Search for the Higgs boson in fermionic channels using ATLAS detector

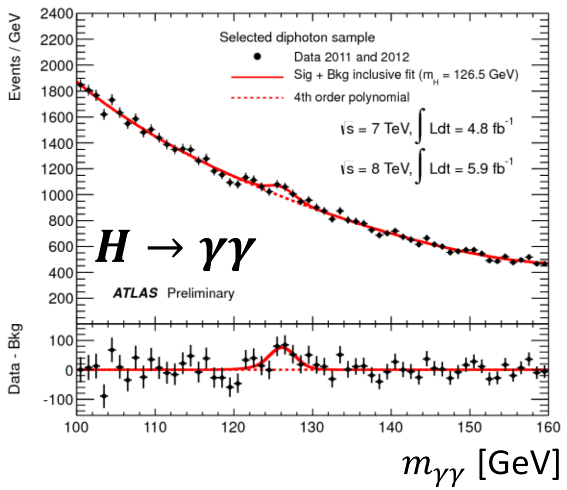
2014 Dec 1st
Discovery Physics at the LHC

Kruger 2014, South Africa

Kazuya Mochizuki,
on behalf of the ATLAS collaboration

Centre de Physique des Particules de Marseille (CPPM)

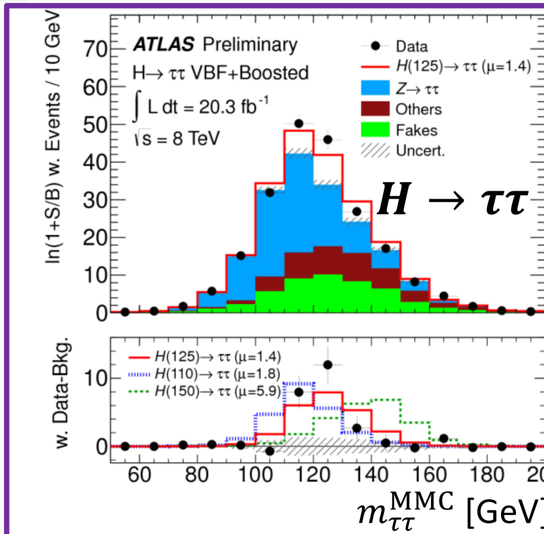
Since the discovery…



2012 July 4th, observation of a new boson @m~125 GeV

2013 Oct.

Nobel Prize in physics 2013

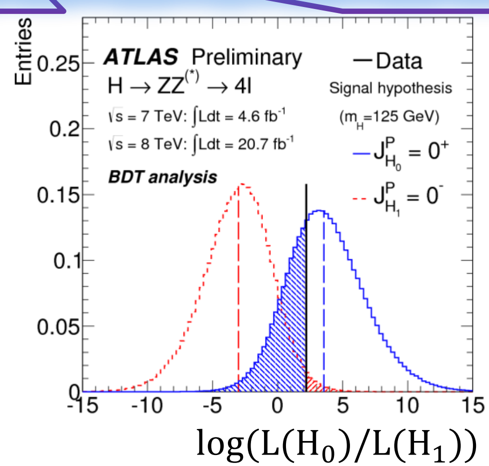


2013 Nov.
Evidence for $H \to \tau\tau$

2012 | **2013** | **2014** | **2015**

LHC Run 1 ------->   Long shutdown --------------------------->

2013 Mar.
Spin 0 with positive parity compatible with SM Higgs boson with Spin CP measurement



2014 Dec.
Everything seems consistent with the SM. ⇒ Precise measurement is very important with

- Mass
- **Couplings**
  Especially with ***fermions***
- Spin / CP

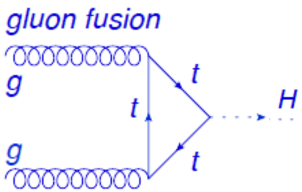
Higgs searches with fermions at ATLAS

Recently updated. Main topics in this talk.

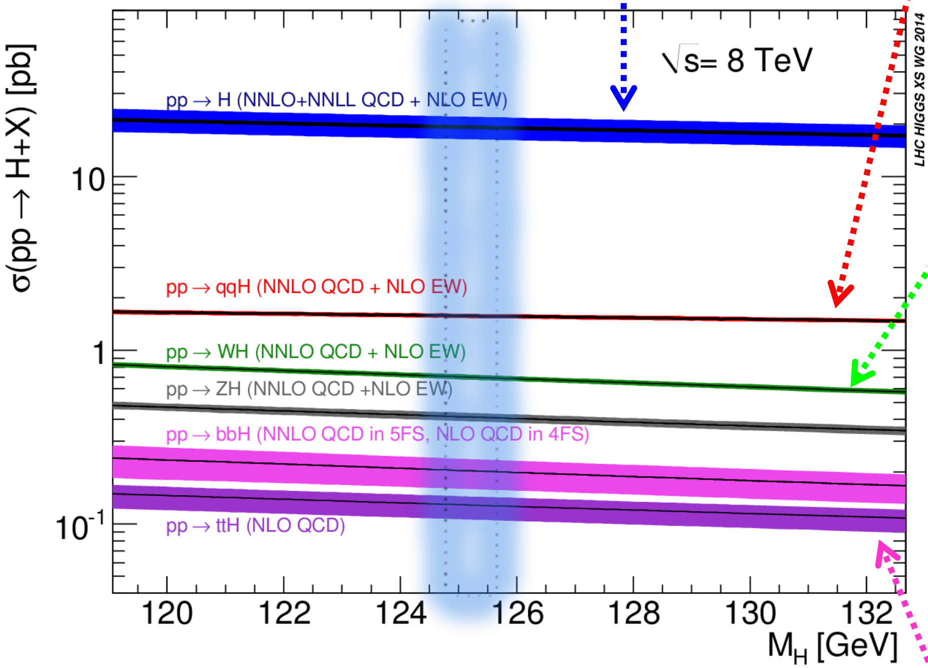
	Channel	Reference and released date	Paper submitted to
New	$H \to \tau\tau$	ATLAS-CONF-2014-061 2014 Oct 7	-
	$H \to \mu\mu$	Physics Letters B doi:10.1016 2014 Jun 30	PLB
New	$VH \to Vbb$	arXiv: 1409.6212 2014 Sep 22	JHEP
	$ttH \to ttbb$	ATLAS-CONF-2014-011 2014 Mar 24	-
	$ttH \to tt\gamma\gamma$	arXiv:1408.7084 2014 Aug 27	PRD
	$tH \to tbb$	arXiv:1409.3122 2014 Sep 10	PLB

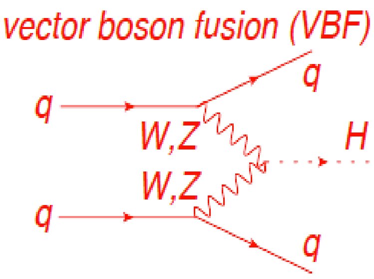
Other related talks on SM Higgs	Wed. 3rd	Speaker
For Higgs combinations and properties	9:15	Kyle CRANMER
For prospect studies	10:45	Philip CLARK
For ttH channels	14:30	Giuseppe SALAMANNA

Higgs production modes

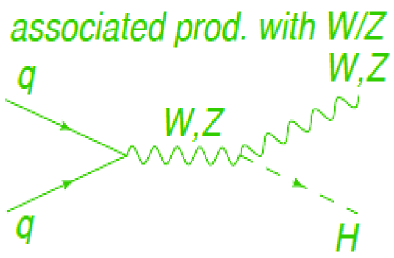


- Largest cross section: 19.27 pb @ 125 GeV
- Large theory uncertainty ~10%

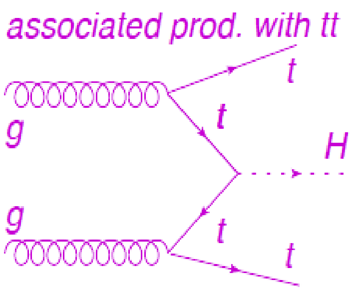




- 2nd Largest cross section: 1.58 pb @ 125 GeV
- Discriminative topology with 2 forward jets
- Main target of $H \to \tau\tau$ analysis



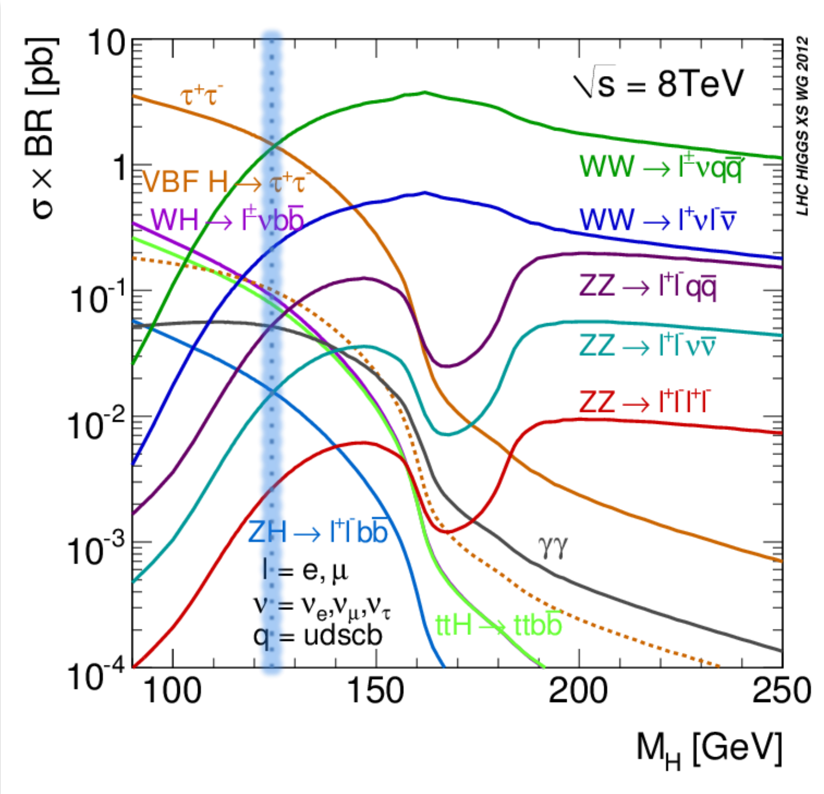
- Cross section @ 125 GeV: 0.7 (0.42) pb for WH (ZH)
- Associated leptonic W/Z for trigger
- Main target of $H \to bb$ analysis



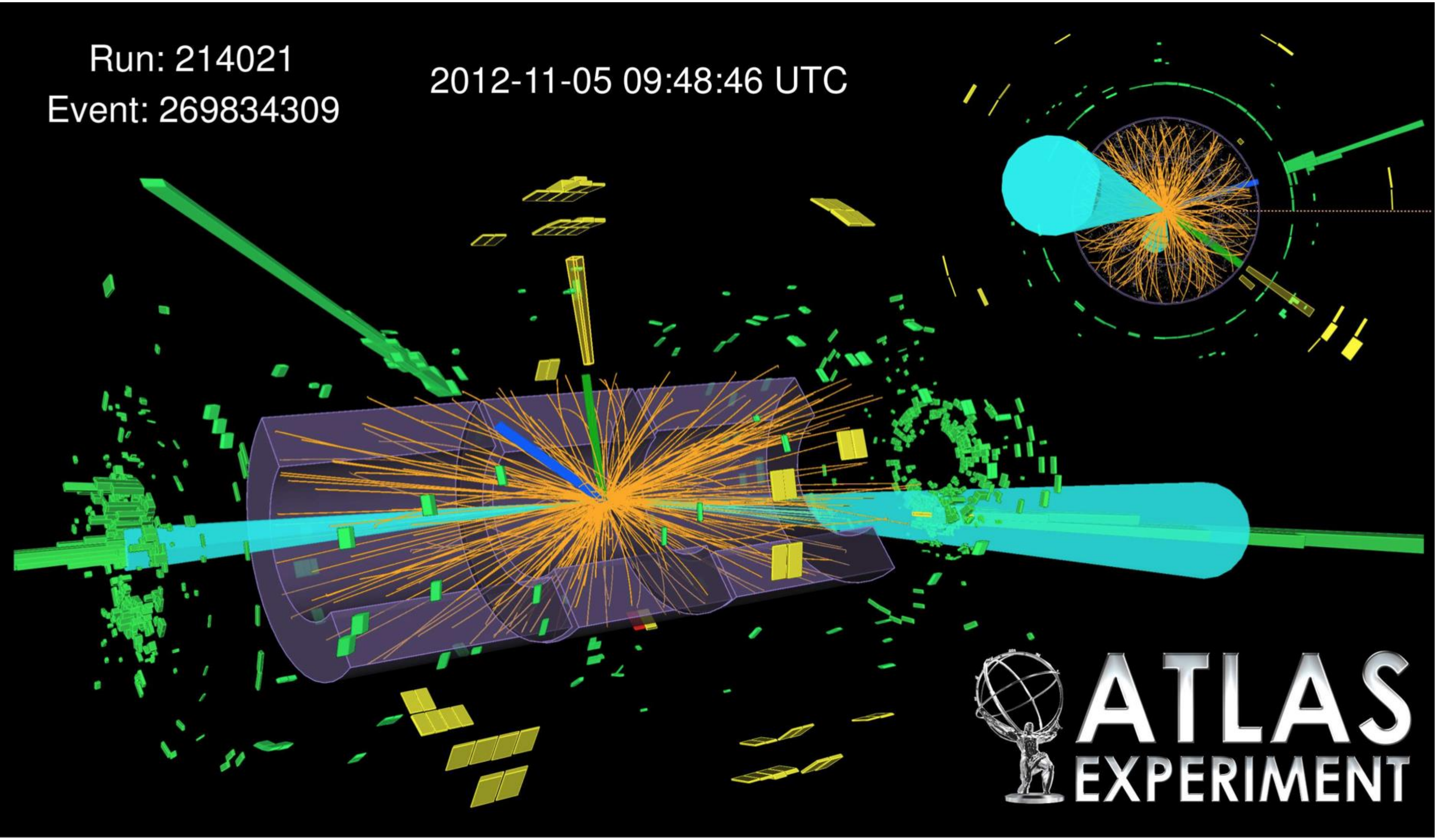
- Cross section: 0.13 pb @ 125 GeV
- Important for top Yukawa coupling measurement
- Busy and complex final state

Talk Outline

1. *Searches with leptons*
    1. $H \rightarrow \tau\tau$
    2. $H \rightarrow \mu\mu$
2. *Searches with quarks*
    1. $VH,\ H \rightarrow bb$



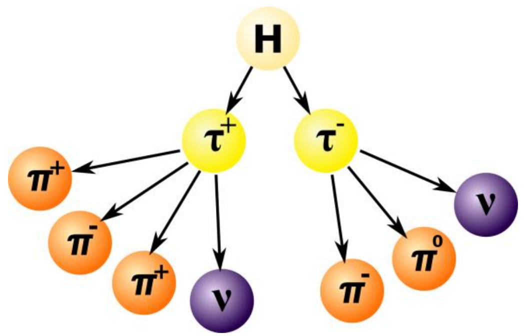
Br($H \rightarrow \tau\tau$) = 6.3%
Br($H \rightarrow \mu\mu$) = 0.02%
Br($H \rightarrow bb$) = 58%
m_H = 125 GeV

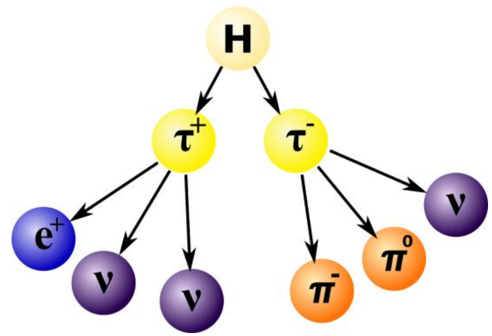


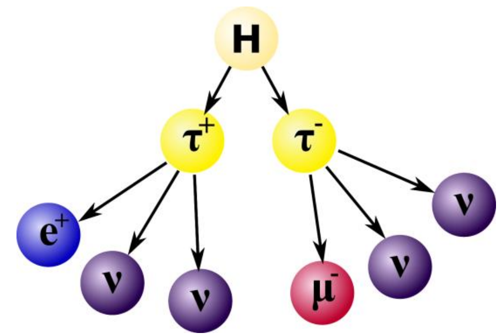
VBF $H \rightarrow \tau_e \tau_{\mathrm{had}}$ candidate in Run 1

$H \rightarrow \tau\tau$ analysis channels

- The search is split into 3 sub-channels based on τ decay modes.







