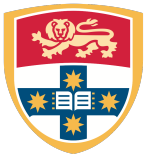


THE UNIVERSITY OF SYDNEY

CoEPP

ARC Centre of Excellence for Particle Physics at the Terascale

Higgs searches with fermions

Geng-Yuan Jeng

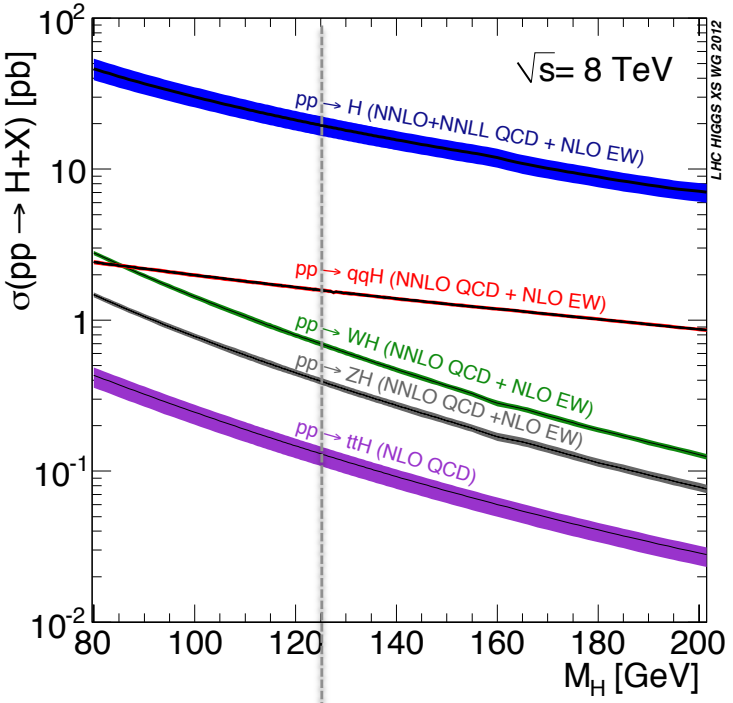
The University of Sydney

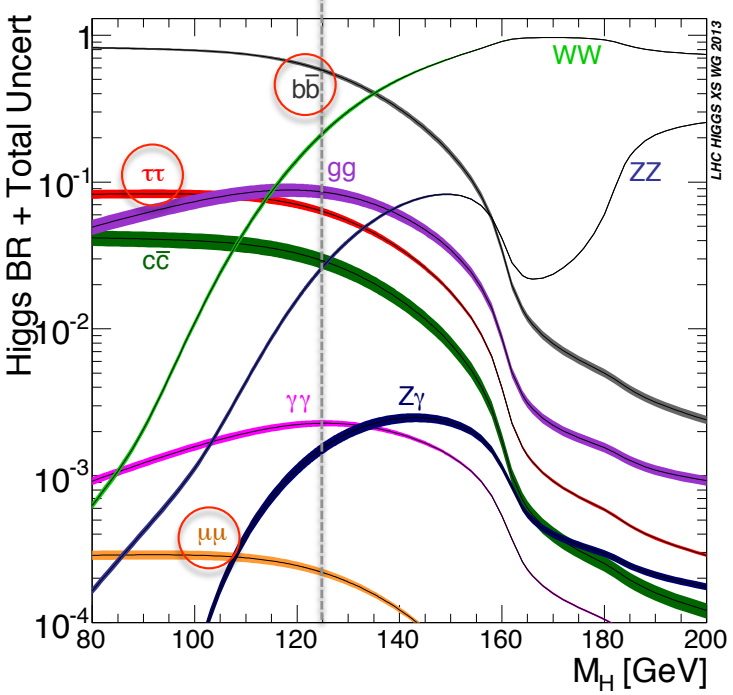
on behalf of the ATLAS collaboration

2014/7/21 – Higgs Hunting, Orsay-LAL, France

Overview

- Introduction
  - H → ττ
  - H → μμ
  - VH(→ bb)
  - ttH(→ γγ/bb)
- Analysis strategy
  - Event selection
  - Signal/Background modeling
- Results
- Summary and outlook





Introduction

- A Standard Model like Higgs boson was discovered in vector boson channels
  - Mass measurement, coupling, spin, CP, etc.
- How about Higgs boson decays into fermions?
  - Evidence for $H \to \tau\tau$ (ATLAS-CONF-2013-108)
    - Ideal to study coupling to leptons
    - Tau lepton provides extra handle against background
  - Search for $H \to \mu\mu$ (arXiv:1406.7663; submitted to Phys. Lett. B)
    - Small BR yet promising direct probe of Higgs lepton coupling
  - Search for W/ZH($\to$bb) (ATLAS-CONF-2013-079)
    - Exploit the dominant branching ratio of $H \to bb$
    - Direct probe of Higgs coupling to down-type quarks
  - ttH ($\to\gamma\gamma$/bb) (ATLAS-CONF-2014-043/ATLAS-CONF-2014-011)
    - Tiny production cross section
    - Direct probe of Higgs coupling to top quark

Analyses

- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $VH (\rightarrow bb)$
- $ttH (\rightarrow \gamma\gamma/bb)$

Higgs to $\tau\tau$

- Largest BR (6.25%@m_H=125.4 GeV) for lepton channels
- Challenging final state
- Mass resolution worsened due to several neutrinos from τ decays
  - Split analysis according to tau lepton decays in final state
- Analysis channels:
  - Categorized by final state of tau decays:
    - $H\to\tau\tau\to 2\ell+4\nu$ "*lep-lep*" (12.4%)
    - $H\to\tau\tau\to \ell+\tau_{had}+3\nu$ "*lep-had*" (45.6%)
    - $H\to\tau\tau\to 2\tau_{had}+2\nu$ "*had-had*" (42%)
  - Main backgrounds: "Fakes"
    - $Z\to\tau\tau$, $Z\to ll$, top, W+jets and multi-jet
  - Multivariate analysis based on Boosted Decision Trees
  - Using 8 TeV (20.3 fb^{-1}) data collected in 2012

Higgs to ττ – Analysis Strategy

Object selection:
e, μ,τ, jets, E_T^{miss}

Preselection

lep-lep	lep-had	had-had
Exactly 2 opposite sign leptons **No tau** $p_T(\ell_1)+p_T(\ell_2) > 35$ GeV $0.1 < x1, x2 < 1$ $\Delta\varphi_{\ell\ell} < 2.5$ Same flavor (SF): • $30 < m_{\ell\ell} < 75$ GeV • $E_T^{miss} > 40$ GeV • HPTO $E_T^{miss} > 40$ GeV Different flavor (DF): • $30 < m_{\ell\ell} < 100$ GeV • $E_T^{miss} > 20$ GeV	**Exactly 1 lepton (e/μ)** **Exactly 1 tau** **Opposite sign** $m_T(\ell, E_T^{miss}) < 70$ GeV	**Exactly 2 opposite charge taus** **No electron or muon** $0.8 < \Delta R(\tau,\tau) < 2.8$ $\Delta\eta(\tau,\tau) < 1.5$ MET > 20 GeV MET between taus in φ or min $[\Delta\varphi(\tau, E_T^{miss})] < \pi/2$

