signal strength: μ = 0.2 ± 0.5(stat.) ± 0.4(syst.)

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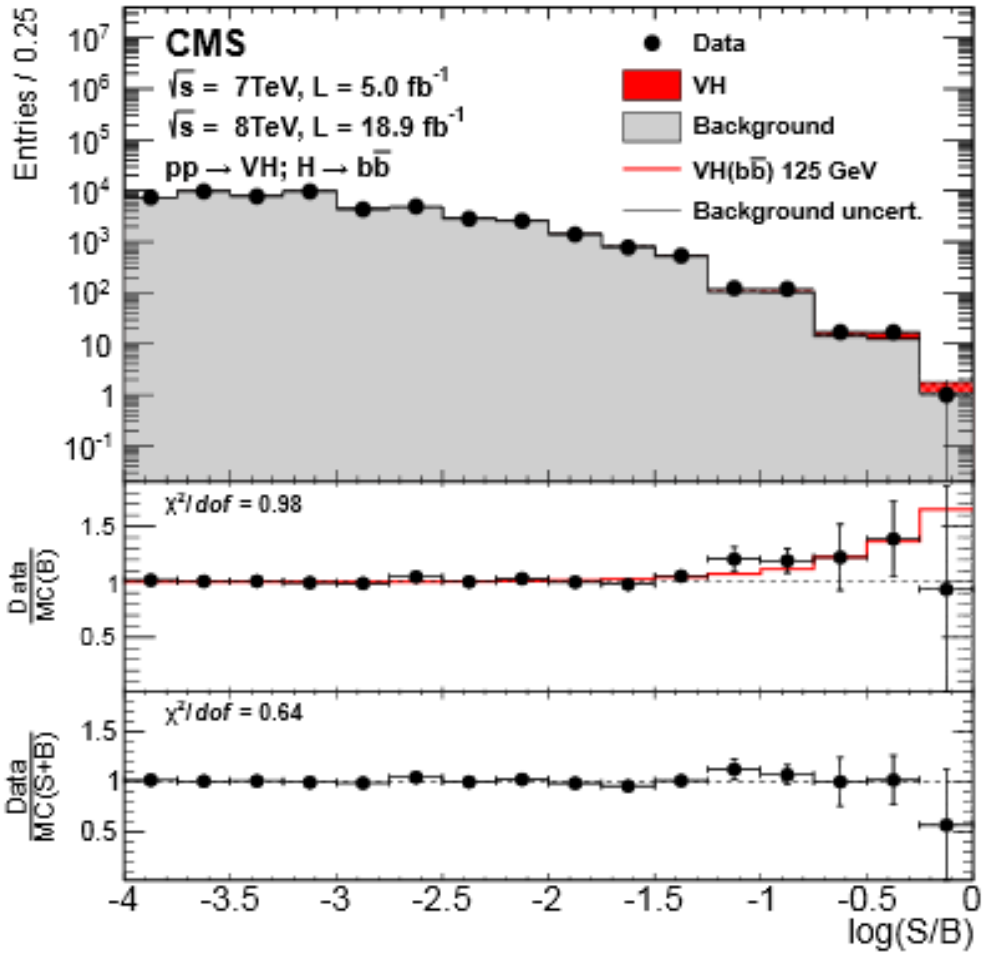
The CMS search for H → $b\bar{b}$: Results

95% C.L for CSxBR
(for m(H) = 125 GeV)
→ expected 0.95
→ observed: 1.89

Signal significance over background
→ expected: 2.1
→ measured: 2.1
(high sensitivity of search)