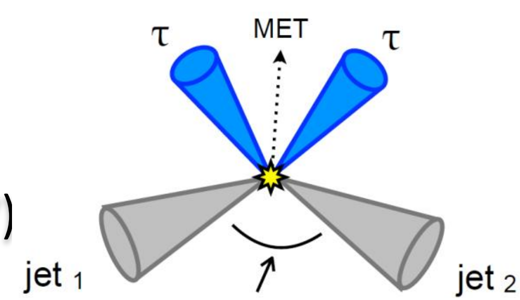
$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm lep}$
42%	45.6%	12.4%
Large BR	Large BR	Small BR
High multi-jet background	Clean final state	Very clean final state

$\tau_{\rm had}\tau_{\rm had}$:
- 2 isolated $\tau_{\rm had}$
- $E_{\rm T}^{\rm miss}$

$\tau_{\rm lep}\tau_{\rm had}$:
- 1 isolated lepton
- 1 isolated $\tau_{\rm had}$
- $E_{\rm T}^{\rm miss}$

$\tau_{\rm lep}\tau_{\rm lep}$:
- 2 isolated lepton
- Higher $E_{\rm T}^{\rm miss}$

- 2 main production modes targeted
  - **Boosted** category ($gg \rightarrow H$):
    The Higgs candidates have high $p_{\rm T}$ (> 100 GeV)
  - **VBF** category:
    VBF event topology tagged with 2 jets with large $\Delta\eta(j_1, j_2)$

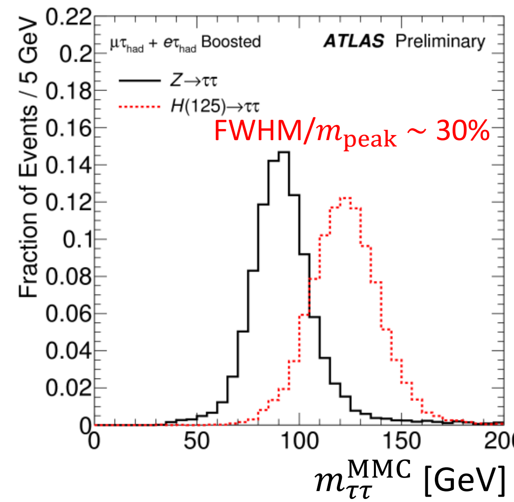


$H \to \tau\tau$ analysis strategy

- 2 analyses to confirm each other
  - Multi-variate analysis(MVA):

    Fit BDT output which combines kinematic variables together with $m_{\tau\tau}^{\mathrm{MMC}}$.
  - Cut-based analysis:

    Fit $m_{\tau\tau}^{\mathrm{MMC}}$ ($m_{\tau\tau}$ reconstructed with missing mass calculator).
    Cross-check for MVA.

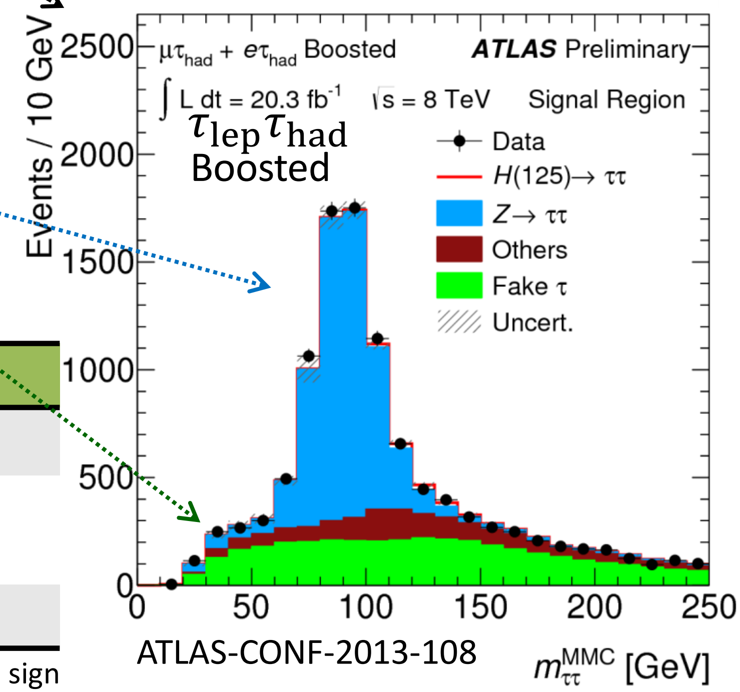


Missing mass calculator (MMC)
Use tau-decay PDFs to pick most likely di-tau invariant mass given visible decay products and $E_{\mathrm{T}}^{\mathrm{miss}}$

- Main backgrounds: modeled by data-driven methods
  - *$Z \to \tau\tau$*, **irreducible background**

    Modeling is based on embedding sample (next page)
  - **Tau fakes or lepton fakes (W+jets, multi-jets)**

    Cannot be predicted by MC => data-driven methods below



ATLAS-CONF-2013-108

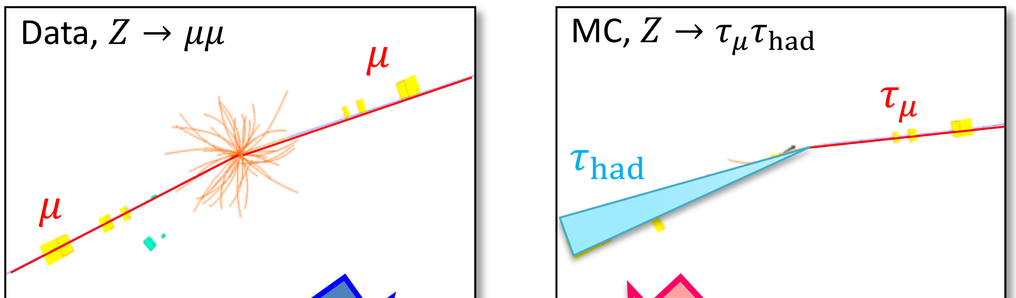
Channel	Estimation method	Control region (CR)
$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	Multijet-fit on $p_{\mathrm{T}}^{\ell_2}$	Inverted lepton isolation
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	Fake-factor method	Inverted τ-id with dedicated CR for different processes
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	Multijet-fit on $\Delta\eta_{\tau\tau}$	OS⇔SS inversion, τ isolation inversion

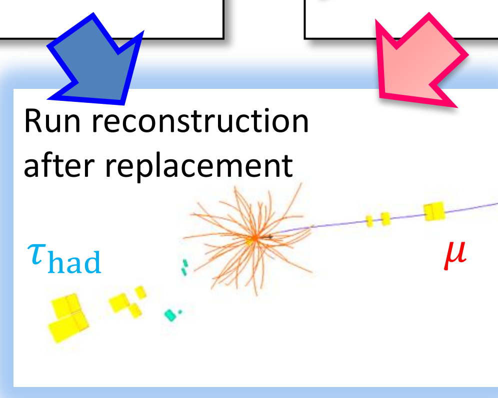
Charge requirements on τ decay product: OS=opposite sign, SS=same sign

$Z \rightarrow \tau\tau$ background estimation

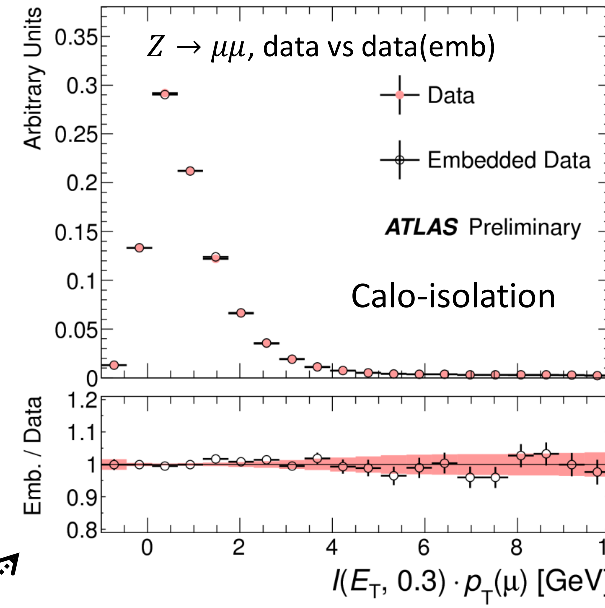
Tau-embedding technique

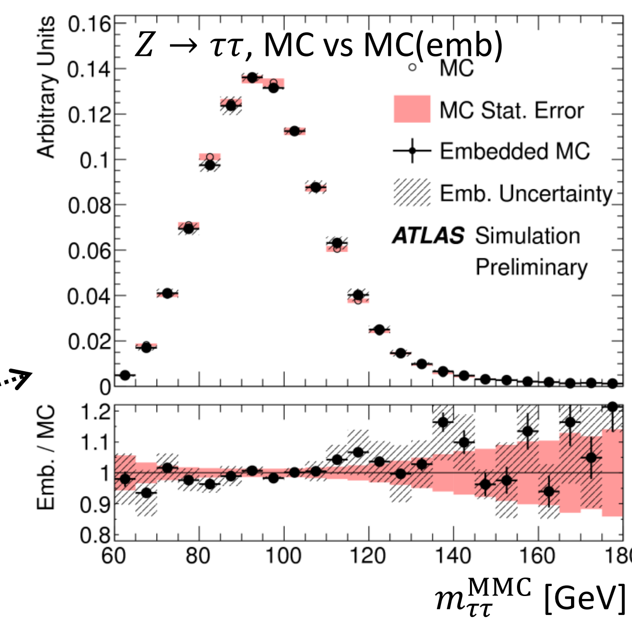
- Estimate shape of $Z \rightarrow \tau\tau$ from $Z \rightarrow \mu\mu$ data
  - Remove μ tracks and calorimeter cells
  - Replace μ with τ from full-simulated $Z \rightarrow \tau\tau$ decays generated with TAUOLA





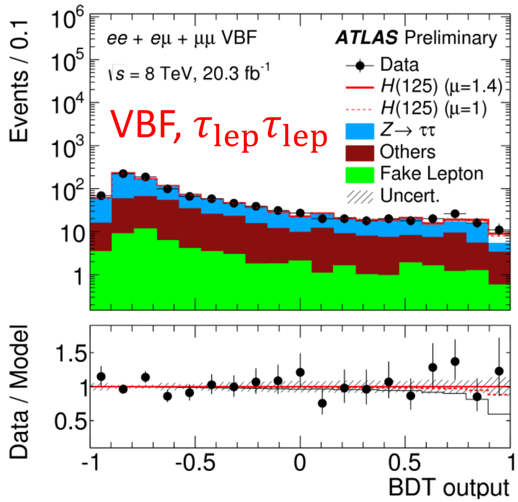
- Event content from data except τ decay
- Validation of the procedure with
  - $\mu \rightarrow \mu$ replacement in data
  - $\mu \rightarrow \tau$ replacement in MC

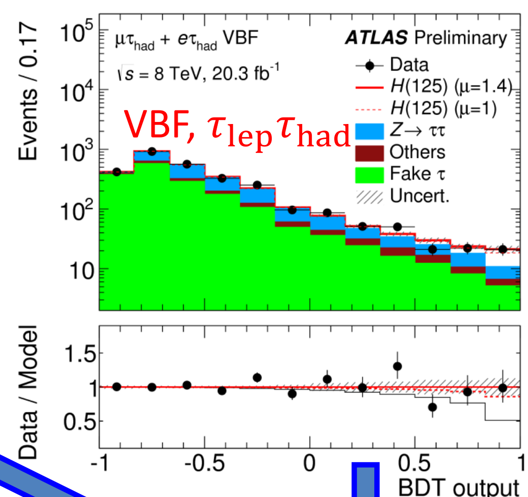


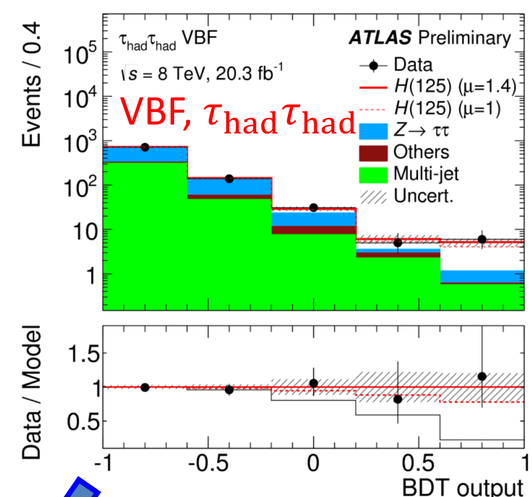


$H \to \tau\tau$ BDT analysis

- 6 BDT trainings for 2(Boosted, VBF) * 3($\tau_{\rm lep}\tau_{\rm lep}$, $\tau_{\rm lep}\tau_{\rm had}$, $\tau_{\rm had}\tau_{\rm had}$)
- Simultaneous fit on the 6 BDT output + control regions



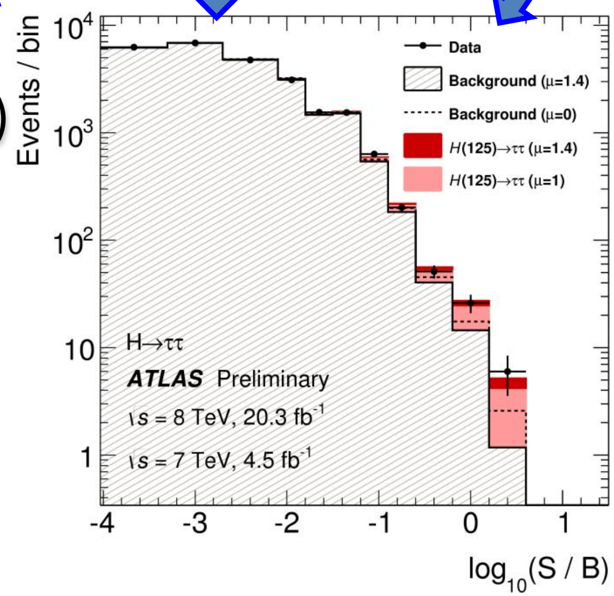




- For m_H= 125.36 GeV, 4.5σ (3.5σ) significance is observed (expected)

  Evidence for Higgs coupling to tau: Y_τ

- Dominant uncertainties
  - Jet energy scale
  - Background normalization
  - BR ($H \to \tau\tau$)
  - Tau energy scale / identification



