ATLAS Results On Higgs Boson Searches in Fermion Final States

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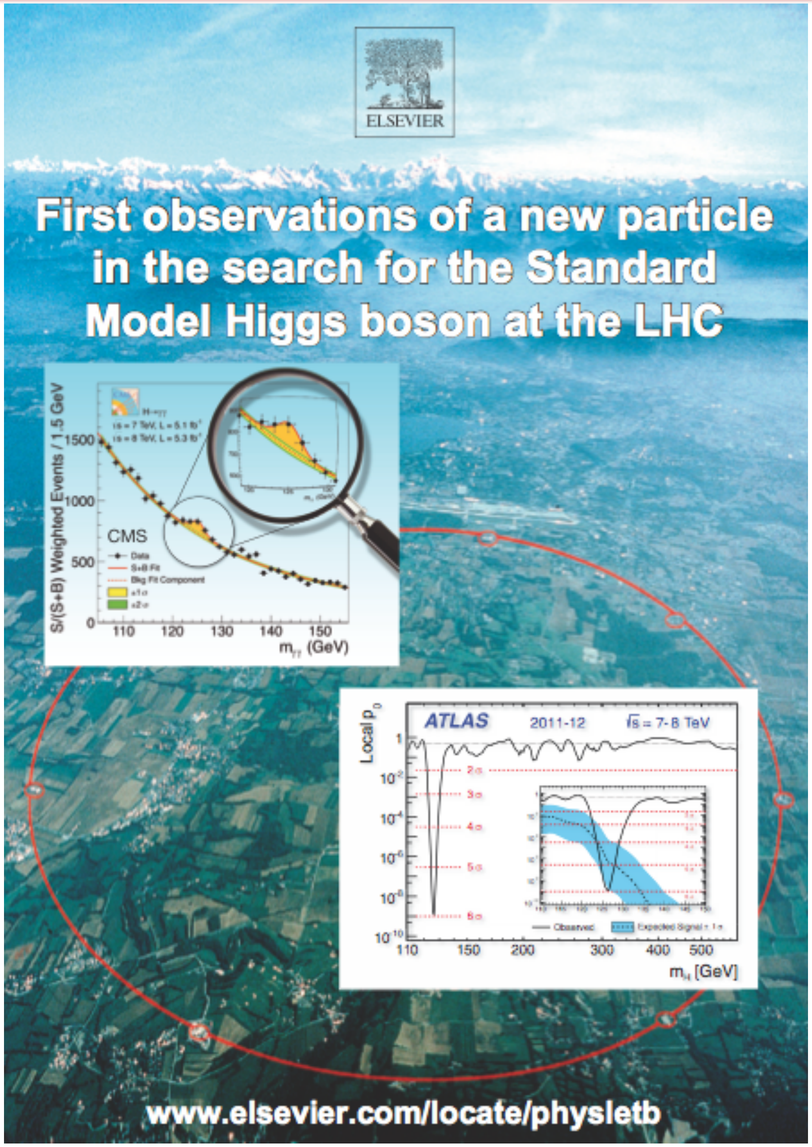
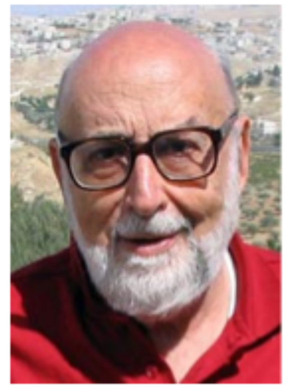
On behalf of the ATLAS collaboration

Higgs Boson Discovery



The Nobel Prize in Physics 2013



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Peter W. Higgs

Which Higgs Boson Did We Find?

- Higgs boson was discovered in ZZ*, γγ, and WW* decays

- Higgs boson mass is ~125.6 GeV
  - measured in $H \to ZZ^* \to 4l$, and $H \to \gamma\gamma$
  - ATLAS: M_H=125.5 ± 0.2 (stat) ± 0.6 (syst) GeV
  - CMS: M_H=125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

- ATLAS and CMS data strongly favor $J^P=0^+$ SM quantum numbers
  - All alternative J^P models tried are excluded at >95%CL

- Signal strength $\mu=\sigma/\sigma_{SM}$ and all couplings are consistent with 1
  - ATLAS: μ=1.33±0.20
  - CMS: μ=0.80±0.14
  - Tevatron: μ=1.44±0.60

- >3σ evidence for V-boson mediated (VBF) production

- **All measured properties are compatible with SM Higgs hypothesis**

Higgs Boson: What is Next?

- **Evidence of coupling to fermions so far**
  - **Tevatron VH(→bb) combination:** 2.8σ excess @ M_H=125 GeV
  - **CMS VH(→bb):** 2.1σ excess @ M_H=125 GeV
  - **CMS H→ττ:** 2.85σ excess @ M_H=125 GeV
    - CMS H→ττ and H→bb combination: 3.4σ excess @ M_H=125 GeV
- **Search for H→fermions decays is one of the most important goals for the Higgs program**
  - In particular, does Higgs couple to leptons?
    - We already indirectly know that it couples to quarks
  - Are $\Gamma_{H\to ff}$ consistent with SM predictions?
  - Is it the same Higgs decaying to H→VV & H→ff?
    - Is mass the same? CP properties?

$$\Gamma_{H\to ff} = \frac{N_C M_H}{8\pi v^2} m_f^2 \beta_f^3, \quad \beta_f = \sqrt{1 - \frac{4m_f^2}{M_H^2}}$$

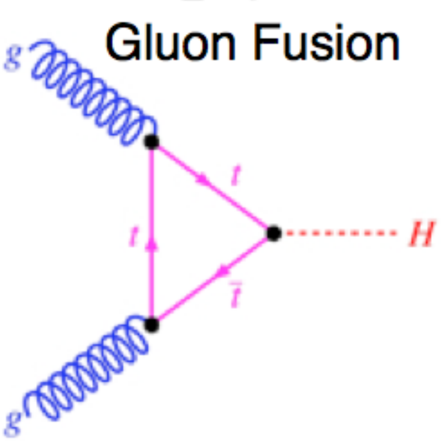
Talk Outline

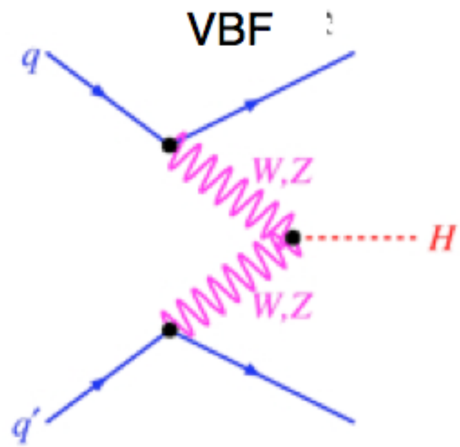
- Higgs boson production
- Highlights of ATLAS Performance
- Results covered in this talk
  - Search for SM $H \rightarrow \mu\mu$ with full 8 TeV dataset
    - ATLAS-CONF-2013-010
  - Search for SM $H \rightarrow bb$ with full 7+8 TeV dataset
    - ATLAS-CONF-2013-079
  - **Search for SM $H \rightarrow \tau\tau$ with 20.3 fb^{-1} of 8 TeV data**
    - ATLAS-CONF-2013-108

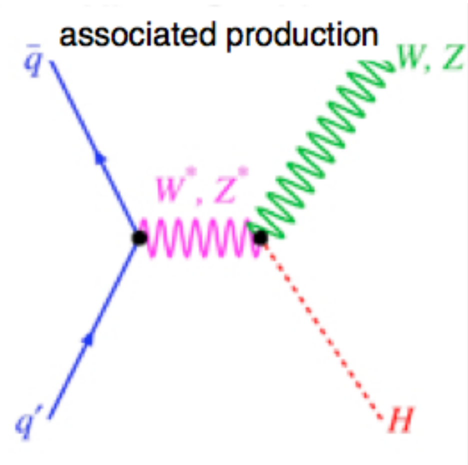
New!

- Not covered in this talk
  - Results on BSM $H \rightarrow ff$ searches at ATLAS

SM Higgs Production (for M_H=125 GeV)







Largest production mode: ~88%
Utilized by H→ττ & H→μμ analyses

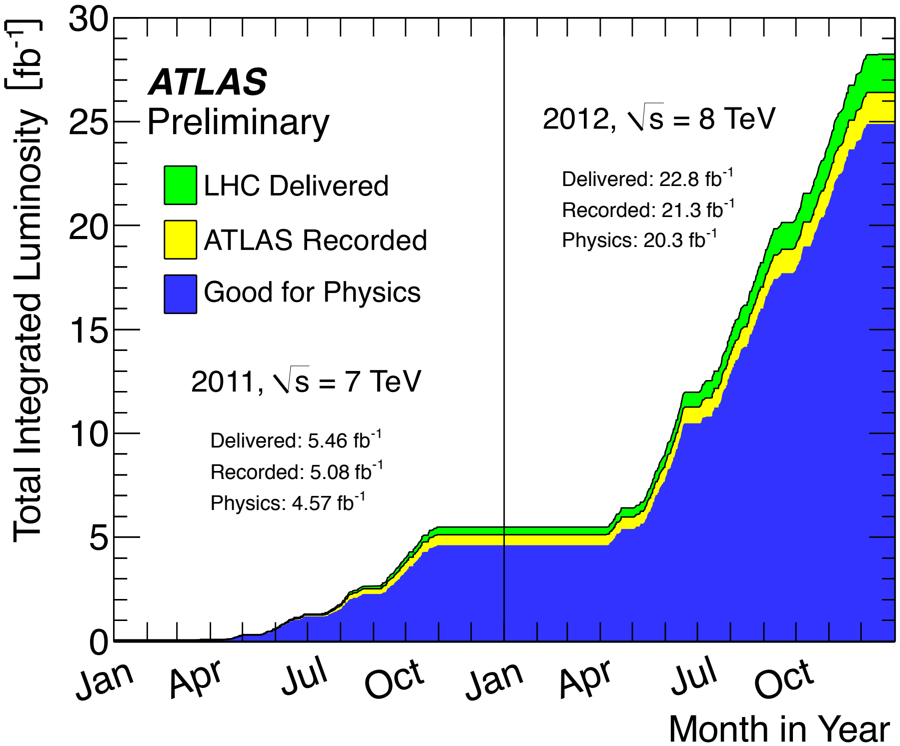
Unique signature of two jets with large M_{jj} & $|\Delta\eta_{jj}|$
Utilized by H→ττ

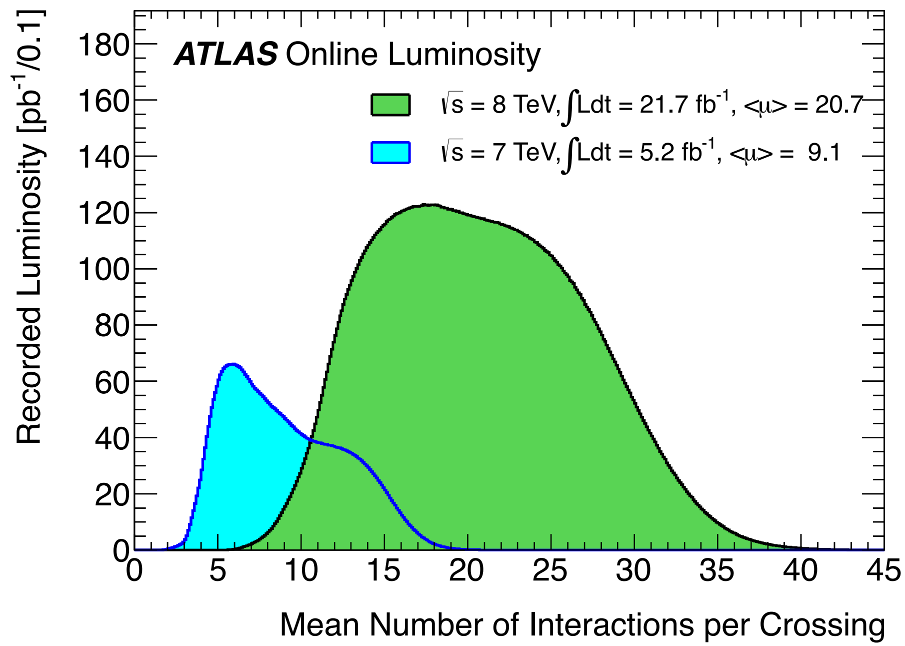
Unique signature with leptons & neutrinos
Utilized by VH(→bb)

	gg→H	**VBF**	**VH**
LHC: 8 TeV	19.5 pb	1.57 pb	1.08 pb

	H→bb	**H→ττ**	**H→μμ**
Br	57.8%	6.32%	0.0219%

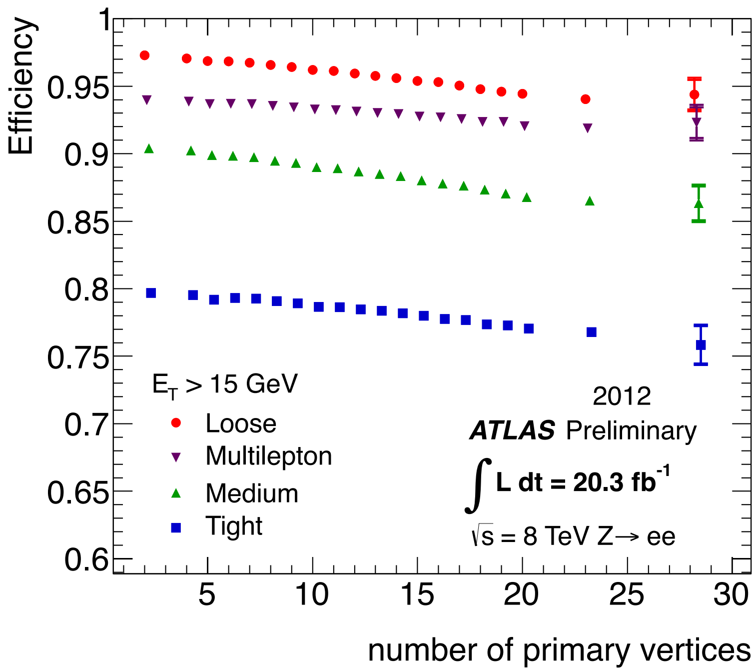
LHC & ATLAS Performance

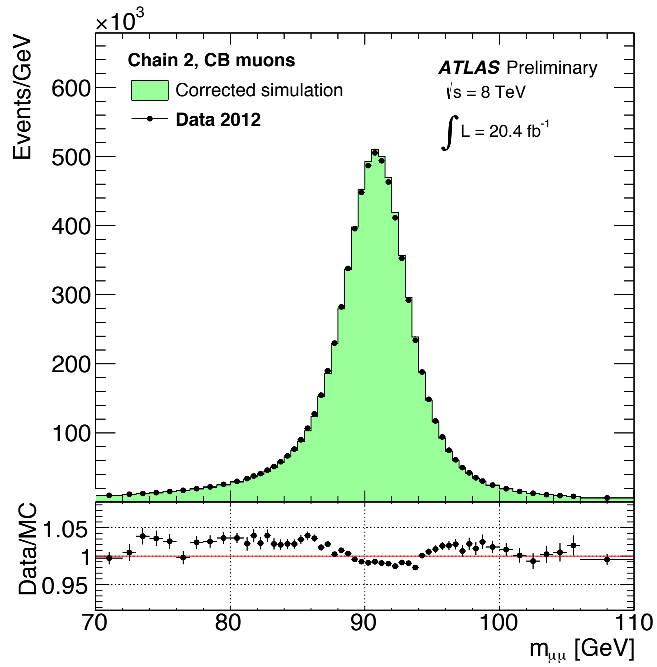




- Higgs boson discovery in 2012 would not be possible without outstanding performance of LHC
- Outstanding ATLAS detector performance in challenging high pile-up conditions with 90% efficiency for Physics