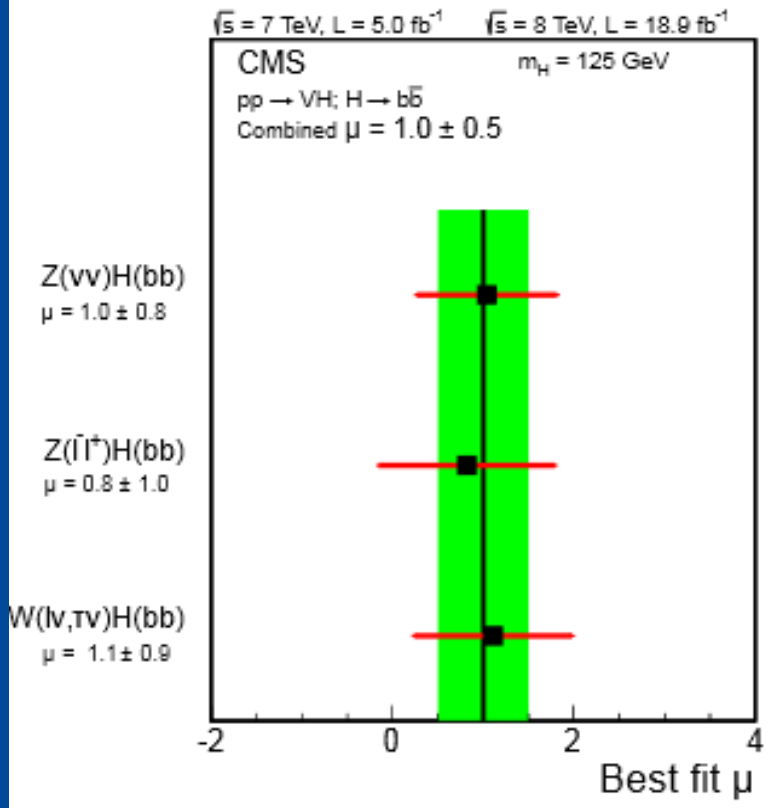
→ signal strength: μ = 1.0 ± 0.5

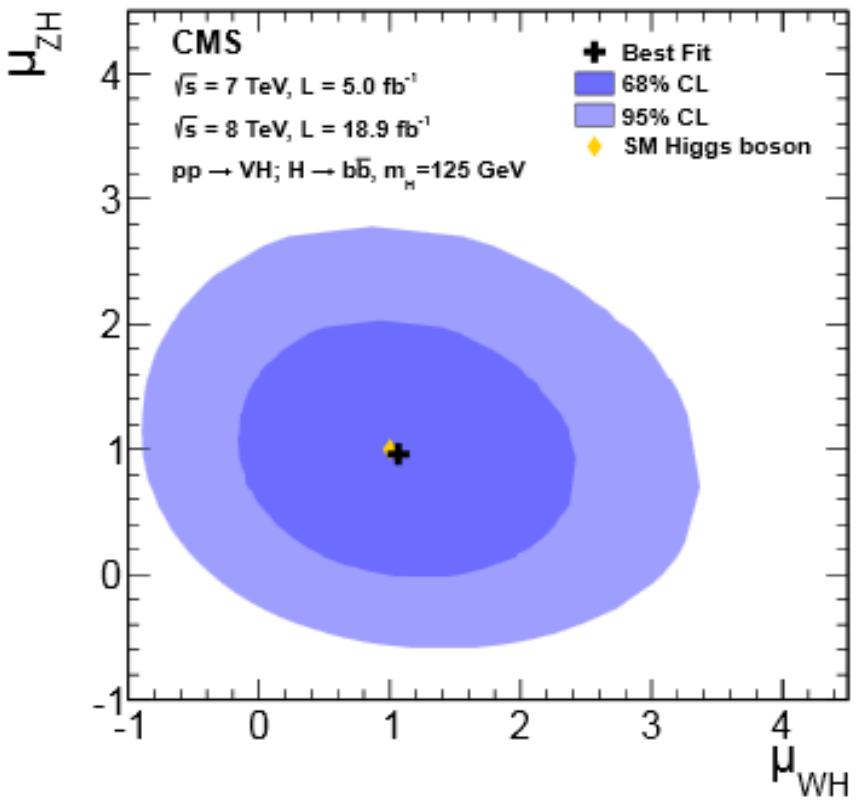
Results from all channels summed up



The CMS search for H → $b\bar{b}$: Results

Comparison with standard model signal strengths





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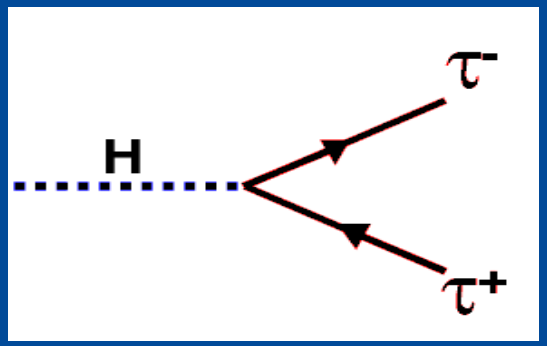
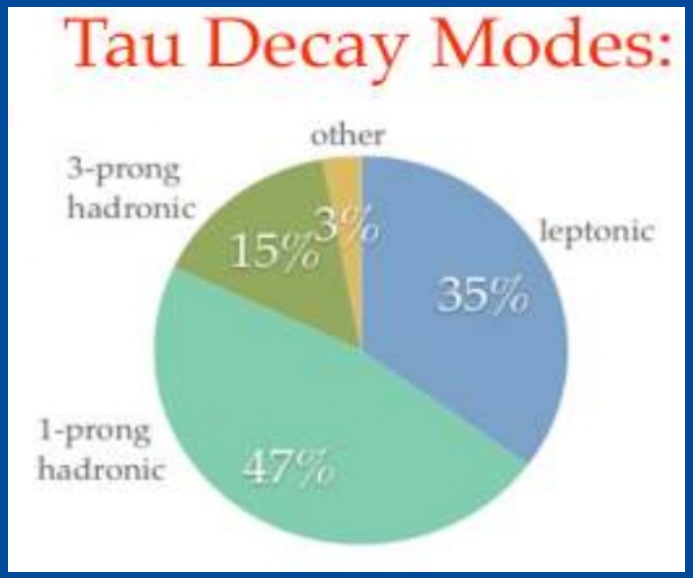
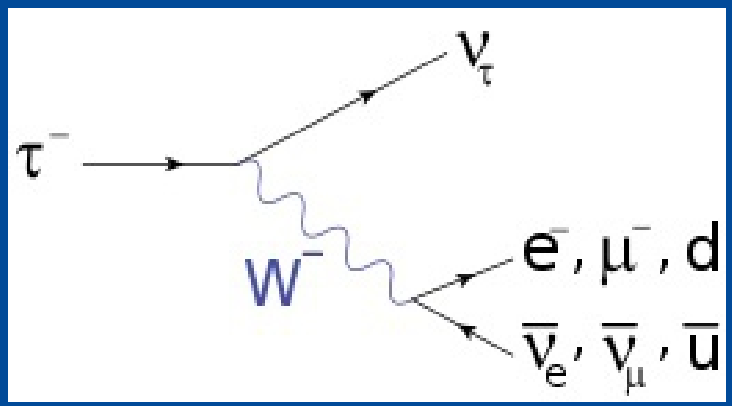
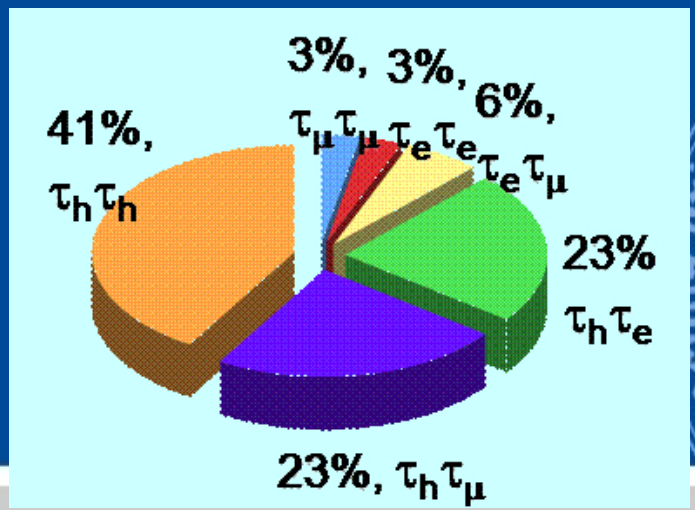
The ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state:









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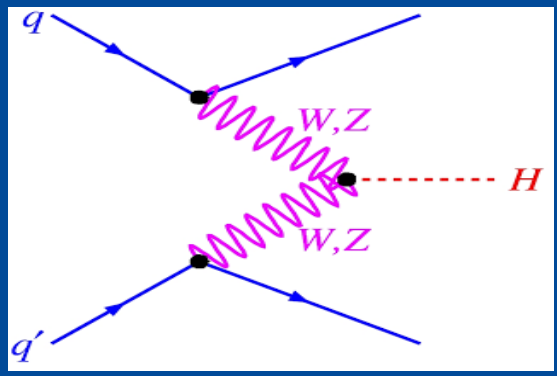
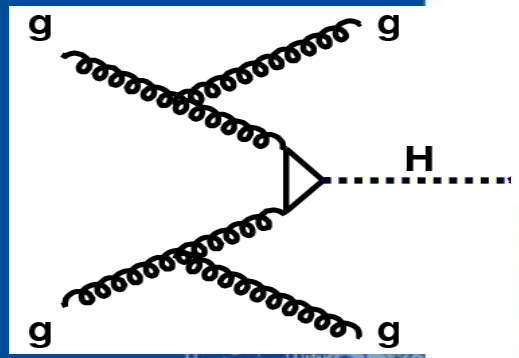
The ATLAS search for the decay of the Higgs Boson to the Tau+ Tau- final state: Analysis categories



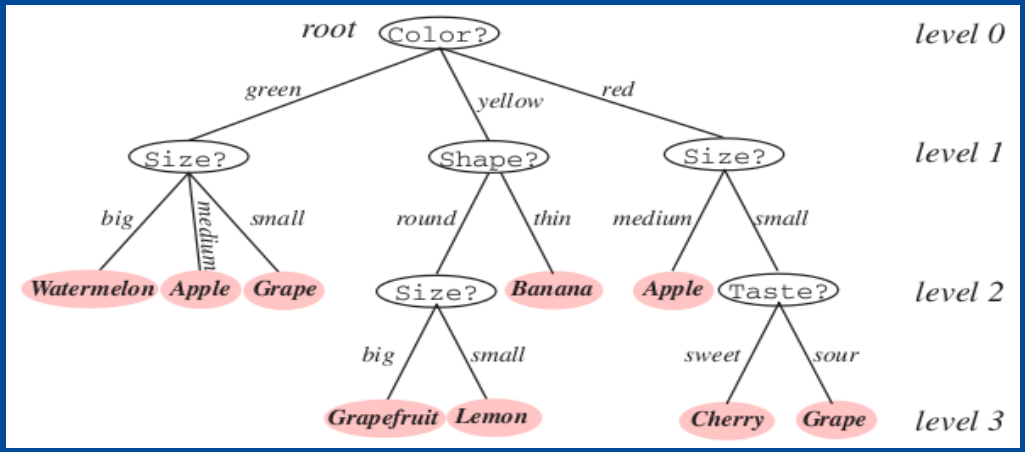
- 2 exclusive production categorys:
  - VBF:
    - 2 jets
    - Large Δη separation
    - background: gg-fusion and VH production
  - Boosted:
    - gg-fusion → large pT(H)
    - Reason: IS gluon readiation
    - Fail in VBF category required
    - background: VBF and VH processes



The ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state: Selection criteria for the categories

Category	Selection	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
VBF	$p_{\text{T}}(j_1)$ (GeV)	40	50	50
	$p_{\text{T}}(j_2)$ (GeV)	30	30	30/35
	$\Delta\eta(j_1, j_2)$	2.2	3.0	2.0
	b–jet veto for jet p_{T} (GeV)	25	30	-
	p_{T}^{H} (GeV)	-	-	40
Boosted	$p_{\text{T}}(j_1)$ (GeV)	40	-	-
	p_{T}^{H} (GeV)	100	100	100
	b–jet veto for jet p_{T} (GeV)	25	30	-

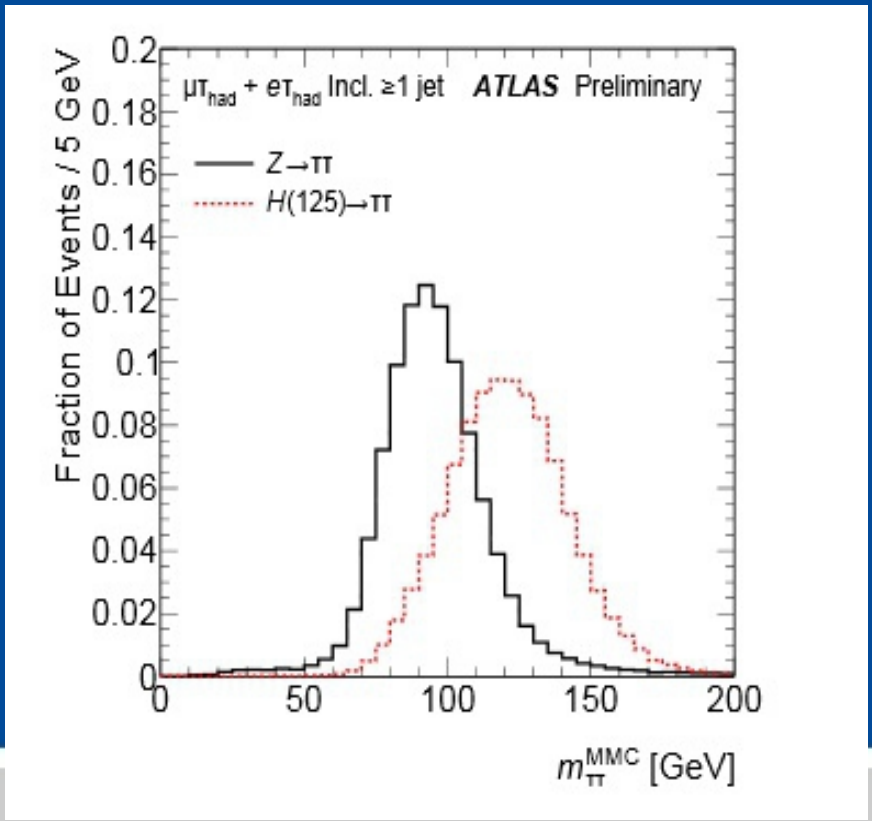
The ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state: BDT

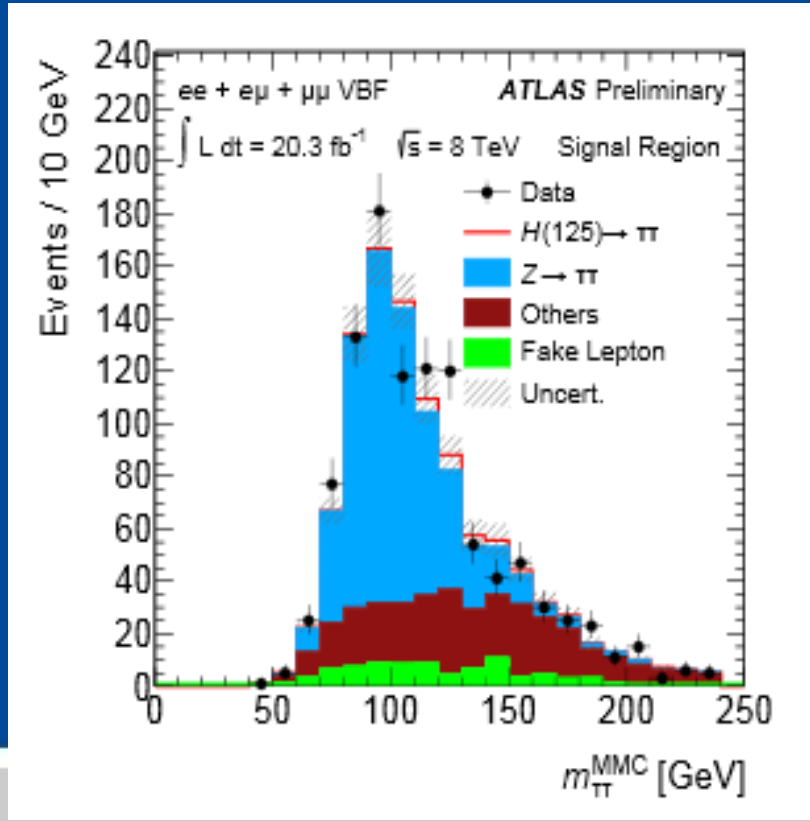


- Boosting: overlap different DT's
- BDT output:
  - Range between -1 and 1
  - → 1 : signal-like
  - → -1 : background-like
- BDT training
  - VBF : VBF samples
  - Boosted : gg-fusion, VBF, VH samples

The ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state: MMC: invariant mass reconstruction

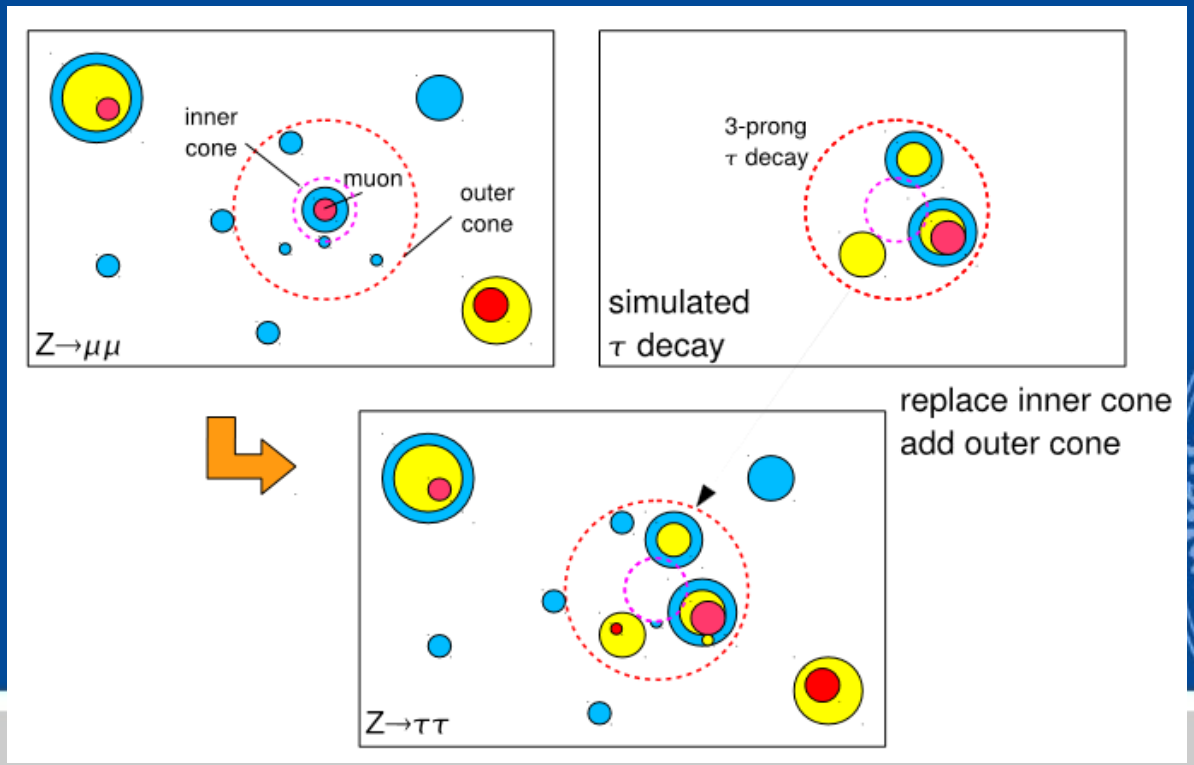
- Problem: Neutrino energy lost in Tau decay
- →MMC: Missing Mass Calculator





The ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state: Background estimation

- Z → Tau+Tau- (main)background: „embedding“-method
- → take Z → μμ data, replace μ by simulated Tau decay



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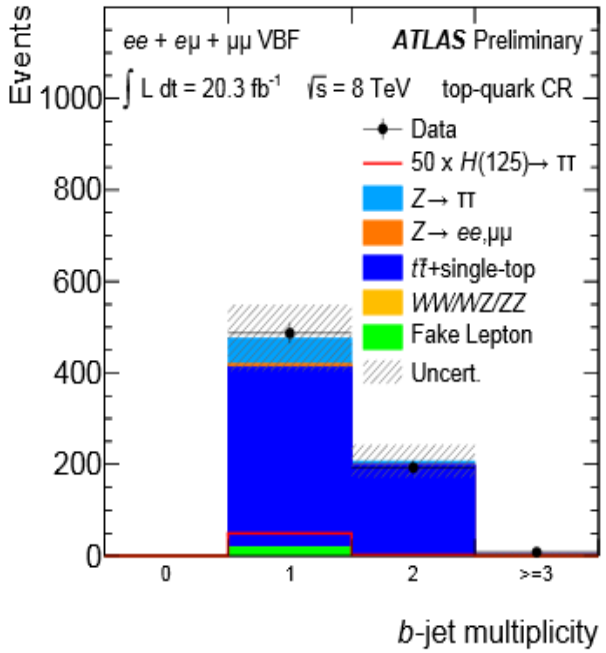
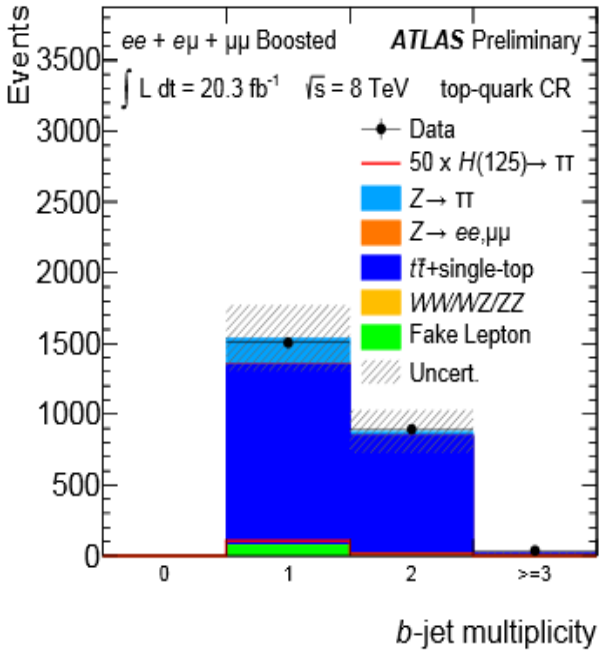
The ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state: Background estimation

- Example: single top quark and top-pair production
- Control region: inverted b-tag veto (>0 tags)

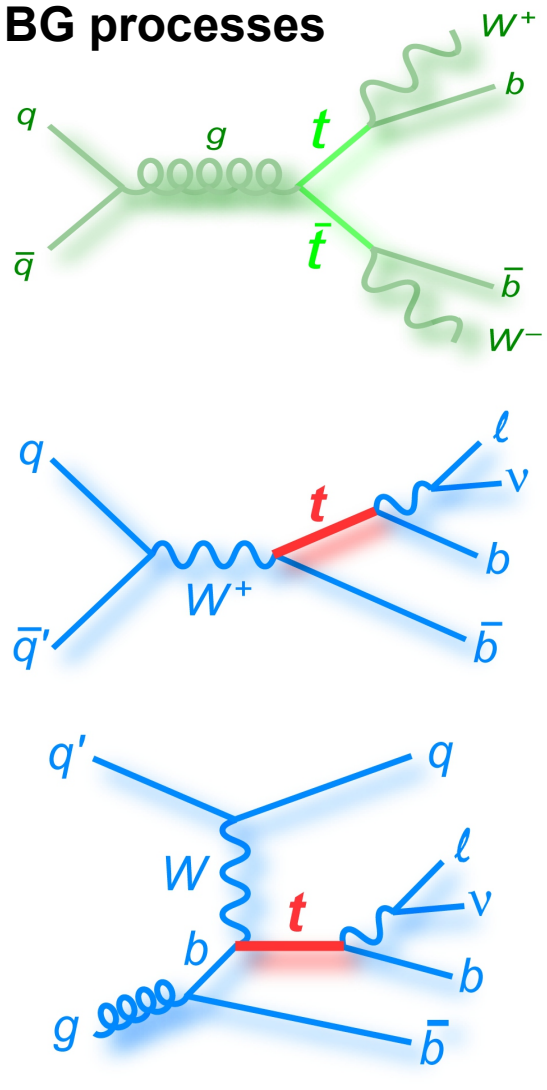


VBF (a)



