LPNHE
PARIS

Higgs boson into fermions at ATLAS

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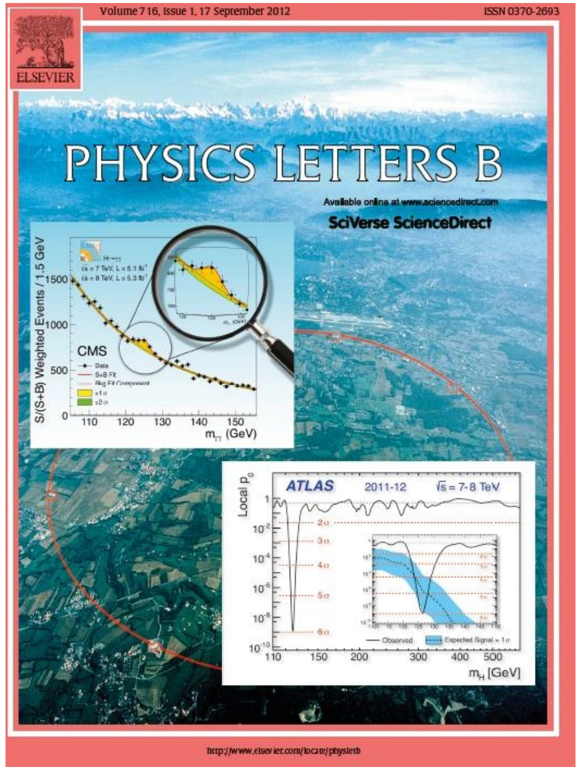
on behalf of the ATLAS Collaboration

La Thuile 2014 conference, Friday 28th February 2014

Higgs boson discovery

- **Summer 2012: Historic observation of Higgs boson particle with a mass of $m_H \simeq 125.5$ GeV from ATLAS and CMS**



- **Autumn 2013:**

The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

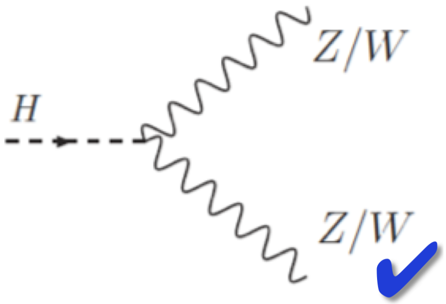
Photo: A. Mahmoud

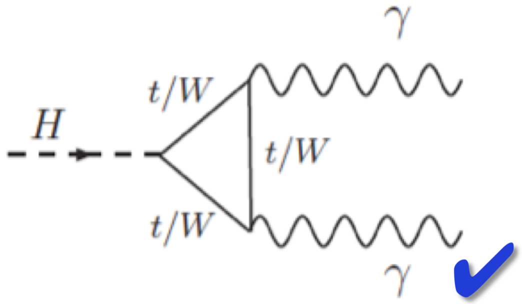
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

What did we discover exactly?

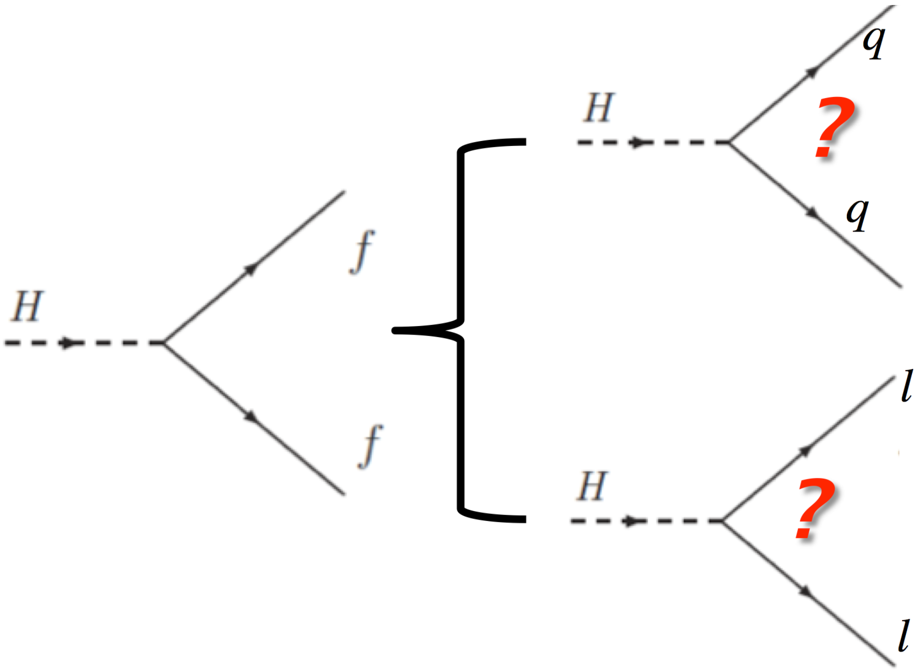
- Observation via ZZ*, WW* and γγ decay modes





- **Results** strongly favour **$J^P=0^+$** quantum numbers, **consistent** with **Standard Model** theory
  ➡ *See Magda's and Jean-Baptiste's talk in a while*

• Is the discovered Higgs boson coupling to fermions?



- quarks?

Most likely yes, because of the quark loop in gg-fusion/photon decay.

Nevertheless a direct measurement to quarks is necessary: H→bb

- leptons?