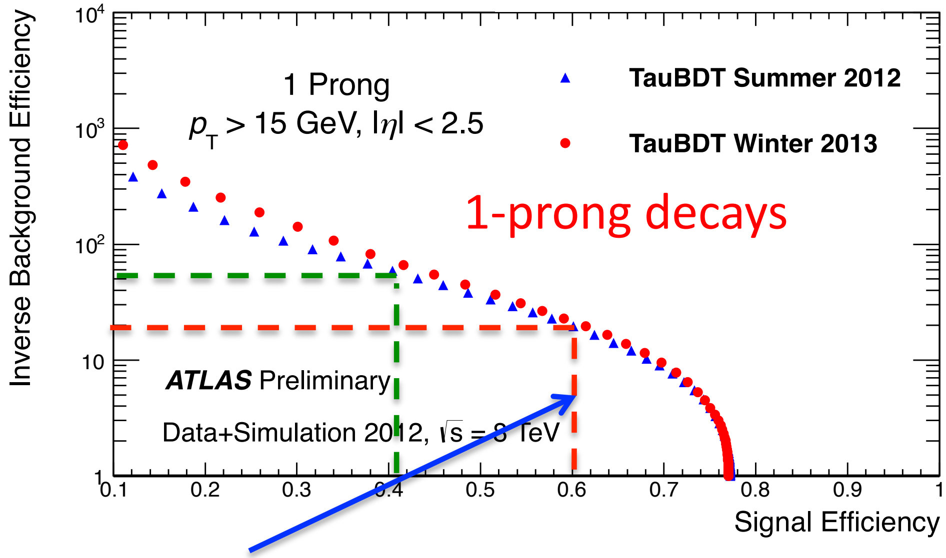
Electrons & Muons @ ATLAS



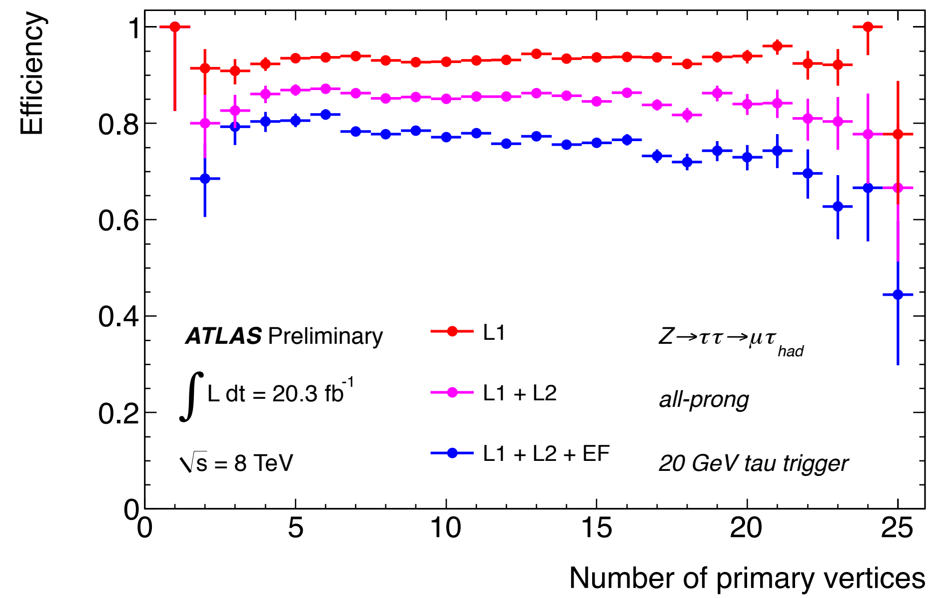


- Stable 97% (98%) muon (electron) reconstruction efficiencies
- Stable (within a few %) electron identification efficiency as a function of N_{vertex}
- ~2 GeV mass resolution for Z→μμ peak
  - Good muon resolution is very important for H→μμ search

Hadronic Tau's @ ATLAS



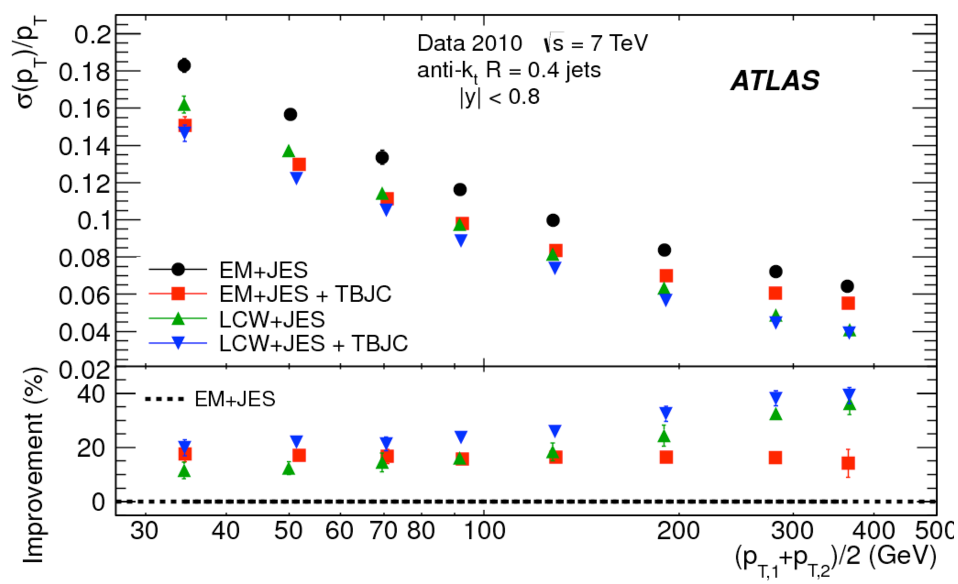
H→ττ search uses ~60% and 35-45% Signal efficiency working points



Stable hadronic tau trigger efficiency as a function of N_{vertex}

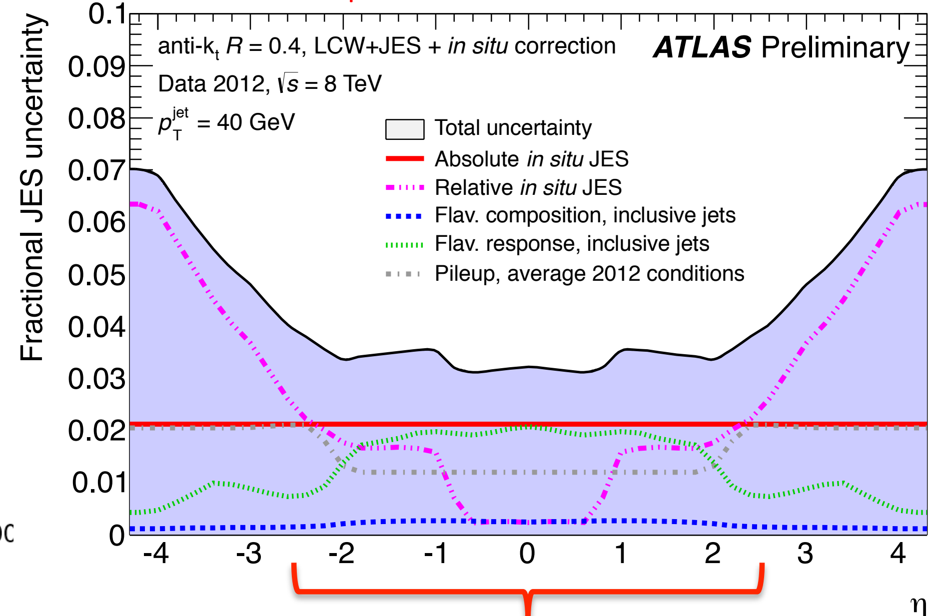
- ATLAS employs multivariate hadronic tau identification techniques
  - Use information about shower shape in calorimeter and tracking detectors
  - TauID systematic uncertainties are 2.5% (5.6%-6.8%) for 1-prong (3-prong) taus
- Tau energy scale (TES) is derived using *in situ* calibration based on Z→ττ peak position

Jets @ ATLAS



JER vs average P_T(jet)

JES vs η at P_T(jet)=40 GeV

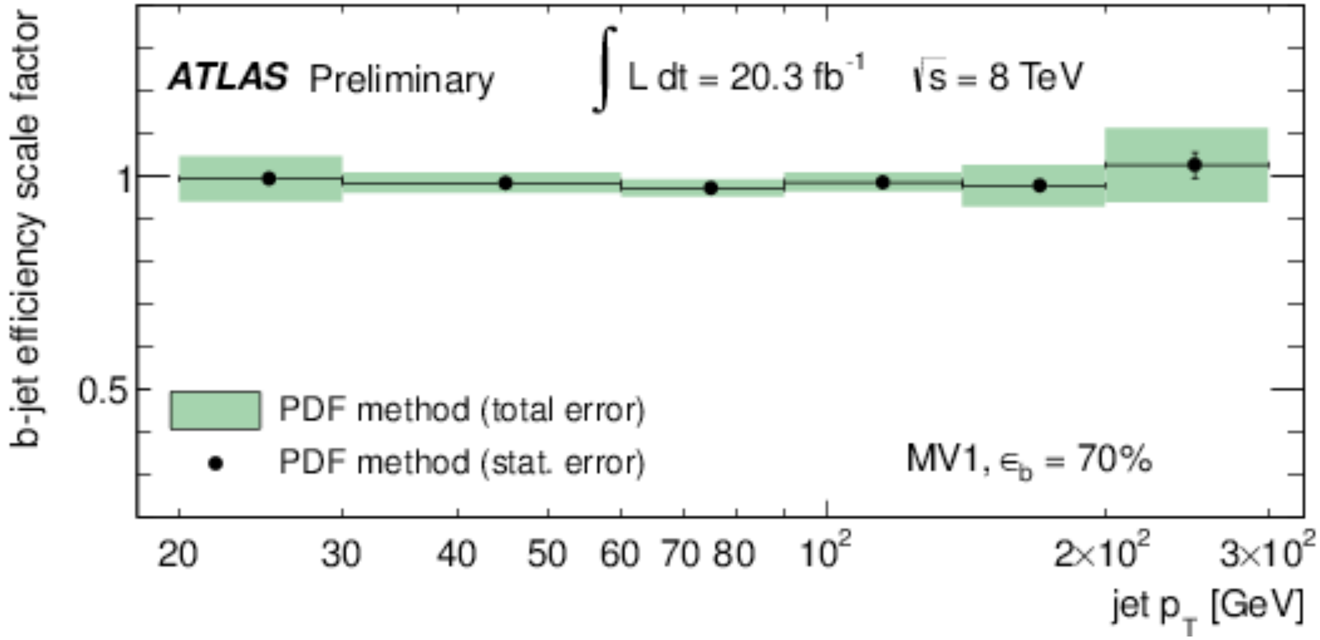


B-jet acceptance in H→bb search

Important region for H→ττ search

- H→bb and H→ττ searches rely on jets and benefit from reduced jet energy scale (JES) uncertainties
- Jet energy resolution (JER) is very important for H→bb search

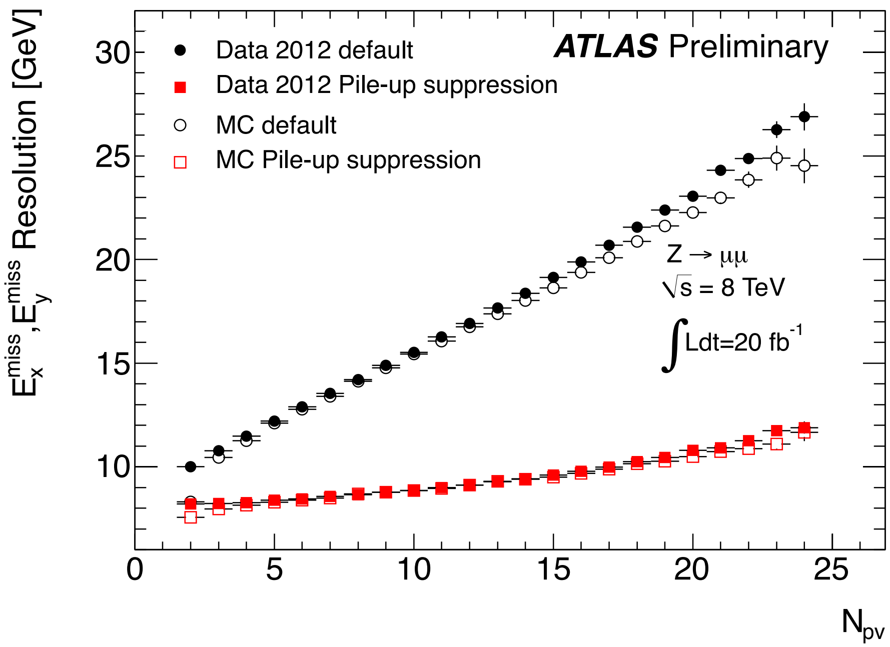
b-Tagging @ ATLAS

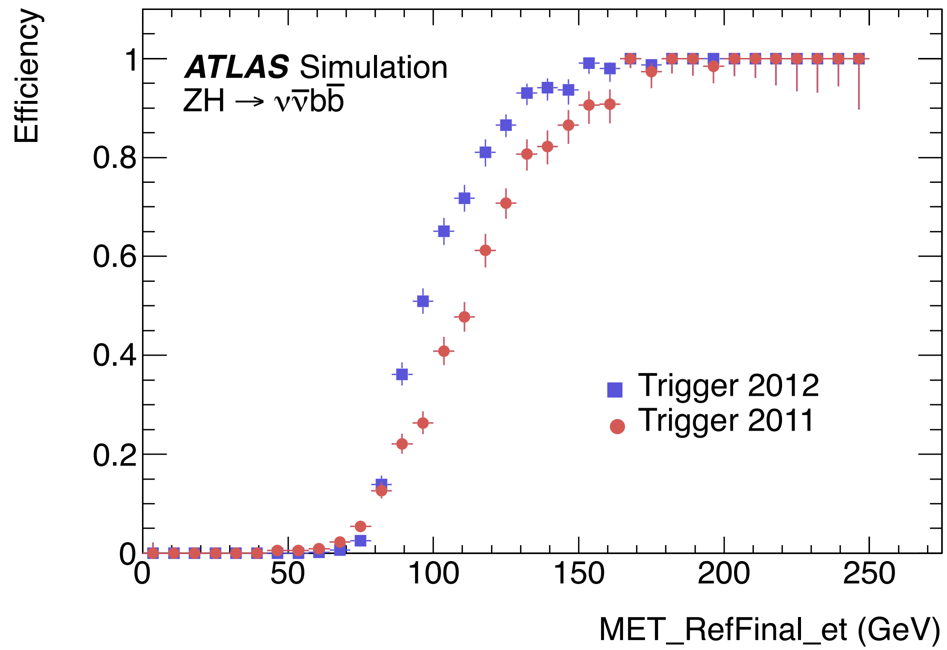


Data-to-MC scale factor vs P_T(jet)