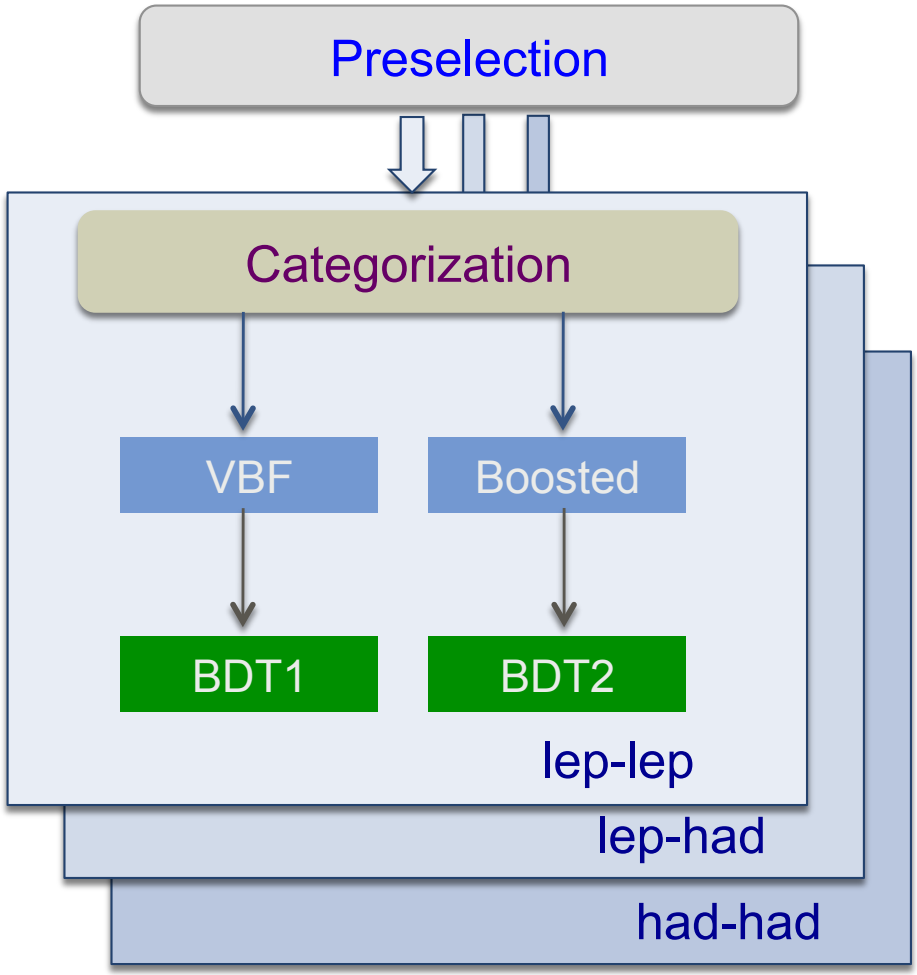
HPTO: High p_T Objects

$$x_{1,2} = \frac{p_{vis1,2}}{(p_{vis1,2}+p_{mis1,2})}$$

$$m_T = \sqrt{2p_T^{lep} E_T^{miss}(1-\cos\Delta\phi)}$$

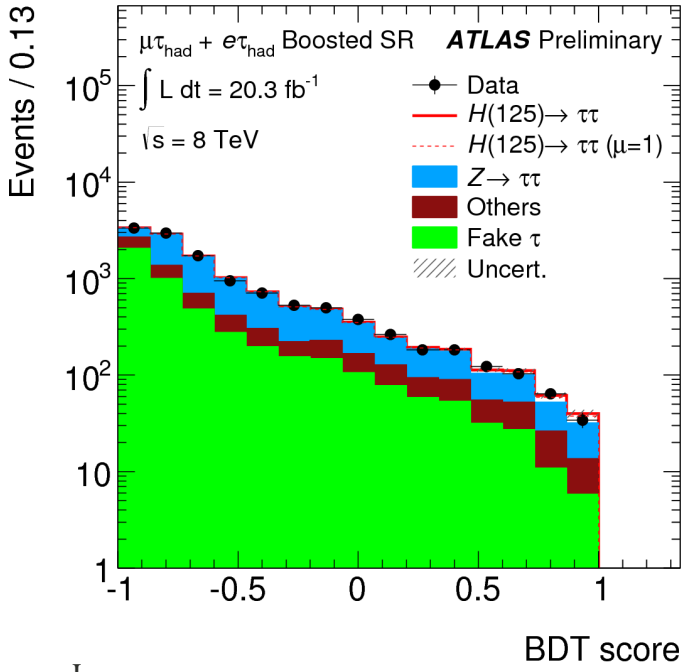
Higgs to $\tau\tau$ – Analysis Strategy

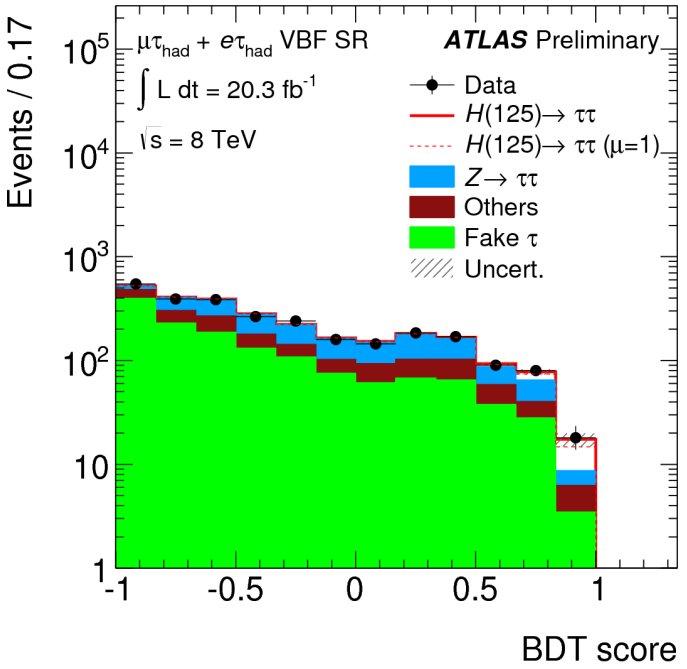
- Categorization (two per channel):
  - Vector Boson Fusion (**VBF**) category:
    - 2 jets separated in eta
  - **Boosted** category:
    - p_T (H) > 100 GeV
- Train and optimize 6 BDTs separately
  - 6-9 input variables (details in backup slides):
    - Resonance properties, e.g. $\Delta R(\tau,\tau)$, $m_{\tau\tau}$ …
    - Event properties (activities, topologies), e.g. $\Delta\eta(j_1,j_2)$ …



Background Modeling

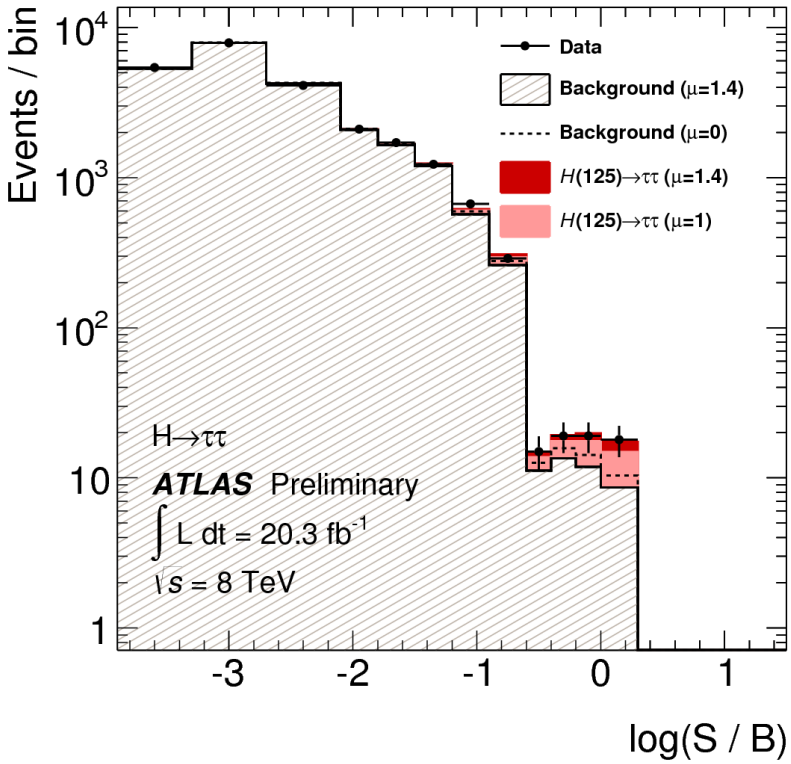
- All major backgrounds from data-driven or normalized to data in relevant control regions
  - $Z \rightarrow \tau\tau$: use sample created by data-driven embedding procedure
  - Others: $Z \rightarrow ll$, top use MC normalized to data in corresponding control regions; diboson and $H \rightarrow WW$ from MC
  - Fake: obtained by data-driven fake-factor method or template fit method

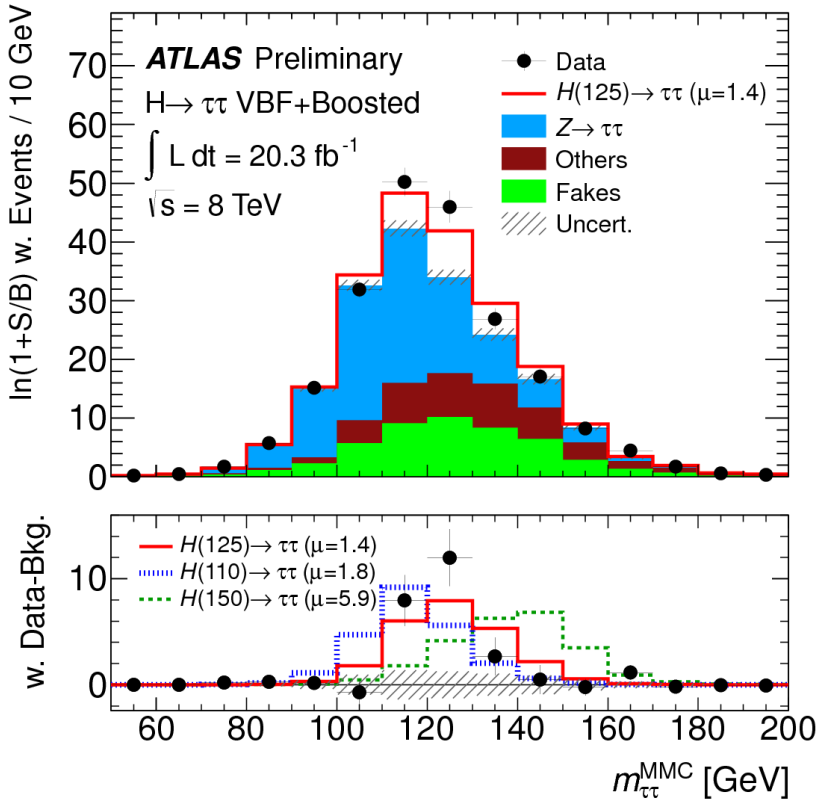




Evidence of Higgs to $\tau\tau$

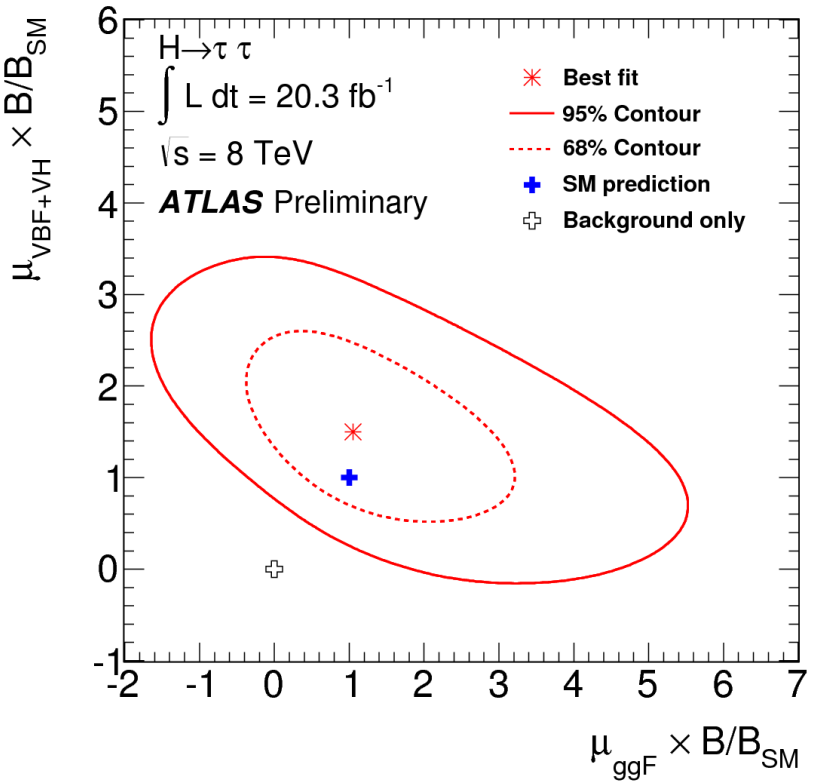
- Observed (expected) significance @ m_H = 125 GeV = 4.1 (3.2)σ
- Consistent with a 125 GeV SM Higgs boson