This is the question that the H→μμ and H→ττ analyses are addressing

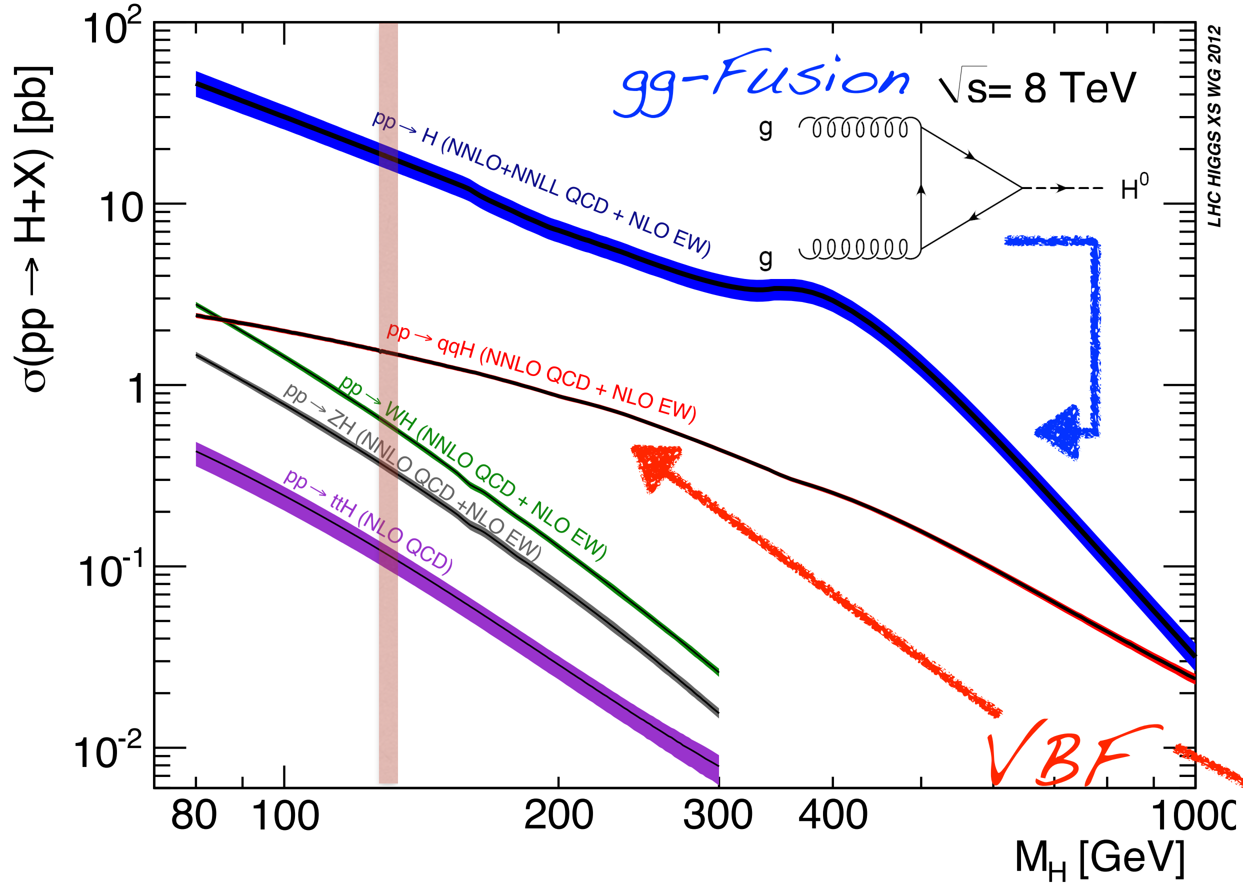
Outline

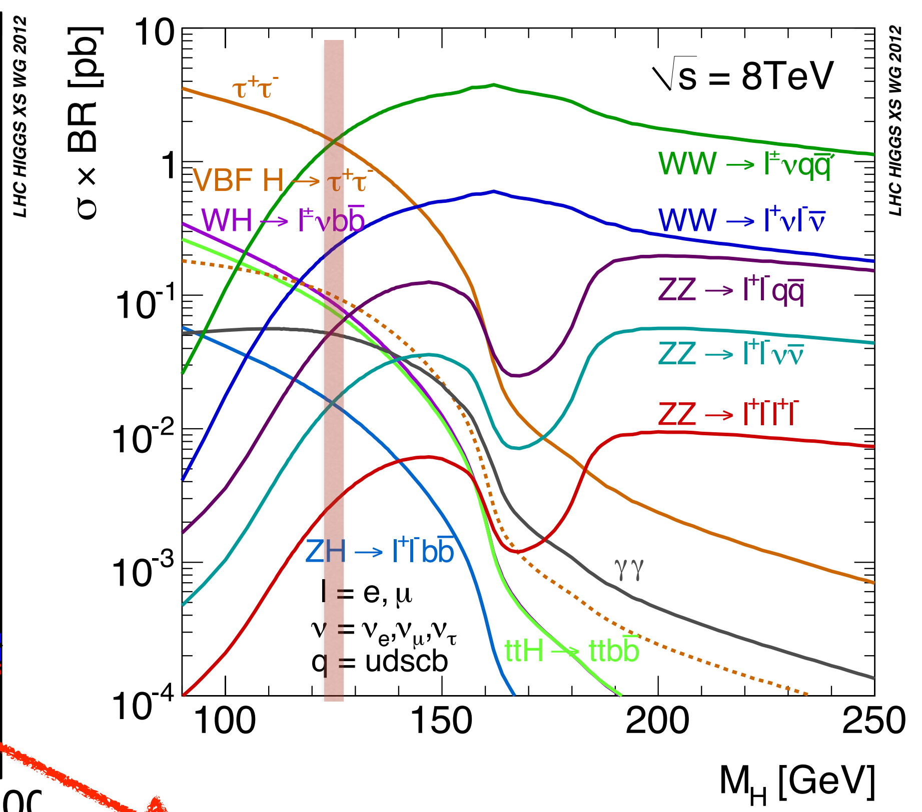
- ATLAS results covered in this talk
  - Search for **SM H→bb** with full 2011 & 2012 (7 & 8 TeV) dataset
    - *ATLAS-CONF-2013-079*
  - Search for **SM H→μμ** with full 2012 (8 TeV) dataset
    - *ATLAS-CONF-2013-010*
  - Search for **SM H→ττ** with full 2012 (8 TeV) dataset
    - *ATLAS-CONF-2013-108*

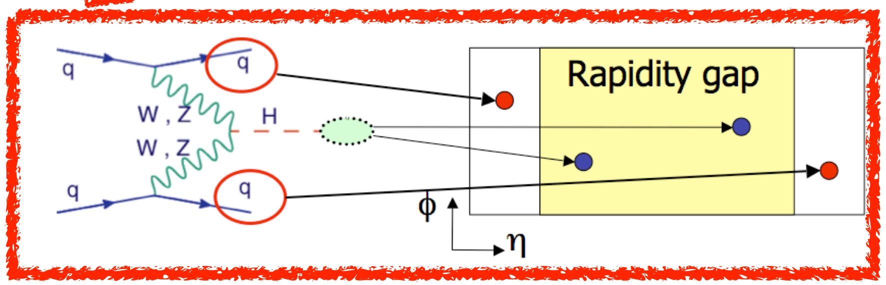
New!
Nov. 2013

- Not covered here
  - ttH (See Magda's talk in a while)
  - BSM searches for H→ff

Higgs phenomenology in LHC







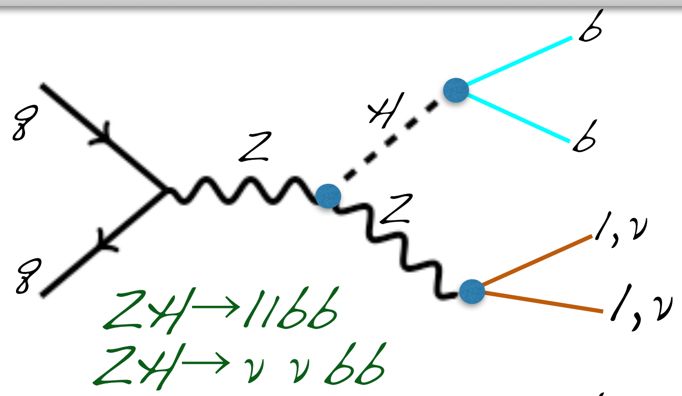
- **gg-Fusion,** dominant production mode
- **VBF** offers interesting topology for **ττ** with two forward jets
- **V(W,Z)H** smaller production rate but the most powerful channel to search for decays to b-quarks

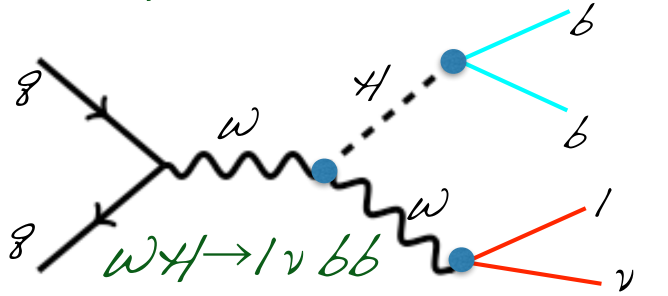
m	ττ	VH(bb)	μμ
σ×BR [pb]	~1.4	~0.08	~0.0002

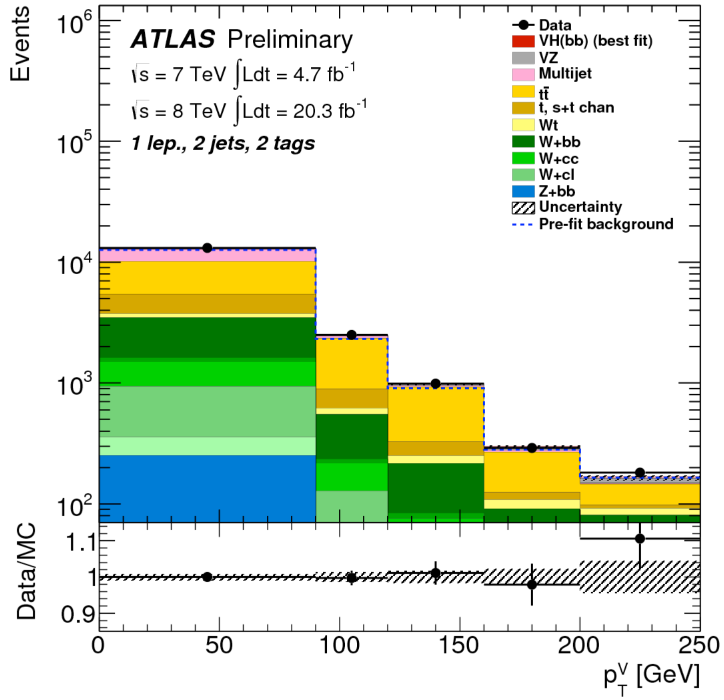
Probing fermionic couplings

- Decays
  - **SM VH→bb** with full 2011 & 2012 (7 & 8 TeV) dataset
    - *ATLAS-CONF-2013-079*
  - **SM H**
    - *ATLAS-CONF-2013-010*
  - **SM H**
    - *ATLAS-CONF-2013-108*