- H→bb and H→ττ searches use NN *b*-tagging algorithm with working point corresponding to 70% *b*-tagging efficiency
  - Provides rejection factor of ~5 and ~150 against *c*-jets and light flavor jets
  - *b*-jet data-to-MC scale factors (SF) derived using *ttbar* di-lepton events
  - *b*-jet SF uncertainty in the range 2-10%
    - ~2% in the most important P_T(jet) range for H→bb search
  - *c*-jet SF uncertainty in the range 8-15%

Missing Transverse Energy (MET) @ ATLAS



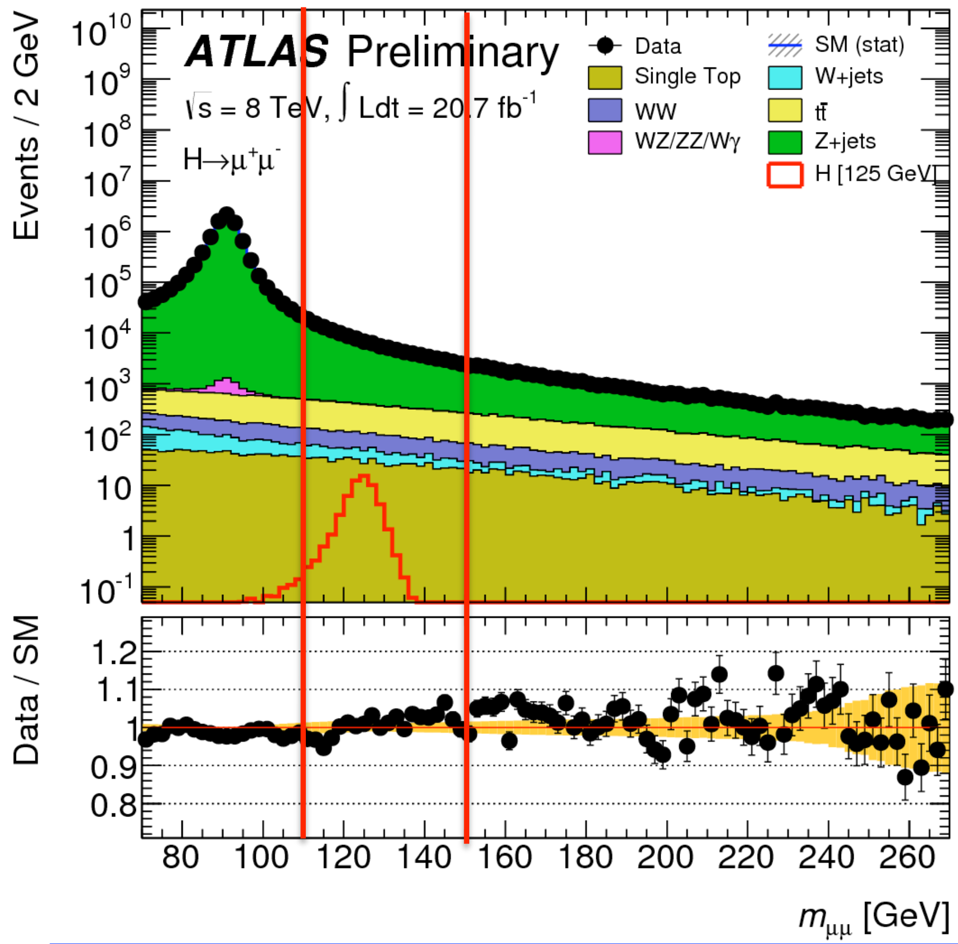


- Good MET resolution is very important for H→bb and H→ττ searches
  - MET is used in event selection and in $M_{\tau\tau}$ reconstruction
  - MET trigger is very important for ZH→νν+bb final state
- Great improvement in MET resolution is achieved by using track-based pile-up suppression
  - Correction is based on the ratio of the Σp_T of the tracks associated to the primary vertex and all tracks

Search for $H \rightarrow \mu\mu$

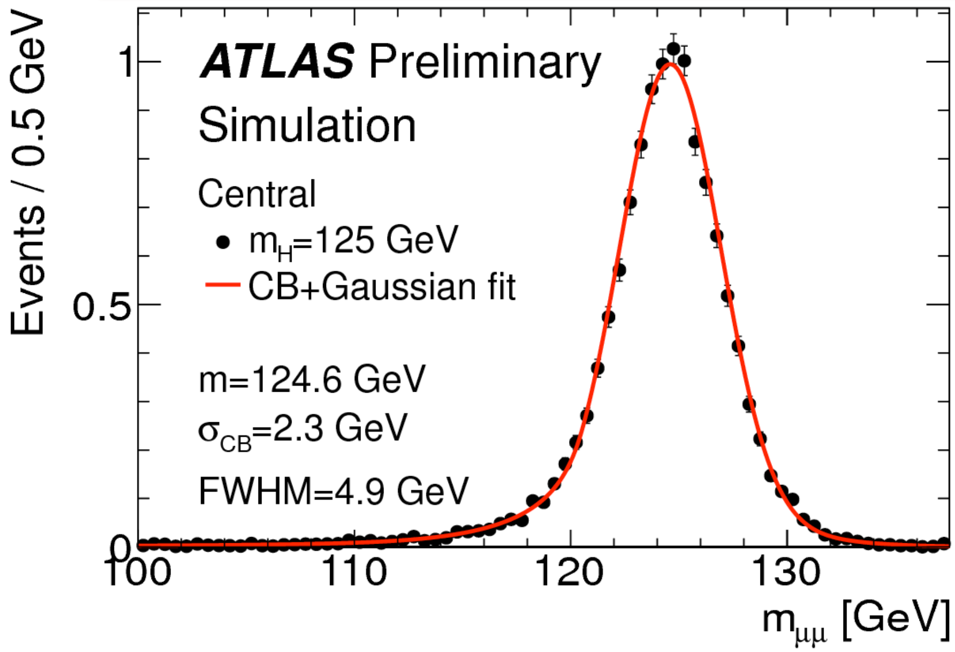
H→μμ Search: Analysis Overview

- Analysis strategy
  - Inclusive search
  - **Fit M(μμ) with analytic Signal +Bckg shape**
  - Two analysis categories based on muon resolution:
    - Central: |η(μ1,2)|<1.0
    - Non-central: rest
- Event selection for signal region
  - Single muon trigger
  - Two isolated opposite-sign muons
  - P_T(μ1)>25 GeV, P_T(μ2)>15 GeV
  - P_T(μμ)>15 GeV

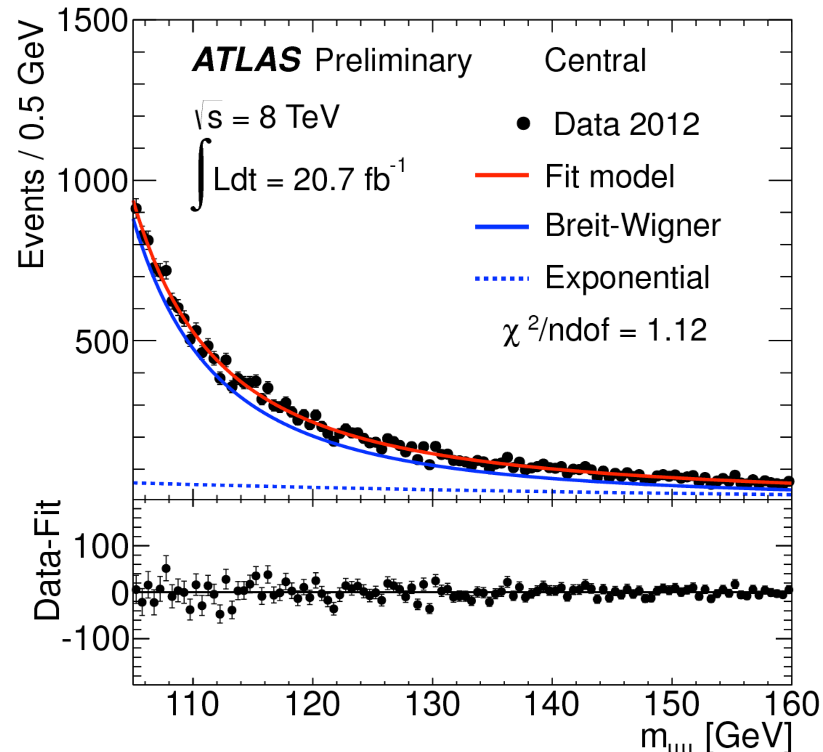


Search window: 110-150 GeV
MC background predictions are not used in the search (for optimization only)

H→μμ Search: Signal & Background Models



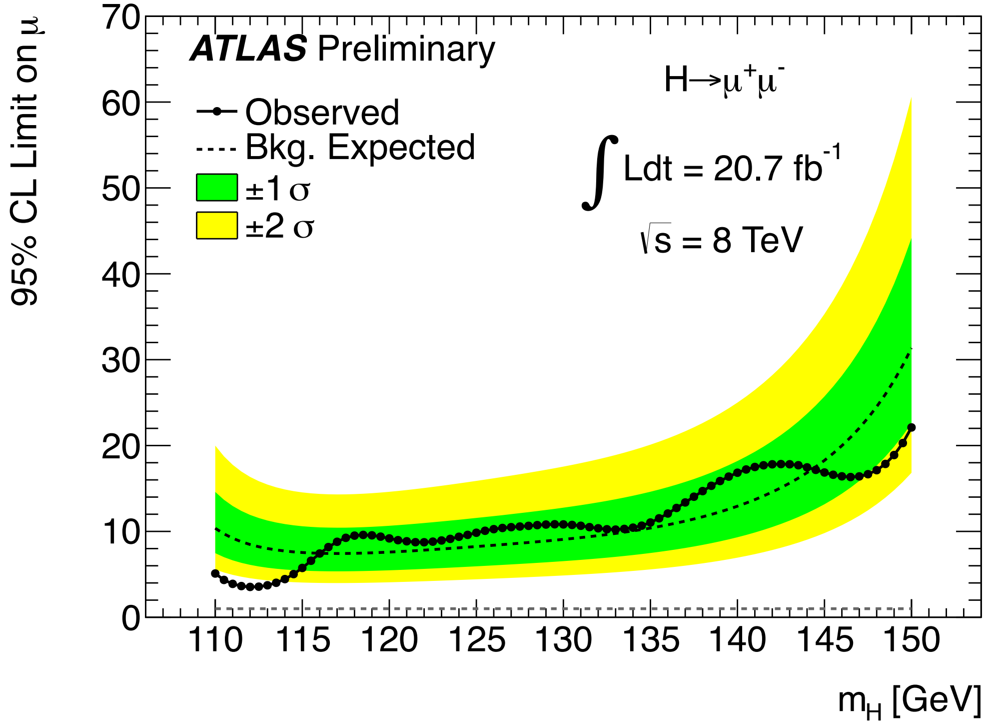
Signal parameterization in central region



Fit to data

- Signal model is a sum of Crystal Ball (CB) and Gaussian (GS) PDFs
- Background model is a sum of Breit-Wigner and exponential PDFs
  - No statistically significant biases in fits to simulation and control regions

H→μμ Search: Results



- Systematic uncertainties on signal normalization @125 GeV
  - Cross-section: 15%
  - Br(H→μμ): ~6%
  - Acceptance uncertainty
    - Theory: ~2.6%
    - Experimental: ~4.2%

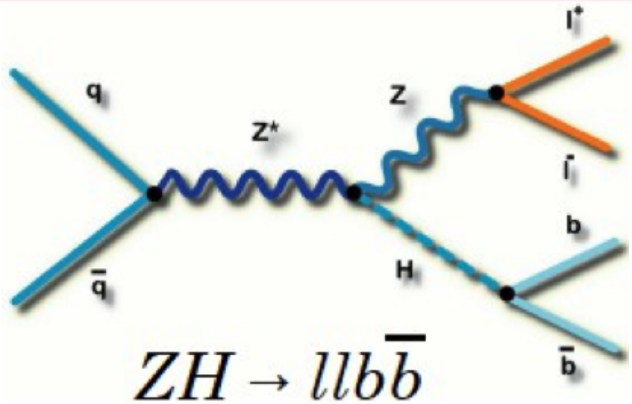
$$\textit{Signal strength } \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$

- ATLAS results with 20.7 fb^{-1} of data at 8 TeV
  - No significant deviations outside uncertainty bands are observed
  - 95% CL limit on μ @ 125 GeV: expected (μ=0) 8.2×SM, observed 9.8×SM

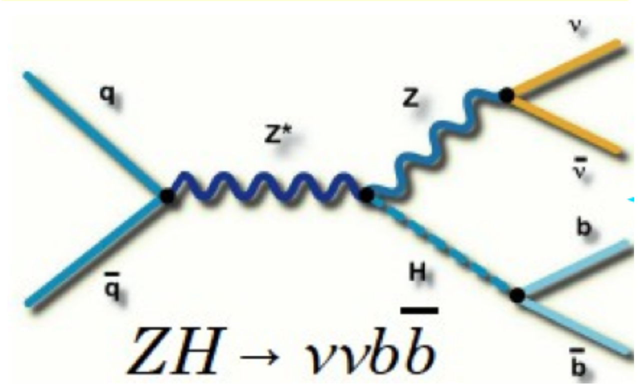
Search for $H \rightarrow bb$ in VH Production