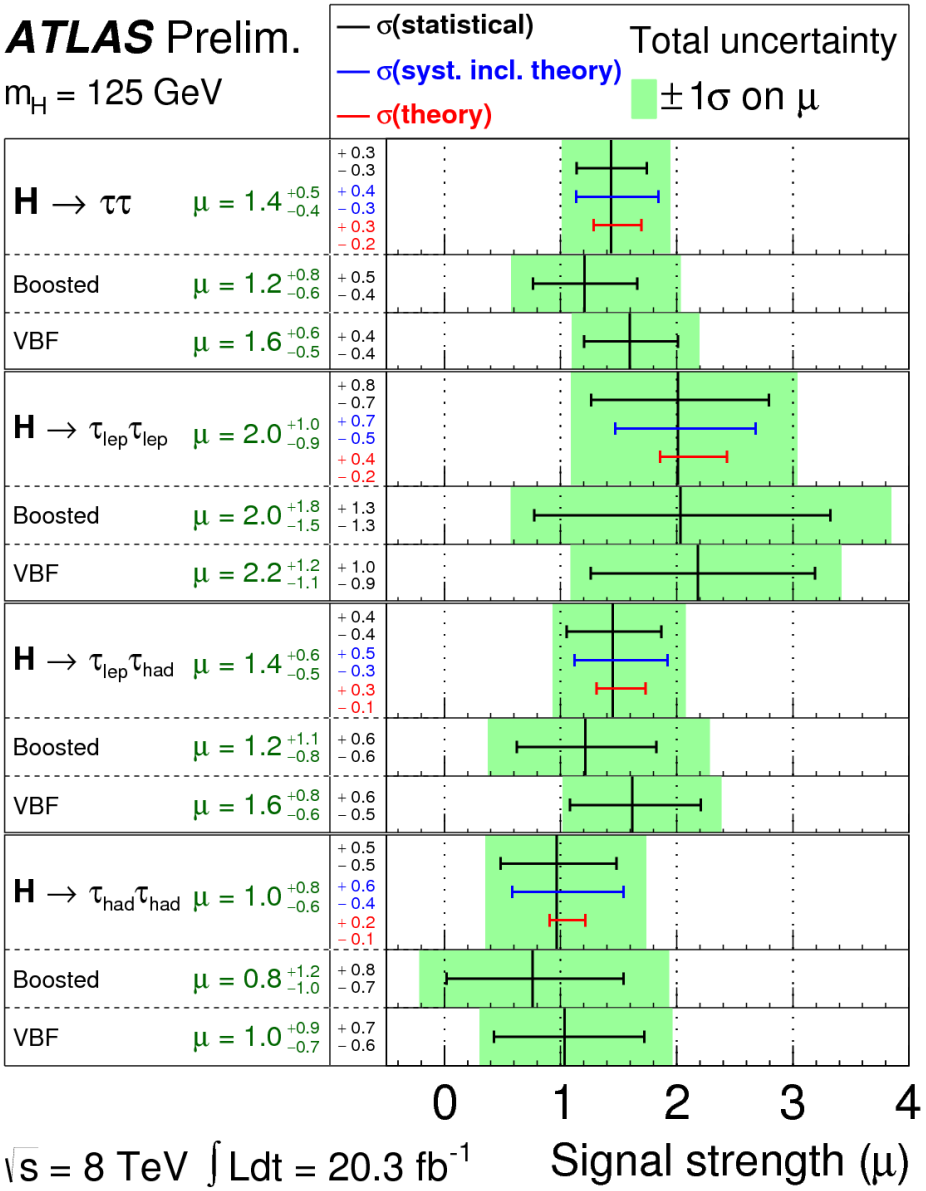




Results - Higgs to ττ

- Combined signal strength:
  - $\mu = 1.4\ ^{+0.5}_{-0.4}$





Analyses

- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $VH(\rightarrow bb)$
- $ttH (\rightarrow \gamma\gamma/bb)$

H→μμ Analysis Strategy

- Small BR (2.17×10^{-4}) yet good mass resolution
  - Search for a narrow μμ resonance peak
  - Fit analytical signal + background modeling

Event Selection:

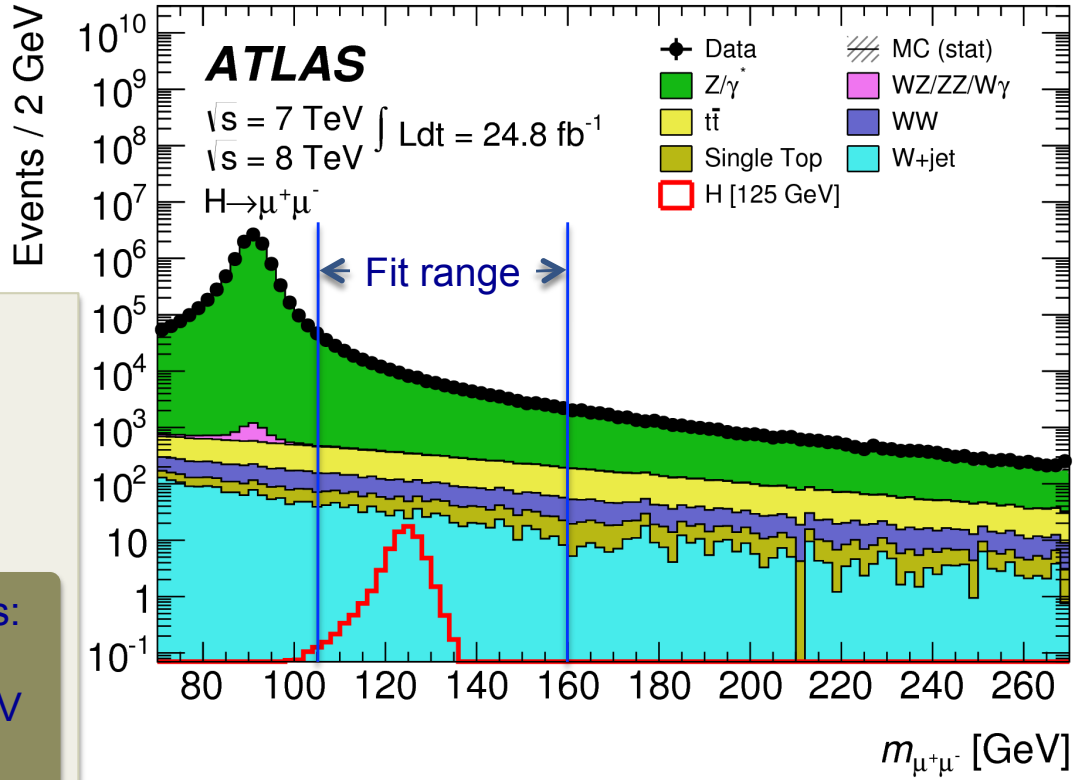
- 2 isolated opposite-sign muons
- $p_T(\mu_1) > 25$ GeV
- $p_T(\mu_2) > 15$ GeV
- $E_T^{miss} < 80$ GeV

7 Categories:

VBF:
- ≥ 2 jets, $M_{jj} > 500$ GeV
- $\Delta\eta_{jj} > 3$, $\eta_{jet1} \times \eta_{jet2} < 0$

	Central muons:	Non-central muons:
"low"	$p_T^{\mu\mu} < 15$ GeV	$p_T^{\mu\mu} < 15$ GeV
"medium"	$15 < p_T^{\mu\mu} < 50$ GeV	$15 < p_T^{\mu\mu} < 50$ GeV
"high"	$p_T^{\mu\mu} > 50$ GeV	$p_T^{\mu\mu} > 50$ GeV

"Central": $|\eta|<1$ for both muons

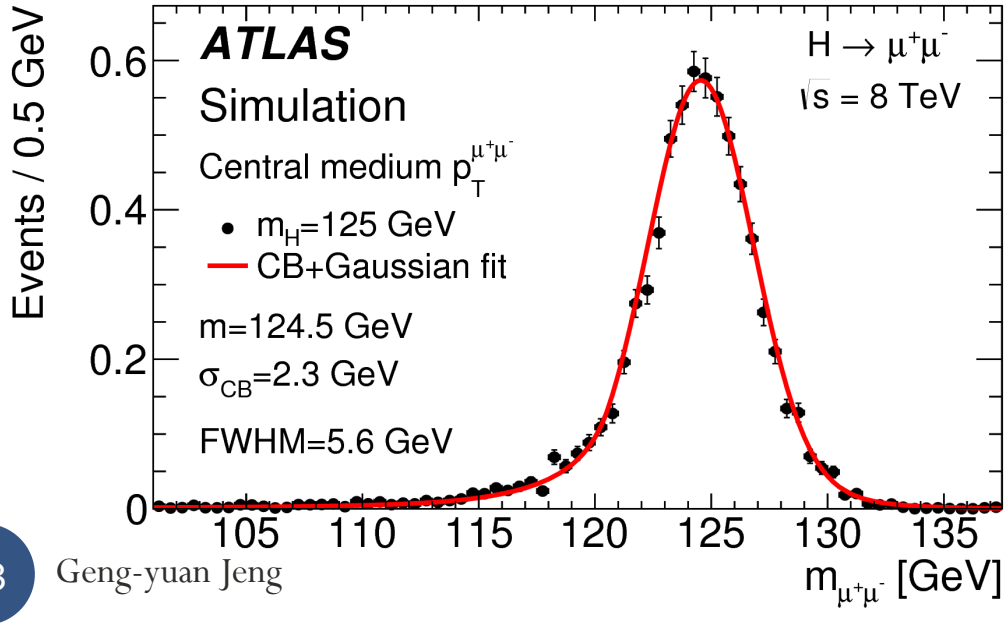


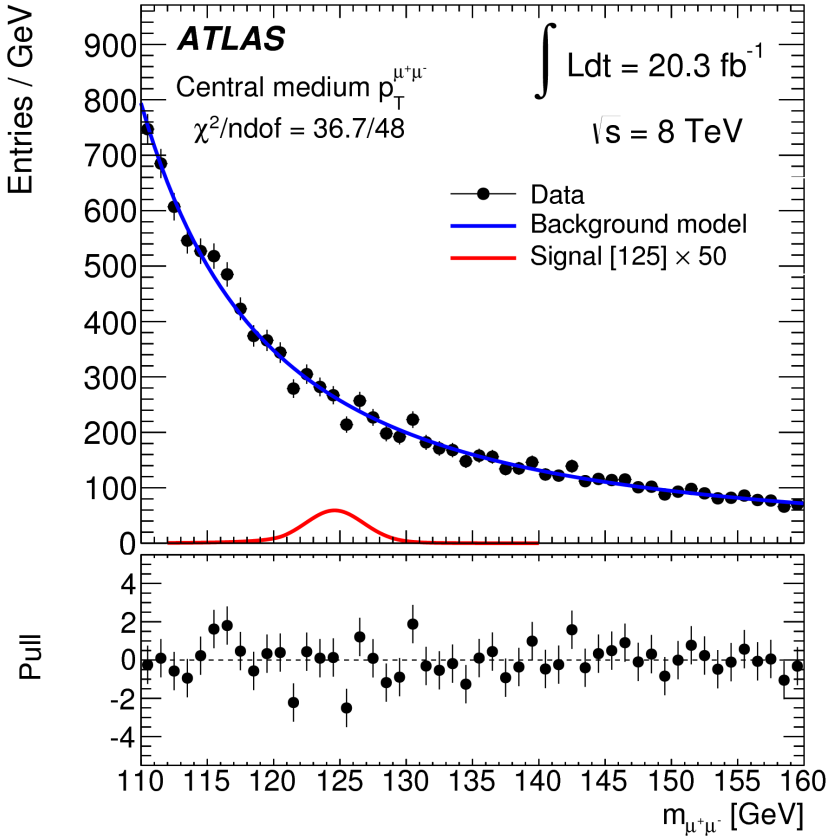
Background Modeling

- Signal
  - Gaussian + Crystal Ball
- Background
  - For $p_T^{\mu\mu}$ categories:

$$P_B(X) = f \cdot [BW(M,\Gamma) * GS(\sigma^B)](x) + (1-f) \cdot C \cdot e^{A \cdot x}/x^3$$

  - For VBF: $P_B(X) = BW(M,\Gamma,x) \cdot e^{A \cdot x}$
  - Validated with high stat. MC samples

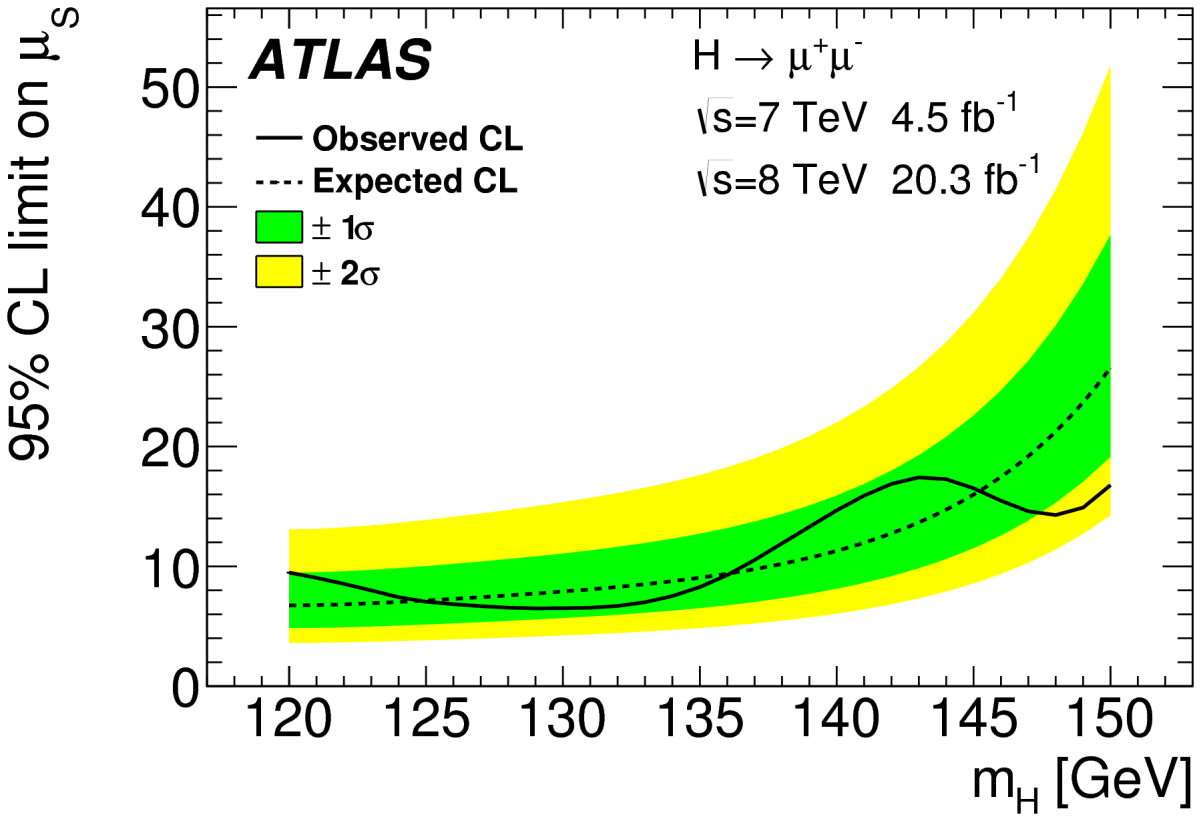




M=91.2 GeV; Γ=2.49 GeV
σ^B from avg. mass resolution of Z/γ* MC in each category

Results - H→μμ

- 95% CL observed (expected) upper limits on σ/σ_{SM} :
  - 7.0 (7.2) for m_H = 125.5 GeV
- 95% CL observed upper limit on BR (H→μμ):
  - 1.5×10^{-3}
    - Much smaller than BR(ττ) confirms Higgs doesn't couple to leptons universally

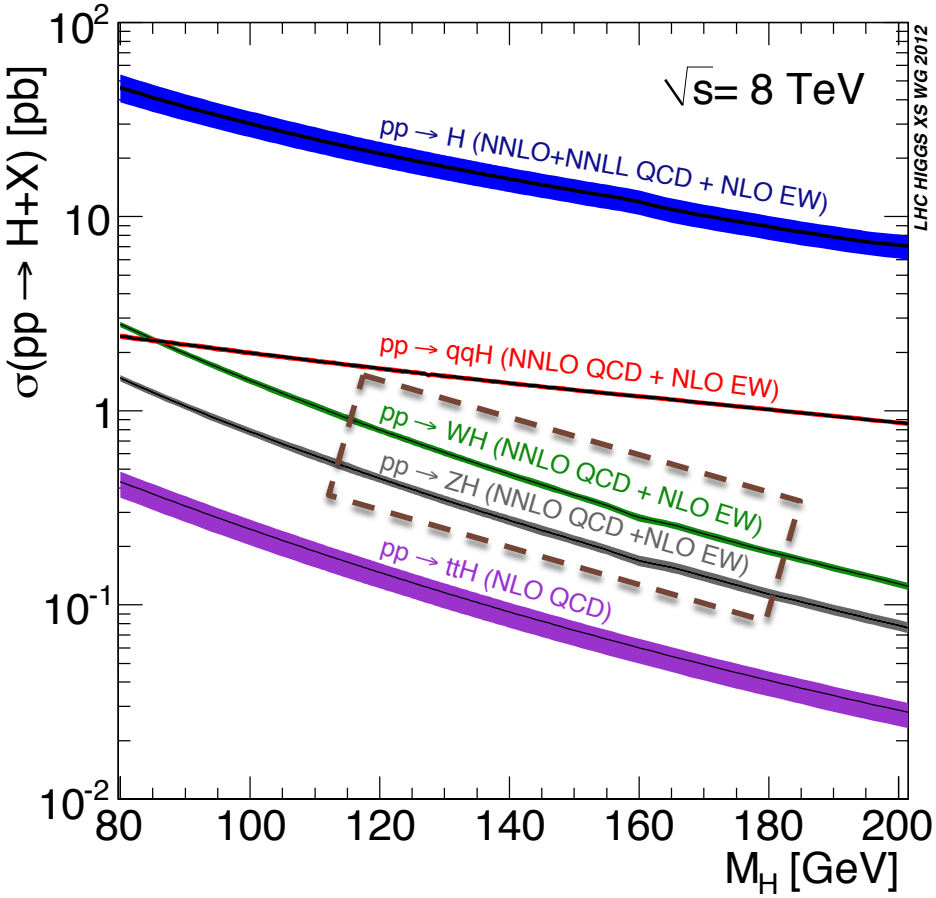


Analyses

- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- VH ($\rightarrow$ bb)
- ttH ($\rightarrow\gamma\gamma$/bb)

VH(→bb)