BDTs from Boosted

$\tau_{\rm lep}\tau_{\rm lep}$

$\tau_{\rm lep}\tau_{\rm had}$

$\tau_{\rm had}\tau_{\rm had}$

$H \rightarrow \tau\tau$ results

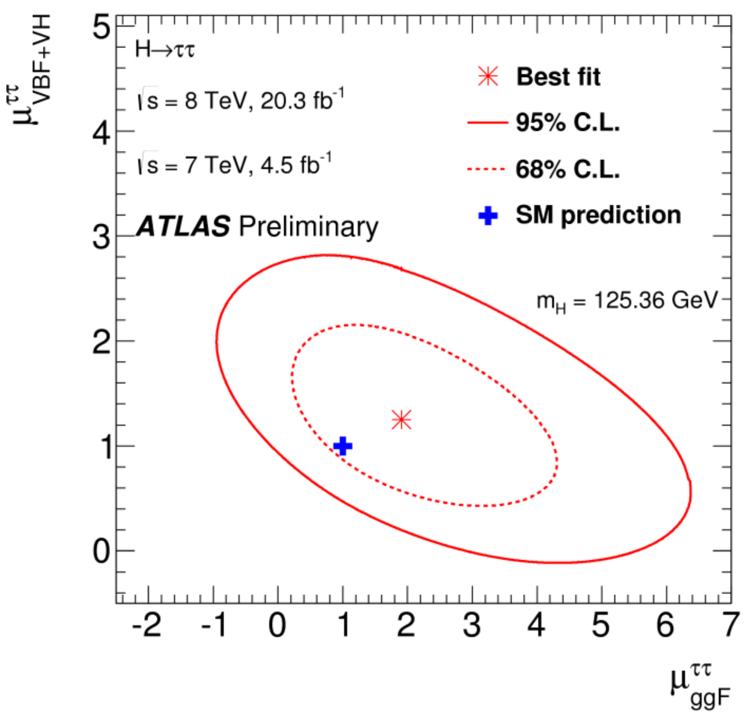
- Signal strength:

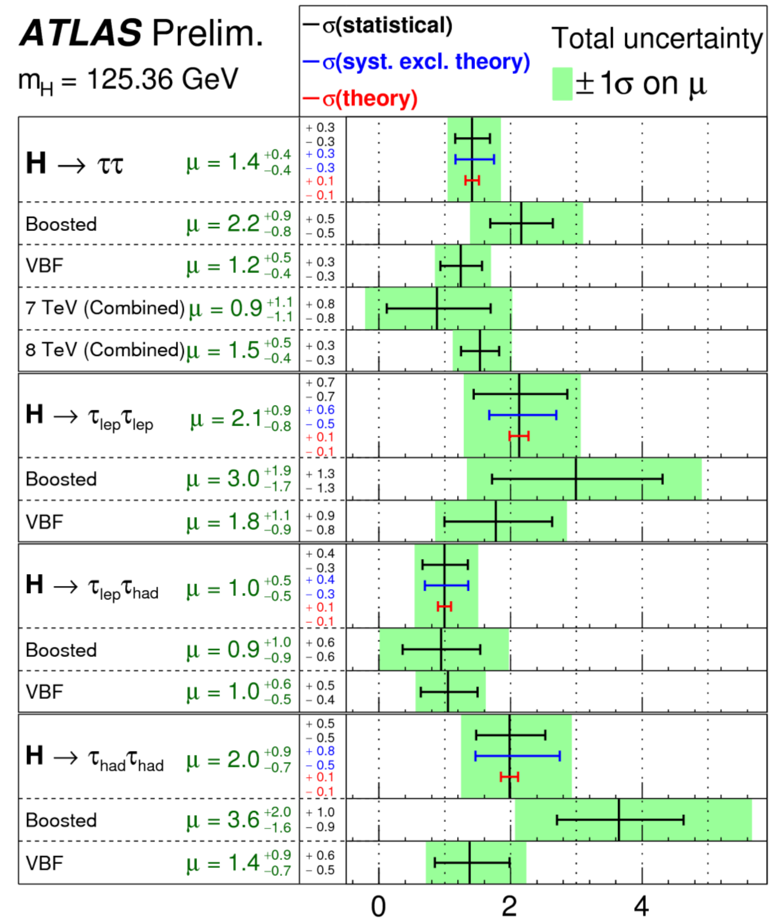
  MVA: $\mathbf{\mu = 1.42^{+0.27}_{-0.26}(stat.)^{+0.32}_{-0.24}(syst.) \pm 0.10(theo.)}$ for m_H= 125.36 GeV

  Cut based cross-check (8TeV only):

  $$\mu = 1.37^{+0.57}_{-0.48}(\text{tot.})$$

- Compatible with SM





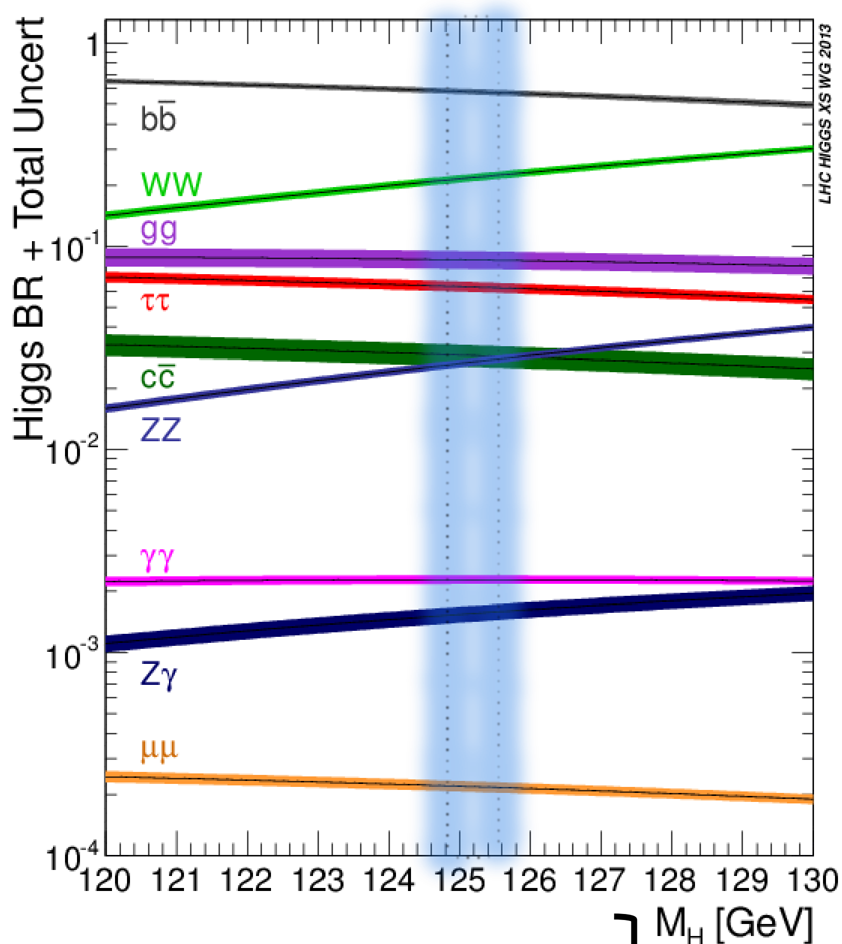
$$\mu^{\tau\tau}_{ggF} = 1.93^{+0.78}_{-0.77}(\text{stat.})^{+1.19}_{-0.80}(\text{syst.}) \pm 0.29(\text{theo.})$$

$$\mu^{\tau\tau}_{VBF+VH} = 1.24^{+0.48}_{-0.45}(\text{stat.})^{+0.31}_{-0.28}(\text{syst.}) \pm 0.08(\text{theo.})$$

for m_H = 125.36 GeV

Talk Outline

1. *Searches with leptons*
   1. $H \to \tau\tau$
   2. **$H \to \mu\mu$**
2. *Searches with quarks*
   1. $VH,\ H \to bb$

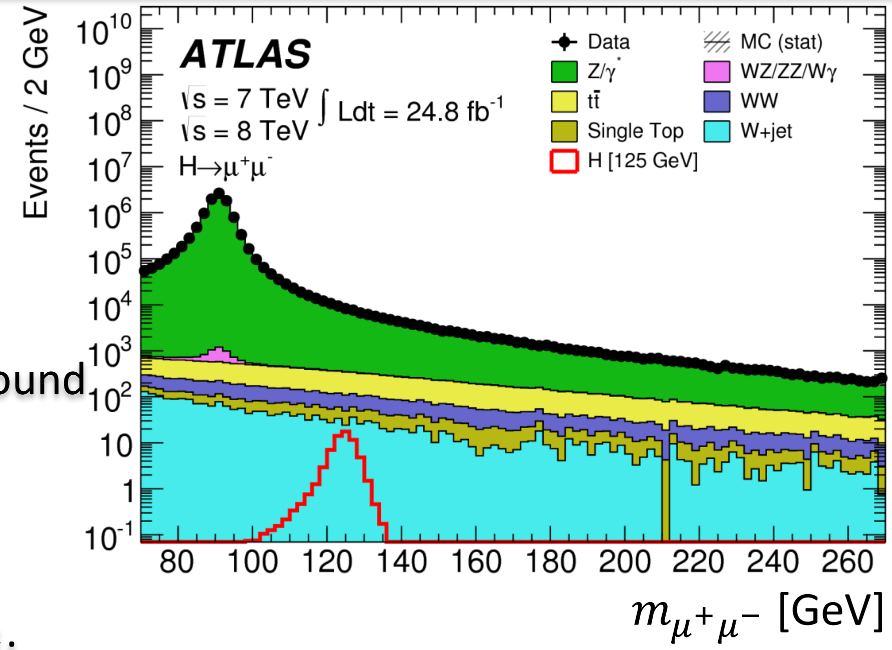


Br($H \to \tau\tau$) = 6.3%
Br($H \to \mu\mu$) = 0.02%
Br($H \to bb$) = 58%

m_H = 125 GeV

$H \rightarrow \mu\mu$ analysis

- Overview
  - Important to measure the 2nd generation couplings
  - Search for a narrow resonance of $H \rightarrow \mu\mu$
  - Fit $m_{\mu\mu}$ in 110-160 GeV range
  - Overwhelming irreducible Drell-Yan background
    - Precise background modeling is an important key



- categorization
  - ggH, VBF with 2 jets
  - For ggH, further categorization based on η^{μ}:
    - Central category: $|\eta^{\mu_1}|<1$ and $|\eta^{\mu_2}|<1$
    - Non-central category: events not passing above
  - $p_T^{\mu\mu}$:
    - Low ($p_T^{\mu\mu}$<15 GeV)
    - Medium (15<$p_T^{\mu\mu}$<50 GeV)
    - High (50<$p_T^{\mu\mu}$ GeV)

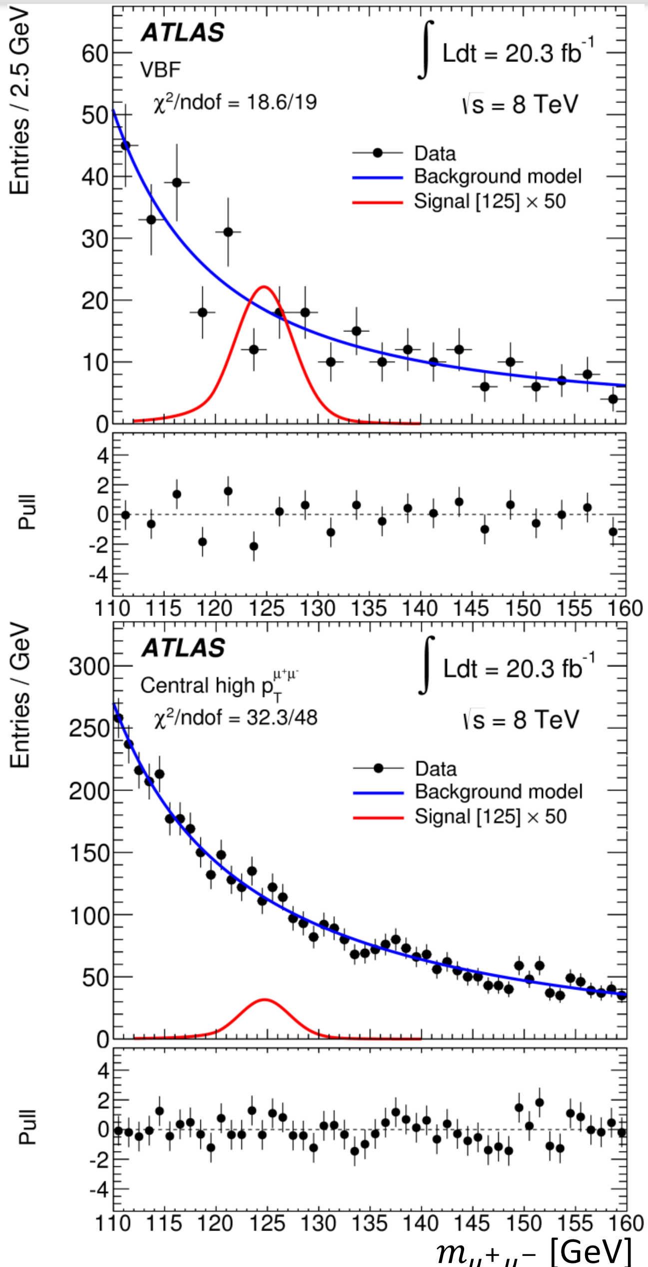
Pre-selection
- 2 isolated opposite sign muons
- $p_T^{\mu_1} > 25$ GeV, $p_T^{\mu_2} > 15$ GeV
- $E_T^{miss} < 80$ GeV

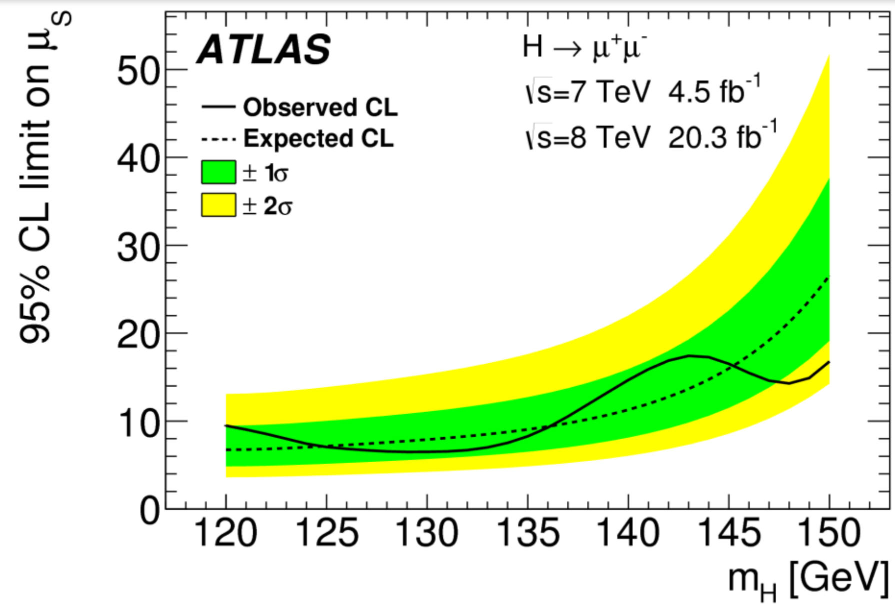
7 categories

Central Muons, $p_T^{\mu\mu}$<15 GeV	Non-central Muons, $p_T^{\mu\mu}$<15 GeV	VBF ≥2 jets M_{jj}>500 GeV $\Delta\eta_{jj}$>3 $\eta_{j1} \times \eta_{j2}$<0
Central Muons, 15<$p_T^{\mu\mu}$<50 GeV	Non-central Muons, 15<$p_T^{\mu\mu}$<50 GeV	
Central Muons, $p_T^{\mu\mu}$>50 GeV	Non-central Muons, $p_T^{\mu\mu}$>50 GeV	

Fit

$H \to \mu\mu$ results





- Observed (expected) limit at 125.5 GeV with 95% CL: 7.0 (7.2) x SM
- 95% CL limit on BR: 1.5×10^{-3}
- Result limited by data statistics
  => Run 2
- Confirmation of non-universality of Higgs-lepton couplings