H→bb Search: Exploit Unique VH Production Signature

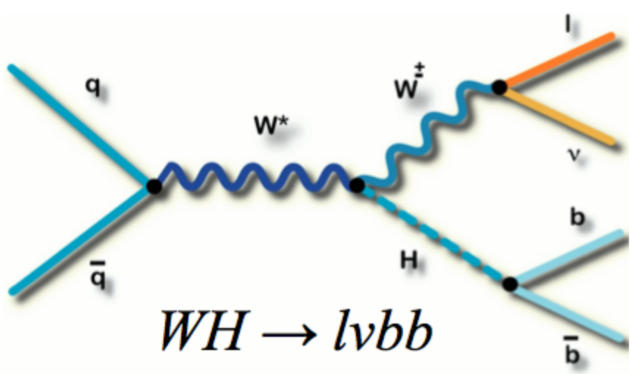
- Cut-based analysis in 3 final states



- ZH→ll+bb
  - **Signature:** two opposite sign leptons and 2 b-tagged jets
  - **Major backgrounds**: Z+ heavy flavor jets



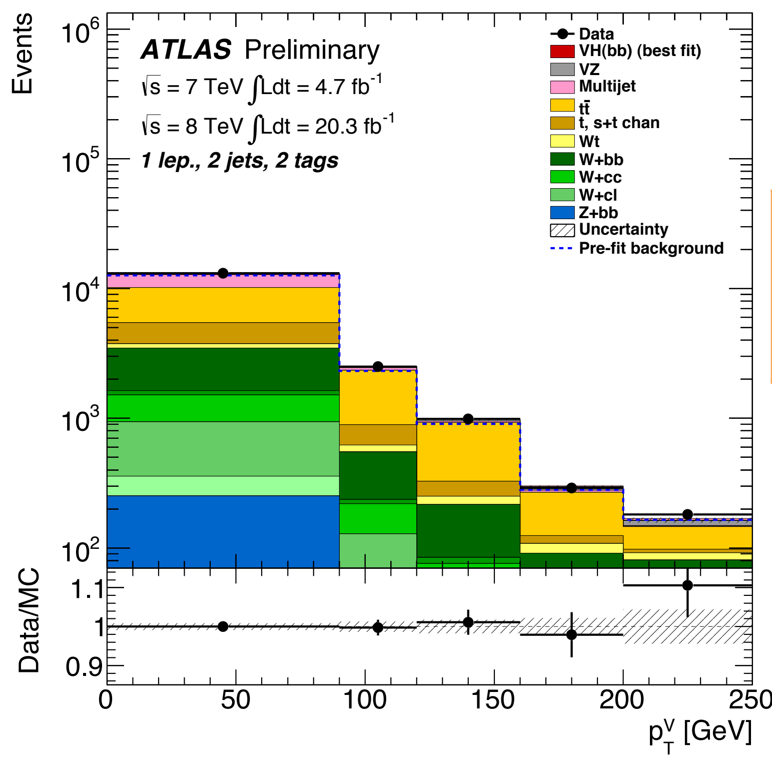
- ZH→νν+bb
  - **Signature:** large MET and 2 b-tagged jets
  - **Major backgrounds**: top, Z/W+ heavy flavor jets



- WH→l+ν+bb
  - **Signature:** one lepton, MET and 2 b-tagged jets
  - **Major backgrounds**: top, W+ heavy flavor jets

H→bb Search: Event Selection

- Common selection
  - At least two jets with P_T(jet1)>45 GeV, P_T(jet2)>20 GeV and |η|<2.5
  - Isolated leading (sub-leading) leptons (e,μ) with P_T>25 (10) GeV
  - Additional channel-specific requirements for boson selection and QCD rejection
- To maximize sensitivity with optimized cuts events split into bins of P_T(V), N_{jets}, $N_{b\text{-}tags}$



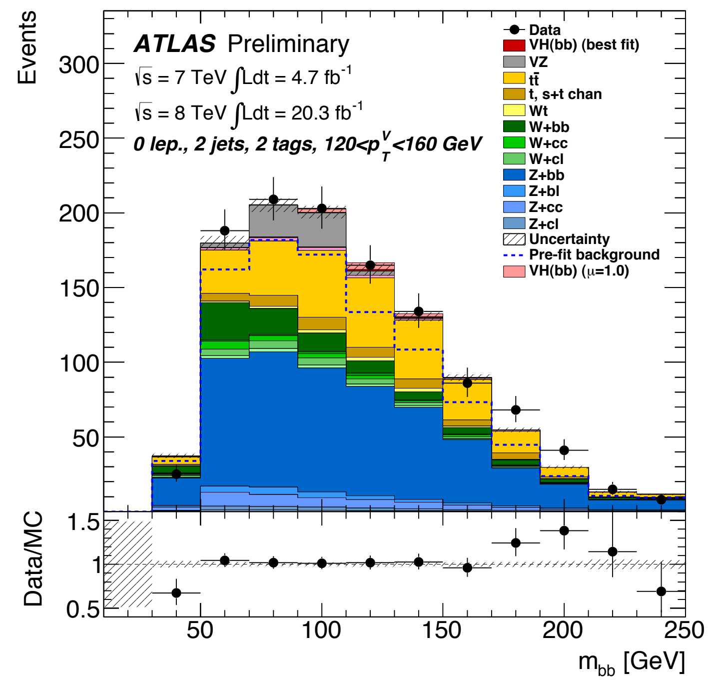
P_T(V), GeV	0-90	90-120	120-160	160-200	>200
	1-lep, 2-lep	1-lep, 2-lep	All channels	All channels	All channels

P_T(V) for events with 1 lepton, 2 jets, 2 b-tags

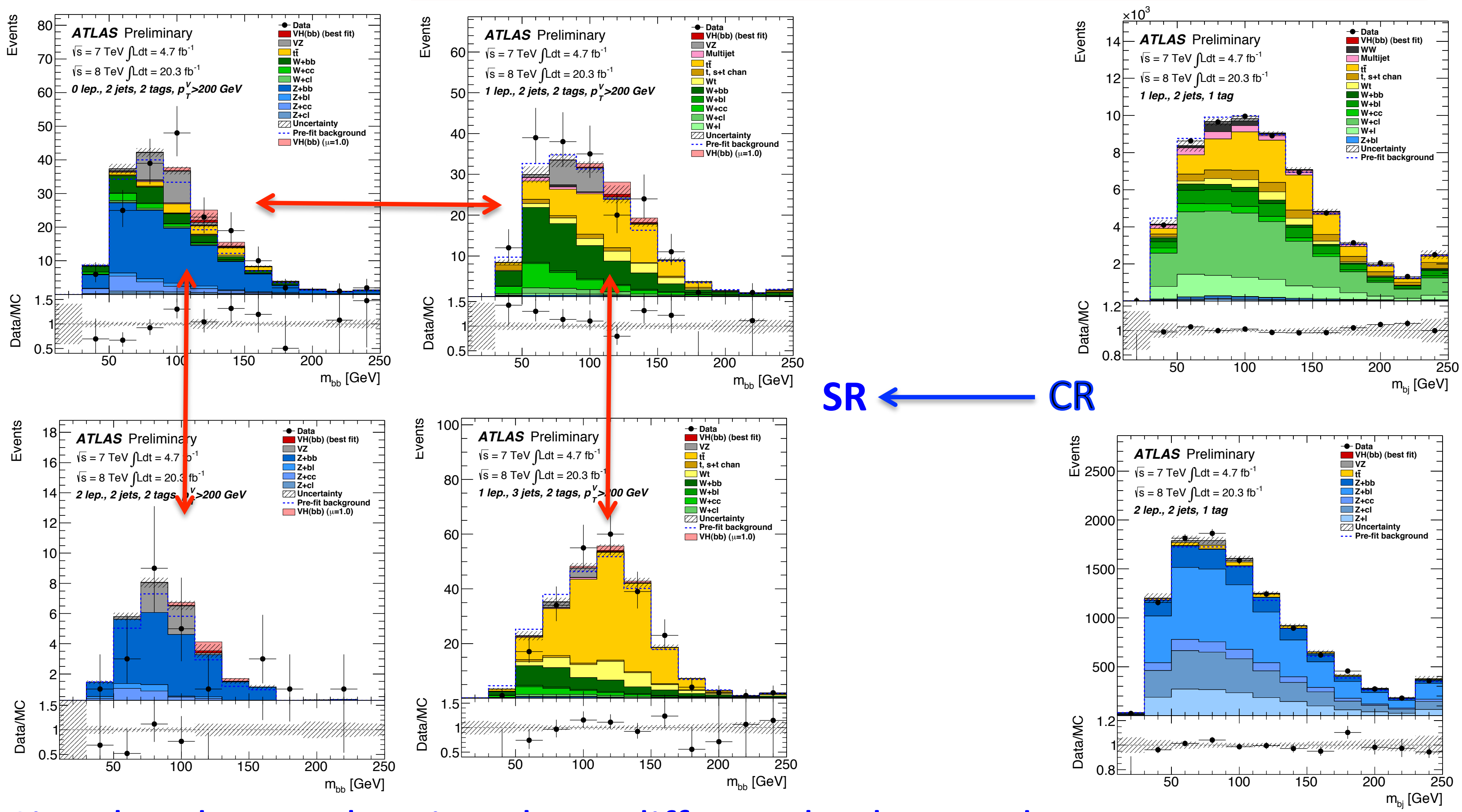
H→bb Search: Signal & Control Regions

		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 2b-tag signal regions, 26 1b-tag control regions and 5 top control regions**
  - CR=control region; **normalization of backgrounds (1-bin only)**
  - SR=signal region; **shape and normalization to m_{bb} distribution**
  - Common nuisance parameters (NP) across SR's and CR's and channels



H→bb Search: Inner Workings Of The Fit

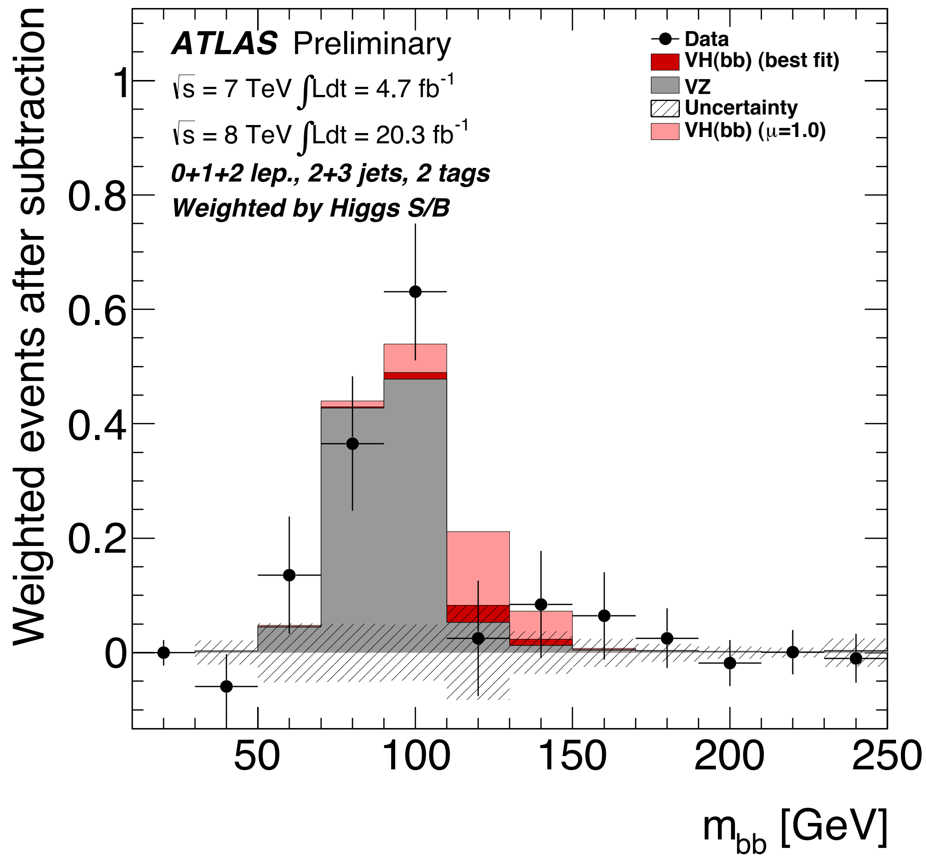


- Signal and control regions have different background compositions & shape
- **Simultaneous fit allows to reduce effect of systematic uncertainties and constrain flavor composition of backgrounds**

H→bb Search: Cross-Check With VZ(→bb)

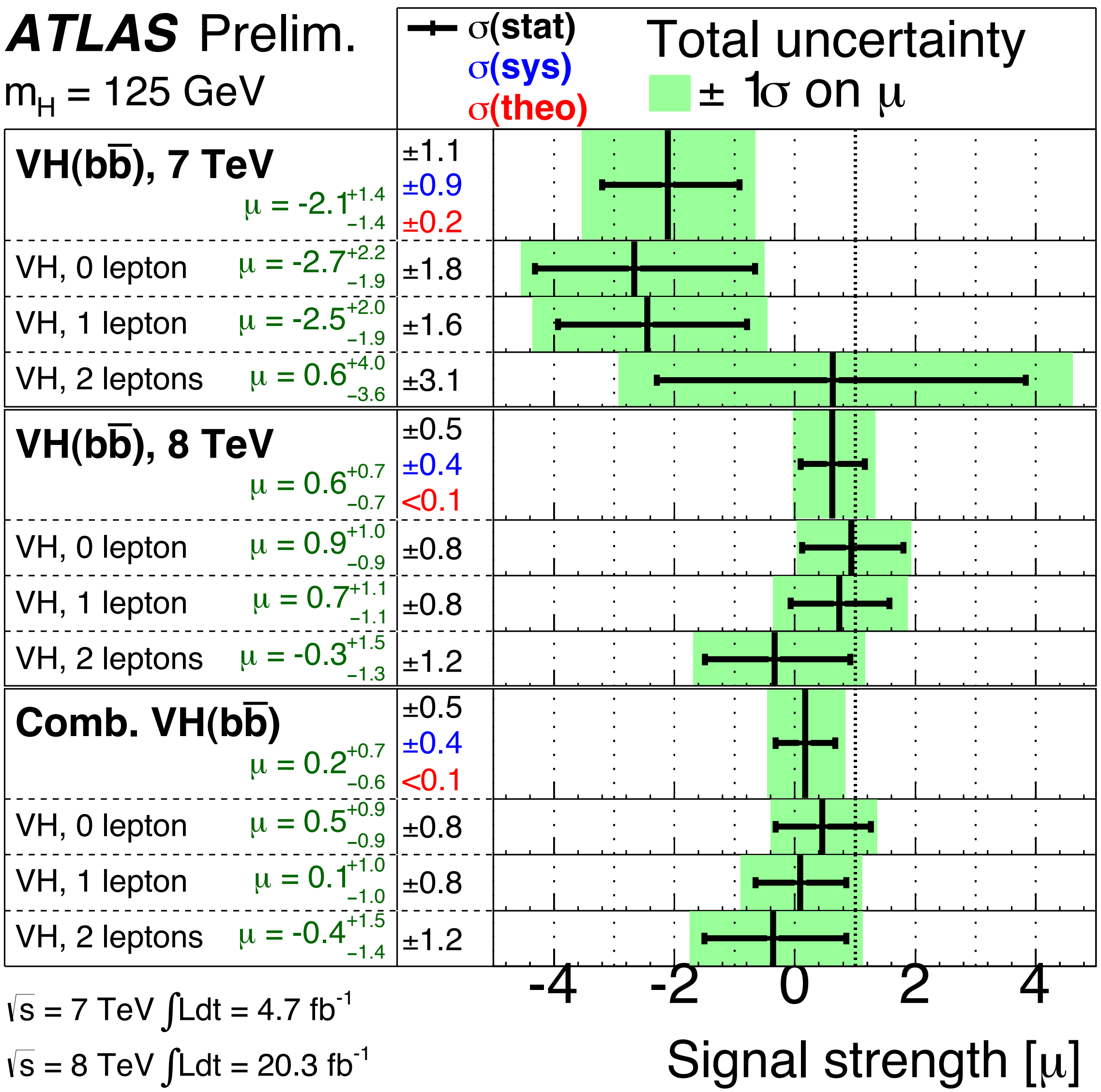
Signal strength

$$\mu_{VZ} = \frac{\sigma^{VZ}_{measured}}{\sigma^{VZ}_{SM}}$$



- Measured VZ(→bb) production cross-section is consistent with SM
  - 4.8σ significance; μ_{VZ}=0.9±0.2
  - Same signature as VH(→bb) allows for direct test of analysis procedure