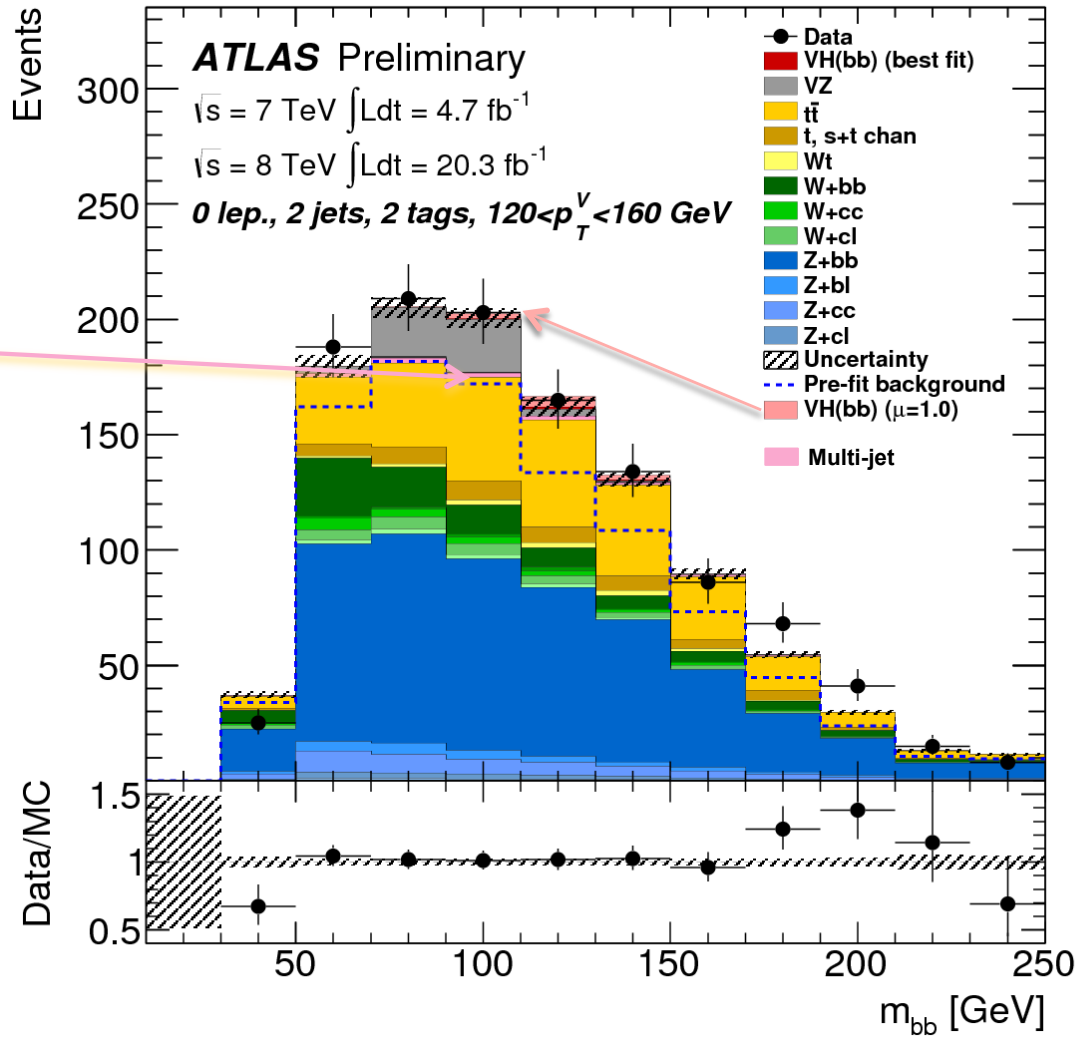
- For m_H=125.4 GeV, BR=0.57
- Probe direct coupling to (down-type) quarks
- Categories according to number of charge leptons
  - 0-lepton:
    - Large MET
    - Z→νν, H→bb
  - 1-lepton:
    - only 1 electron or muon
    - W→lν, H→bb
  - 2-lepton:
    - 2 electrons or 2 muons
    - Z→ll, H →bb



ATLAS-CONF-2013-079

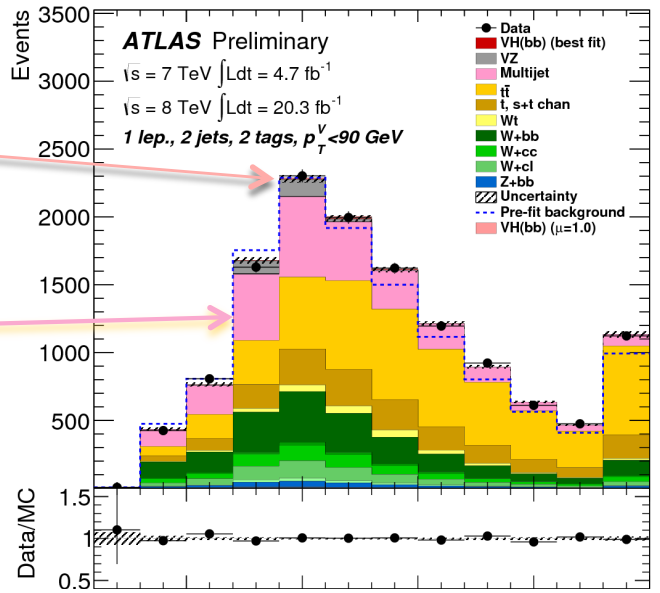
Background Modeling – 0-Lepton

- Signal:
  - WH/ZH (PYTHIA8)
- Background:
  - VZ (HERWIG)
  - Multi-jet (data-driven)
  - Top (POWHEG+PYTHIA)
  - Single Top (AcerMC/ POWHEG+PYTHIA)
  - W+jets (SHERPA)
  - Z+jets (SHERPA)

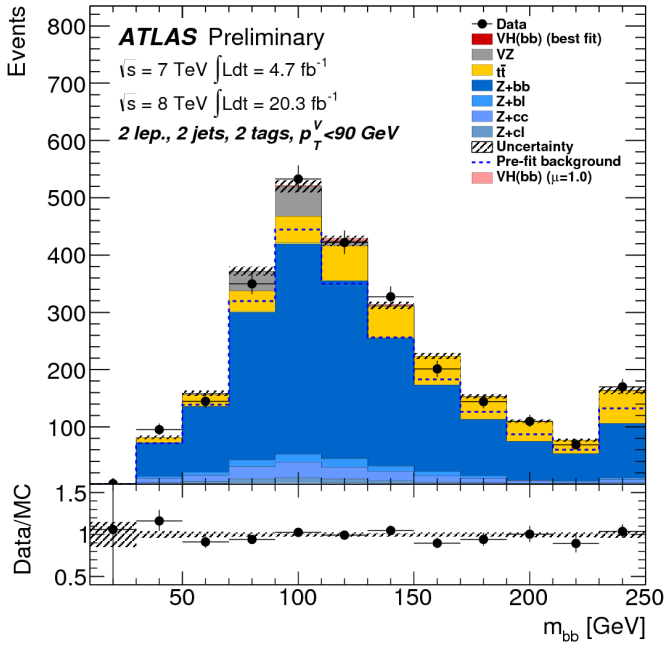


Background Modeling – Other

- Signal:
  - WH/ZH (PYTHIA8)
- Background (1-Lepton):
  - VZ (HERWIG)
  - Multi-jet (data-driven)
  - Top (POWHEG+PYTHIA)
  - Single Top (AcerMC/POWHEG +PYTHIA)
  - W+jets (SHERPA)
  - Z+jets (SHERPA)
- Background(2-Lepton):
  - VZ (HERWIG)
  - Top (POWHEG+PYTHIA)
  - Single Top (AcerMC/POWHEG +PYTHIA)
  - Z+jets (SHERPA)



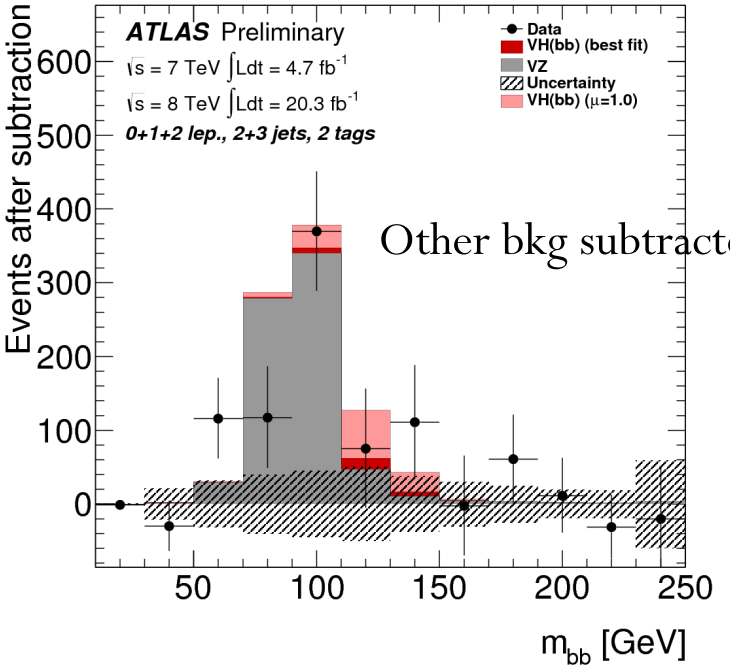
1-Lepton

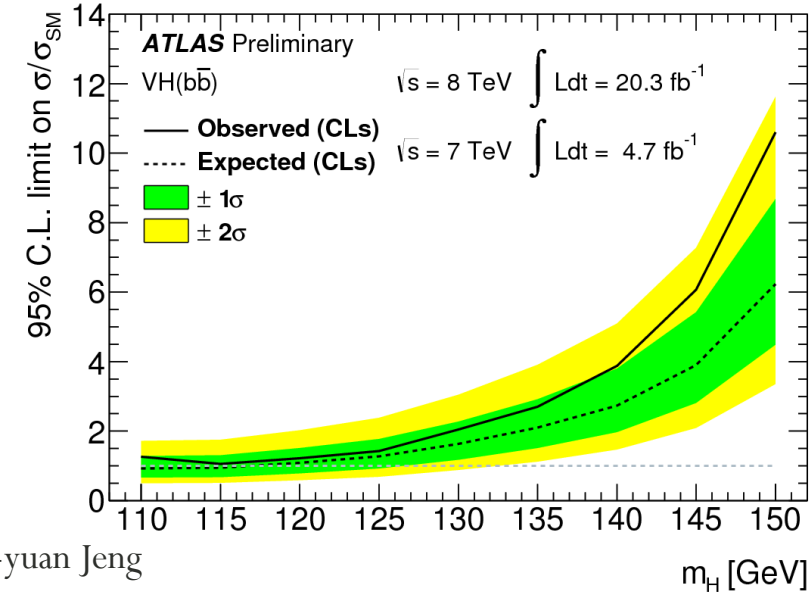


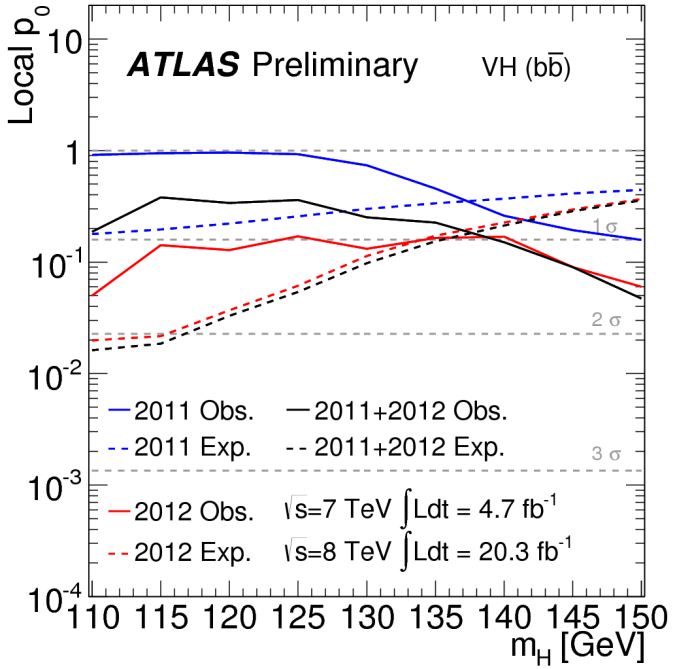
2-Lepton

Results - VH(→bb)