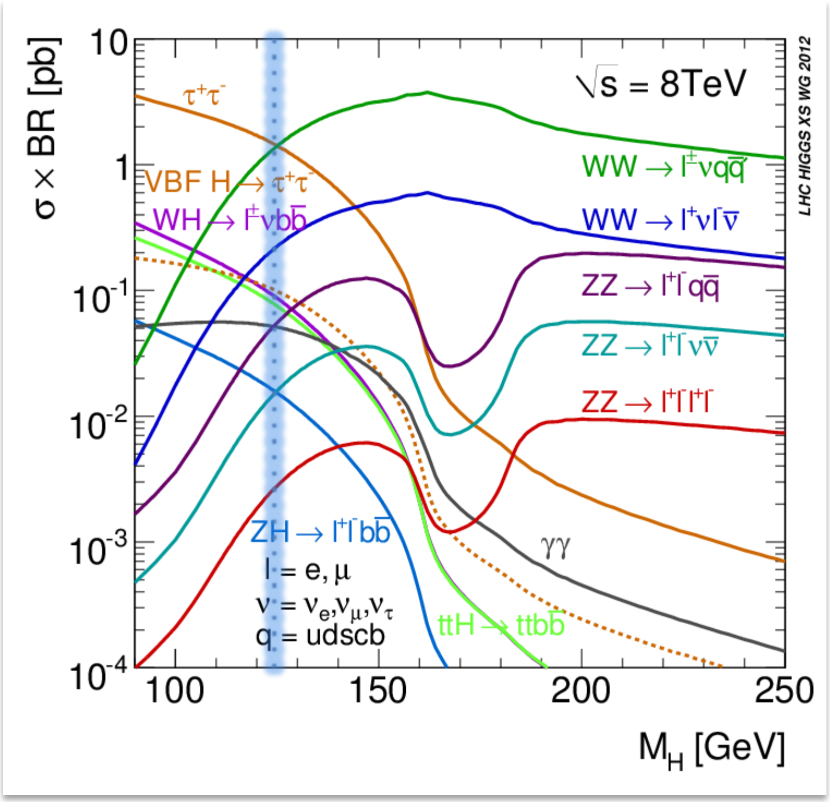
Talk Outline

1. *Searches with leptons*
    1. $H \rightarrow \tau\tau$
    2. $H \rightarrow \mu\mu$
2. *Searches with quarks*
    1. $\boldsymbol{VH,\ H \rightarrow bb}$

       $\boldsymbol{ZH \rightarrow \nu\nu bb}$

       $\boldsymbol{WH \rightarrow \ell\nu bb}$

       $\boldsymbol{ZH \rightarrow \ell\ell bb}$



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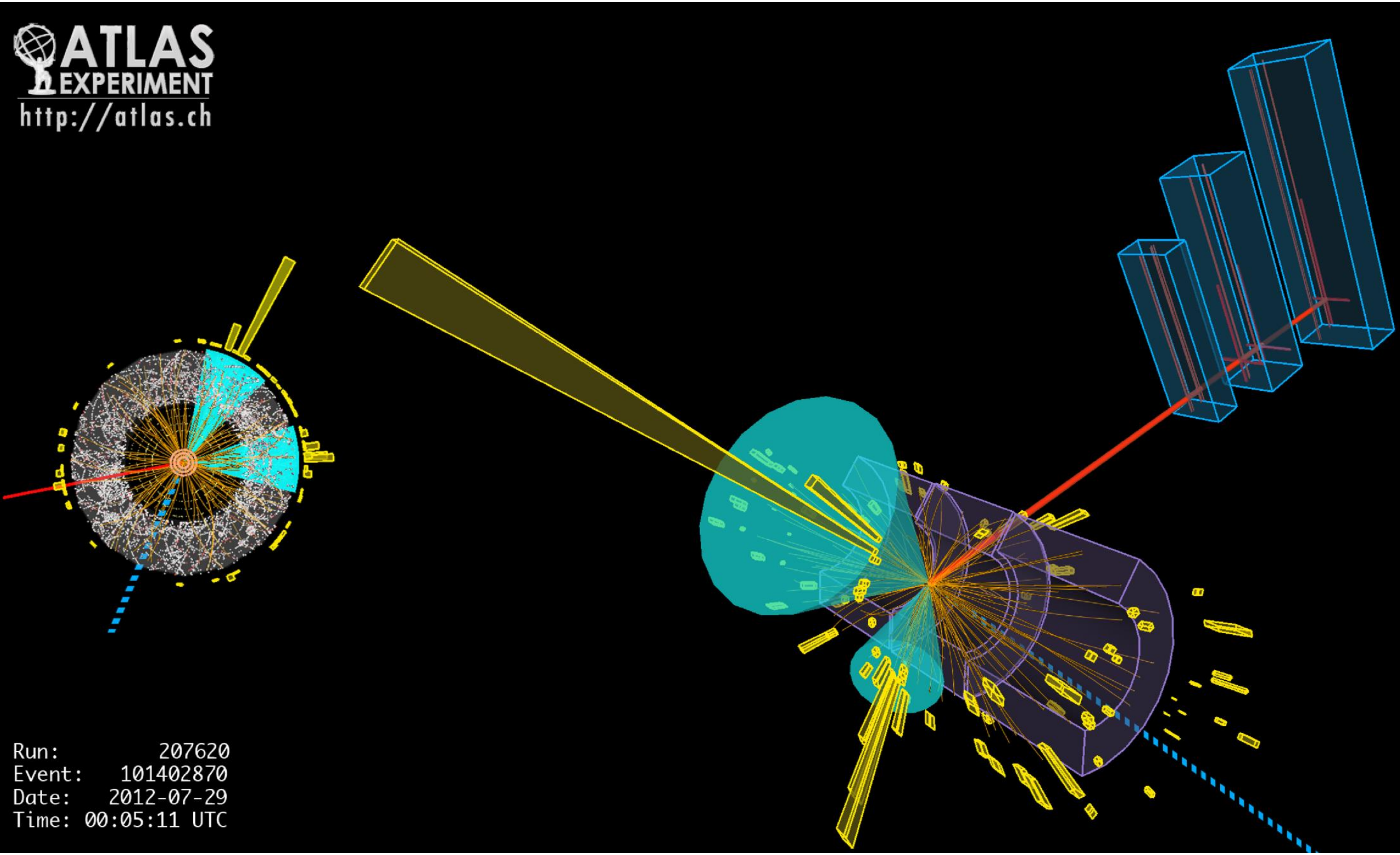
Br($H \rightarrow \mu\mu$) = 0.02%

Br($\boldsymbol{H \rightarrow bb}$) = 58%

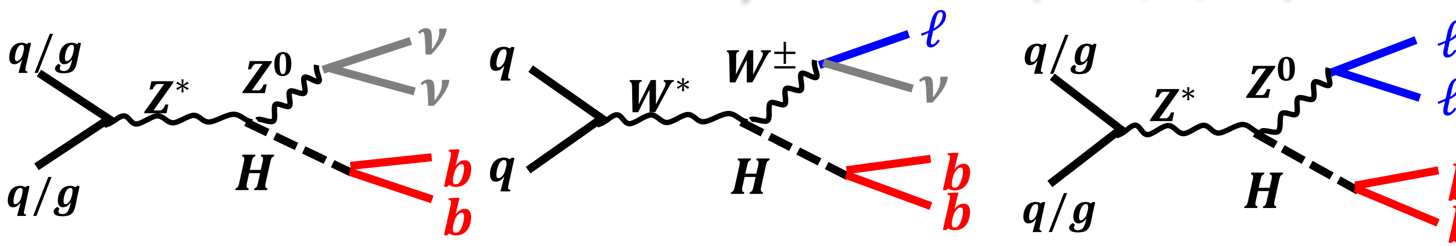
m_H = 125 GeV



$WH \rightarrow \mu\nu bb$ candidate in Run 1

$VH \to Vbb$ analysis I

- Large BR (~58%), but $pp \to bb$ overwhelms ggH and VBF production to search
  ⇒ Use associated W/Z production for probe and distinguish signal from backgrounds
- 2 analyses to confirm each other
  - Multi-variate analysis (MVA): fit BDT output which combines kinematic variables in addition to m_{bb}
  - Cut-based analysis: fit di-jet invariant mass (m_{bb}). Cross-check for MVA.
- Analysis splits into 3 sub-channels based on decay modes of W/Z: 0-, 1-, 2-lepton



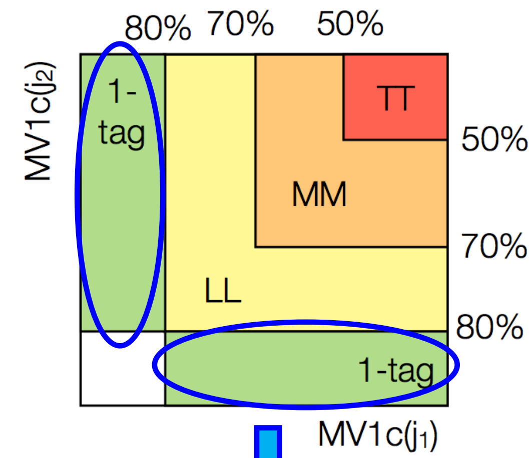
Process	$Z \to \nu\nu$	$W \to e\nu$ / $W \to \mu\nu$	$Z \to ee$ / $Z \to \mu\mu$
#leptons	0	1	2
Branching fraction	20%	11% / 11%	3.3% / 3.3%
Main background	Top, *W/Z*+jets	Top, *W*+jets	*Z*+jets
Event signature (Selection/BDT-input)	• Large E_T^{miss} and p_T^{miss} • E_T^{miss} and di-jet in back-to-back	• E_T^{miss} and H_T to kill multi-jet • m_T^W	• Low E_T^{miss} • $m_{\ell\ell}$ window cut for m_Z

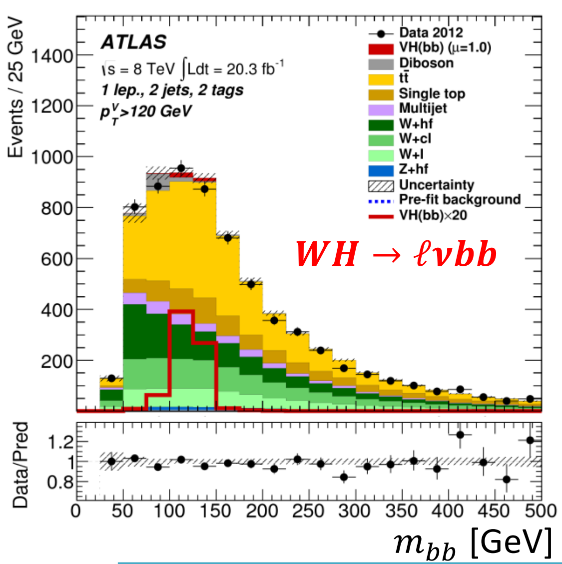
p_T^{miss}: track based E_T^{miss}

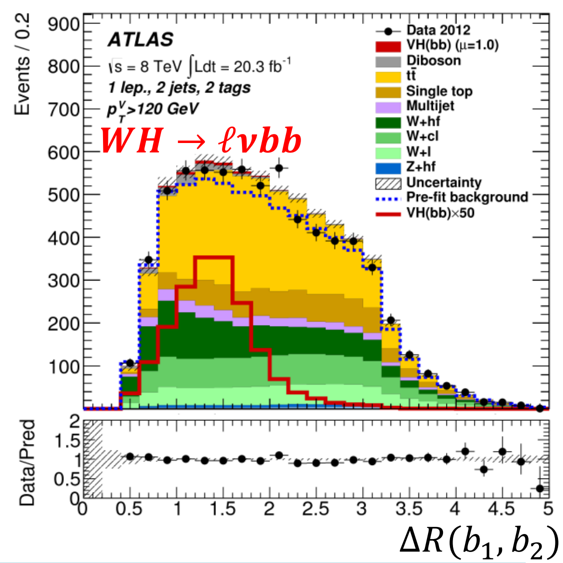
H_T: Scalar sum of jets, lepton, and E_T^{miss}

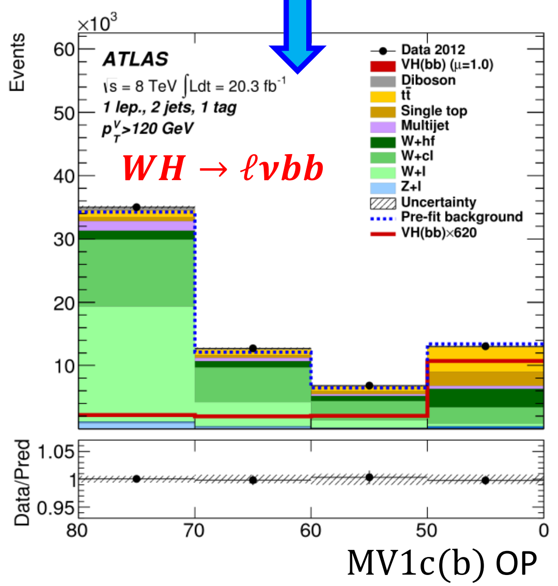
$VH \to Vbb$ analysis II

- To maximize sensitivity and cope with different background composition, analysis further splits into
  - 2-jet and 3-jet categories
  - Low and high p_T^V categories (p_T^V boundary @ 120 GeV)
- Select exactly 2 tagged b-jets
  - MV1c tagger is used: improved c-jet rejection
  - Thanks to ***continuous calibration*** of *b*-tagging, three 2-tag categories are used based on tightness of MV1c tagger.
- In addition to three 2-tag regions, simultaneously fit MC1c in 1-tag region to constraint background









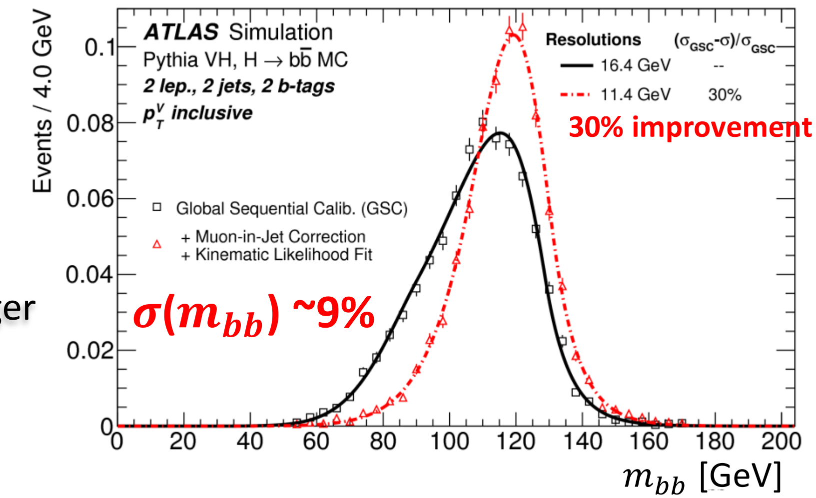
Boosted decision trees

VH improvements

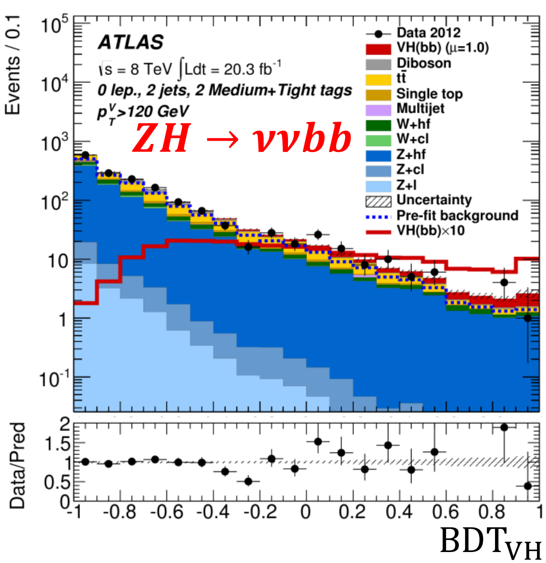
- m_{bb} resolution improvement
  - Most important variable in BDT inputs
  - Muon-in-jet correction
  - Kinematic likelihood fit in 2-lepton channel