H→bb: Exploit unique production mode VH







- Production in association with a **leptonically** decaying **W/Z**
- Main challenges are **triggering** and **large backgrounds** over very small expected signals
  - **Trigger using leptonic W/Z decays or MET**
  - **Boost of W/Z** to control backgrounds
- Cut-based analysis in **3 final states** according to the number of leptons from W or Z decay
  - **ZH→ll+bb**: **2 opposite-sign leptons**, 2 b-tagged jets
    - Backgrounds: Z+heavy flavour
  - **ZH→νν+bb**: large MET, 2 b-tagged jets, **0 leptons**
    - Backgrounds: top, Z/W+heavy flavour
  - **WH→lν+bb**: **1 lepton**, MET, 2 b-tagged jets
    - Backgrounds: top, W+heavy flavour
- To maximise sensitivity split into bins of N_{jets}, $\mathbf{p_T^V}$
- **Search for peak in di-jet m_{bb} invariant mass**

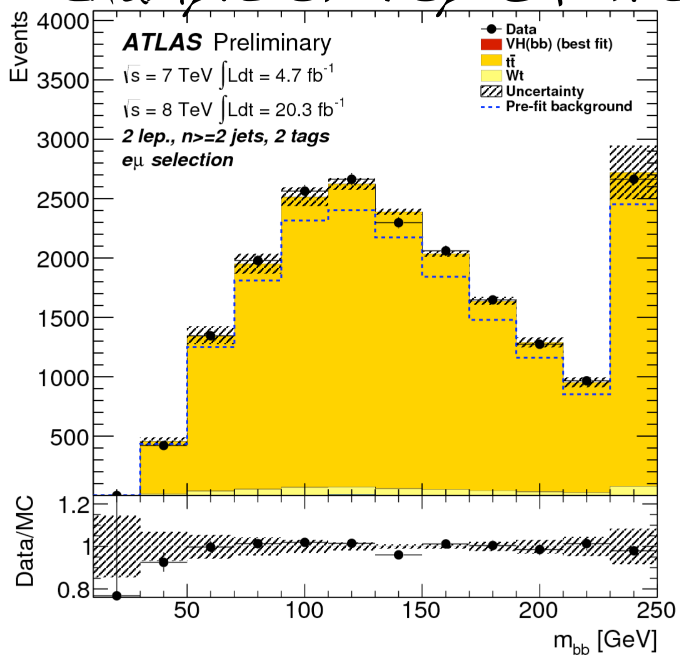
Background modelling

- Multijet: **Data driven** method
- Non multijet backgrounds: **Shape** from **MC**, **normalisation** from **Data** control regions (CR) included in the fit

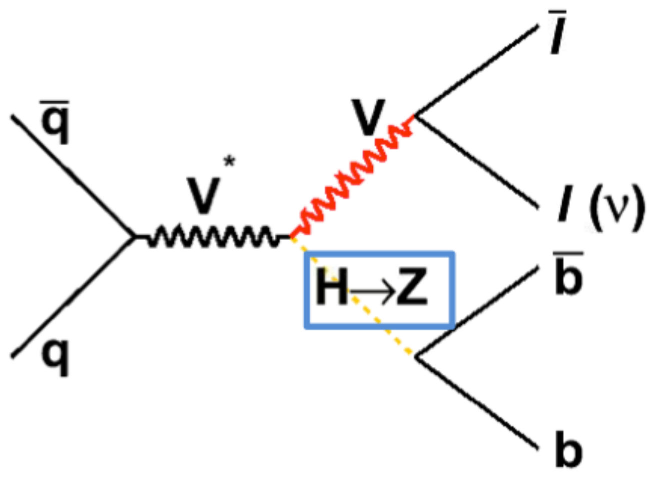
		2 jets 1 b-tag	3 jets 1 b-tag	2 jets 2 b-tags	3 jets 2 b-tags	Top CR eμ events
3 $p_T(V)$ bins	0-leptons	**CR**	**CR**	**SR**	**SR**	
5 $p_T(V)$ bins	1-lepton	**CR**	**CR**	**SR**	**SR**	
5 $p_T(V)$ bins	2-leptons	**CR**	**CR**	**SR**	**SR**	**CR**

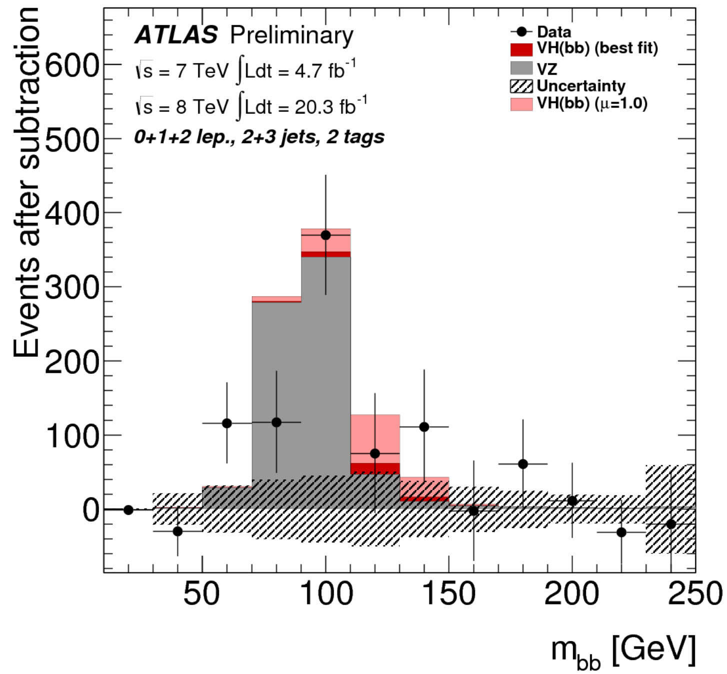
- Simultaneous fit in 26 signal regions (SR), 26 1b-tag CR's and 5 top CR's
- **Common nuisance parameters** (reflecting the systematic uncertainties) across SR's and CR's and channels/categories

Example of Top CR in eμ

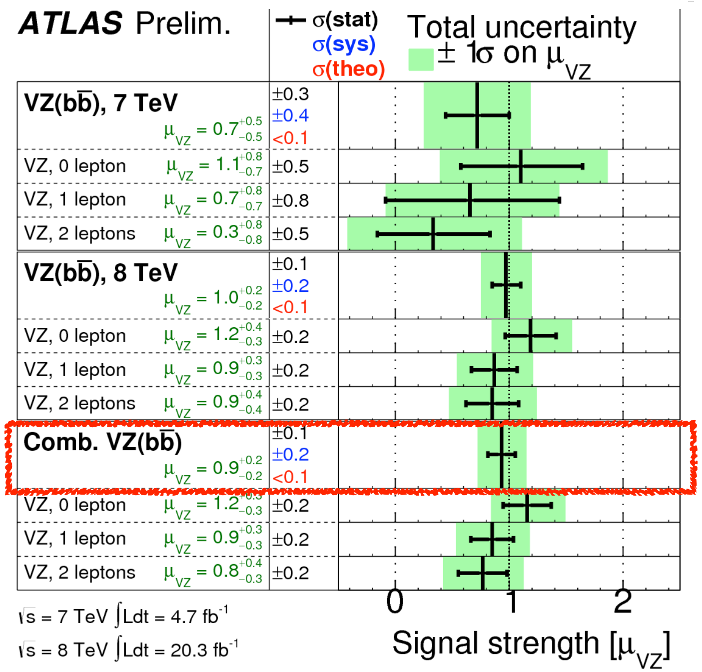


H→bb: Cross-check with VZ(bb)





- **VZ(bb)** similar signature with 5 times larger cross section than VH(bb)
- Measure VZ(bb): a direct **test** of the **analysis procedure**
- The obs. (exp.) significance of VZ is **4.8 (5.1) σ**
- $\mu_{VZ} = \sigma_{meas}(VZ)/\sigma_{SM}(VZ) = 0.9 \pm 0.2$