H→bb Search: Results



- Fitted signal strength
  - 7+8 TeV: $\mu=0.2^{+0.7}_{-0.6}$
- 95% CLs @125 GeV
  - Expected: 1.3×SM
  - Observed: 1.4×SM
- Results consistent with SM H→bb and background-only hypotheses
- Dominant uncertainties:
  - Modeling of ttbar: M_{bb}, $P_T(V)$, 2-jet/3-jet ratio
  - c-jet tagging efficiency
  - Multijet normalization in 1-lepton channel
  - Signal acceptance

$$\text{Signal strength } \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$

Search for $H \rightarrow \tau\tau$

H→ττ Search: Analysis Concept

- Question that this analysis attempts to address
  - **Does the Higgs boson with M_H=125.5 GeV decay to pair of τ-leptons?**
    - Is the H→ττ decay rate consistent with SM predictions?

- Analysis strategy
  - Achieve maximum sensitivity for SM Higgs boson with M_H=125.5 GeV
    - Design and perform multivariate analysis (based on BDT technique)
  - Perform "blind" analysis

- Perform analysis in all final states of tau decays
  - Lep-lep channel: H→ττ→2l+4ν, Br=12.4%
  - Lep-had channel: H→ττ→l+τ_{had}+3ν, Br=45.6%
  - Had-had channel: H→ττ→2τ_{had}+2ν, Br=42%

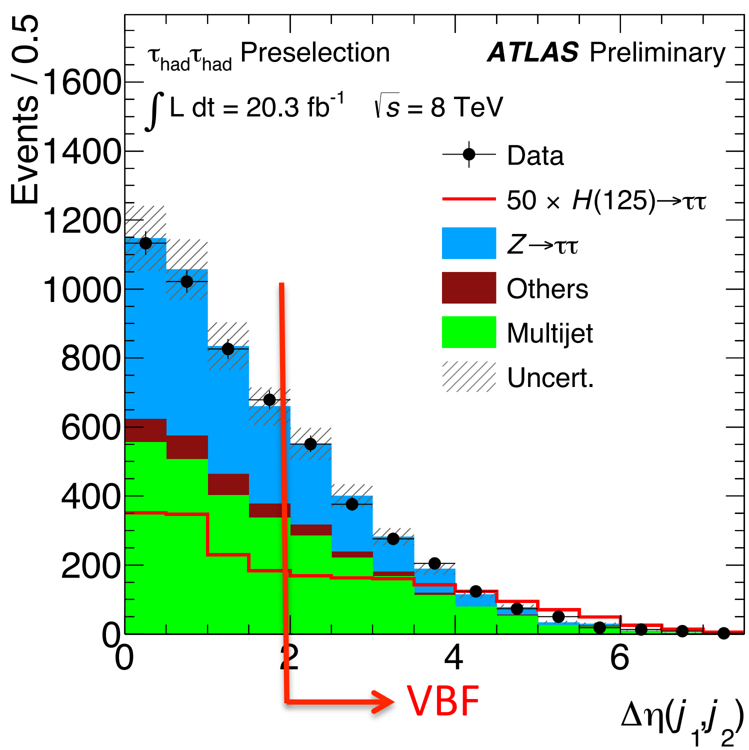
- Major backgrounds
  - Z→ττ (irreducible), Z(ee/μμ)+jets, W+jets, top, QCD multijets and di-bosons

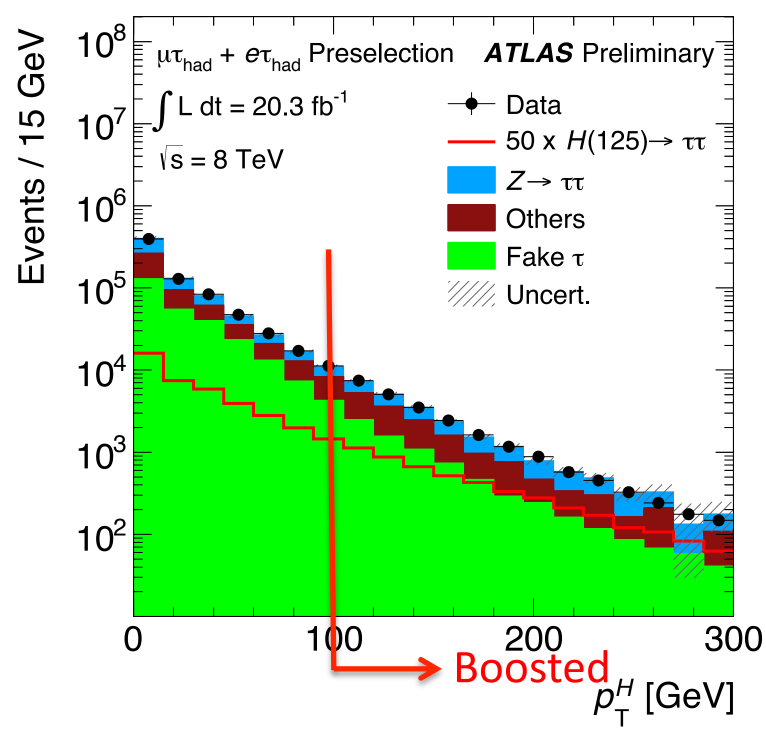
H→ττ Search: Event Selection

- Triggers
  - **Lep-lep channel**: combination of single- and di-lepton triggers
  - **Lep-had channel**: single-lepton triggers
  - **Had-had channel:** di-tau triggers
- Strategy
  - Keep simple common selection and let MVA separate signal and background
  - Use events after common selection to validate background modeling
- Common selection
  - **Lep-lep channel:** N_{lepton}=2, $N_{jet}(P_T>40$ GeV)≥1
    - M_{ll} and MET cuts to suppress Drell-Yan and multijet backgrounds
  - **Lep-had channel:** N_{lepton}=1, N_{τ}=1
    - M_T<70 GeV cut to suppress W+jets background
  - **Had-had channel:** N_{τ}=2
    - MET>20 GeV, ΔR(ττ) and Δη(ττ) cuts to suppress multijet background

H→ττ Search: Analysis Categories

- Analysis is performed in two simple categories
  - **VBF**: 2 jets with leading (sub-leading) P_T>40-50 (30-35) GeV; Δη(jj) cut
    - targeting VBF Higgs production (VBF signal fraction: 54%-63%)
  - **Boosted:** P_T(H)>100 GeV
    - dominated by gluon fusion (ggF signal fraction71%-74%)
  - **Lep-lep & Lep-had:** veto events with b-tags to suppress top background
- **"Rest" category in Had-had:** events failing Boosted & VBF selection used to constrain multijet and Z→ττ backgrounds

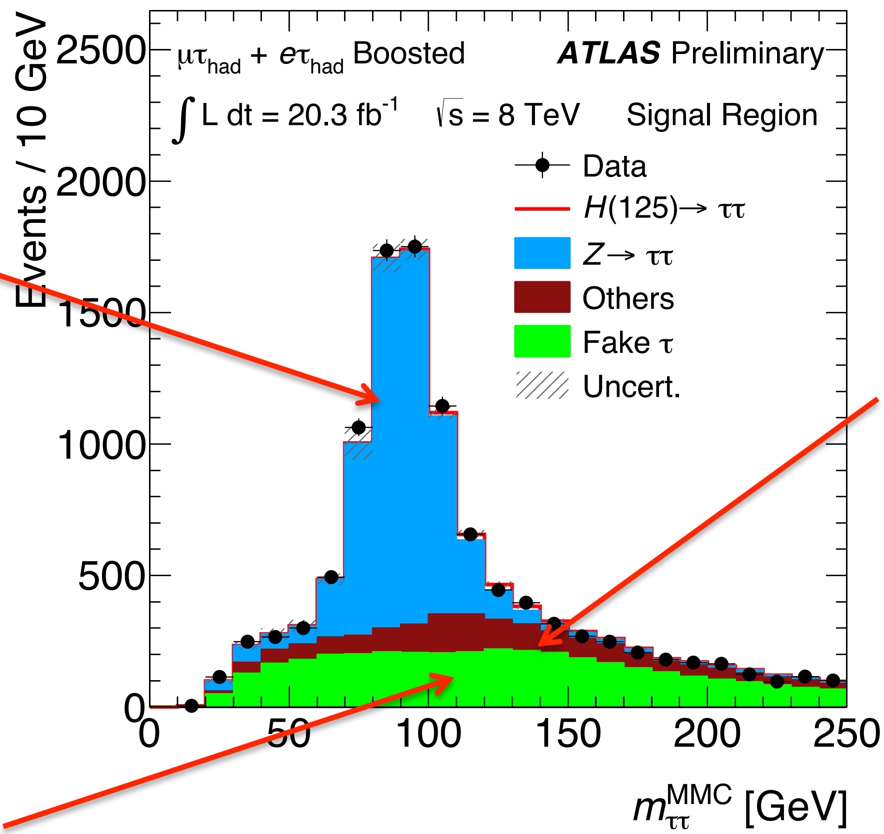




H→ττ Search: Background Estimation

- All major backgrounds are either directly estimated from data or normalized to data in dedicated control regions

Z→ττ: major background; modeled by data

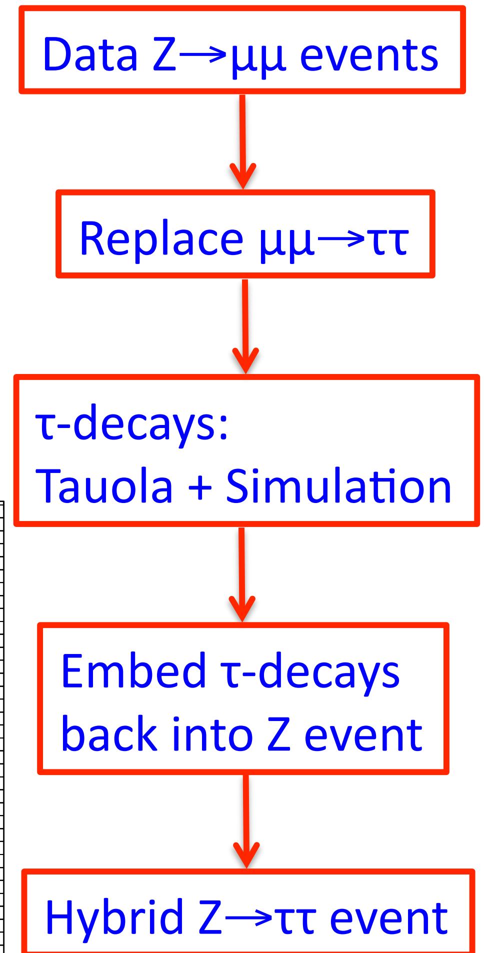


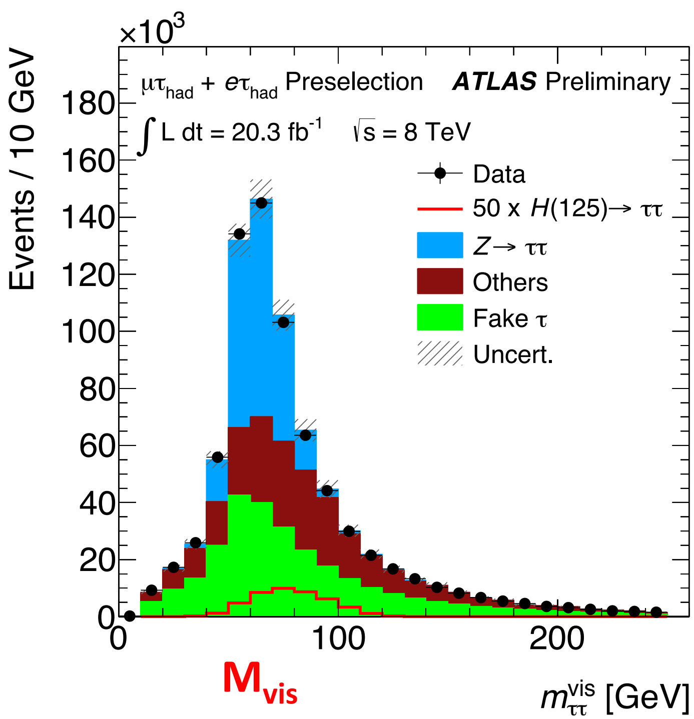
"Others": Dibosons & H→WW* modeled by MC; Z→ee/μμ & top modeled by MC and normalized to data