- Fit to m_{bb} peak consistent with both one and zero SM Higgs boson
- 95% CL observed (expected) upper limits on σ/σ_{SM} :
  - 1.4 (1.3) for m_H = 125 GeV
- Combined signal strength:
  - $\mu = 0.2 \pm 0.5$ (stat.) ± 0.4 (syst.)
- MVA analysis under way; expected to improve search sensitivity







Analyses

- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $VH (\rightarrow bb)$
- $ttH (\rightarrow \gamma\gamma/bb)$

ttH ($\gamma\gamma$/bb)

- Direct measurement of top-Higgs coupling (Y_t ~1)
  - Probe new physics in ggH and $\gamma\gamma$H effective vertices
- Search channels:

This talk

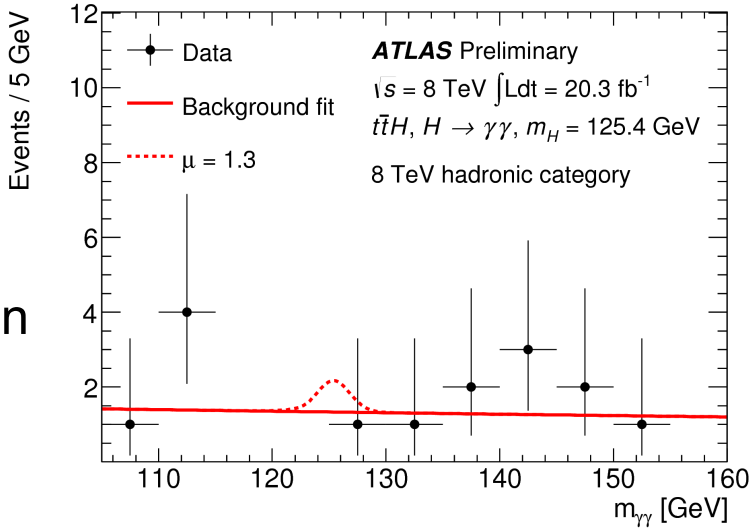
  - H→bb: large BR (0.57) and background
    - 20.3 fb^{-1}@8 TeV
  - H→$\gamma\gamma$: tiny BR (2.3×10^{-3}) but clean resonance signature
    - 4.5 fb^{-1}@7 TeV+20.3 fb^{-1}@8 TeV
  - H→others: multi-lepton final states, BR~0.3
- Main background:
  - tt + X

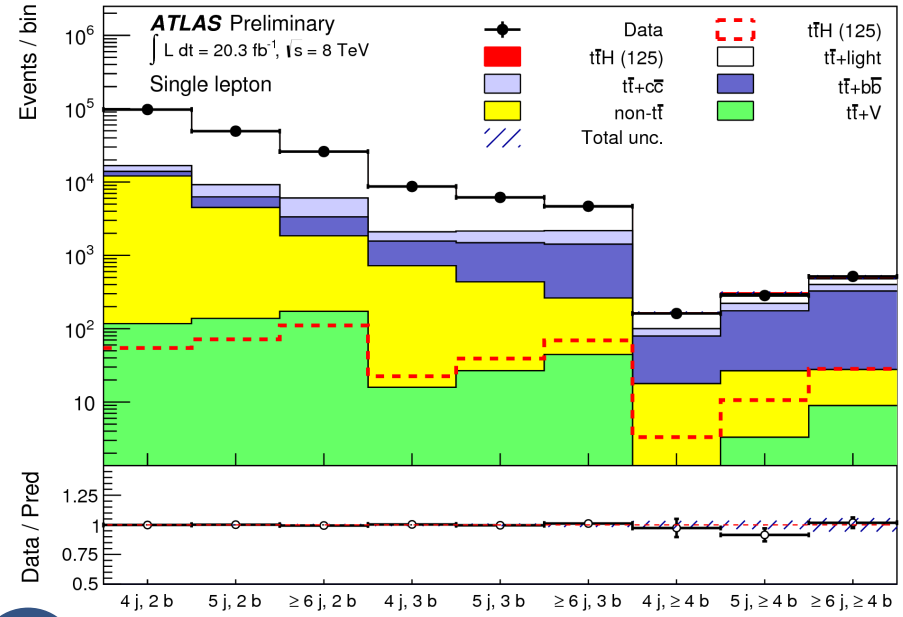
Analysis Strategy

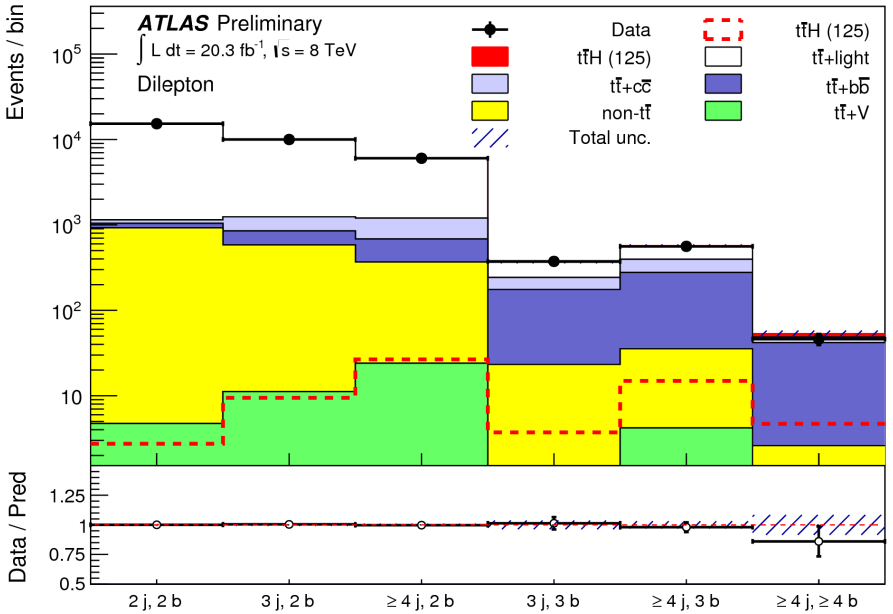
- ttH ($\gamma\gamma$): ATLAS-CONF-2014-043
  - Leptonic channel (≥1 lepton, ≥ 1 b-jet)
  - Hadronic channel (5 or ≥ 6 jets, 1 or ≥ 2 b-jets with variable p_T cuts and b-tag working points)
  - Search for a resonance in $m_{\gamma\gamma}$
    - Unbinned likelihood fit to extract signal
- ttH (bb): ATLAS-CONF-2014-011
  - Single lepton and dilepton channels:
    - Categorize events by jet and b-jet multiplicity
    - Build Neural Network (NN) discriminator from kinematic variables to distinguish signal from background in signal-rich regions (e.g. ≥6 jets, ≥4 tags in single lepton channel)
    - Extract signal by simultaneous fit in jet and b-jet multiplicity bins

Background Modeling

- ttH ($\gamma\gamma$):
  - Background modeled by exponential function
- ttH (bb):
  - tt + jets modeled by POWHEG+PYTHIA
  - tt + bb/cc comparable to MADGRAPH (ME-PS MC)
    - Calibrated to data in fit in background dominating bins in signal-rich regions

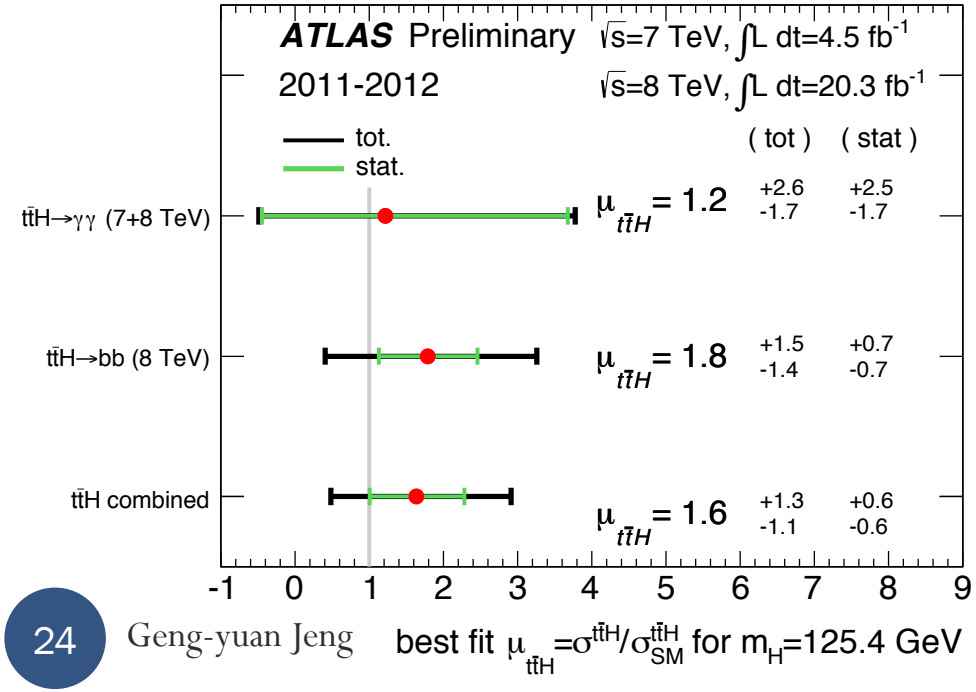


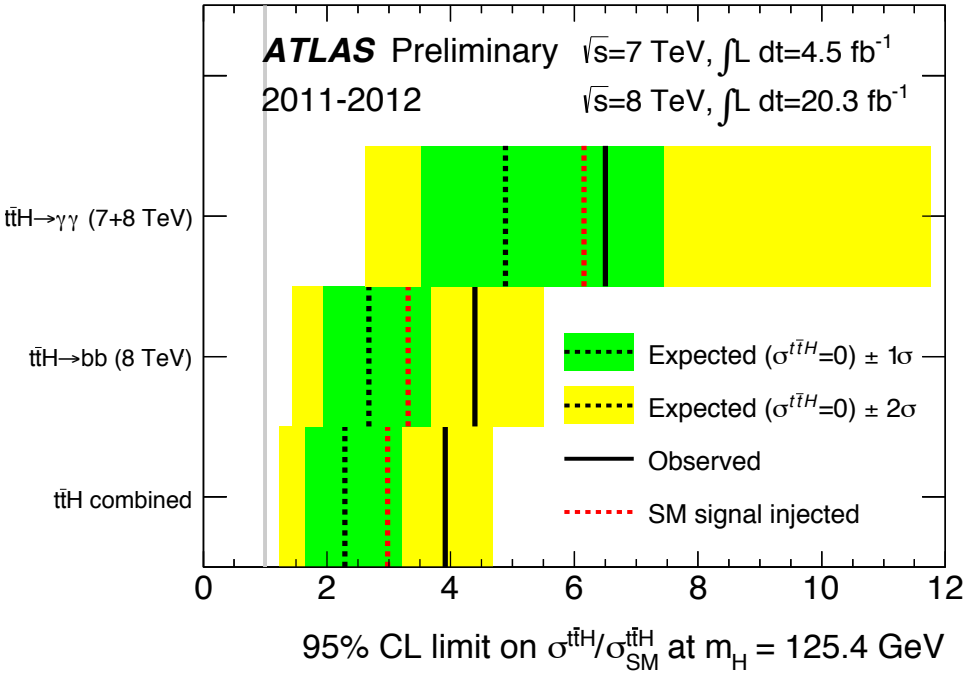




Results - ttH (γγ/bb)