H→bb: Measured signal strength

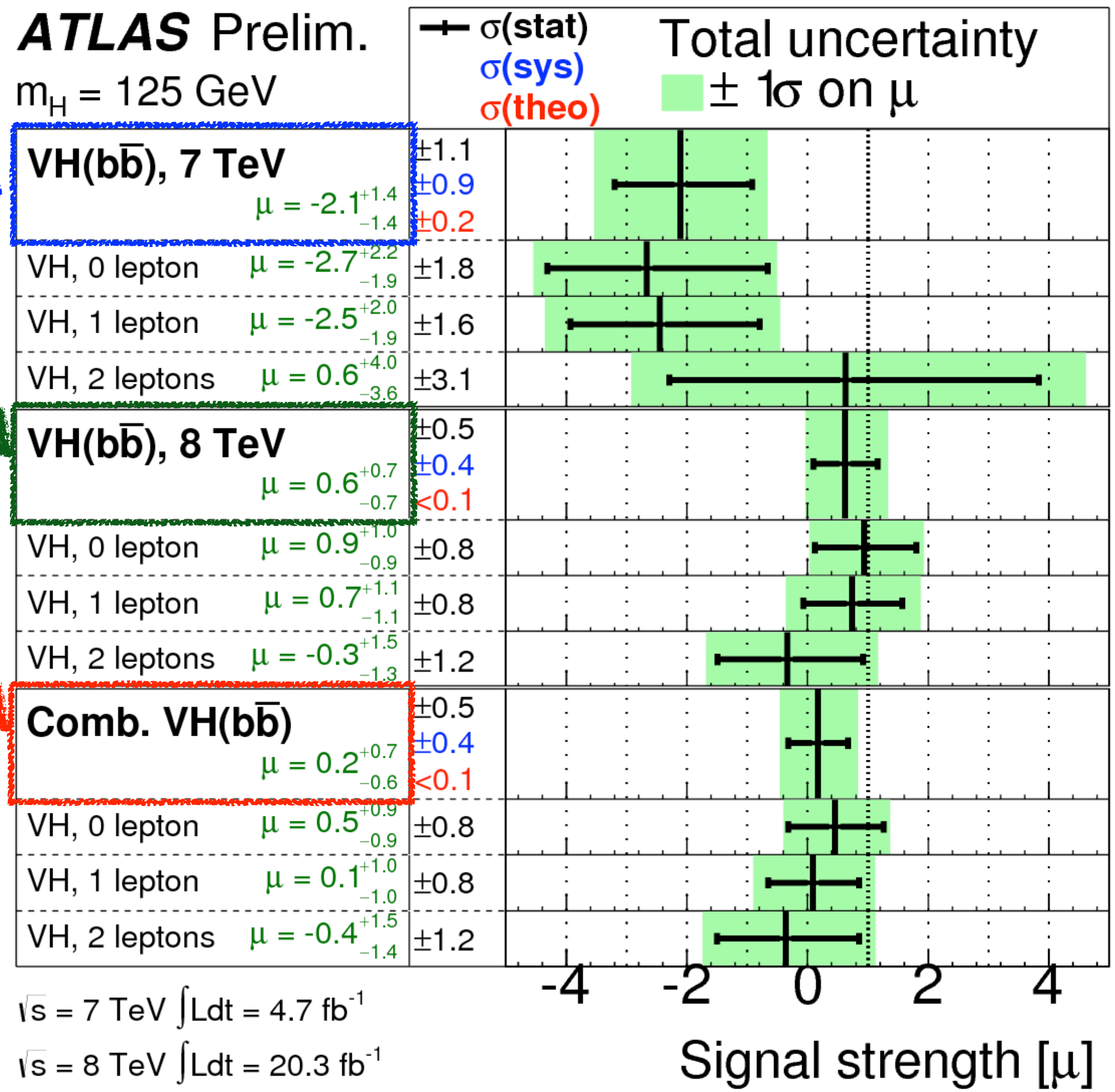
For m_H=125 GeV

- **7 TeV**
  - 2σ deficit wrt SM expectation
- **8 TeV**
  - Consistent with both S+B and B-only hypotheses within 1σ
- Combined result

$$\mu = \frac{\sigma^{VH\to b\bar{b}}_{measured}}{\sigma_{SM}} = 0.2^{+0.7}_{-0.6}$$

- **Observed**(**expected**) upper limit at 95% CL: **1.4**(**1.3**) x σ_{SM}

- Dominant uncertainties
  - ttbar modelling
  - b-tagging jet efficiency
  - Multijet normalisation in 1-lepton channel



- Most powerful channel: 0-lepton
- Small theory uncertainties for VH mode

Probing fermionic couplings

- Decays
  - **SM VH**
    - *ATLAS-CONF-2013-079*
  - **SM $H \to \mu\mu$** with full 2012 (8 TeV) dataset
    - *ATLAS-CONF-2013-010*
  - **SM H**
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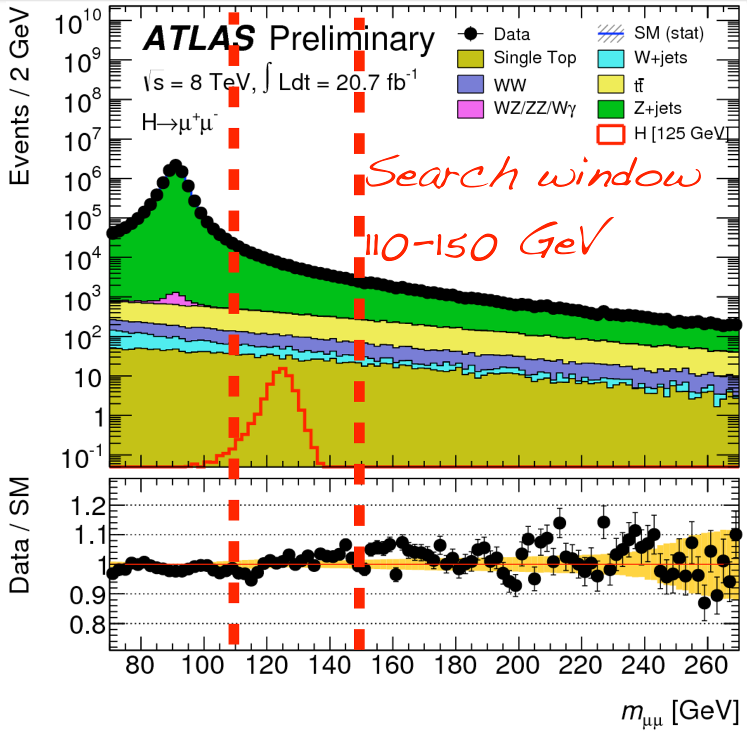
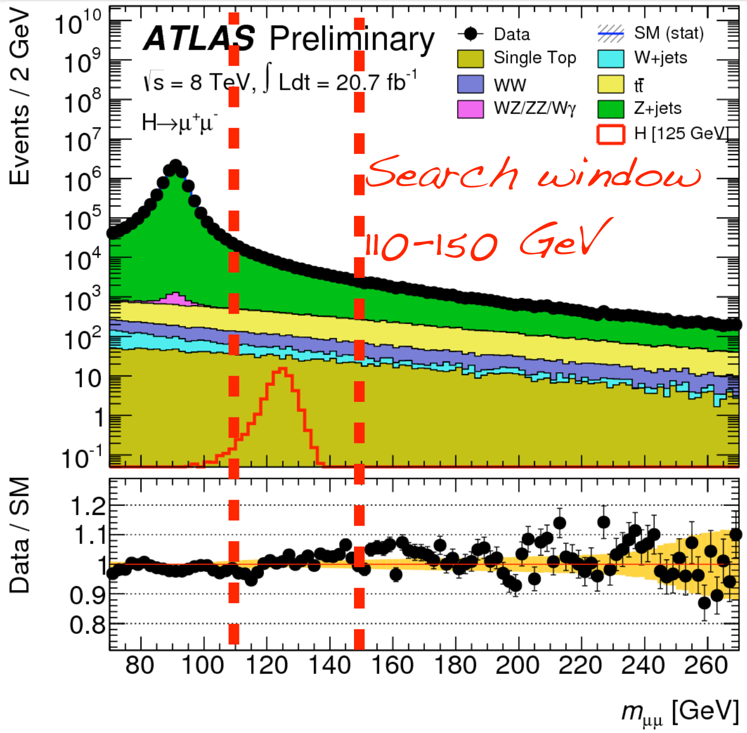
H→μμ: Analysis overview