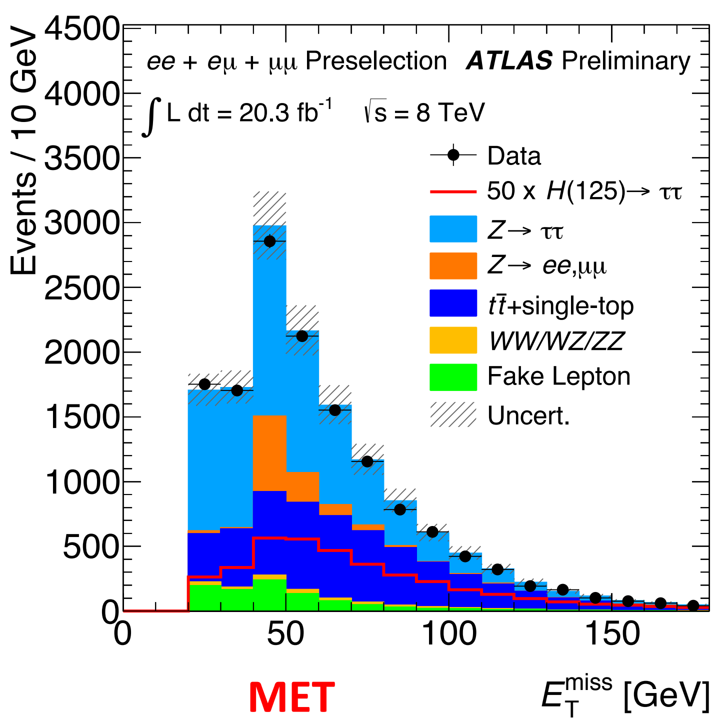
"Fakes": multijet, W+jets, top (with fake tau); modeled by data

H→ττ Search: Z→ττ Background

- **Z→ττ embedding: except for τ-decays, all properties of a Z→ττ event are modeled by actual Z→μμ data**
- **Major advantages of embedding:** Z-boson kinematics, jets, MET resolution, pile-up, and VBF/EWK production are directly modeled by data



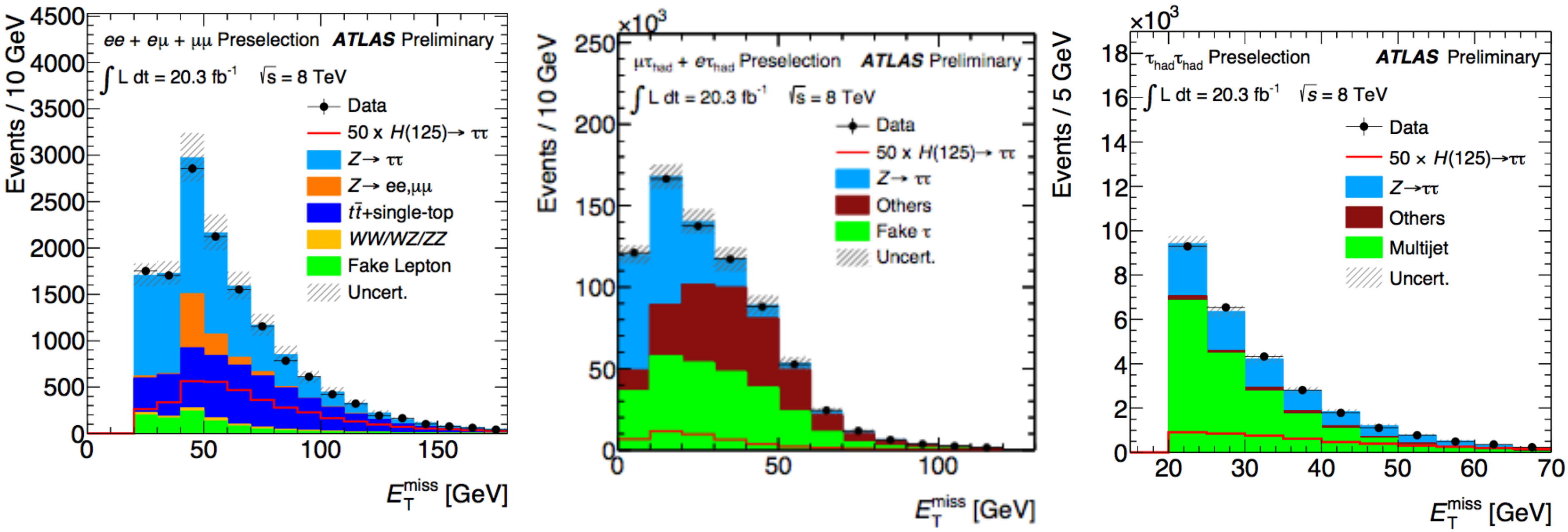




H→ττ Search: Backgrounds With "Fakes"

- "Fakes" are estimated directly from data
  - **Lep-lep:** from sample of "anti-isolated" leptons
  - **Lep-had:** from sample where hadronic tau fails ID requirements
  - **Had-had:** from not OS data events (where OS pairs removed)
  - Modeling of "Fakes" is checked in same-sign (SS) events
  - Uncertainties vary from 8% to 50% (depending on channel & category)

Examples of MET distributions after pre-selection

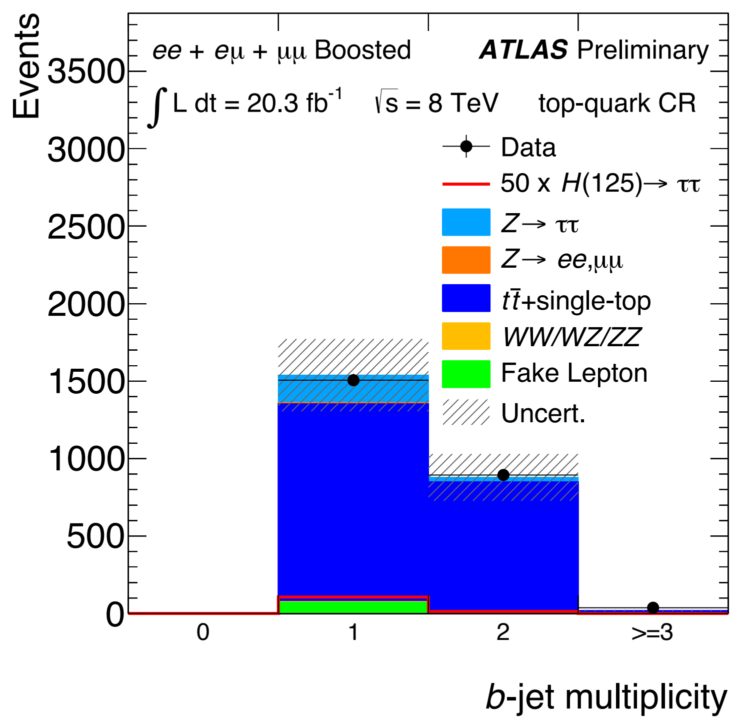


"Fakes" are shown by **green** histogram

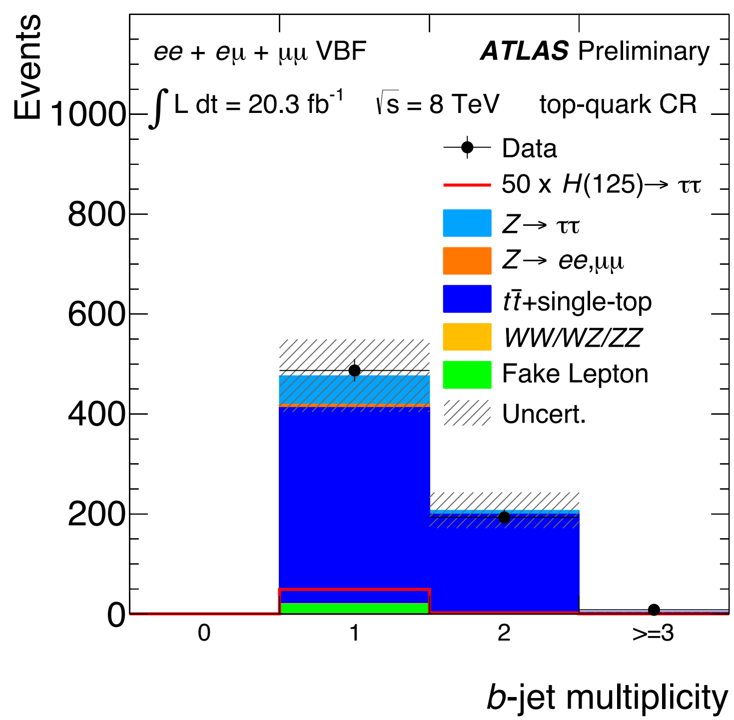
H→ττ Search: Top Background

- Top background is modeled by MC (shape) and normalized in b-tag control region to total integral of events
  - Separate normalization for Boosted & VBF categories
  - Modeling is also cross-checked in validation regions defined by M_{ll}>100 GeV (lep-lep) and H_T>350 GeV (lep-had) cuts

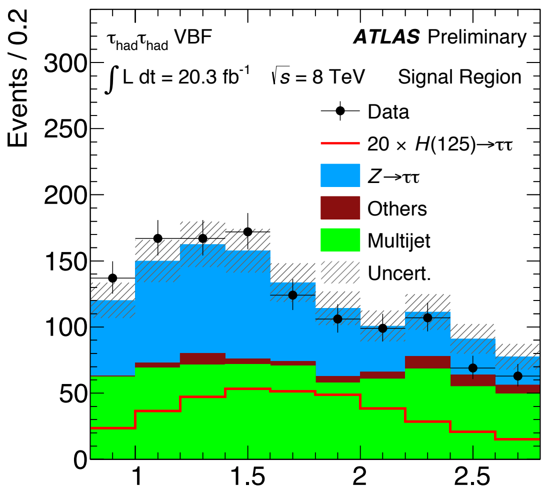
Boosted lep-lep



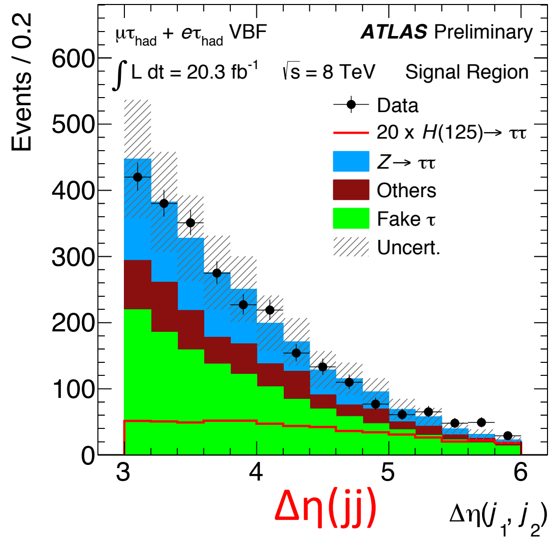
VBF lep-lep



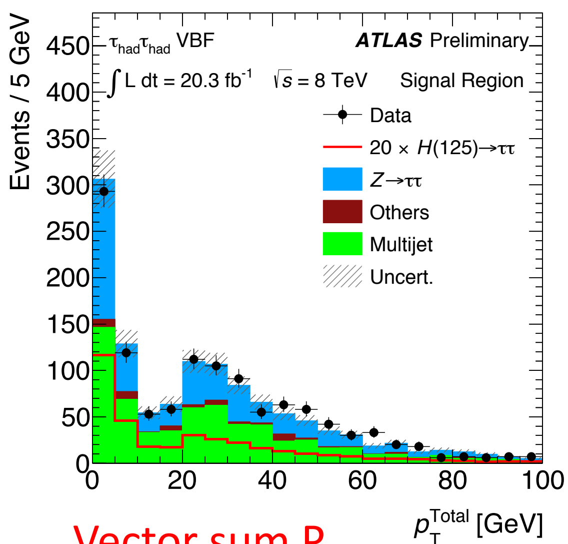
H→ττ Search: Input Variables to BDT



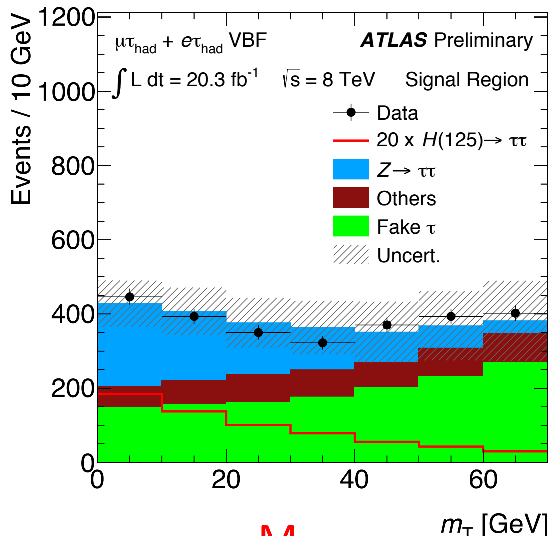
ΔR(ττ)



Δη(jj)



Vector sum P_T

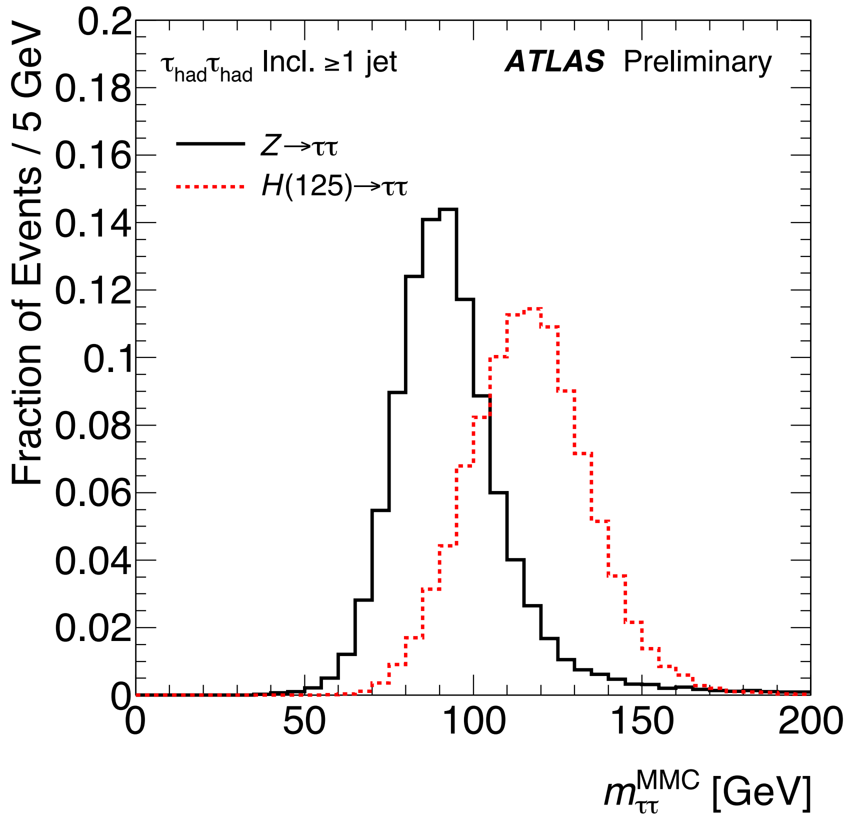


M_T

- Resonance properties
  - m(ττ), ΔR(ττ), etc
- VBF topology
  - m_{jj}, $\Delta\eta_{jj}$, etc
- Event activity
  - Scalar & vector P_T-sum
- Event topology
  - m_T, object centralities, $P_T(\tau_1)/P_T(\tau_2)$, etc
- Number of variables
  - VBF: 7-9
  - Boosted: 6-9