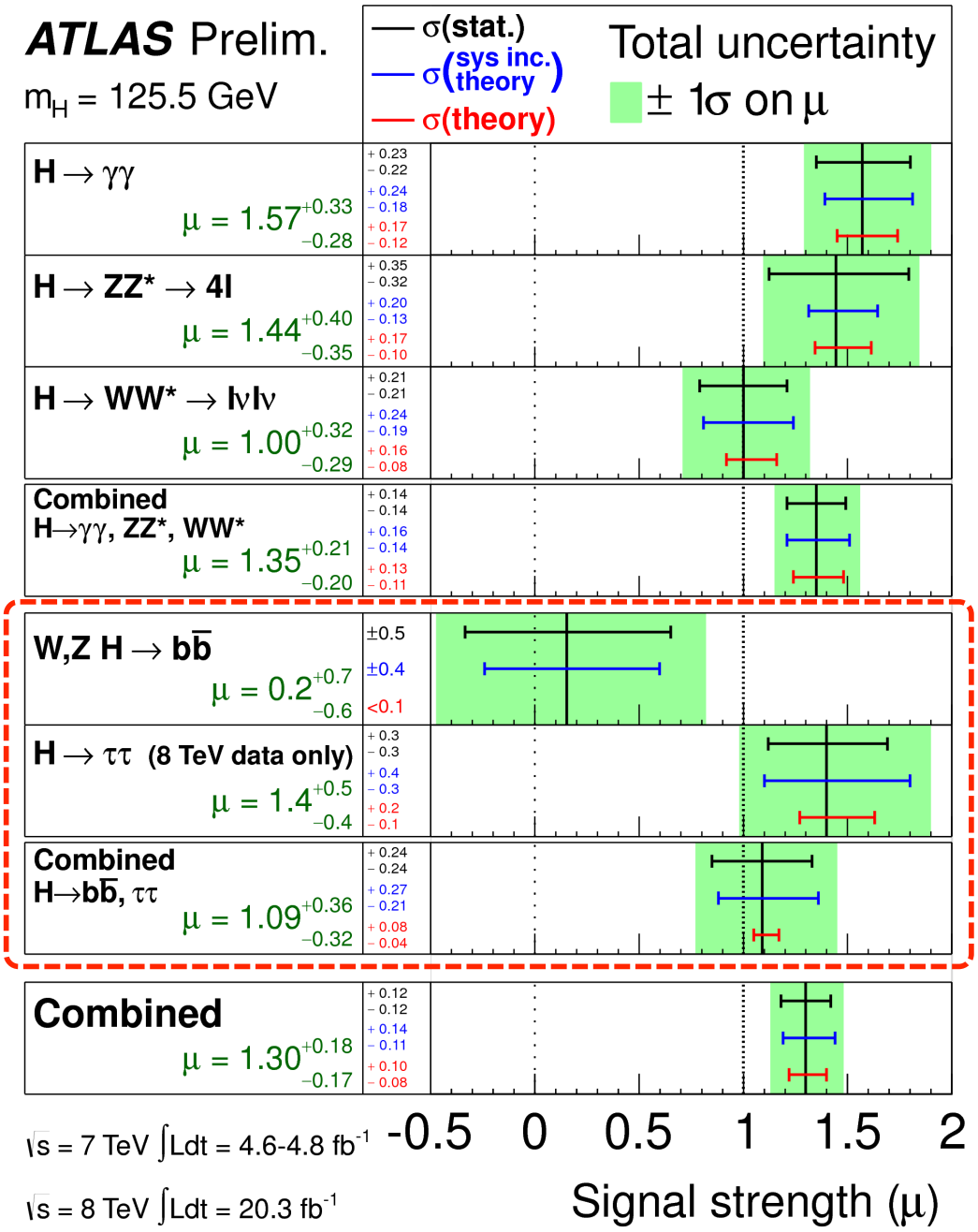
- Combine 19 categories: 15 from ttH(bb)+4 ttH(γγ)
- 95% CL observed (expected) upper limits on σ/σ_{SM} for m_H = 125.4 GeV:
  - bb: 4.1 (2.6); γγ: 6.5 (4.9); combined: 3.9 (2.3)
- Best fit signal strength:
  - $\mu = 1.6 \pm 0.6\ (\text{stat.})\ ^{+1.1}_{-1.0}\ (\text{syst.})$





Combination

- Combined gauge boson and fermion channels compatible with the Standard Model
- Combination with ttH under way



Summary and Outlook

- Evidence for Higgs coupling to fermions observed
  - So far in $H \to \tau\tau$ channel
  - VBF, ggF production channels exploited in $H \to \tau\tau$ /$\mu\mu$ searches
    - Study in $H \to \mu\mu$ indicates non-universal fermion couplings
  - Search in VH($\to$bb) channel consistent with either zero or one Higgs boson
  - Search for ttH production performed in the $\gamma\gamma$/bb decay modes
  - Search for VH($\to\tau\tau$) and ttH($\to$WW/ZZ/$\tau\tau$) modes on-going
  - ttH measurement boosted by energy in LHC Run II
    - Signal production increases by 4.7 while background 3.7 (@14 TeV)
    - Sensitive for probing new physics in ggH/$\gamma\gamma$H effective vertices
- Properties measurement, e.g. couplings, spin, CP, etc in Run II
  - 7(3)% on κ_F expected with 300 (3000) fb^{-1} (ATL-PHYS-PUB-2013-014) at 14 TeV

Backup

BDT Input variables - Higgs to $\tau\tau$

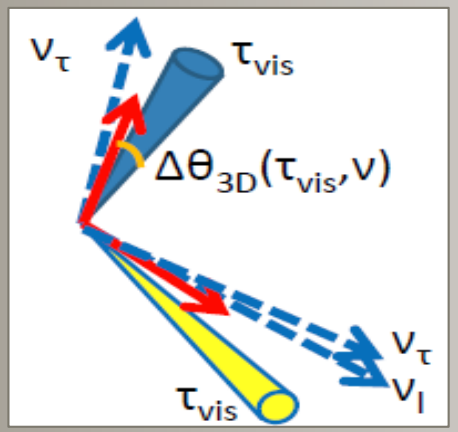
Variable	VBF			Boosted		
	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$m_{\tau\tau}^{\text{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau,\tau)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\text{T}}^{\text{Total}}$		•	•			
sum p_{T}					•	•
$p_{\text{T}}(\tau_1)/p_{\text{T}}(\tau_2)$					•	•
$E_{\text{T}}^{\text{miss}}\phi$ centrality		•	•	•	•	•
$x_{\tau 1}$ and $x_{\tau 2}$						•
$m_{\tau\tau,j_1}$				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi_{\ell_1,\ell_2}$				•		
sphericity				•		
$p_{\text{T}}^{\ell_1}$				•		
$p_{\text{T}}^{j_1}$				•		
$E_{\text{T}}^{\text{miss}}/p_{\text{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\text{jets}})$	•					
j_3 η centrality	•					
$\ell_1 \times \ell_2$ η centrality	•					
ℓ η centrality		•				
$\tau_{1,2}$ η centrality			•			

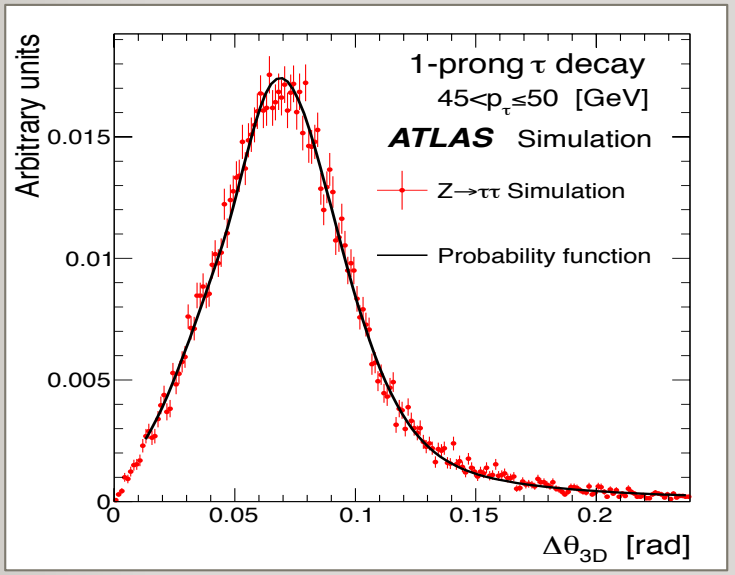
$$p_{\text{T}}^{\text{Total}} = |\vec{p}_{\text{T}}^{\,\ell \text{ or } \tau_{\text{had-vis}}} + \vec{p}_{\text{T}}^{\,\tau_{\text{had-vis}}} + \vec{p}_{\text{T}}^{\,j1} + \vec{p}_{\text{T}}^{\,j2} + \vec{E}_{\text{T}}^{\text{miss}}|$$

Missing Mass Calculator (MMC)(*):