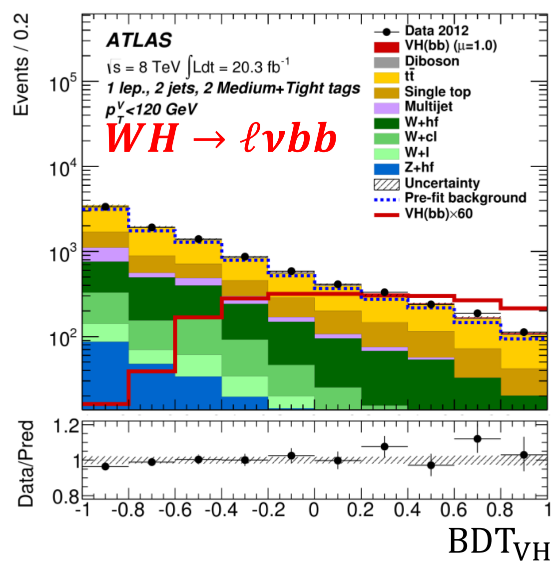
    No intrinsic $E_{\mathrm{T}}^{\mathrm{miss}}$ except semi-leptonic b-decay
- $E_{\mathrm{T}}^{\mathrm{miss}}$ triggered muon channel in $WH \rightarrow \ell \nu bb$

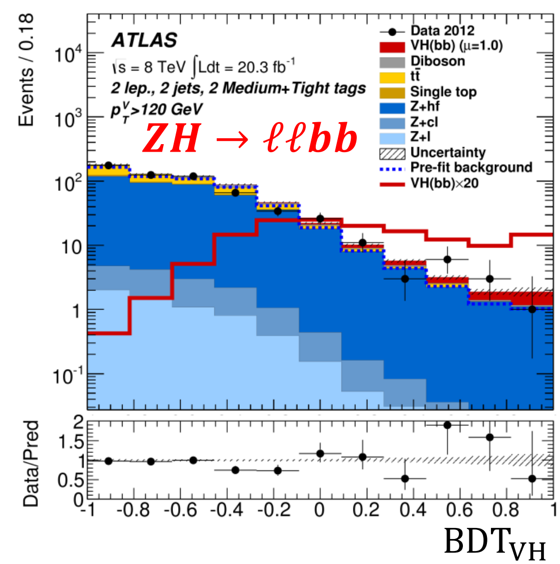
  Compensate the inefficiency of muon trigger
- Low $E_{\mathrm{T}}^{\mathrm{miss}}$ (100<$E_{\mathrm{T}}^{\mathrm{miss}}$<120 GeV) bin in $ZH \rightarrow \nu\nu bb$
- Improvement from MVA



Use BDTs in **3(0-, 1-, 2-)** lepton-channels x **2(2-,3-)** jet bins x **2(low, high)** p_{T}^{V} bins x 3**(LL, MM, TT)** 2-tag regions



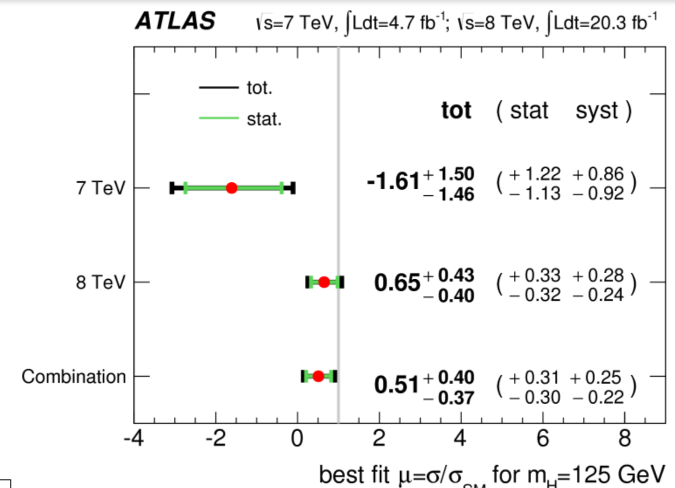




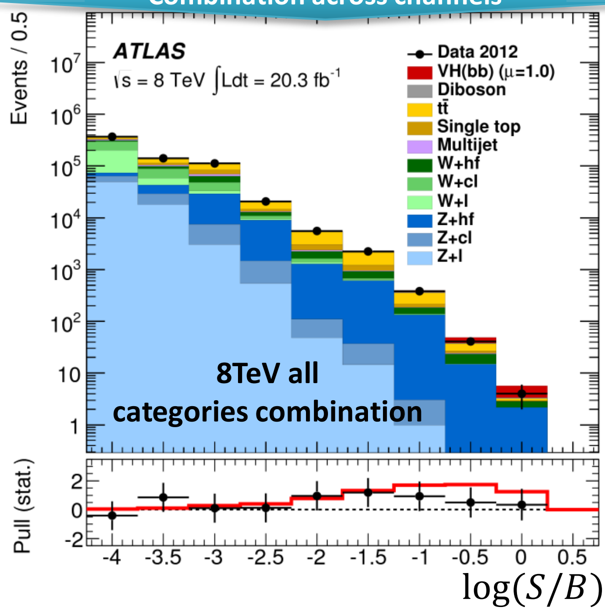
Combination across channels

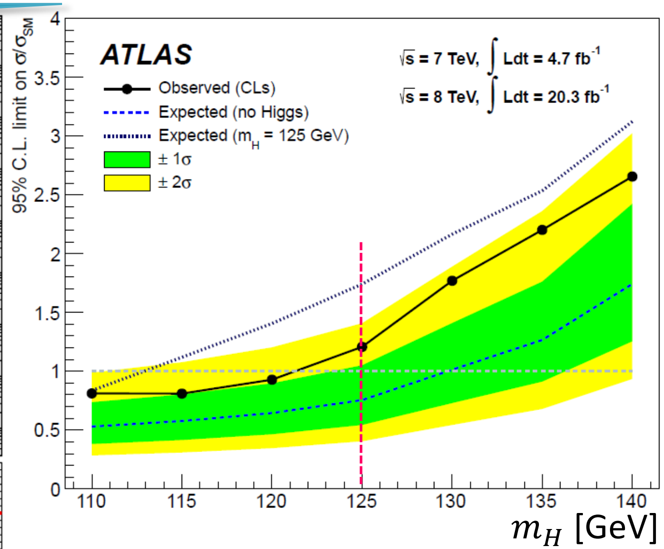
$VH \rightarrow Vbb$ results

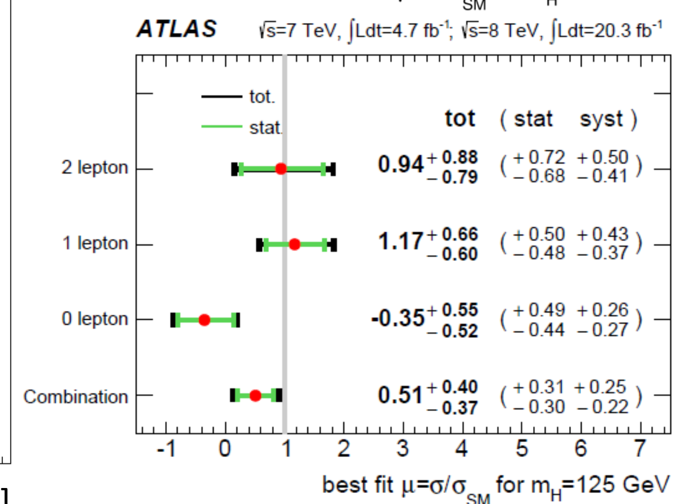
- For SM Higgs search at m_H=125.36 GeV:
  MVA: 1.4σ (2.6σ) significance is observed (expected)
  Cut-based cross check: 2.2σ (1.9σ) observed (expected)
- Signal strength:
  MVA: μ = 0.52 $\pm$ 0.32 (stat.) $\pm$ 0.24 (syst.) for m_H= 125.36 GeV
  Cut based cross-check: μ= 1.23 $\pm$ 0.44(stat.) $\pm$ 0.41 (syst.)
  Dominant systematic source :
  W/Z + heavy flavor modeling (shape, normalization)
- Compatible with SM



Combination across channels

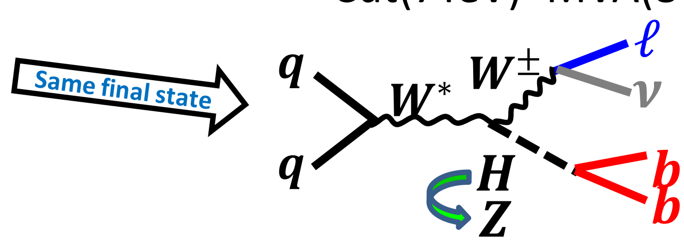






Cut(7TeV)+MVA(8TeV)

- Diboson (VZ) production is measured as a cross-check
  $\Rightarrow$ compatible with the SM
  – 4.9 σ (6.3σ) is observed (expected) for VZ production
  – Signal strength μ= 0.74 $\pm$ 0.09(stat.) $\pm$ 0.14(syst.)

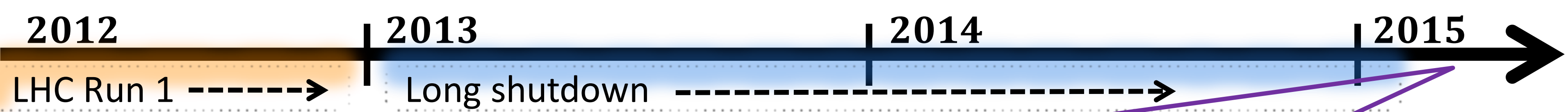


Summary

Decay channels	Signal strength (μ)	Significance / limit
$H \to \tau\tau$	$1.4^{\pm 0.3(\text{stat})}_{\pm 0.3(\text{sys})}$	$4.5\ (3.5)\ \sigma$
$H \to \mu\mu$	–	μ/μ_{SM} = 7.0 (7.2)
$VH \to Vbb$	$0.5^{\pm 0.3(\text{stat})}_{\pm 0.2(\text{sys})}$	$1.4\ (2.6)\ \sigma$

- **$H \to \tau\tau$: Evidence for Y_τ**
- $H \to \mu\mu$: No excess observed yet at m_H=125 GeV
- $H \to bb$: An excess with 1.4 σ significance observed at m_H=125 GeV

- So far, everything looks compatible with the SM expectations



LHC will restart next year!!

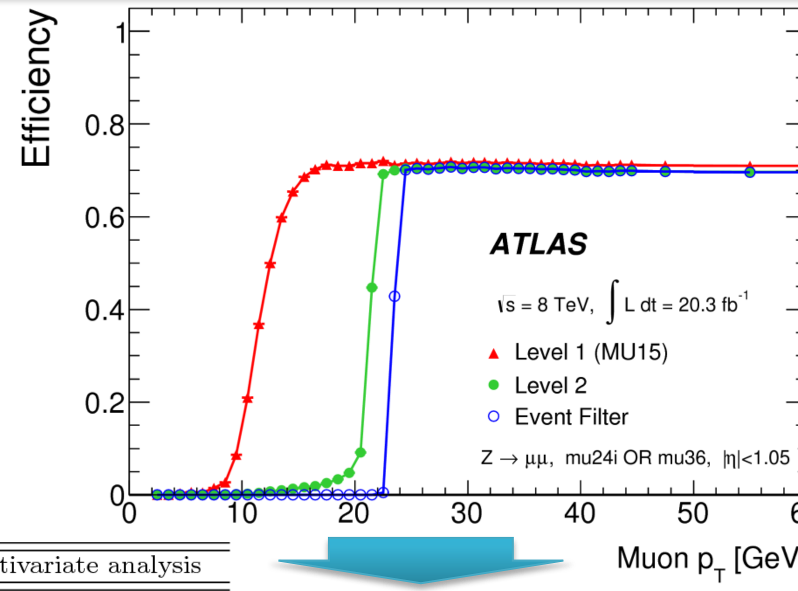
- Increased center-of-mass energy (13 TeV)
- Increased luminosity
- New innermost pixel layer (IBL) in ATLAS

STAY TUNED!

BACKUP BUCKET

$VH \rightarrow Vbb$ selection

- Cut-based selection has 5 bins in p_{T}^{V} in stead of 2 bins of MVA.
- To cope with the different background composition, cuts vary in p_{T}^{V} bins in cut-based selection, e.g. ΔR_{jj}.



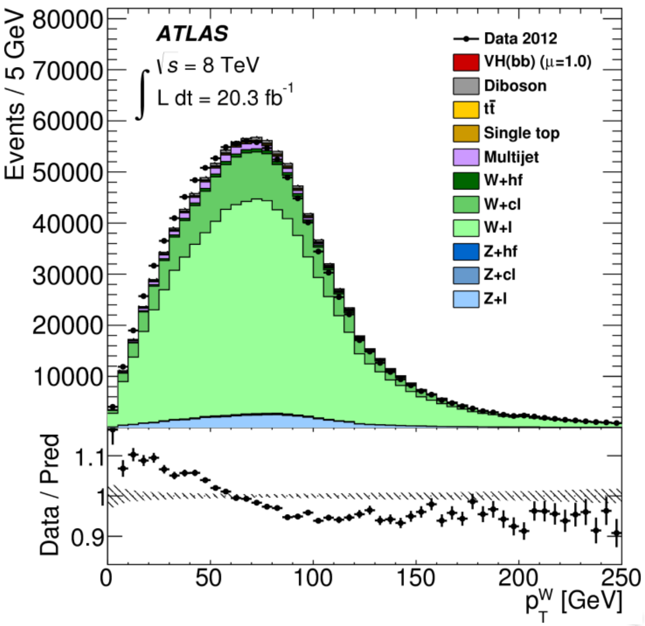
Variable	Dijet-mass analysis					Multivariate analysis	
Common selection							
p_{T}^{V} [GeV]	0–90	90$^{(*)}$–120	120–160	160–200	>200	0–120	>120
$\Delta R(\mathrm{jet}_1, \mathrm{jet}_2)$	0.7–3.4	0.7–3.0	0.7–2.3	0.7–1.8	<1.4	>0.7 (p_{T}^{V}<200 GeV)	
0-lepton selection							
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	NU	>30	>30			NU	>30
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}} vec)$		$<\pi/2$	$<\pi/2$				$<\pi/2$
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})]$		–	>1.5				>1.5
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{dijet})$		>2.2	>2.8				>2.8
$\sum_{i=1}^{N_{\mathrm{jet}}=2(3)} p_{\mathrm{T}}^{\mathrm{jet}_i}$ [GeV]		>120 (NU)	>120 (150)				>120 (150)
		See text	–				–
1-lepton selection							
m_{T}^{W} [GeV]	<120					–	
H_{T} [GeV]	>180		–			>180	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	–		>20		>50	–	>20
2-lepton selection							
$m_{\ell\ell}$ [GeV]	83-99					71-121	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	<60					–	