H→ττ Search: m(ττ) Reconstruction

- **Good m(ττ) resolution is single most effective tool against Z→ττ**
  - m(ττ) is one most highly ranked BDT input variables
- m(ττ) reconstructed by Missing Mass Calculator (MMC)
  - MMC is sophisticated technique to reconstruct m(ττ) in presence of neutrinos from τ-decays



- MMC resolution in events with at least one jet (table below)
  - MMC resolution depends on τ-decay type and event topology
  - It is better in VBF and Boosted category

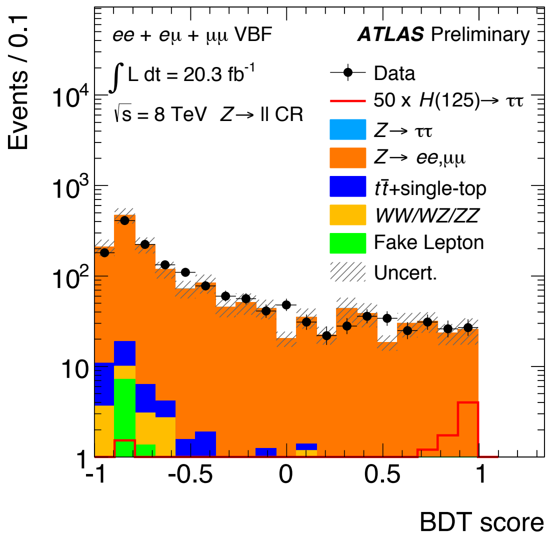
	Z→ττ
Lep-lep	21.4%
Lep-had	18.1%
Had-had	14.3%

H→ττ Search: Cross-Checks

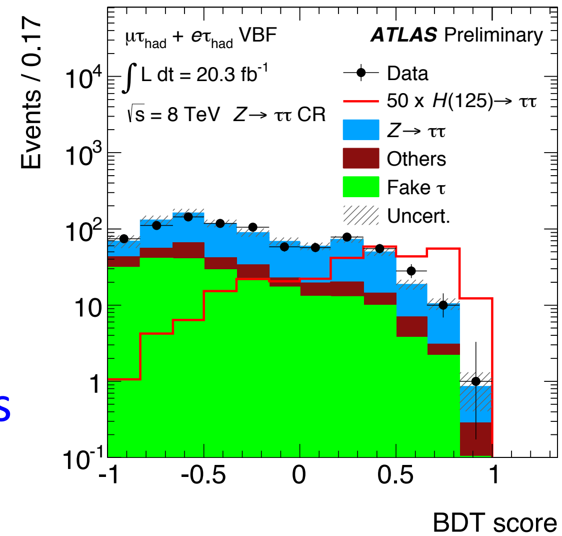
- Rigorous checks of background model and fitting technique
  - ✓ Check modeling of all input variables
  - ✓ Check modeling of correlation between each pair of input variables: $\langle V_i \rangle$ vs V_j
  - ✓ Dedicated control regions (CR) for all major backgrounds
    - **Z→ee/μμ + jets CR** in lep-lep & lep-had
    - **Top CR** in lep-lep & lep-had
    - **W+jets CR** in lep-had
    - **"Fakes"-enriched CR** in lep-lep
    - **QCD-enriched CR** in had-had
  - ✓ Perform fit in mass sidebands (outside 100-140 GeV window)
    - Check of Z→ττ background and overall background model
  - ✓ Study each constrained or pulled fit nuisance parameter

H→ττ Search: Building Confidence in Background Model

- Examples of BDT distributions in data CR's for major backgrounds

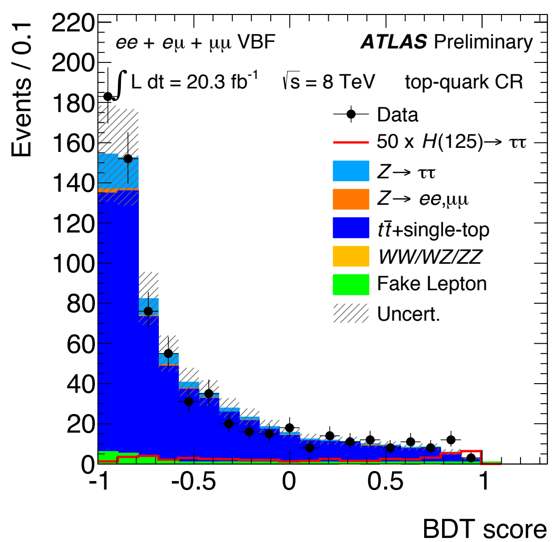


Lep-lep VBF:
Z→ee/μμ CR

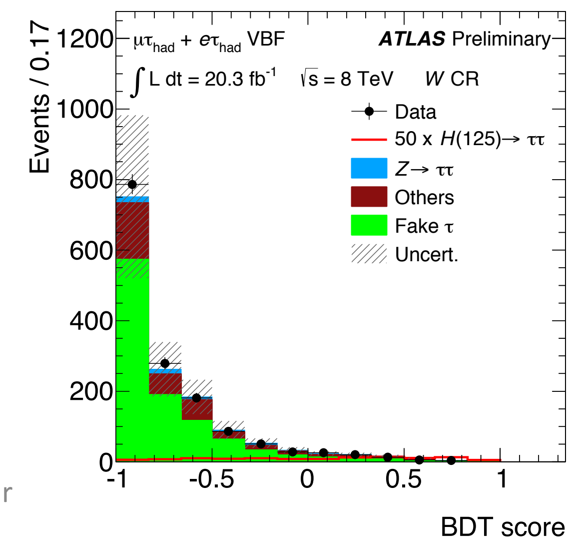


Lep-had VBF:
Z→ττ CR

Good agreement in all BDT distributions with background normalizations before fit!



Lep-lep VBF:
Top CR



Lep-had VBF:
W+jets CR

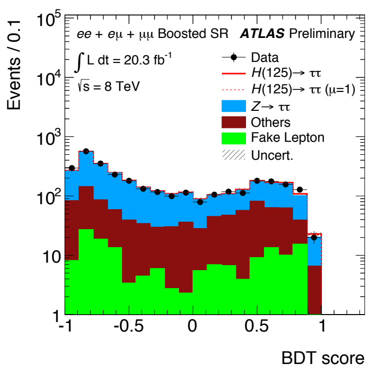
H→ττ Search: Signal Extraction

Lep-lep & Lep-had channels

Signal region (BDT shape)

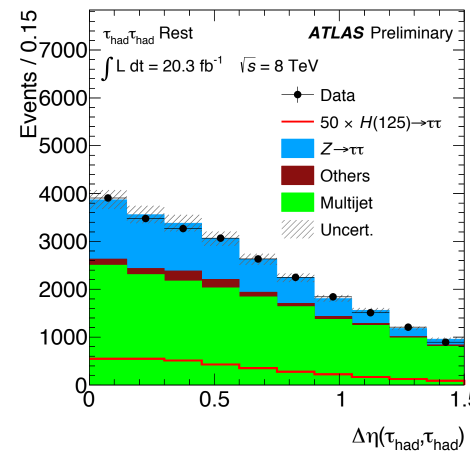
Z→*ll* CR (1 bin)

Top CR (1 bin)



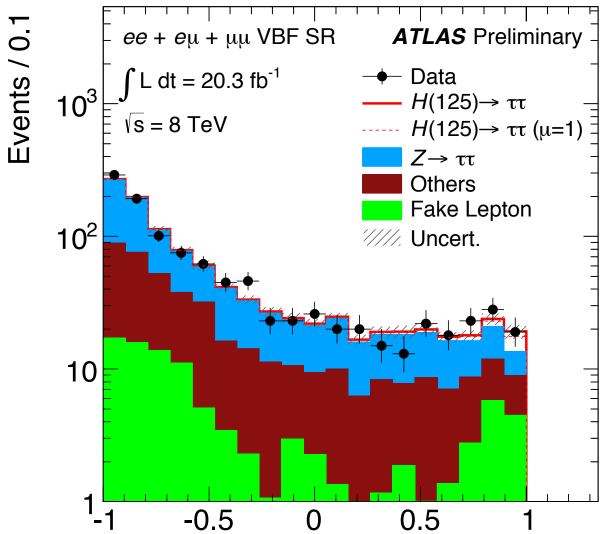
Had-had channels

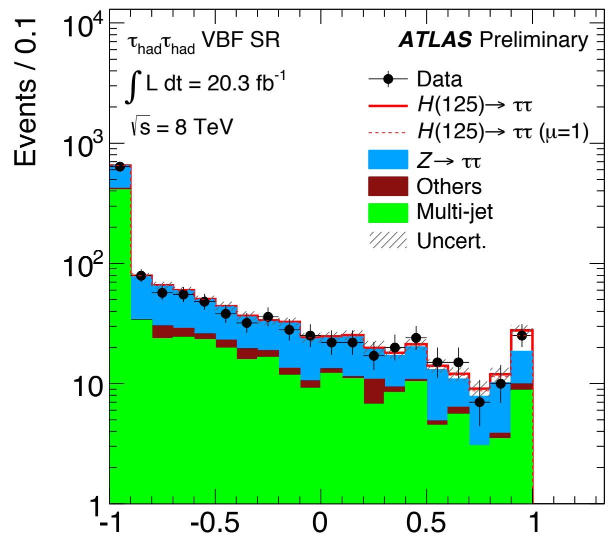
Signal region (BDT shape) ← Rest category Δη(ττ) shape

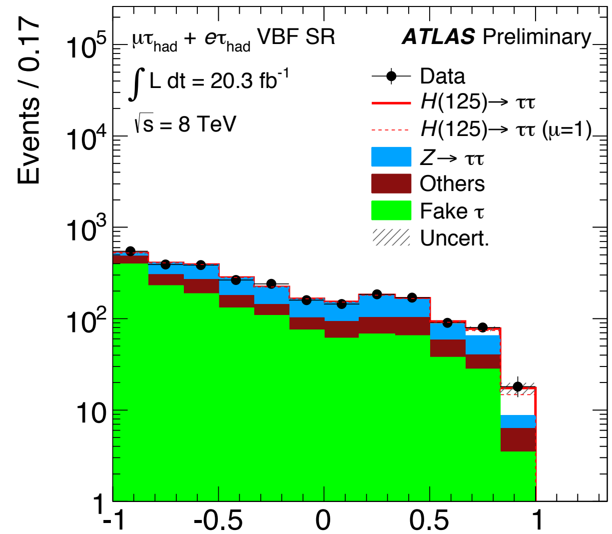


- **Fit BDT shape with signal+background templates**
  - Simultaneous fit in 6 SR and 5 CR with common systematics NP's
  - Z→ττ, Top, multijet (in had-had) & Z→ll normalizations are free in the fit
    - Control regions to constrain normalization of Top & Z→ll
    - **Had-had channel:** multijet & Z→ττ constrained in Rest category

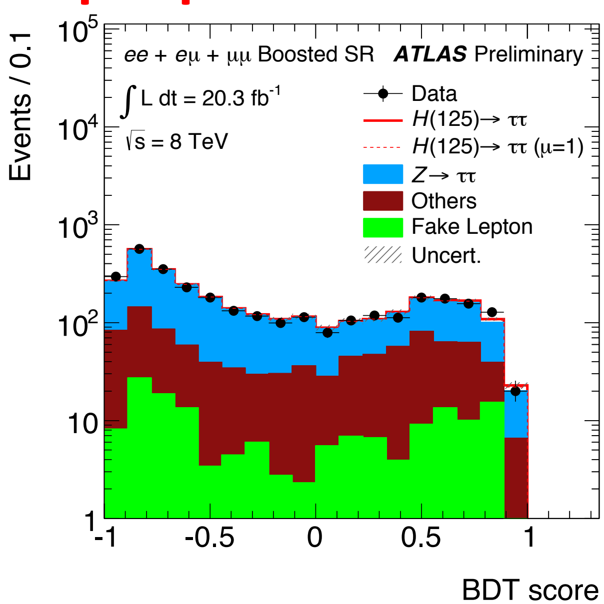
H→ττ Search: BDT-score Distributions After Fit

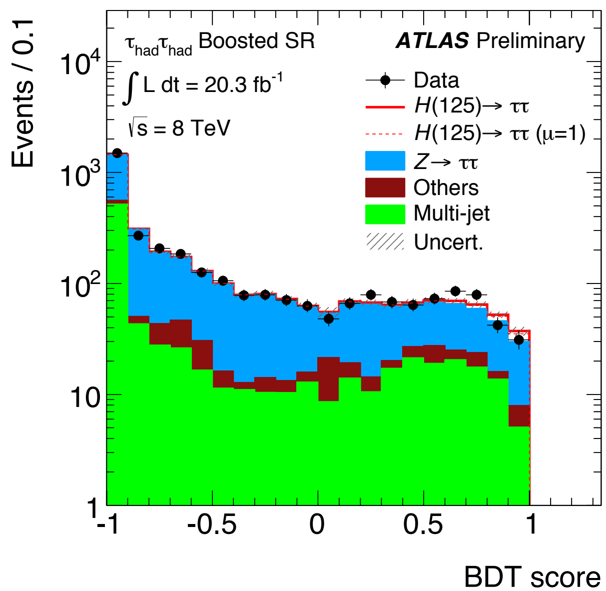


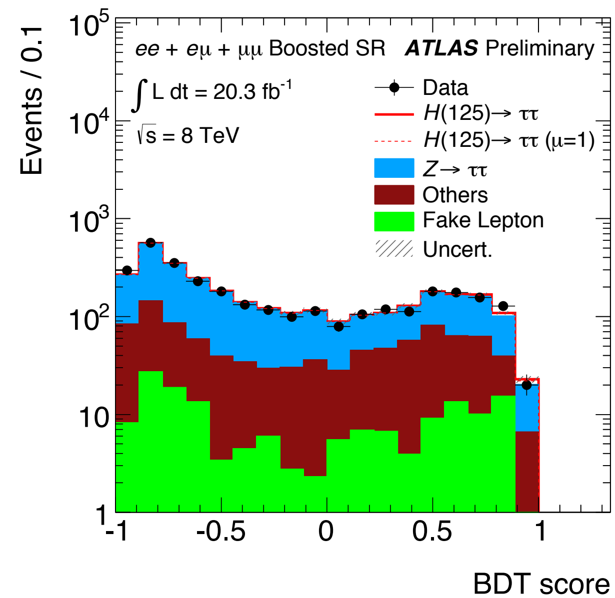




Lep-lep channel **Had-had channel** **Lep-had channel**







H→ττ Search: Leading Uncertainties

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \to \ell\ell$ normalization ($\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ boosted)	0.13
ggF $d\sigma/dp_T^H$	0.12
JES η calibration	0.12
Top normalization ($\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ VBF)	0.12
Top normalization ($\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ boosted)	0.12
$Z \to \ell\ell$ normalization ($\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ VBF)	0.12
QCD scale	0.07
di-τ_{had} trigger efficiency	0.07
Fake backgrounds ($\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$)	0.07
τ_{had} identification efficiency	0.06
$Z \to \tau^+\tau^-$ normalization ($\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$)	0.06
τ_{had} energy scale	0.06