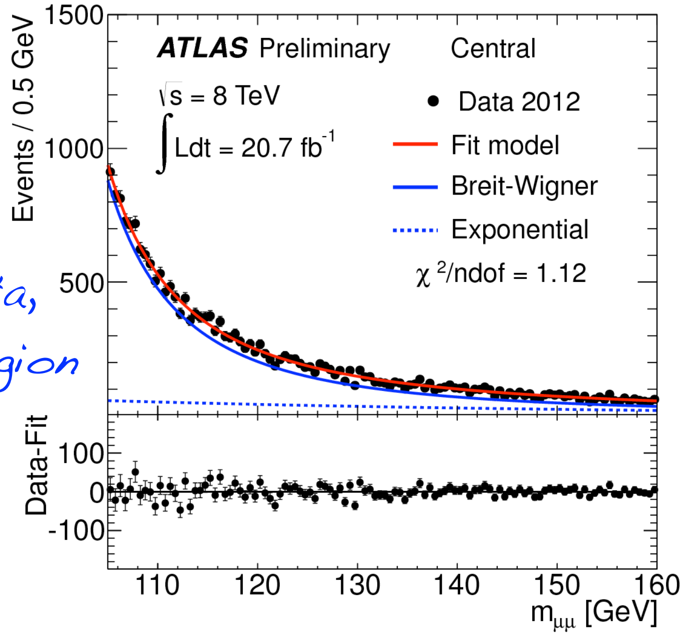
- **σ×BR (H→μμ) very small ~2×10^{-4} pb**
- Very good di-muon, $m_{\mu\mu}$, mass resolution
- Two categories based on muon resolution
  - ✦ a) Central: $|\eta|<1.0$ b) Non-central: rest
- ➡ Two isolated, opposite-charge muons: $p_T(\mu_1)>25$ GeV, $p_T(\mu_2)>15$ GeV

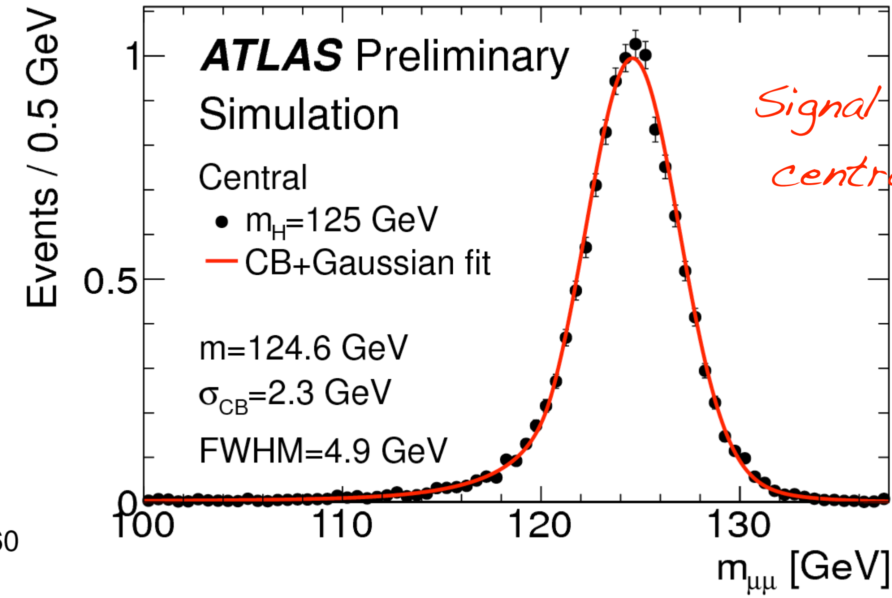
$H \rightarrow \mu\mu$: Analysis overview



- **σ×BR ($H \rightarrow \mu\mu$) very small ~2×10^{-4} pb**
- Very good di-muon, $m_{\mu\mu}$, mass resolution
- Two categories based on muon resolution
  - a) Central: $|\eta|<1.0$ b) Non-central: rest
- ➡ Two isolated, opposite-charge muons: $p_T(\mu_1)>25$ GeV, $p_T(\mu_2)>15$ GeV
- Fit $m_{\mu\mu}$ with analytic Signal+Background shape
  - **Background model:** Breit-Wigner + exponential PDFs
  - **Signal model:** Crystal Ball(CB) + Gaussian PDFs

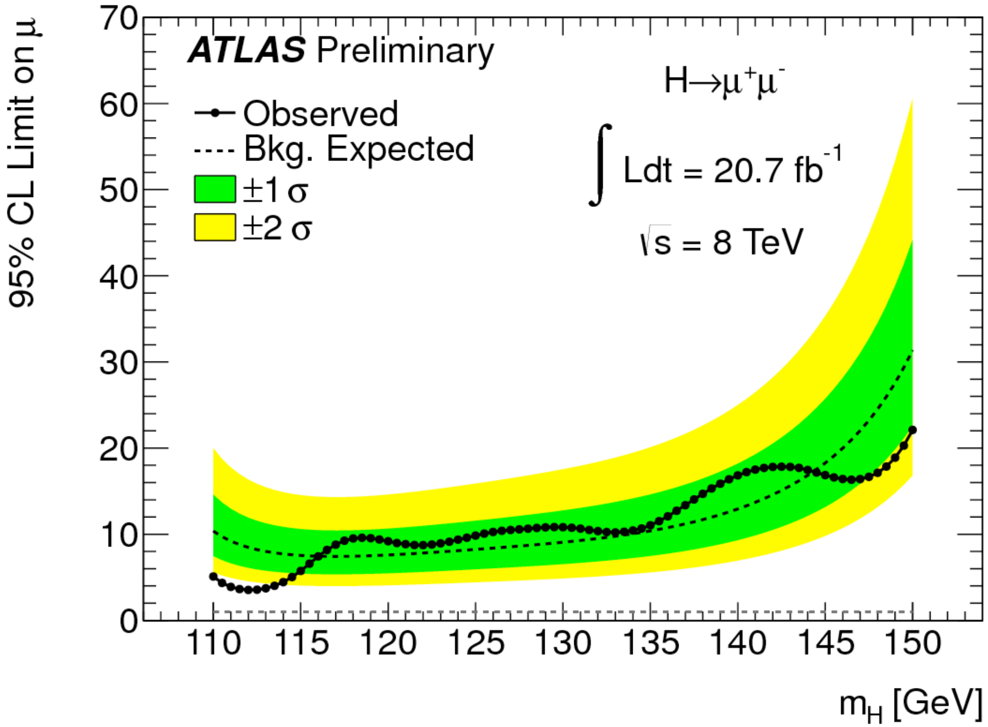
Fit to Data, central region





Signal fit, central region

H→μμ: Results



- Dominant systematic uncertainties
  - Cross section: 15%
  - BR(H→μμ): 6%
  - Acceptance uncertainty
    - Theory: ~3%
    - Experimental: ~4%

ATLAS results with 20.7 fb^{-1} at 8TeV

- No significant deviations observed
- Current sensitivity **not sufficient** for **conclusive statement**
- 95% CL limit @ 125 GeV: **observed**(**expected**) **9.8**(**8.2**)$\times\sigma_{SM}$

Probing fermionic couplings

- Decays
  - **SM VH**
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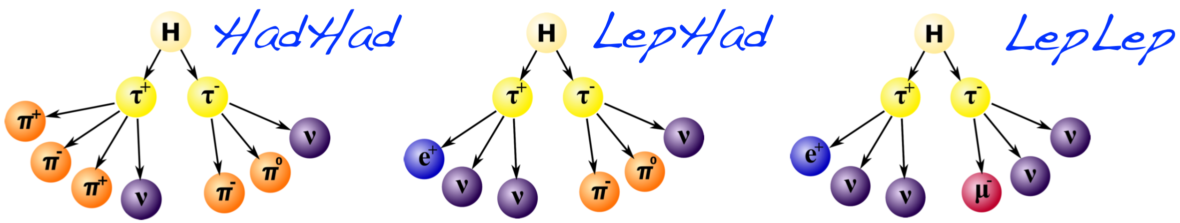
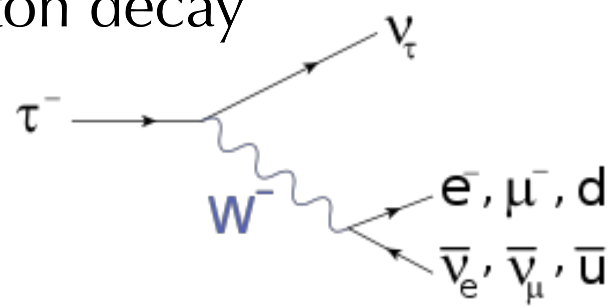
New!
Nov. 2013

H→ττ search: Analysis concept

- Question that this analysis attempts to address
  - ✦ **Does the Higgs boson with $m_H \simeq 125.5$ GeV decay to a pair of τ-leptons?**
- Analysis strategy
  - ✦ Achieve maximum sensitivity by performing a **multivariate analysis: Boosted Decision Trees (BDT)**
- Perform analysis in **3 channels** according to the τ lepton decay