$E_{\mathrm{T}}^{\mathrm{miss}}$ triggered μ-ch in WH

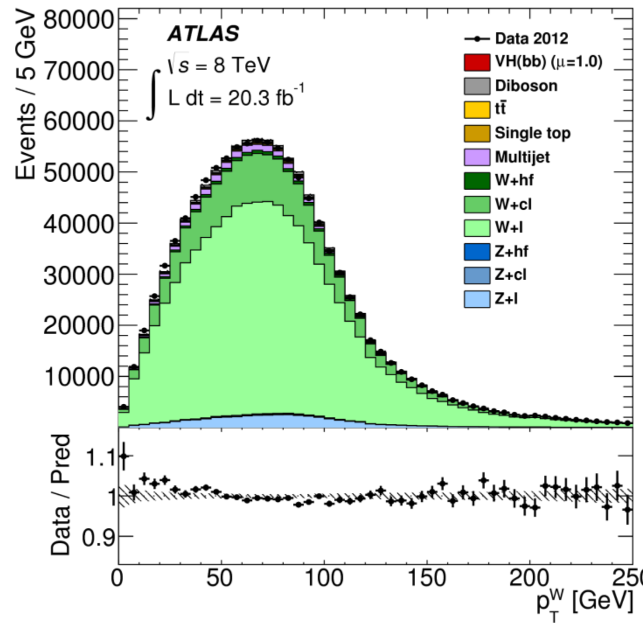
- Single muon trigger does not reach 100% efficiency
- Thanks to well measured $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger turn on, we can apply $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger for the recovery of muon trigger in $WH \rightarrow \ell\nu bb$, applied in p_{T}^{W}> 120 GeV.
- Contribution to significance gain: ~2%

$VH \to Vbb$ background modeling

2-jet 0-tag control region

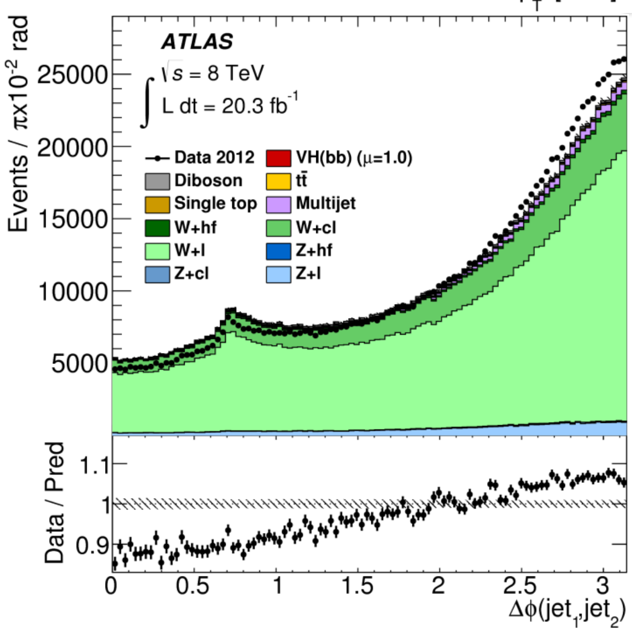


$\Delta\phi$ corrction

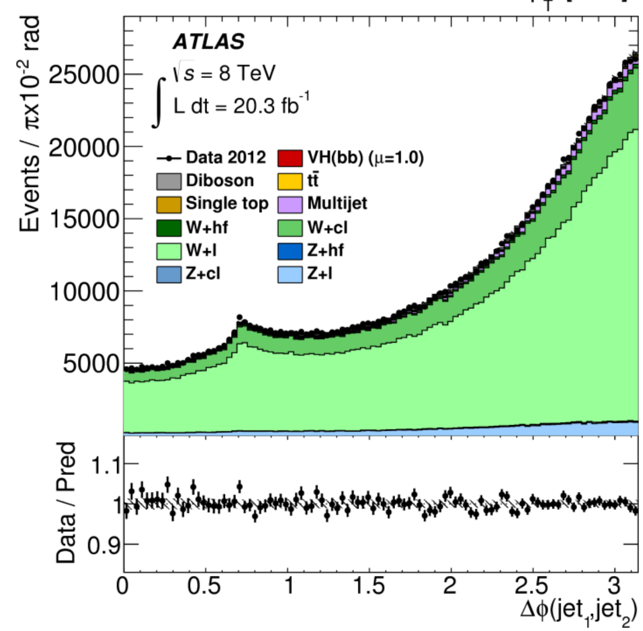


Sub-division of signal regions based on p_{T}^{V}

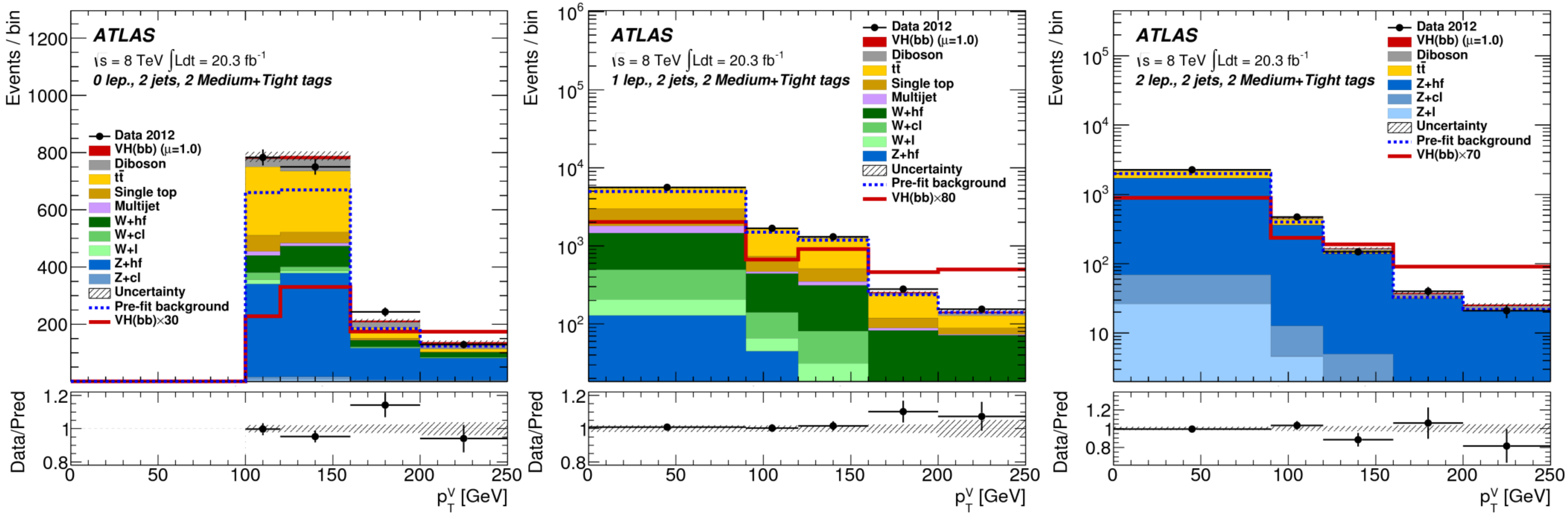
$\Rightarrow$ Modeling of p_{T}^{V} is crucial



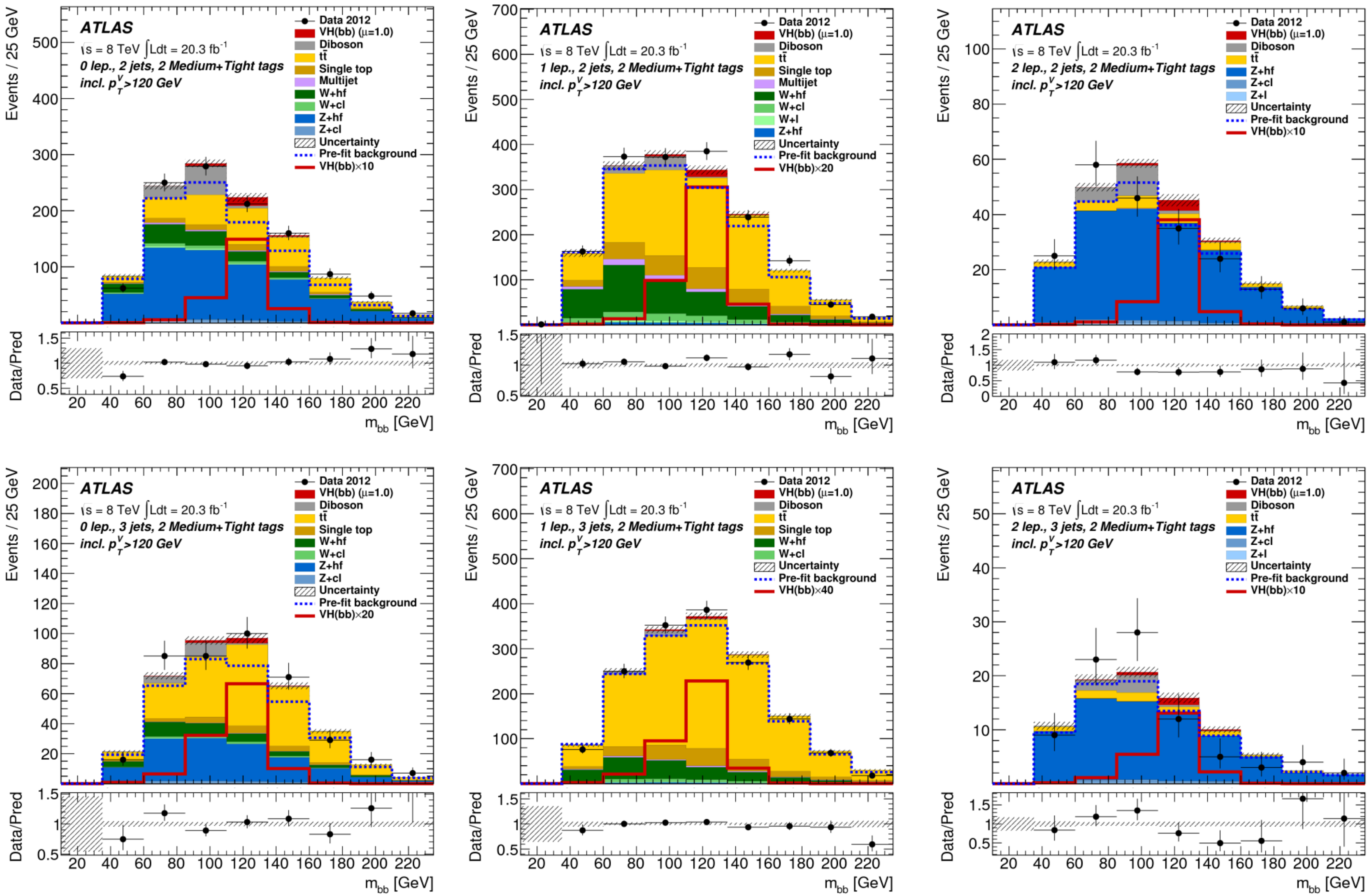
$\Delta\phi$ corrction



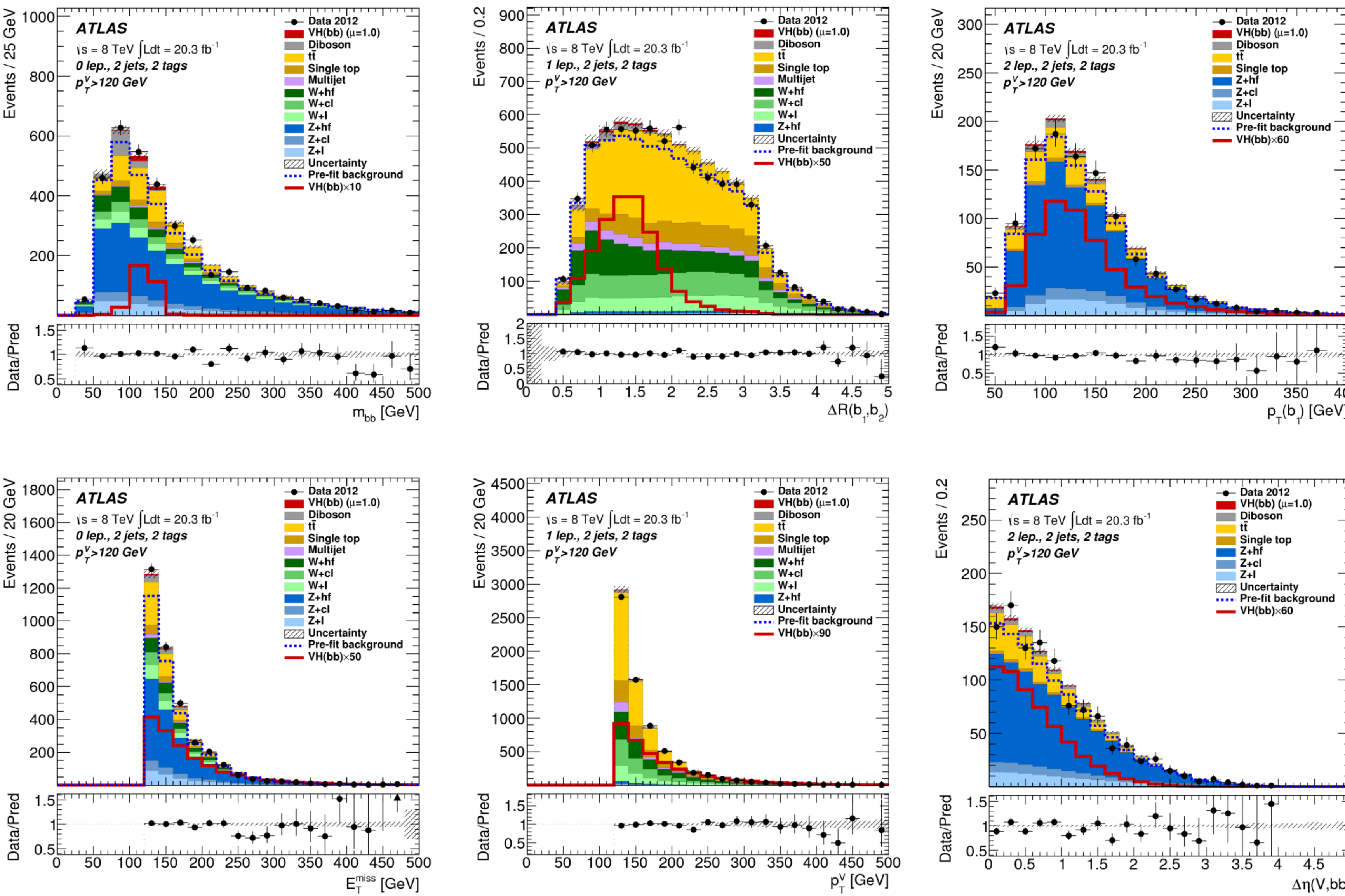
$VH \rightarrow Vbb\ \ p_T^V$ distributions



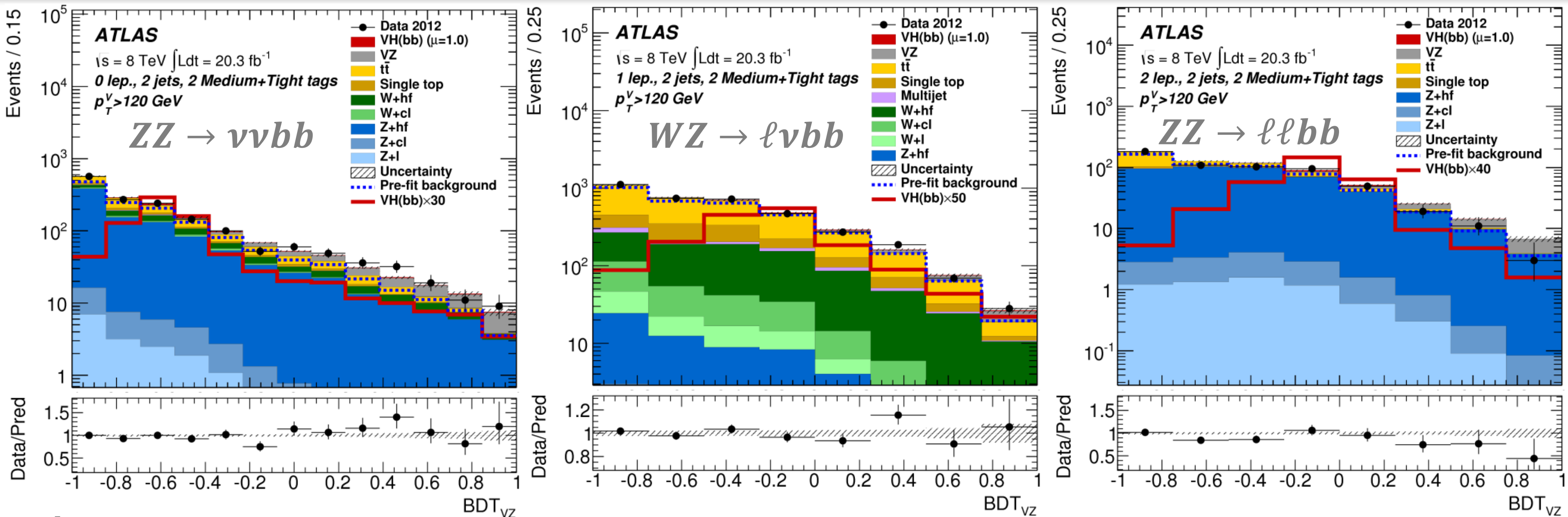
$VH \rightarrow Vbb$ m_{bb} distrubutions