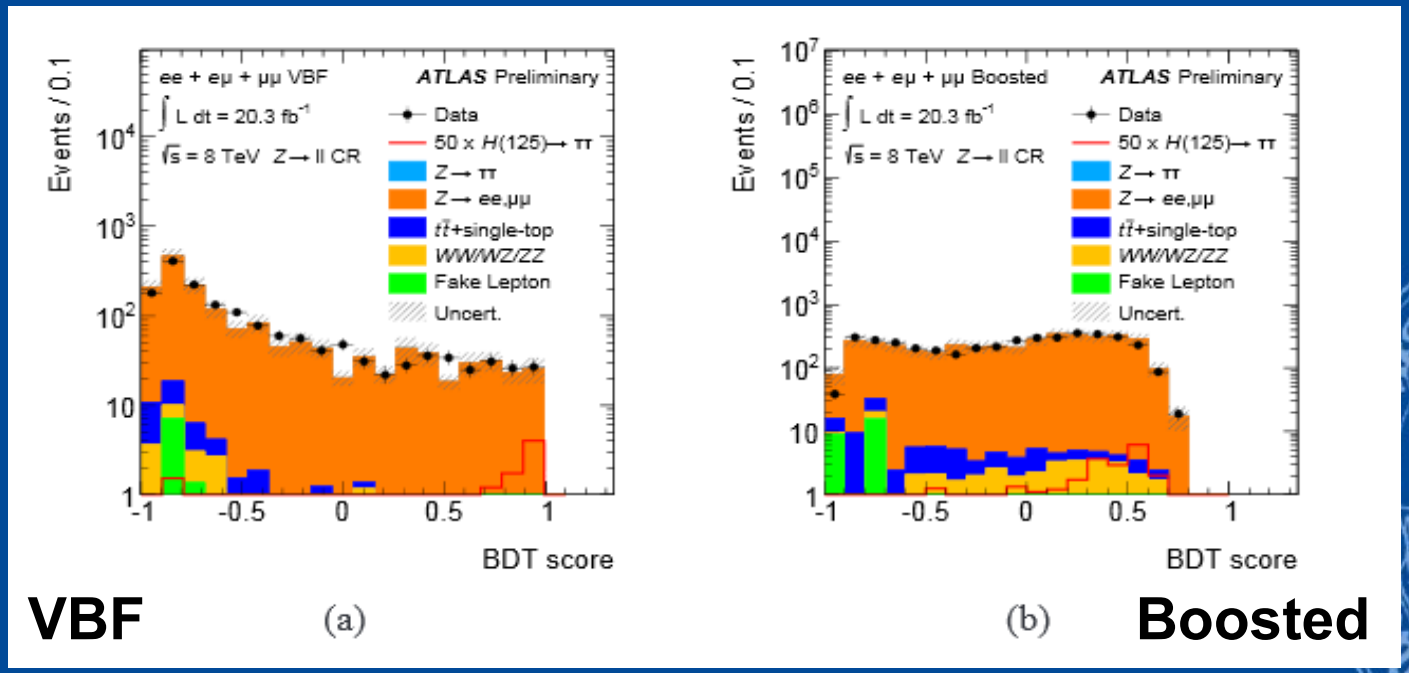
(b) Boosted

BG processes



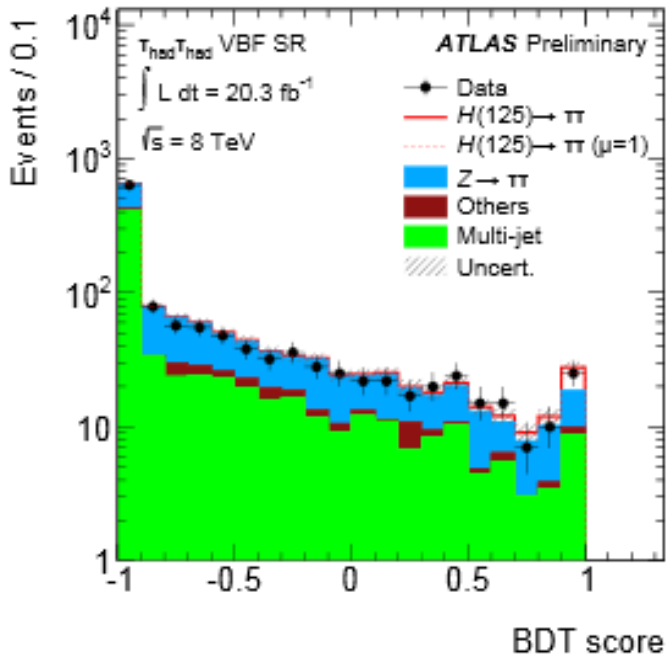
The ATLAS search for the decay of the Higgs Boson to the Tau+ Tau- final state: validation of simulations in the control regions

- Example:T(lep)T(lep): Z→ll enriched control region inverted cut on m(TT,vis) : 80 GeV < m(TT,vis) < 100 GeV)

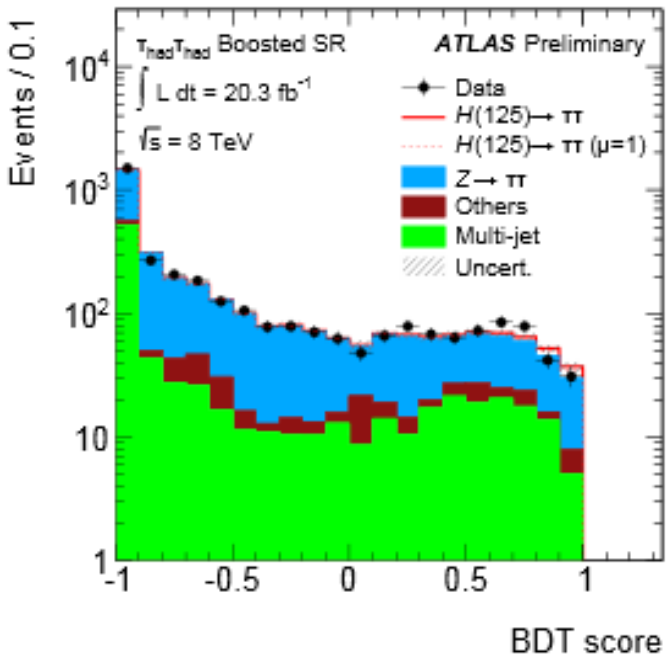


The ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state: signal analysis

- Example: T(had)T(had) signal region



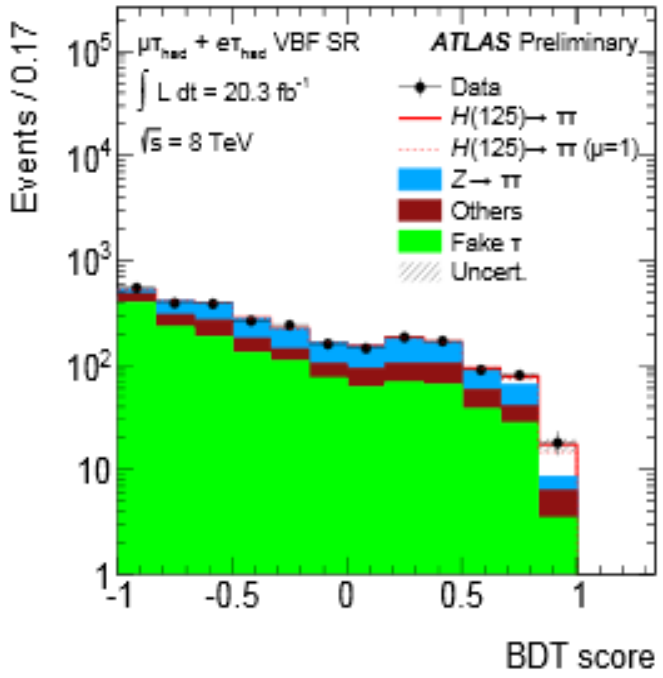
VBF (e)