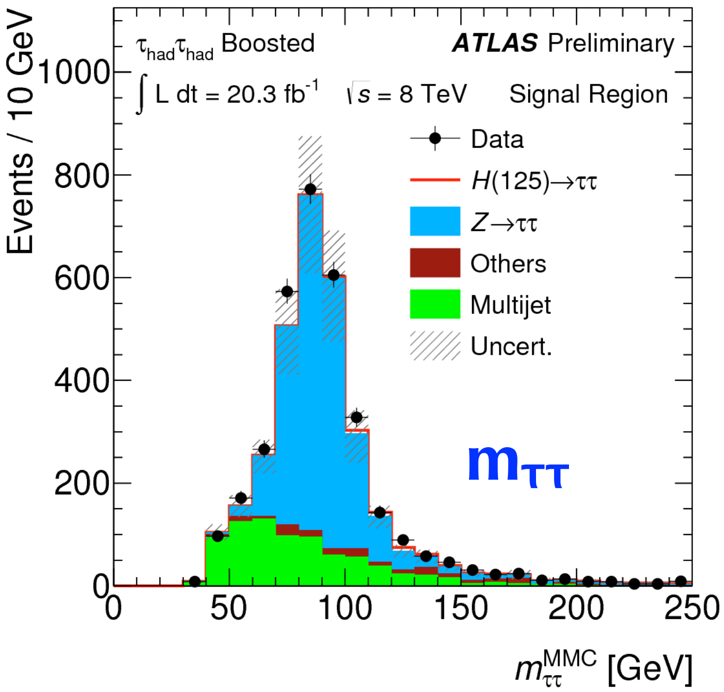


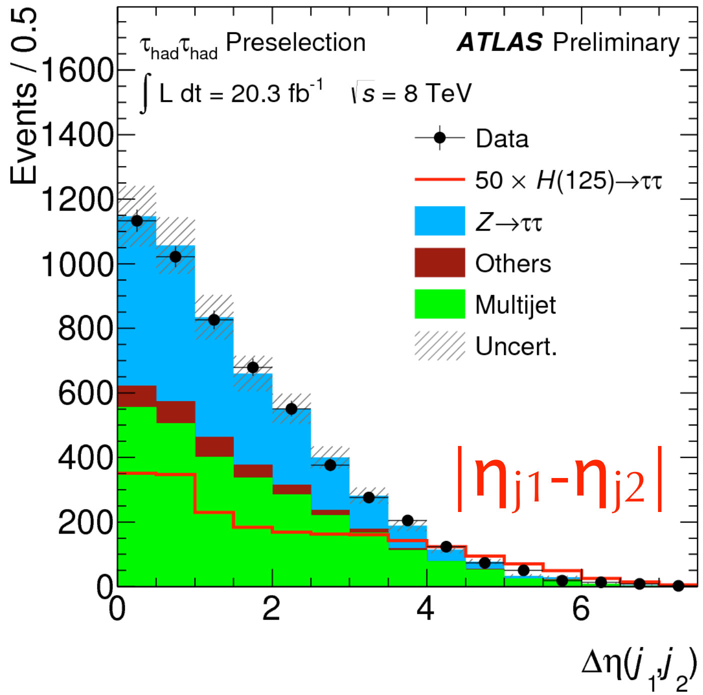
$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$	$\tau_{lep}\tau_{lep}$
hadronic-hadronic	**leptonic-hadronic**	**leptonic-leptonic**
42%	46%	12%



- And in **2 categories** per channel
  - ✦ **VBF:** 2 jets with leading(sub-leading) p_T>50(30) GeV, $\Delta\eta(jj)$>3
  - ✦ **Boosted:** $p_T(H)$>100 GeV , $p_T(H)$: MET + $p_T(\tau_1)$ + $p_T(\tau_2)$
- Different **BDT** per channel and per category: **6** BDT's
  - ✦ Keep simple selection and let the **BDT separate signal and background**
  - ✦ **Final discriminant: BDT score**

Input variables to BDT



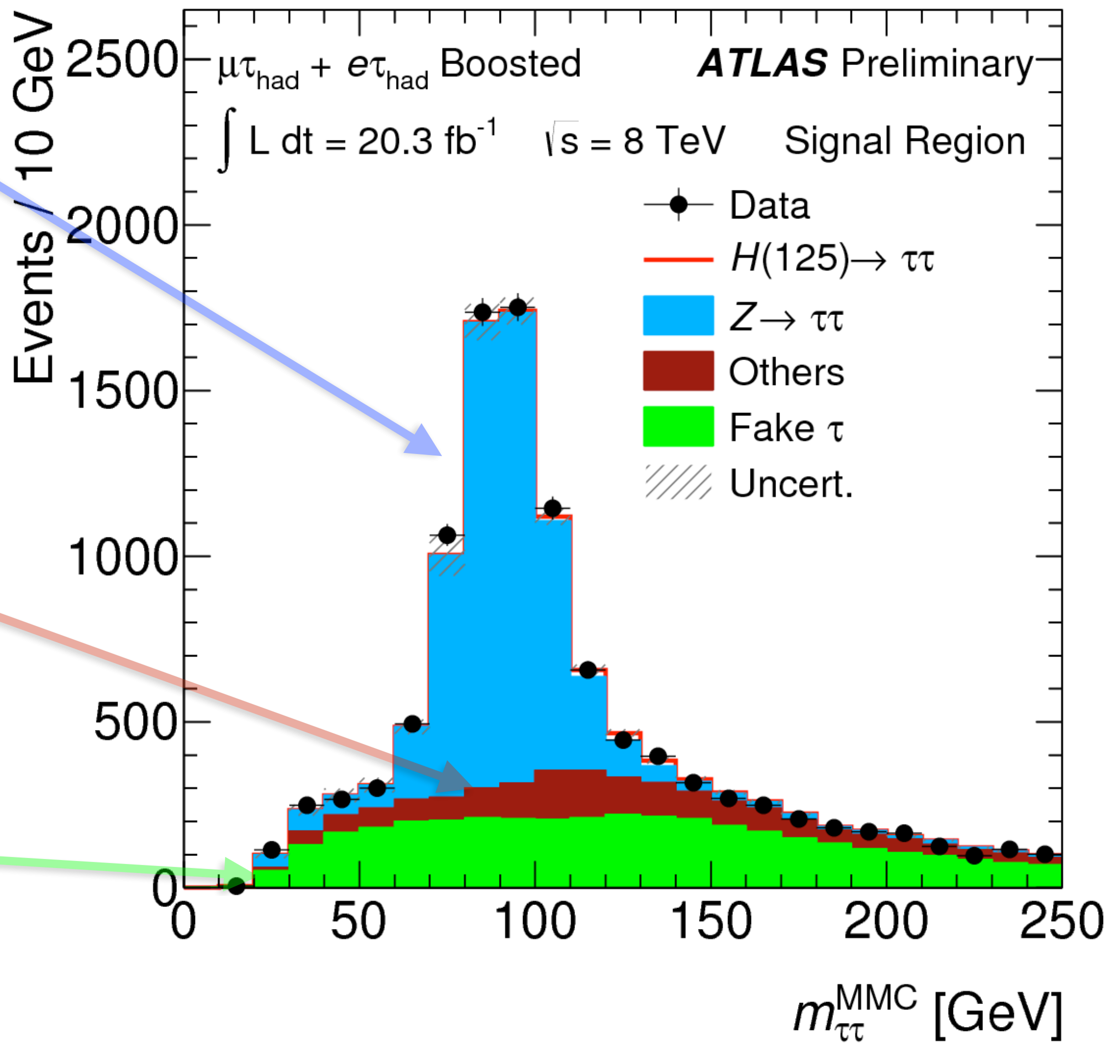


- Probe **resonance properties**
  - $m_{\tau\tau}$, $\Delta R(\tau\tau)$
  - **$m_{\tau\tau}$: Missing Mass Calculator (MMC)** Precise di-tau mass estimator based on a kinematics likelihood, $\sigma_{m_{\tau\tau}}$~16%
- Explore event topology
  - MET, m_T, object centralities
- **VBF** specific, for the 2 VBF jets

- $m_{\tau\tau}$ the most important discriminating variable
- Careful **validation** of BDT input variables and BDT output score distribution in dedicated **background enriched control regions**

Estimating the backgrounds

- Dominant $Z \rightarrow \tau\tau$
  - Embedded samples: Except for tau decays, all event properties are taken from data $Z \rightarrow \mu\mu$ events
- Others
  - Di-boson, $Z \rightarrow ee/\mu\mu$, top
  - $H \rightarrow WW$ for LepLep channel
  - Shape from simulation, normalisation from data
- Fake τ
  - Multijet, W+jets
  - Data-driven methods