- Construct $\mathcal{P}(\Delta\theta, p_\tau)$ by solving τ kinematics for grid points in $(\phi_{\text{mis1}}, \phi_{\text{mis2}}, m_{\text{mis1}})$ parameter space using $\Delta\theta_{3D}(\tau_{\text{vis}}, \nu, \text{type})$ template from simulated $Z\to\tau\tau$ events
- Final estimator of $m_{\tau\tau}$ is derived as the most probable value from the invariant mass distribution constructed from all phase space points weighted by:

$$\mathcal{P}_{event} = \mathcal{P}(\Delta\theta_1, p_{\tau_1}) \times \mathcal{P}(\Delta\theta_2, p_{\tau_2}) \times \mathcal{P}(\Delta\not{E}_x) \times \mathcal{P}(\Delta\not{E}_y)$$



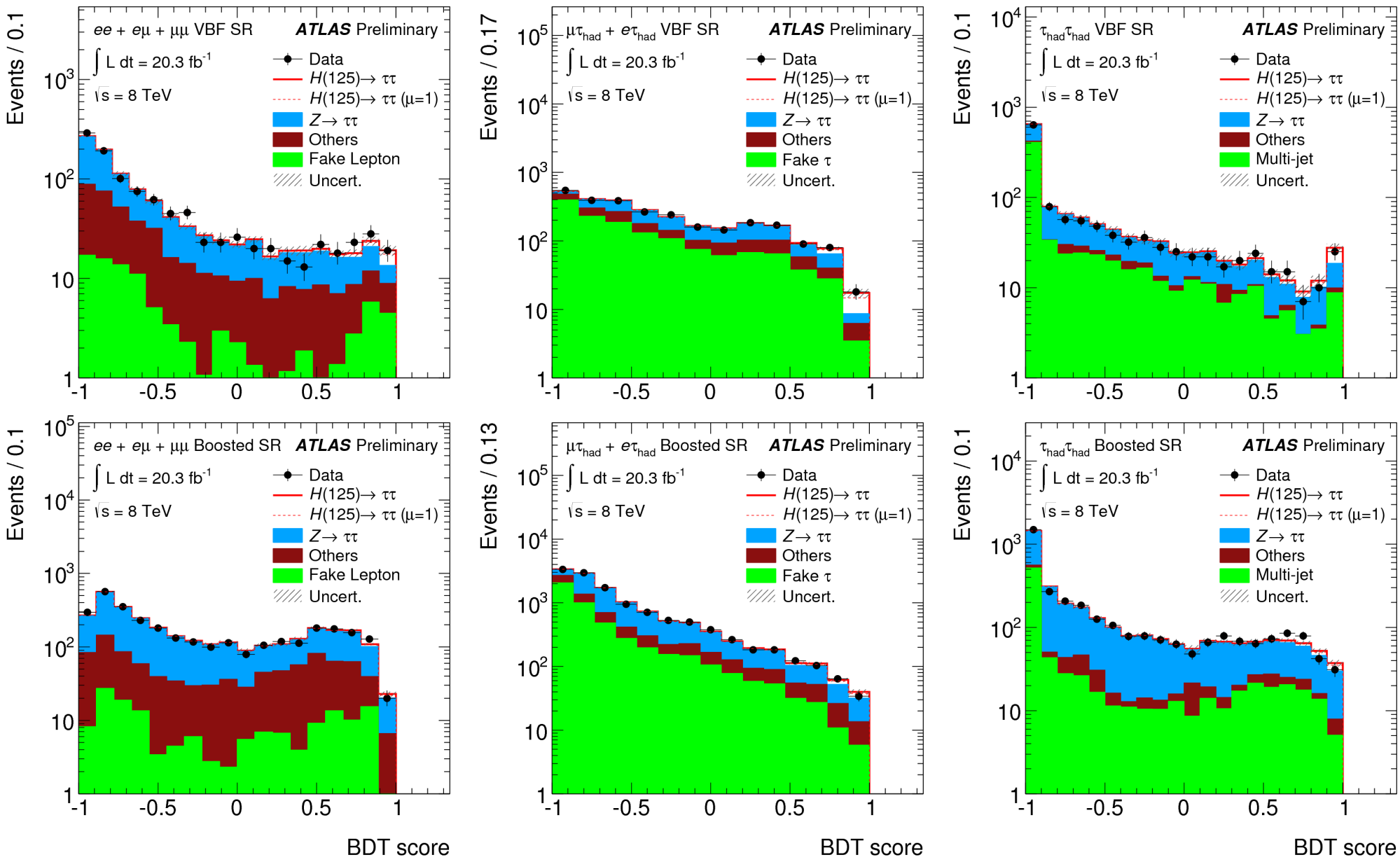


$$E_x^{\text{miss}} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$
$$E_y^{\text{miss}} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$
$$m_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2p_{\text{vis}_1}p_{\text{mis}_1}\cos\Delta\theta_{vm_1}$$
$$m_{\tau_2}^2 = m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2}p_{\text{mis}_2}\cos\Delta\theta_{vm_2}$$

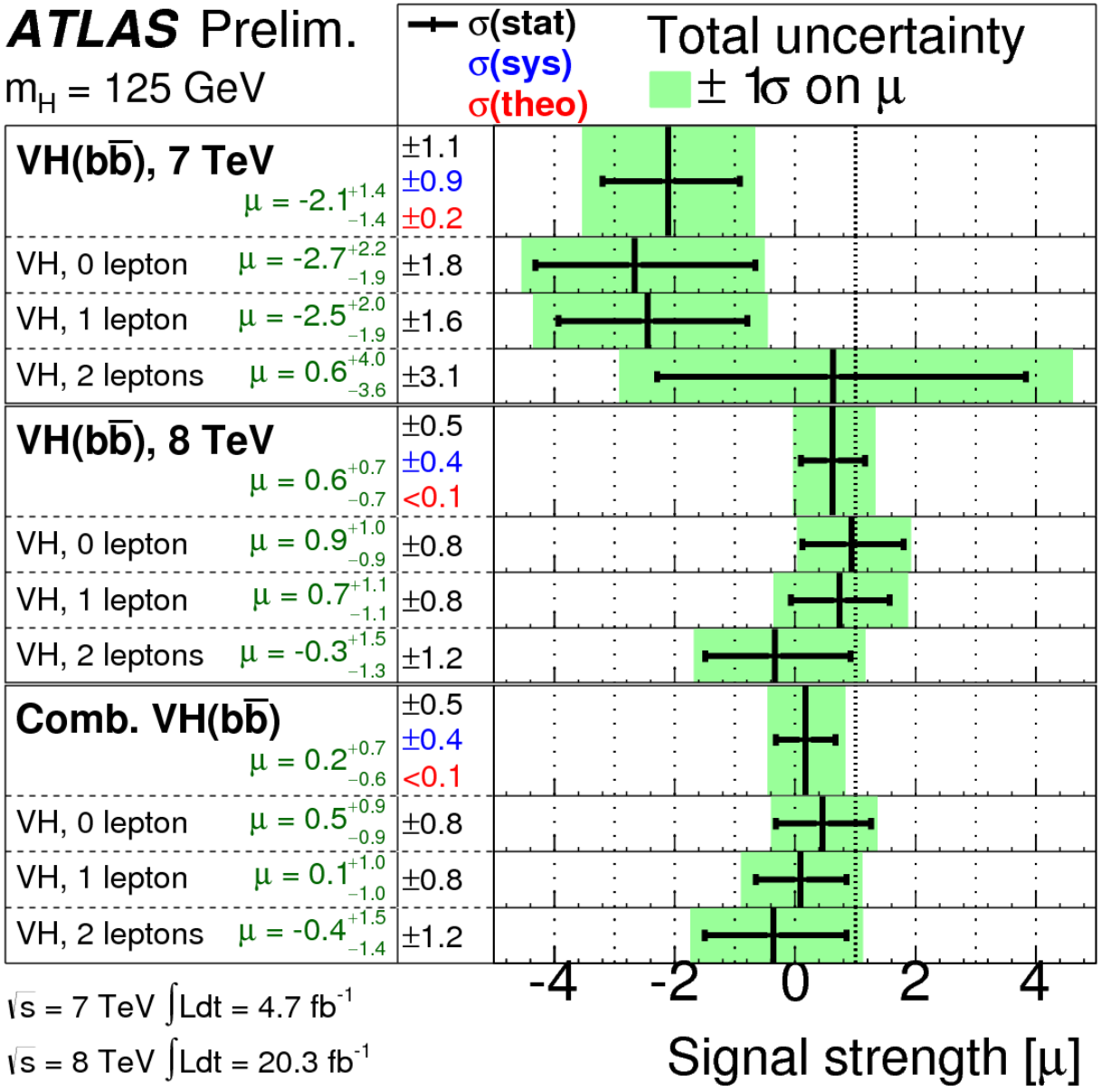
(*) NIM A654 (2011) 481

BDT Distributions – H to $\tau\tau$

LepLep | **LepHad** | **HadHad**



VH (bb)


ATLAS Prelim.
m_H = 125 GeV
σ(stat)
σ(sys)
σ(theo)
Total uncertainty
± 1σ on μ
VH(bb̄), 7 TeV
μ = -2.1 +1.4 −1.4
±1.1
±0.9
±0.2
VH, 0 lepton μ = -2.7 +2.2 −1.9 ±1.8
VH, 1 lepton μ = -2.5 +2.0 −1.9 ±1.6
VH, 2 leptons μ = 0.6 +4.0 −3.6 ±3.1
VH(bb̄), 8 TeV
μ = 0.6 +0.7 −0.7
±0.5
±0.4
<0.1
VH, 0 lepton μ = 0.9 +1.0 −0.9 ±0.8
VH, 1 lepton μ = 0.7 +1.1 −1.1 ±0.8
VH, 2 leptons μ = -0.3 +1.5 −1.3 ±1.2
Comb. VH(bb̄)
μ = 0.2 +0.7 −0.6
±0.5
±0.4
<0.1
VH, 0 lepton μ = 0.5 +0.9 −0.9 ±0.8
VH, 1 lepton μ = 0.1 +1.0 −1.0 ±0.8
VH, 2 leptons μ = -0.4 +1.5 −1.4 ±1.2
-4
-2
0
2
4
Signal strength [μ]
√s = 7 TeV ∫Ldt = 4.7 fb-1
√s = 8 TeV ∫Ldt = 20.3 fb-1

NN Output – ttH(bb)