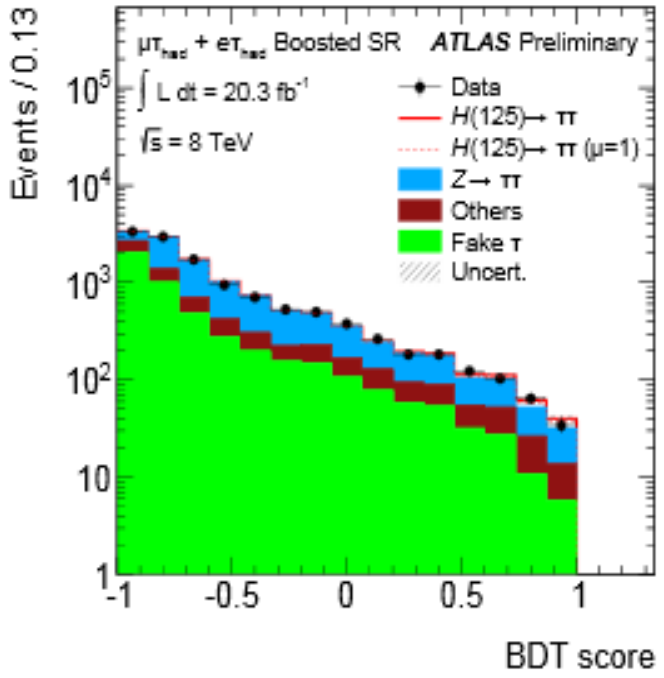
(f) Boosted

The ATLAS measurement of the Tau+ Tau- final state: signal analysis

- T(lep)T(had): signal region



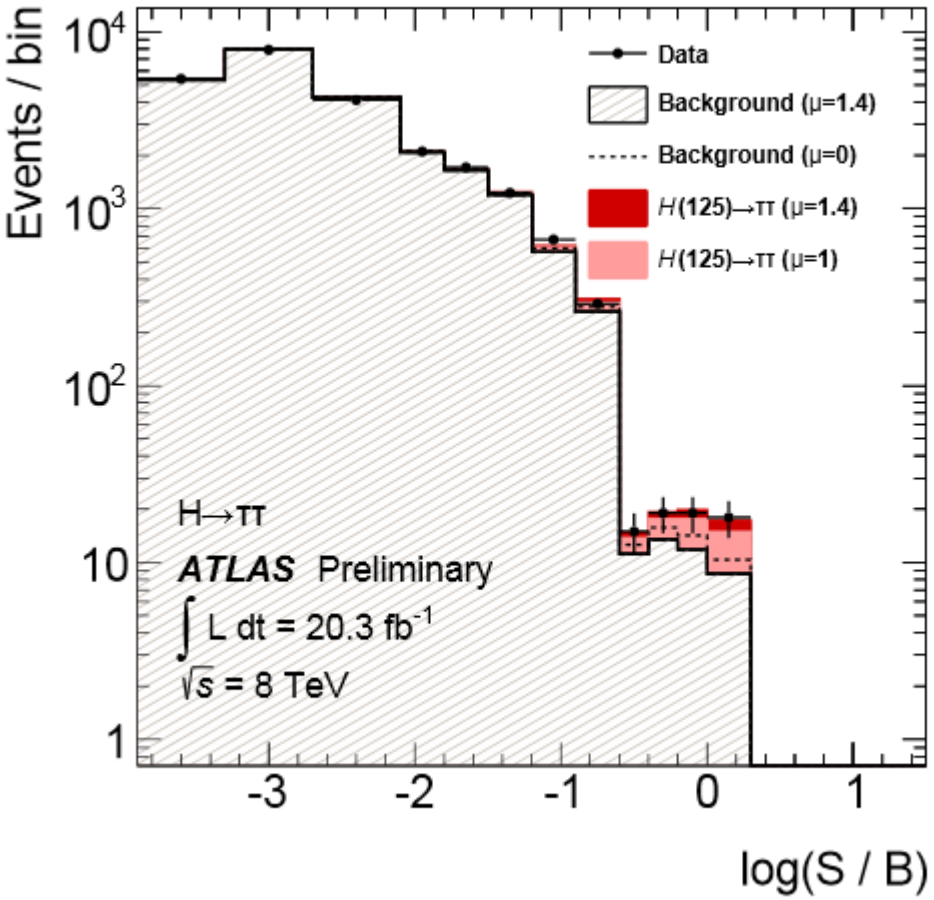
VBF (c)



(d) Boosted

The results of the ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state:

- signals from all BDT channels combined
- signal significance:
  → expected: 3.2 σ
  → observed: 4.1 σ
- → evidence for decay:
  H → τ+ τ-
- signal strength:
  μ=1.0(+0.5/-0.4)
- Result compatible with SM



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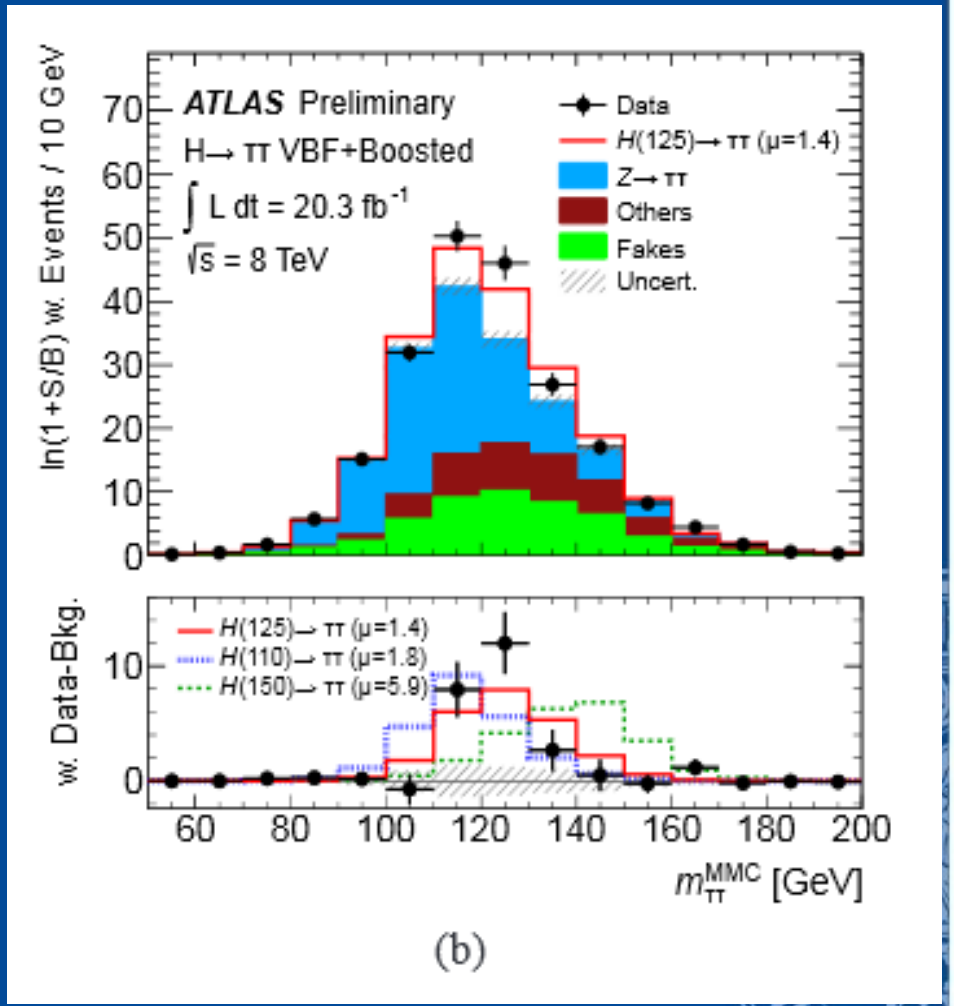
The results of the ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state:

- log(1+S/B) weighted signal

→ comparison of different mass hypotheses



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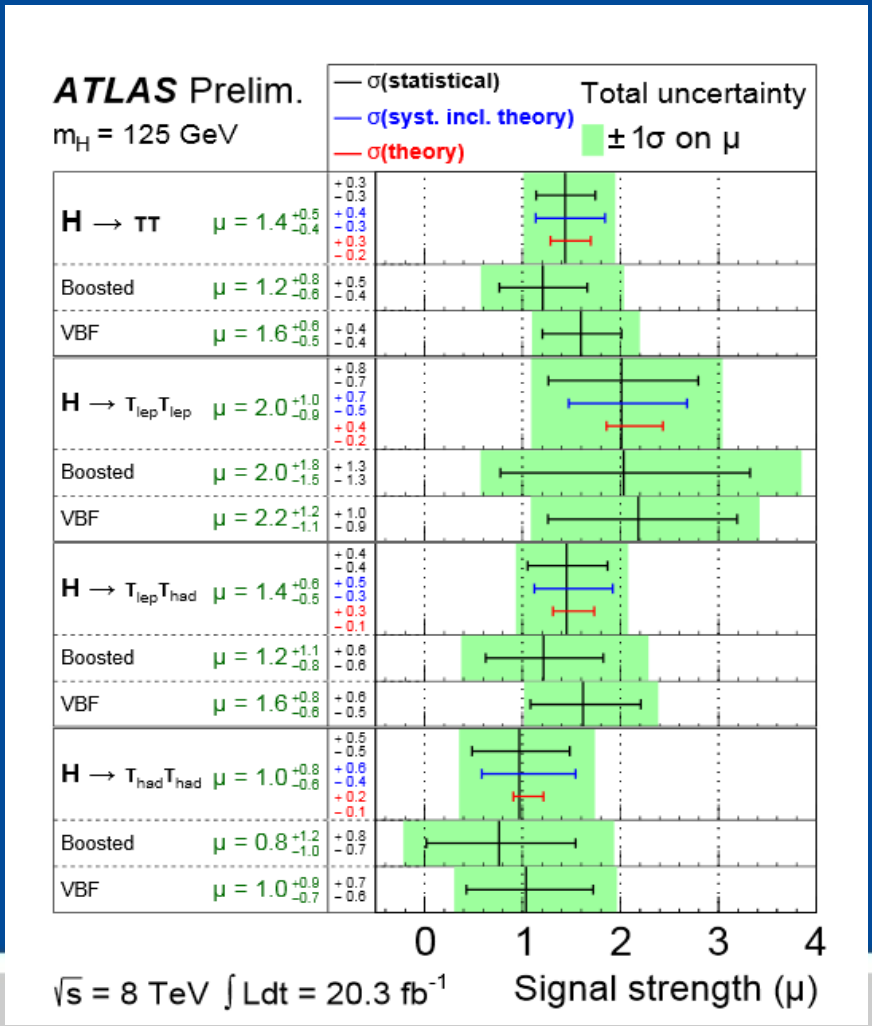
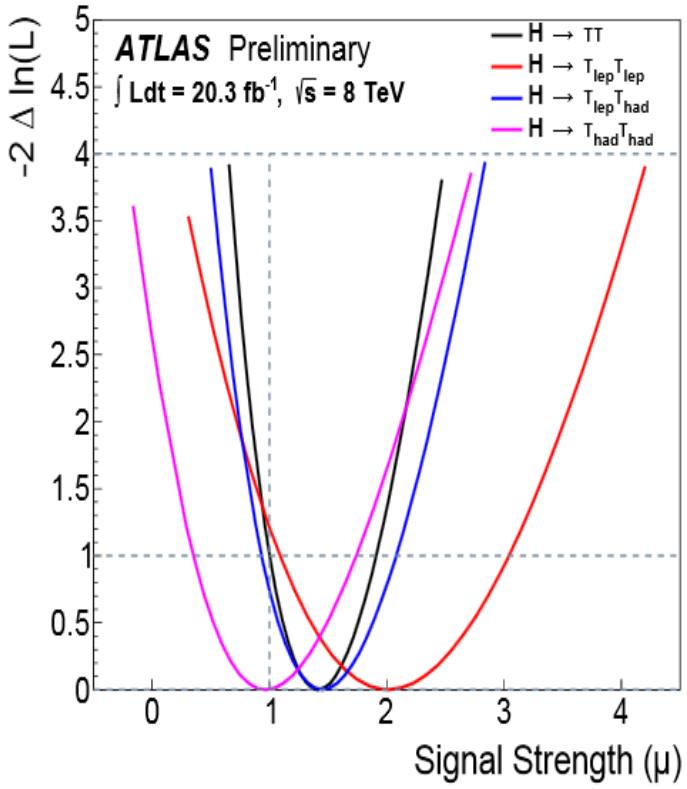
The results of the ATLAS search of the decay of the Higgs Boson to the Tau+ Tau- final state: Results





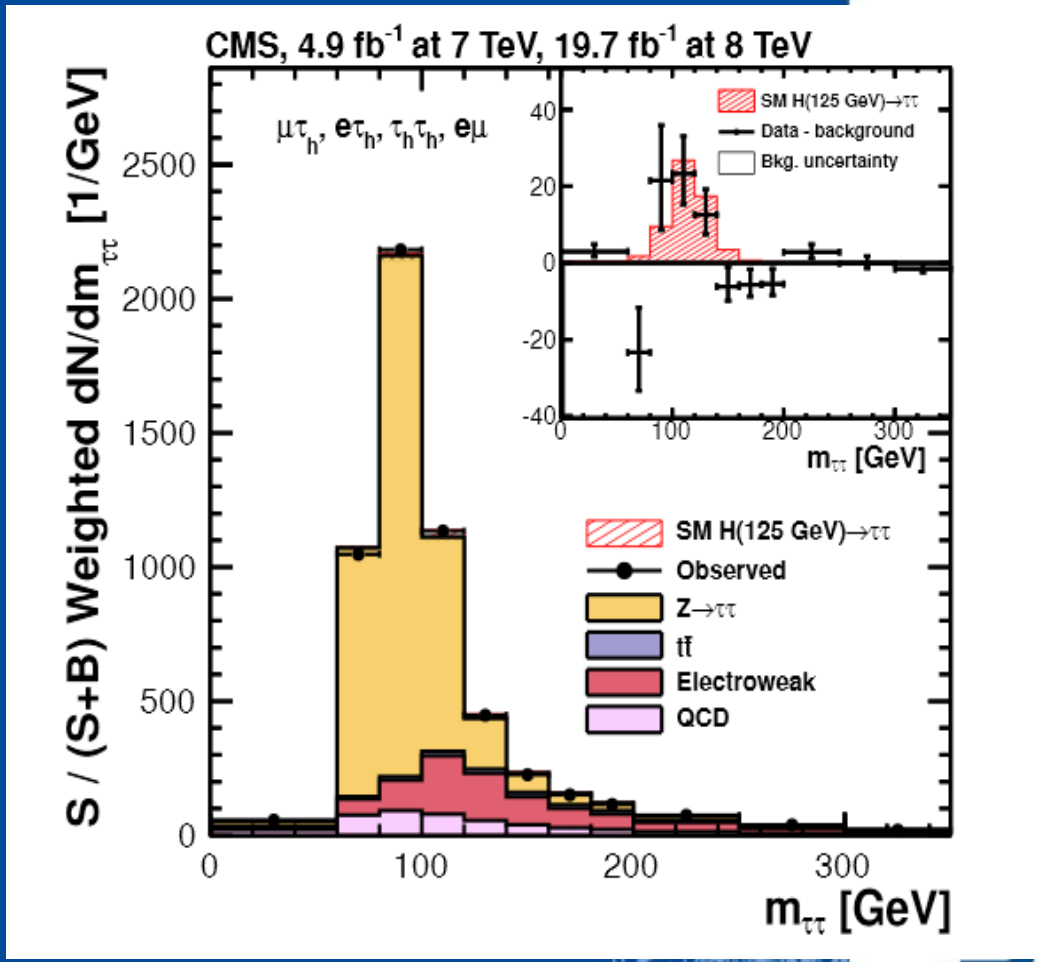
The CMS results of the search on the decay of the Higgs Boson to a pair of Tau leptons

- For m(H) = 125 GeV:

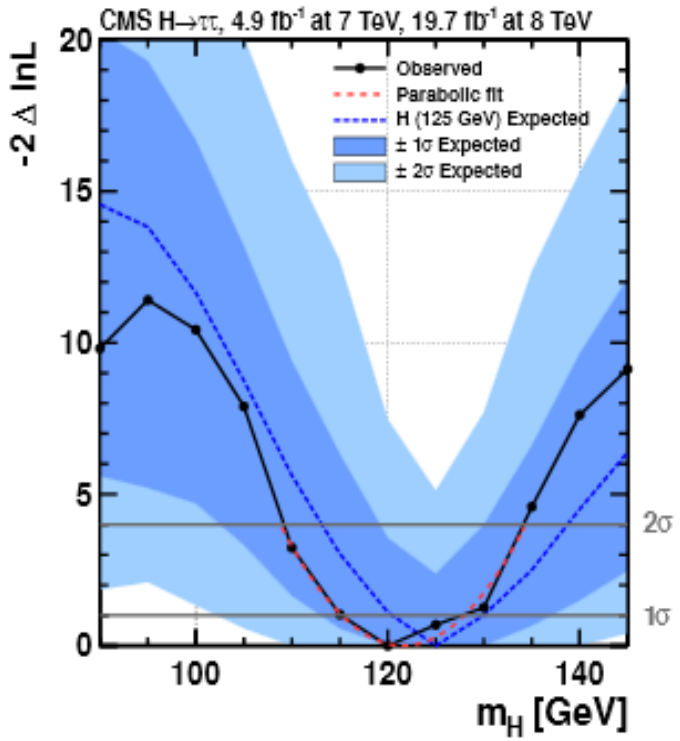
  → local significance over background only hypothesis:
  → expected: 3.7
  → observed: 3.2

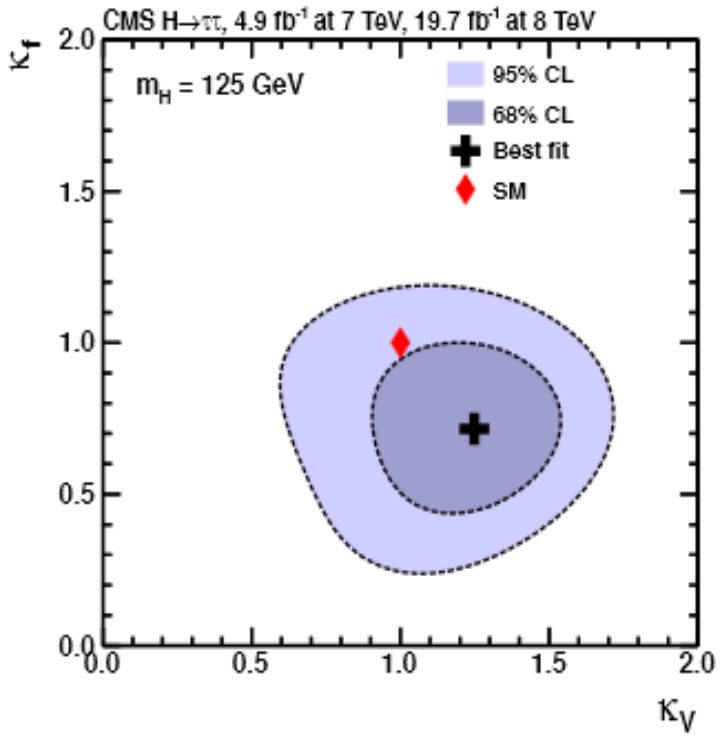
  → signal strength:
  $\mu = 0.78 \pm 0.2$

→ evidence for Higgs Boson coupling to tau leptons



The CMS results of the search on the decay of the Higgs Boson to a pair of Tau leptons





→ measured m(H):
m(H) = 122 ± 7 GeV

→ compatible with the standard model expectation

Summary: Higgs Boson decay to fermions

For m(H) = 125 GeV:

- **$b\bar{b}$ decay of the 125 GeV Higgs Boson**

  → **ATLAS**: no significance
  $\mu = 0.2 \pm 0.5(\text{stat.}) \pm 0.4(\text{syst.})$
  → **CMS** : observed significance for signal 2.1
  $\mu = 1.0 \pm 0.5$

- **$\tau^+\tau^-$ decay of the 125 GeV Higgs Boson**

  → **ATLAS**: significance for signal 4.1
  $\mu = 1.0(+0.5/-0.4)$
  → **CMS** : significance for signal 3.2
  $\mu = 0.78 \pm 0.2$
  measured: m(H) = 122 ± 7 GeV

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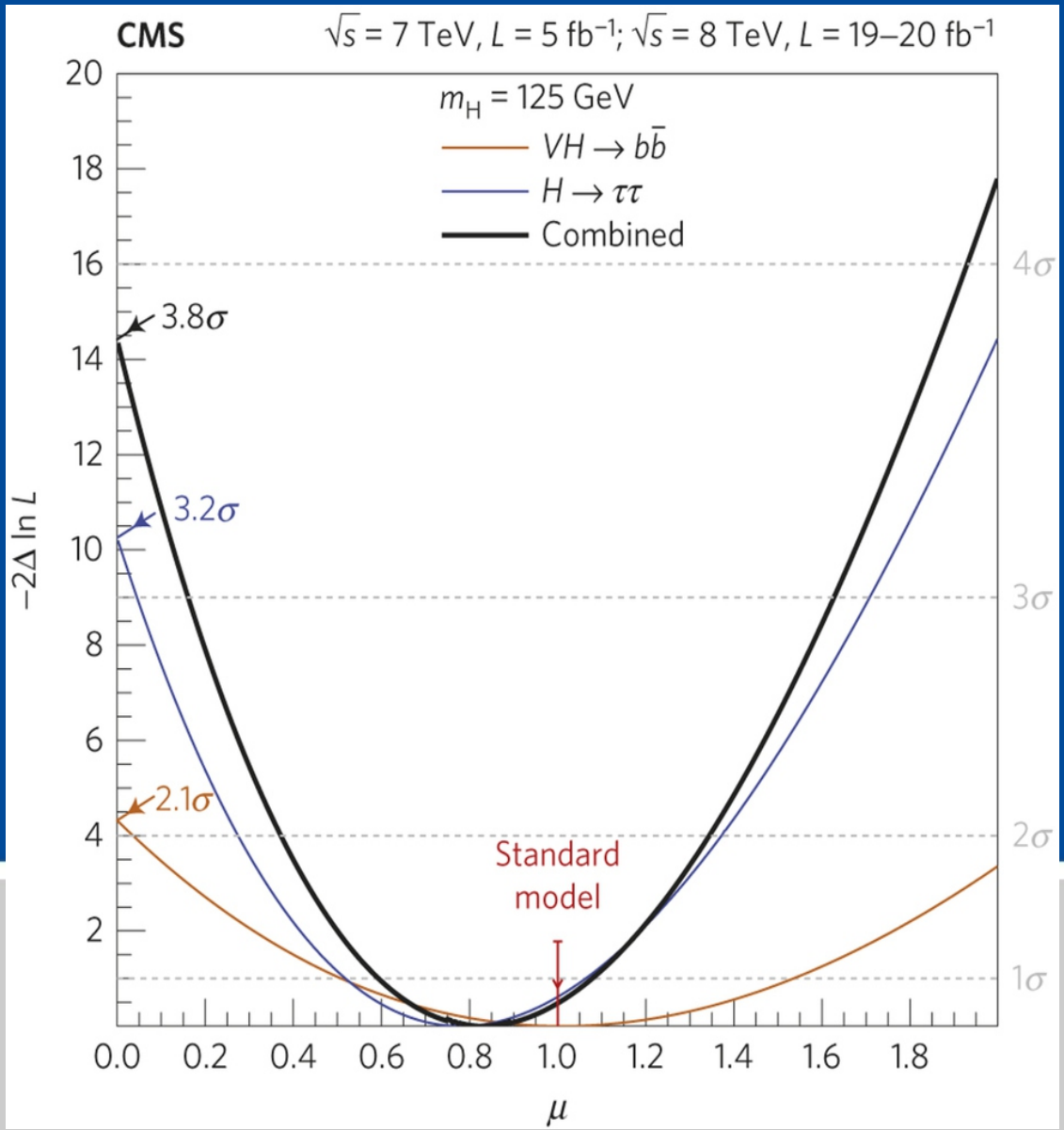
Summary:
CMS combined results for the Higgs Boson decay to fermions



Thank you for your attention

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