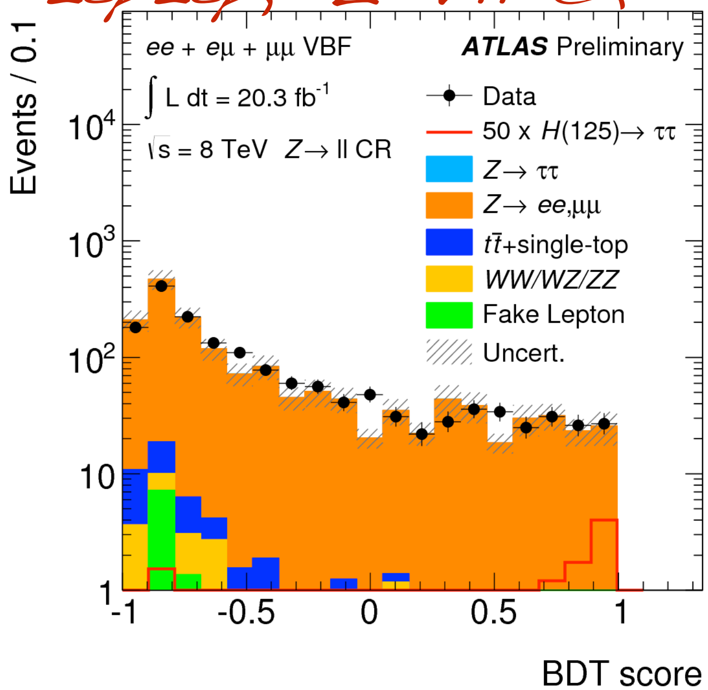
Signal extraction

	VBF Category		Boosted Category		Rest Category*
	SR	CR	SR	CR	CR
$H \to \tau_{lep}\tau_{lep}$	✔	✔ Z→ll (1 bin) & Top (1 bin)	✔	✔ Z→ll (1 bin) & Top (1 bin)	✘
$H \to \tau_{lep}\tau_{had}$	✔	✔ Z→ll (1 bin) & Top (1 bin)	✔	✔ Z→ll (1 bin) & Top (1 bin)	✘
$H \to \tau_{had}\tau_{had}$	✔	✘	✔	✘	✔ $\Delta\eta(\tau_1,\tau_2)$ (shape)

- We fit the **Background** + $\boxed{\mu}$×**Signal** model to the data using the BDT score distributions
- **6 Signal Regions (SR)** & **9 Control Regions (CR)** used in the fit

$$\boxed{\mu = \frac{\sigma_{measured}}{\sigma_{SM}}}$$

LepLep, Z->ll CR



*Rest category:
Events failing VBF &
Boosted selection

Signal extraction

	VBF Category		Boosted Category		Rest Category*
	SR	CR	SR	CR	CR
$H \rightarrow \tau_{lep}\tau_{lep}$	✔	✔ Z→ll (1 bin) & Top (1 bin)	✔	✔ Z→ll (1 bin) & Top (1 bin)	✘
$H \rightarrow \tau_{lep}\tau_{had}$	✔	✔ Z→ll (1 bin) & Top (1 bin)	✔	✔ Z→ll (1 bin) & Top (1 bin)	✘
$H \rightarrow \tau_{had}\tau_{had}$	✔	✘	✔	✘	✔ $\Delta\eta(\tau_1,\tau_2)$ (shape)

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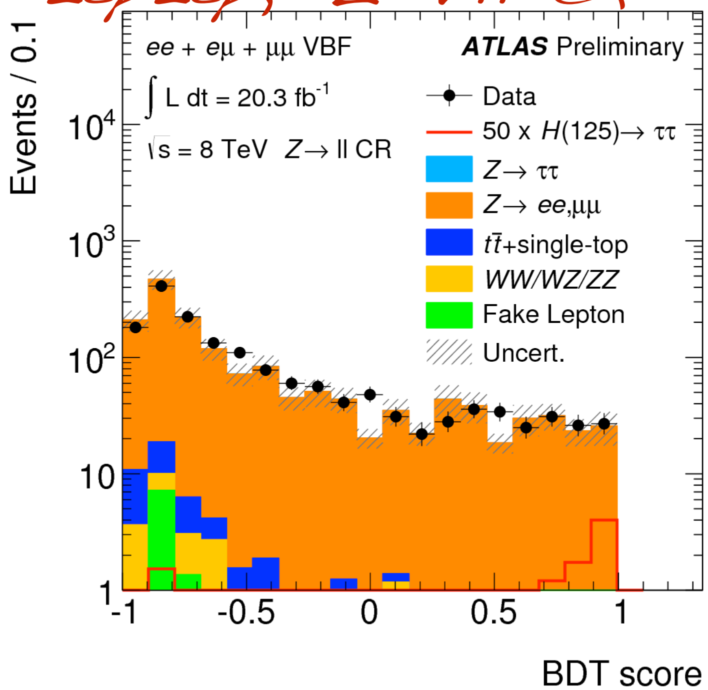
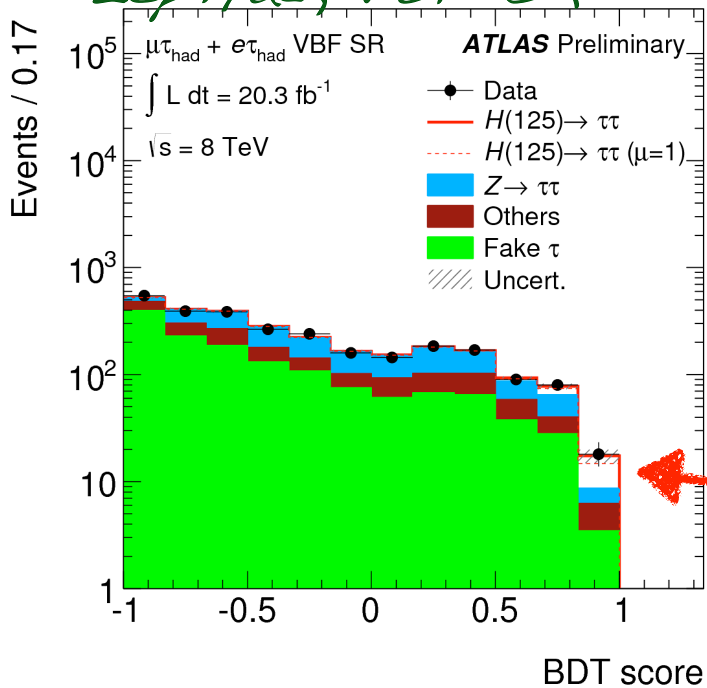