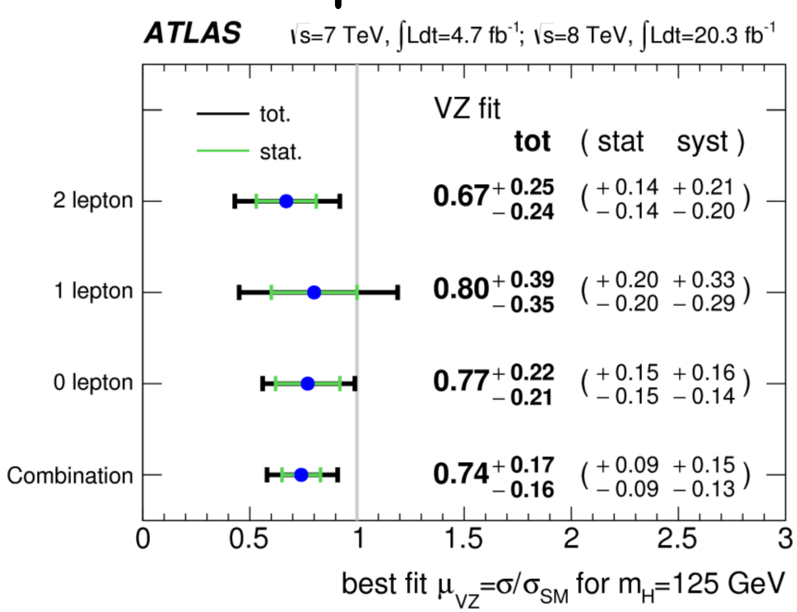


$VH \rightarrow Vbb$ input variables



$VH \rightarrow Vbb$ cross-check with diboson production (VZ)





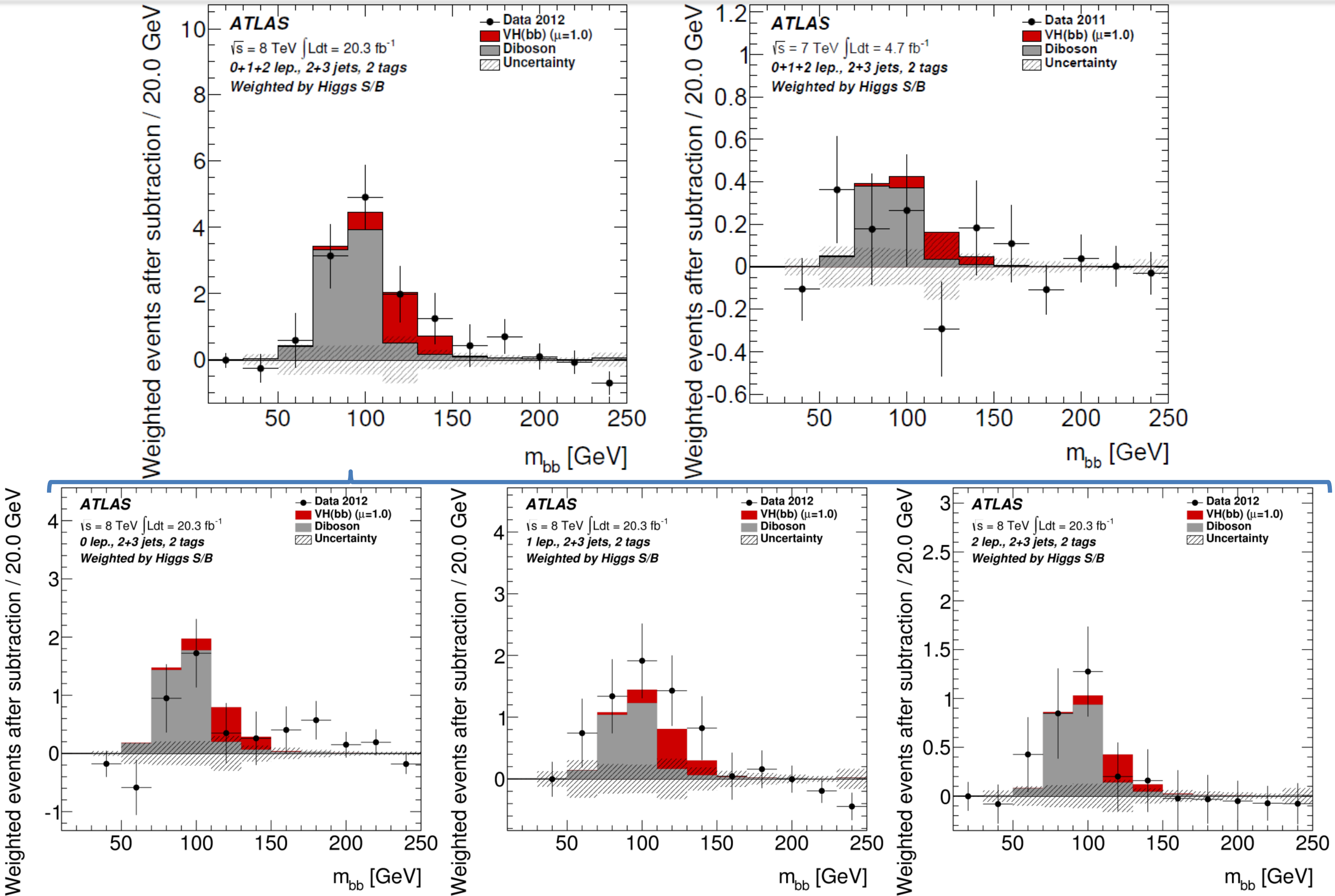
- Use VZ as cross-check which produces exactly the same final states
- Data and background + signal yield are compatible
- Significance for VZ:

  4.9 σ observed

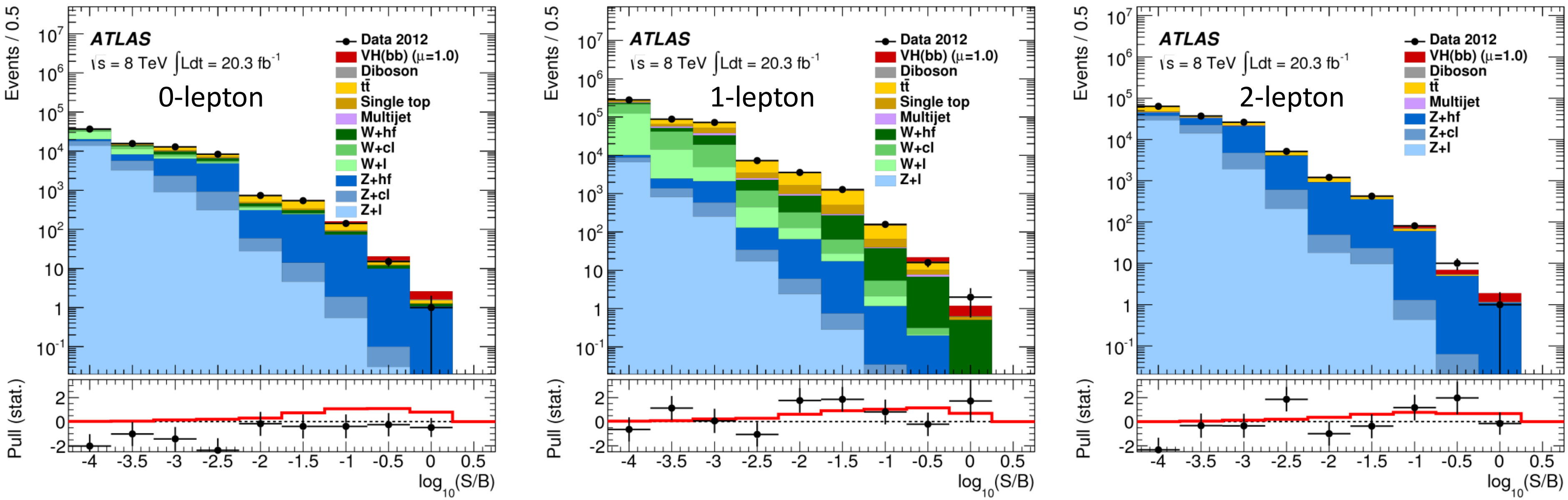
  6.3 σ expected
- **Signal strength for VZ :**

  μ = 0.52 $\pm$ 0.32 (stat.) $\pm$ 0.24 (syst.)

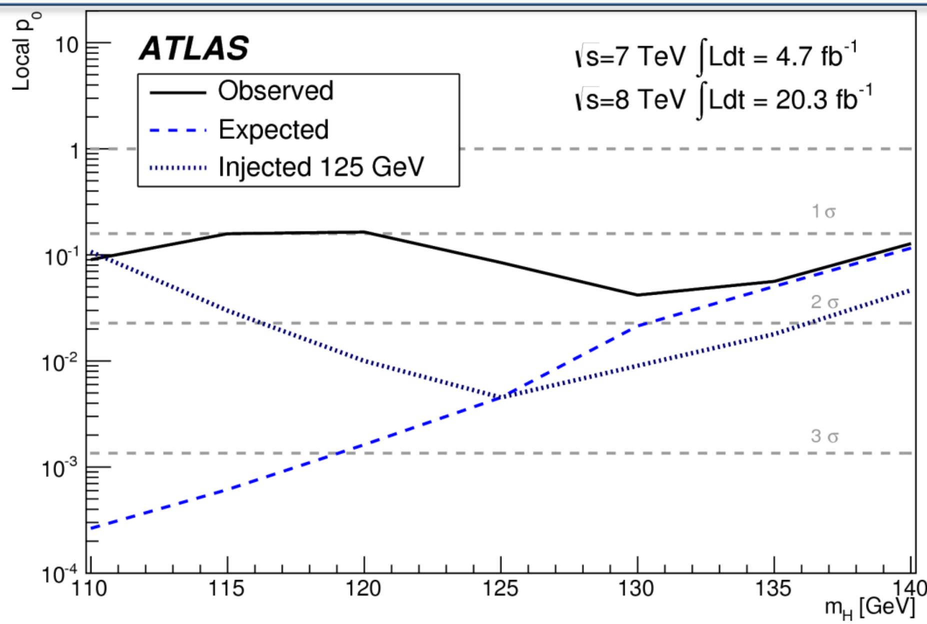
$VH \to bb$ Cut-based (di-jet) mass analysis

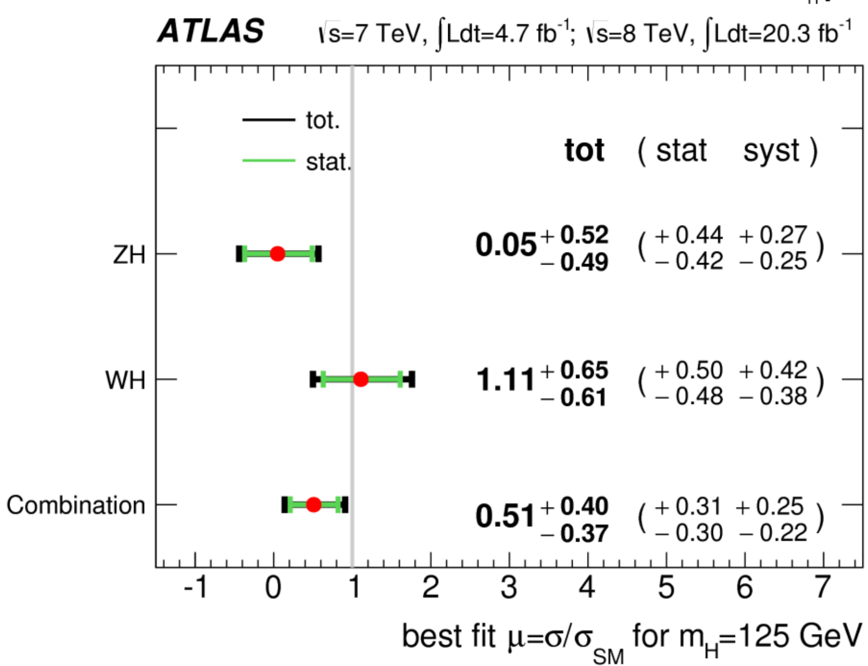


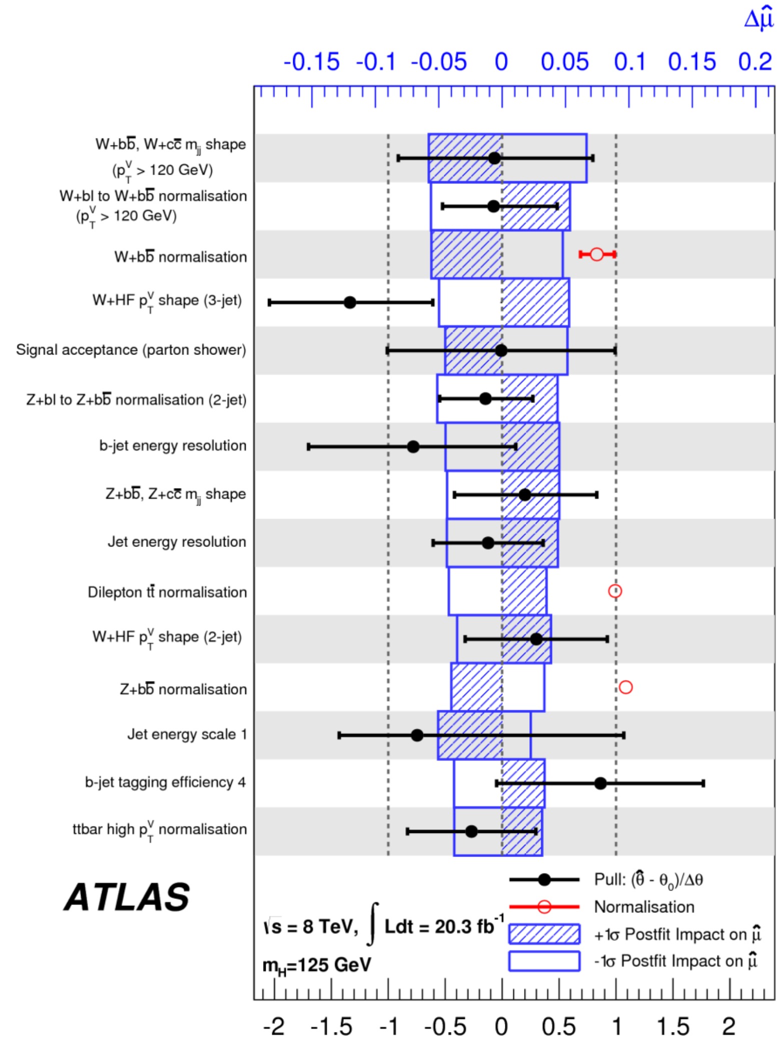
$VH \rightarrow Vbb$ S/B sorted events



$VH \rightarrow Vbb$ results







BDT inputs

$H \rightarrow \tau\tau$

Variable	VBF $\tau_{lep}\tau_{lep}$	VBF $\tau_{lep}\tau_{had}$	VBF $\tau_{had}\tau_{had}$	Boosted $\tau_{lep}\tau_{lep}$	Boosted $\tau_{lep}\tau_{had}$	Boosted $\tau_{had}\tau_{had}$
$m_{\tau\tau}^{MMC}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
p_T^{Total}		•	•			
Sum p_T					•	•
$p_T(\tau_1)/p_T(\tau_2)$					•	•
$E_T^{miss}\phi$ centrality		•	•	•	•	•
m_{ℓ,ℓ,j_1}				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_T^{\ell_1}$				•		
$p_T^{j_1}$				•		
$E_T^{miss}/p_T^{\ell_2}$				•		
m_T		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,jets})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1,\eta_2}(\eta_\ell)$		•				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	•					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			•			