LepHad, VBF SR



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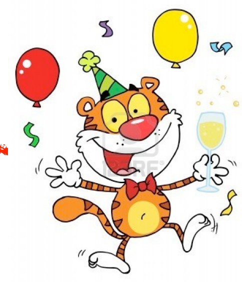
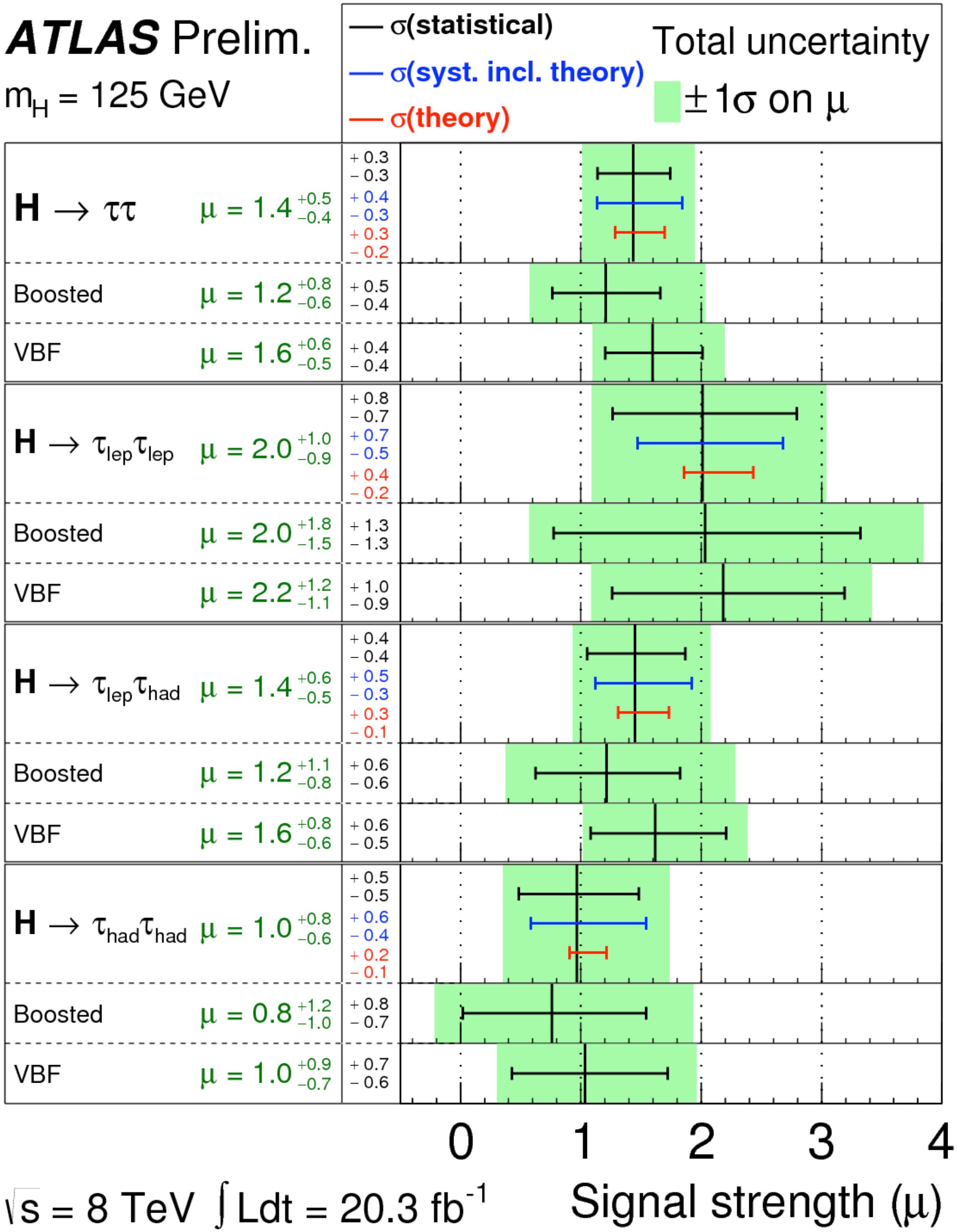


Signal Strength μ

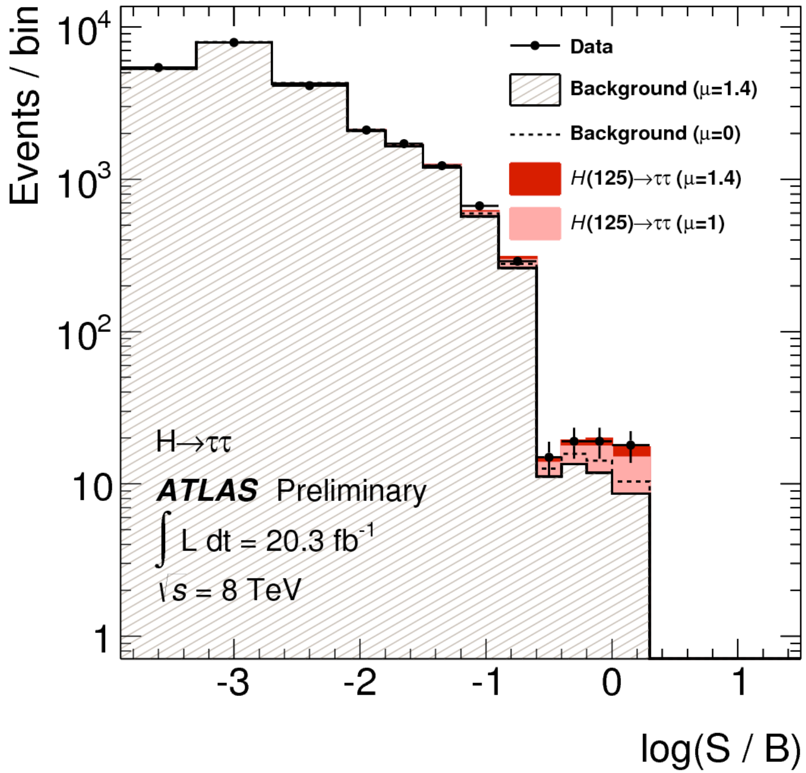


- Measured signal strength
  - $\mu = 1.4^{+0.5}_{-0.4}$
  - Boosted category: $\mu = 1.2^{+0.8}_{-0.6}$
  - VBF category: $\mu = 1.6^{+0.6}_{-0.5}$

Consistent with SM Higgs boson predictions !

- Leading uncertainty due to **limited statistics** in the **high BDT score bins** that drive the best fit value
- **Theory uncertainty** ranked high
- Leading experimental uncertainties come from the **background normalisation**

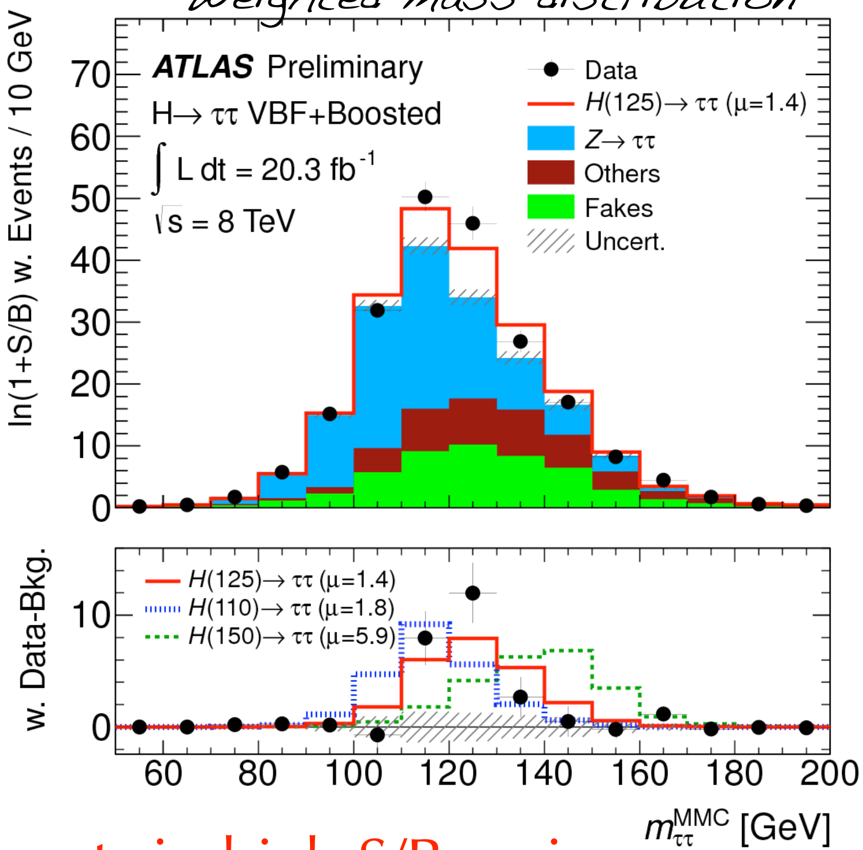
H→ττ significant excess observed



Number of events in highest BDT-score bin

VBF	LepHad
Signal	8.7±2.5
Bckgr.	8.7±2.4
Data	19

Weighted mass distribution



- ATLAS observes significant excess of data events in high S/B region
  - ✦ **Expected** significance @ m_H=125 GeV : **3.2σ** (Probability: **6.6×10^{-4}**)
  - ✦ **Observed** significance @ m_H=125 GeV : **4.1σ** (Probability: **2×10^{-5}**)
  - ✦ Excess observed in all three channels
  - ✦ **Observed signal compatible with m_H=125 GeV**
- **Direct evidence of 4.1σ that the Higgs boson couples to leptons**

Conclusions

- **Fermionic sector: an exciting and active constituent of the Higgs boson physics programme in ATLAS**

- Presented the ATLAS results
  - **VH(bb): μ=0.2±0.7** compatible both with signal+background and background-only hypothesis
  - **$\mu\mu$:** 95% CL limit: **$<10\times\sigma_{SM}$**
  - **$\tau\tau$:** Strong evidence of **4.1σ**, signal strength **$\mu = 1.4^{+0.5}_{-0.4}$**

- Stay tuned, preliminary results will be updated by papers

VBF H→ττ event

- LepLep event from May 2012

- mu p_T=53 GeV
- el p_T=34 GeV
- E_T^{miss}=102 GeV

- $m_{\tau\tau}$=127 GeV
- BDT=0.99