$VH \rightarrow Vbb$

Variable	0-Lepton	1-Lepton	2-Lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\|\Delta\eta(b_1, b_2)\|$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\|\Delta\eta(V, bb)\|$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$	×	×	×
$MV1c(b_2)$	×	×	×
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

SR & CR

$H \rightarrow \tau\tau$ CR

Process	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
$Z \rightarrow \ell\ell$-enriched	$80 < m_{\tau\tau}^{vis} < 100$ GeV (same-flavour)		
Top control region	invert b-jet veto	invert b-jet veto and $m_T > 40$ GeV	
Rest category			pass preselection, fail *VBF* and *Boosted* selections
$Z \rightarrow \tau\tau$-enriched	$m_{\tau\tau}^{HPTO} < 100$ GeV	$m_T < 40$ GeV and $m_{\tau\tau}^{MMC} < 110$ GeV	
Fake-enriched	same sign τ decay products	same sign τ decay products	
W-enriched		$m_T > 70$ GeV	
Mass sideband			$m_{\tau\tau}^{MMC} < 110$ GeV or $m_{\tau\tau}^{MMC} > 150$ GeV

- These CRs are used together with 6 BDT output in SR

$VH \rightarrow Vbb$ SR

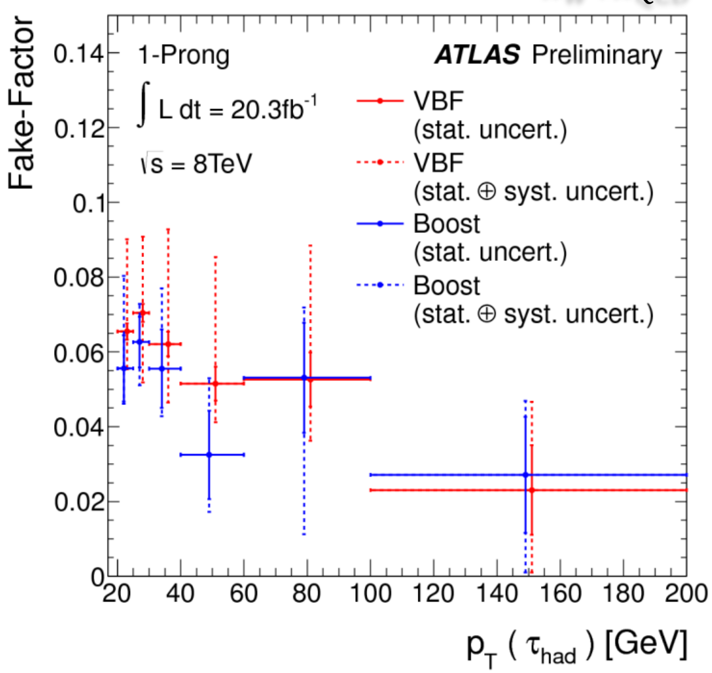
		Dijet-mass analysis			MVA		
Channel		0-lepton	1-lepton	2-lepton	0-lepton	1-lepton	2-lepton
	1-tag	$MV1c$			$MV1c$		
LL	2-tag	m_{bb}			$BDT^{(*)}$	BDT	
MM	2-tag	m_{bb}			$BDT^{(*)}$	BDT	BDT
TT	2-tag	m_{bb}			$BDT^{(*)}$	BDT	BDT

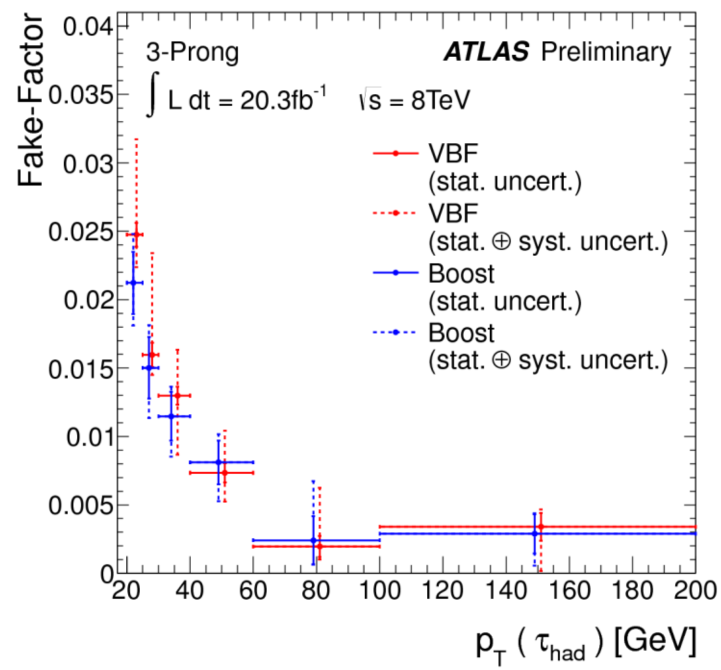
- MV1c in 1-tag is used for background constraint.

$H \to \tau_{\text{lep}}\tau_{\text{had}}$ *fake factor method*

- Quark / gluon contribution for fake- τ
  - Fake-τ contribution from W+jets is dominated by quark-jets
  - Fake-τ contribution from multi-jet production is dominated by gluon-jets
- Define "anti-τ" control regions by inverting τ-identification criteria
  - Inverting m_{T} selection for W+jets
  - low $E_{\text{T}}^{\text{miss}}$ and loose lepton isolation for multi-jet
- Obtain different mis-identification probabilities ("Fake-Factor"), calculate weighted mean value according to

$$r_W = \frac{N_W}{N_W + N_{\text{QCD}}},\ F = r_W F_W + (1 - r_W) F_{\text{QCD}}$$





- Differences between quark- and gluon-dominated Fake-Factors used as systematic uncertainty (combined with statistical uncertainty from anti-τ data)

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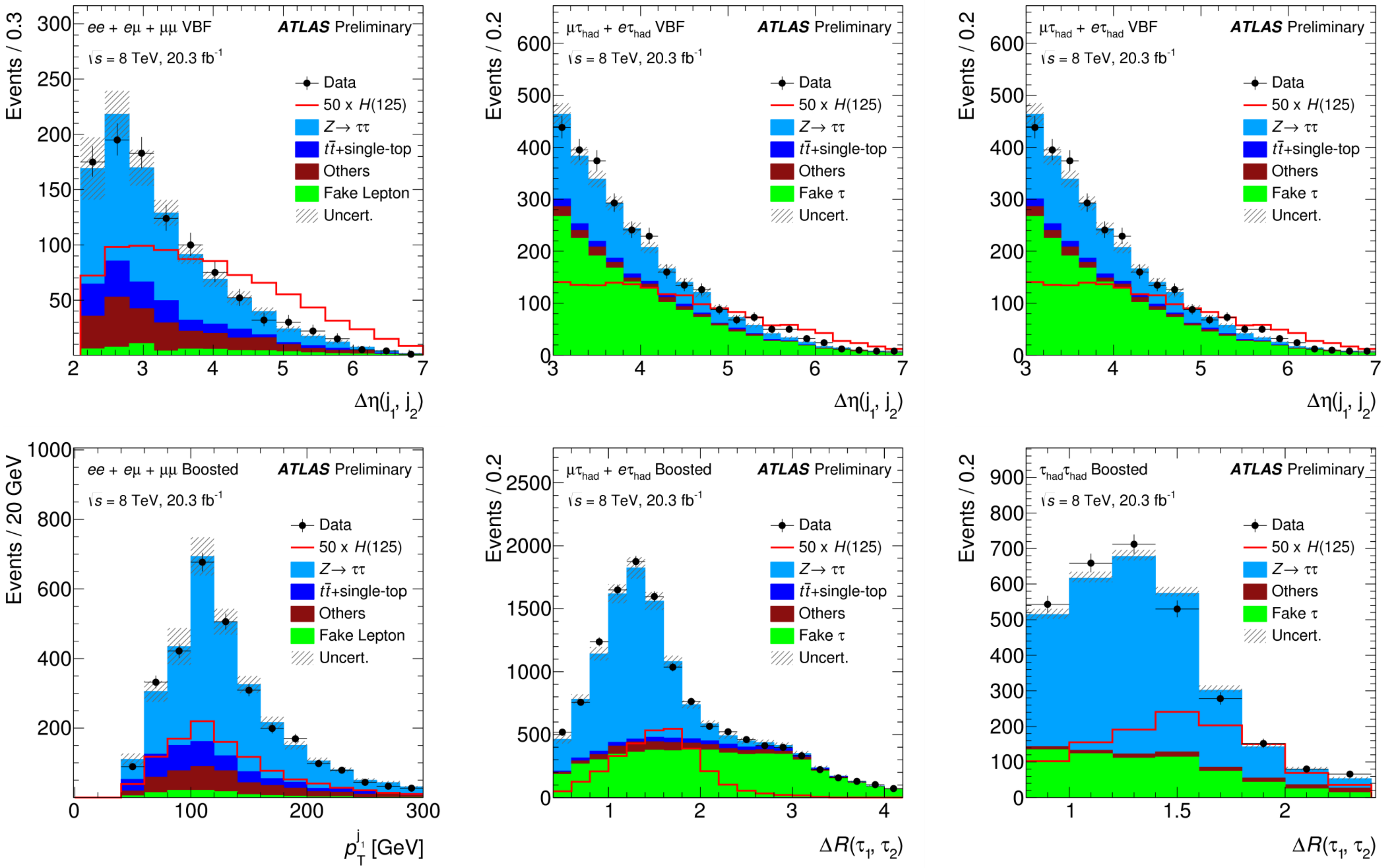
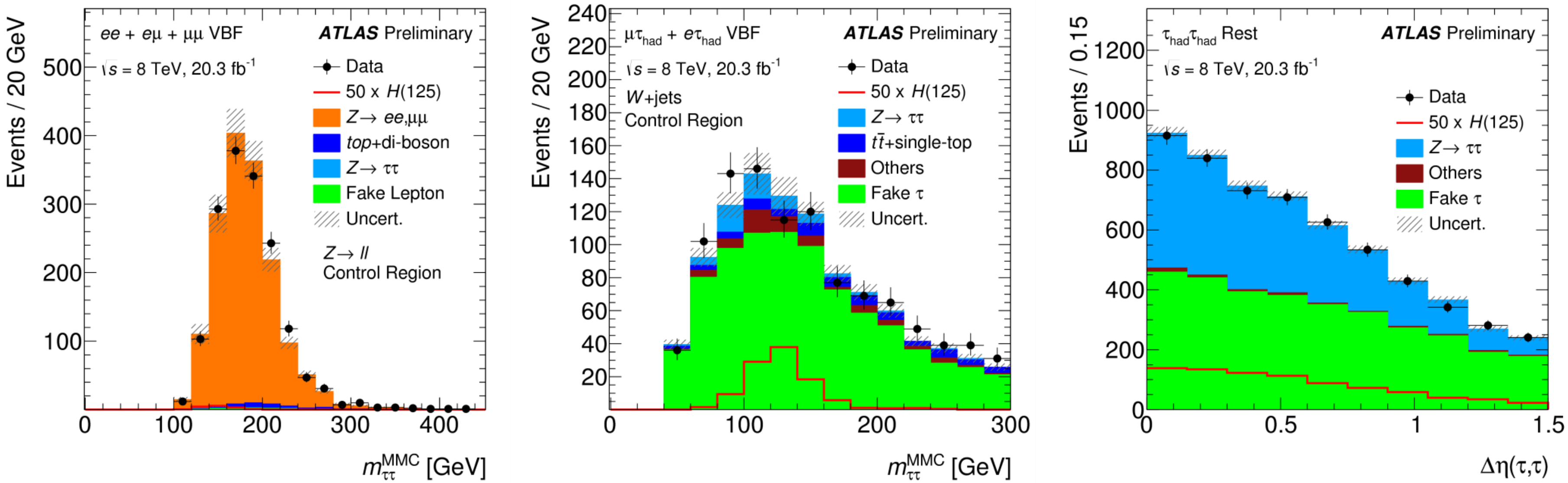
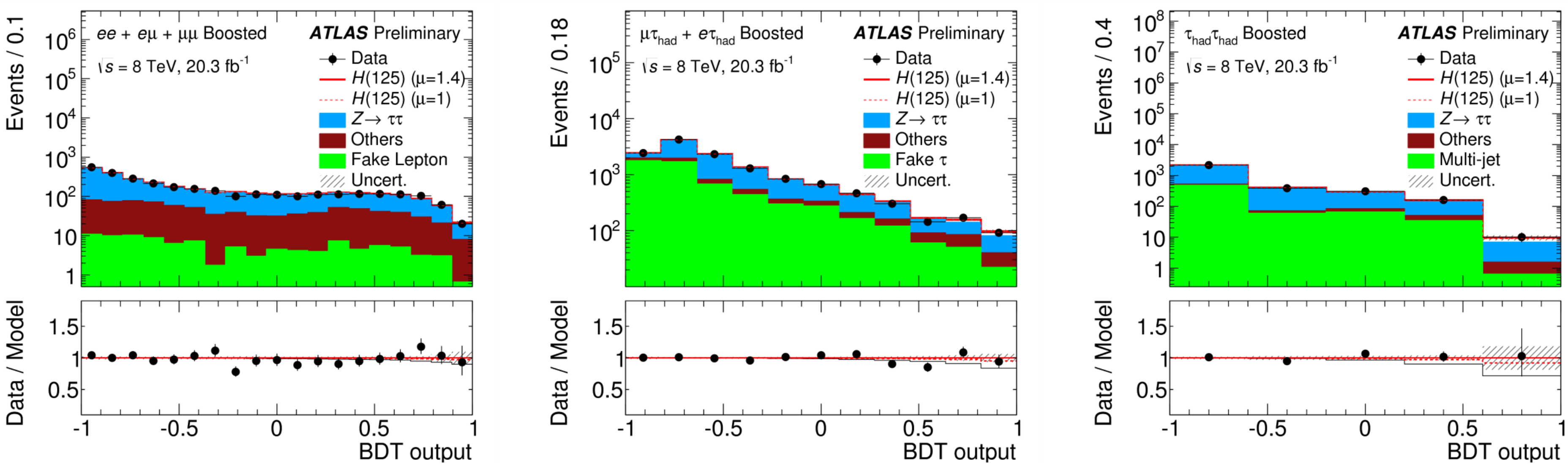
$H \rightarrow \tau\tau$ important input variables



$H \rightarrow \tau\tau$ control regions



$H \rightarrow \tau\tau$ boosted signal regions



$H \to \tau\tau$ results