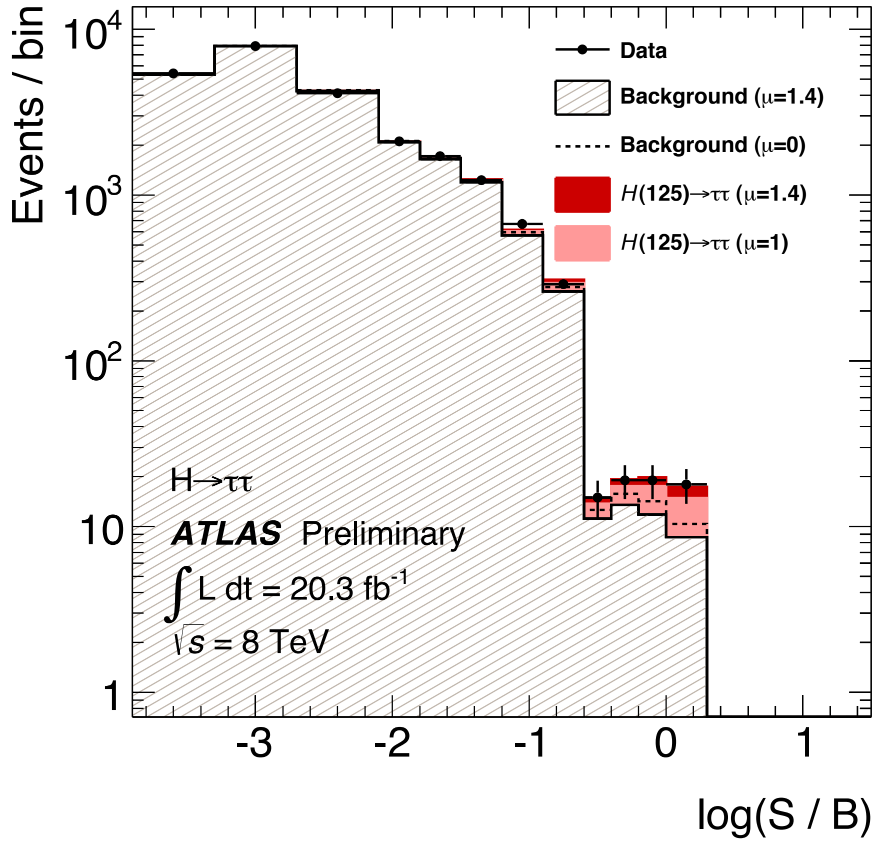
$$Signal\ strength\ \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$

$\Delta\mu \approx 0.5$

MC statistical uncertainties not included in Table

- Leading theory uncertainty is due to effect of top & bottom quark masses on P_T(H) spectrum in gluon fusion production (~30%)
- Leading experimental uncertainties are due to background normalizations (up to ~20%)

H→ττ Search: Results

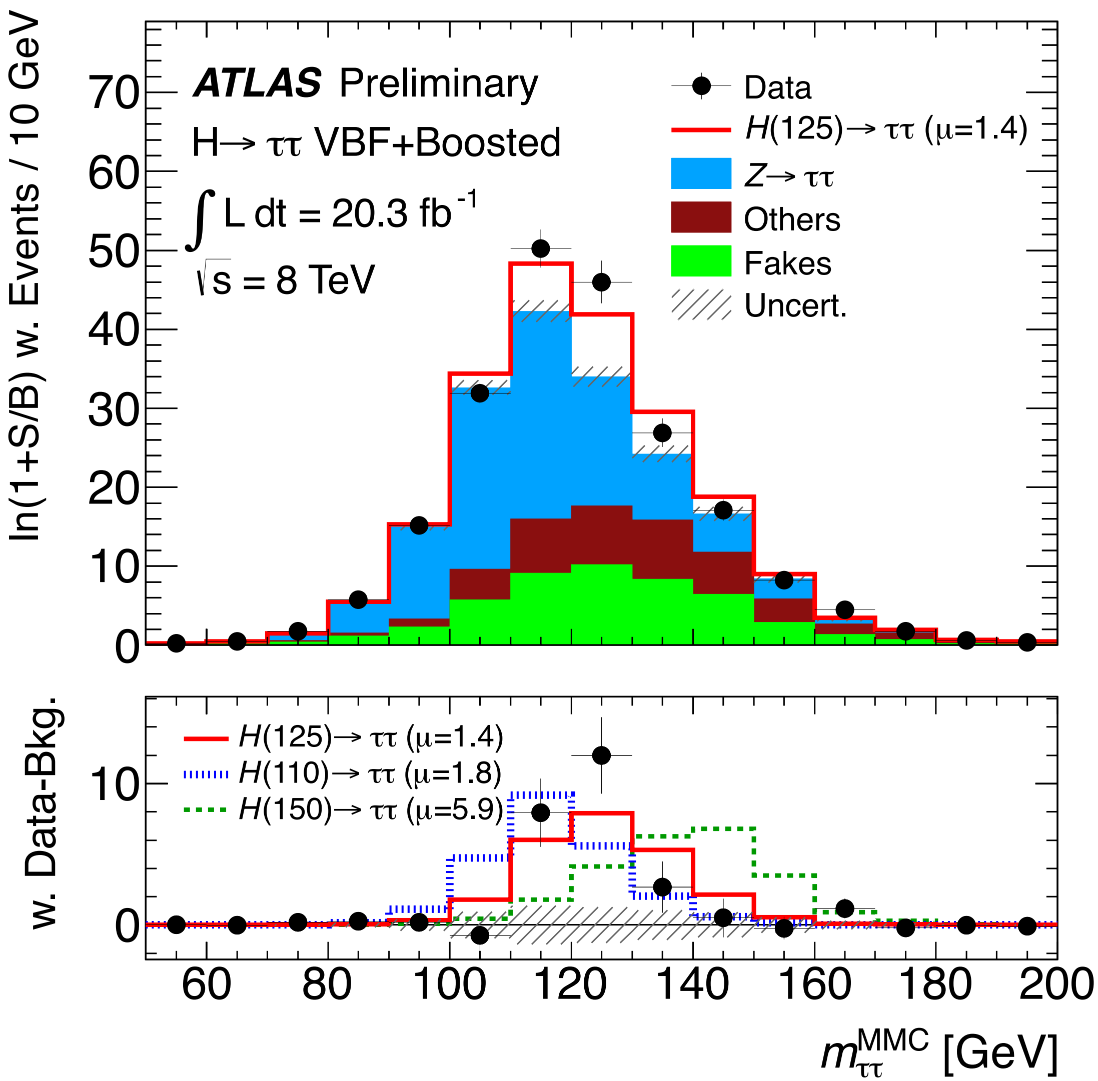


Numbers of events in highest BDT-score bin

		Lep-lep	Lep-had	Had-had
VBF	Signal	5.7±1.7	8.7±2.5	8.8±2.2
	Bckg	13.5±2.4	8.7±2.4	11.8±2.6
	Data	**19**	**18**	**19**
Boosted	Signal	2.6±0.8	8.0±2.5	3.6±1.1
	Bckg	20.2±1.8	32±4	11.2±1.9
	Data	20	34	15

- **ATLAS observes significant excess of data events in high S/B region**
  - Excess is observed in all three channels
  - **Expected** significance at M_H=125 GeV corresponds to **3.2 sigma**
  - **Observed** significance at M_H=125 GeV corresponds to **4.1 sigma**

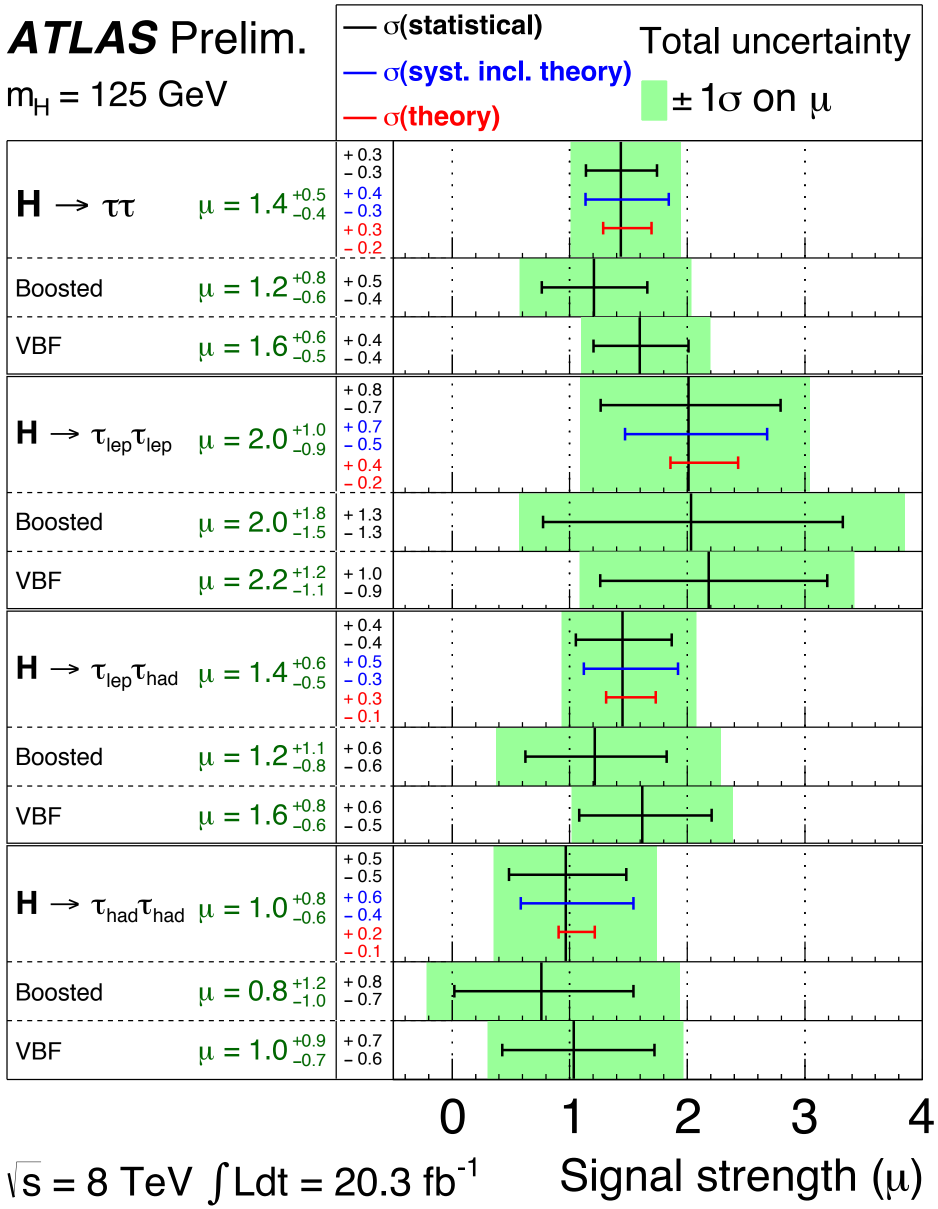
H→ττ Search: Compatibility With M_H=125 GeV



- Each event is weighted by ln(1+S/B) for corresponding bin in BDT-score
- **Excess of data events is consistent with presence of Higgs at 125 GeV**

Signals at M_H=110, 125 and 150 GeV are shown at best fit μ; post-fit background normalizations

H→ττ Search: Results Per Channel



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

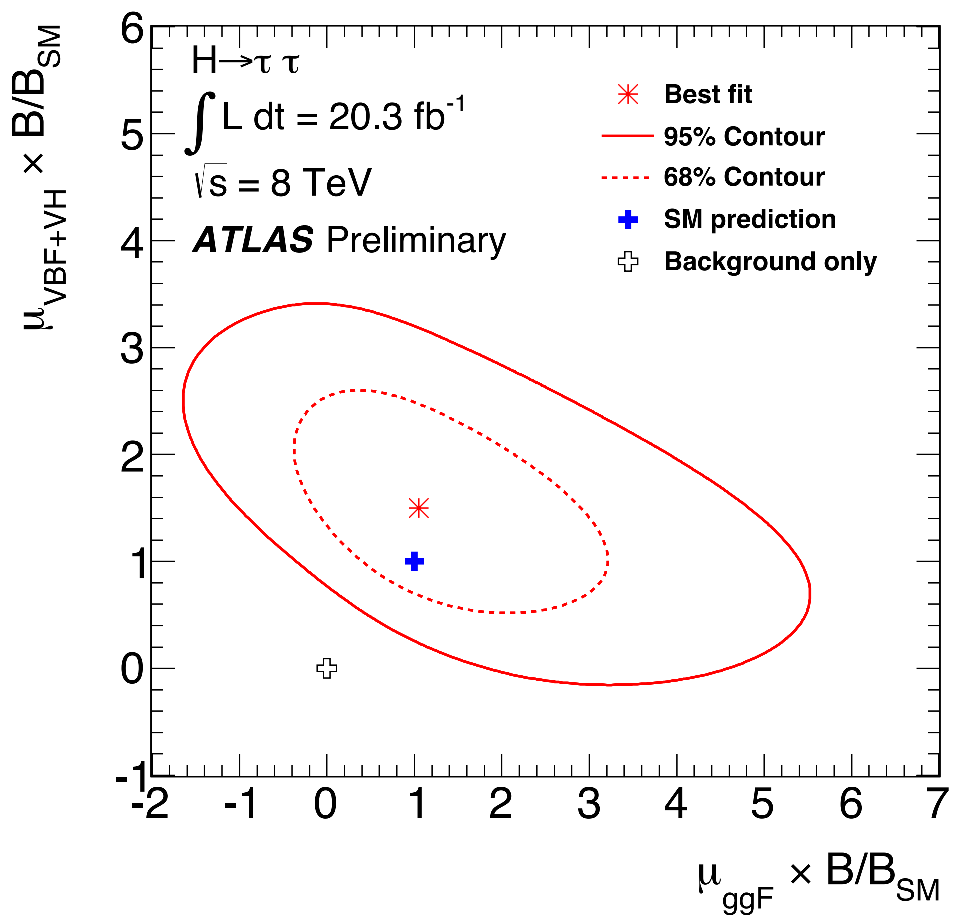
Uncertainties on μ:

Statistical: ±0.3

Systematic: +0.3/-0.2

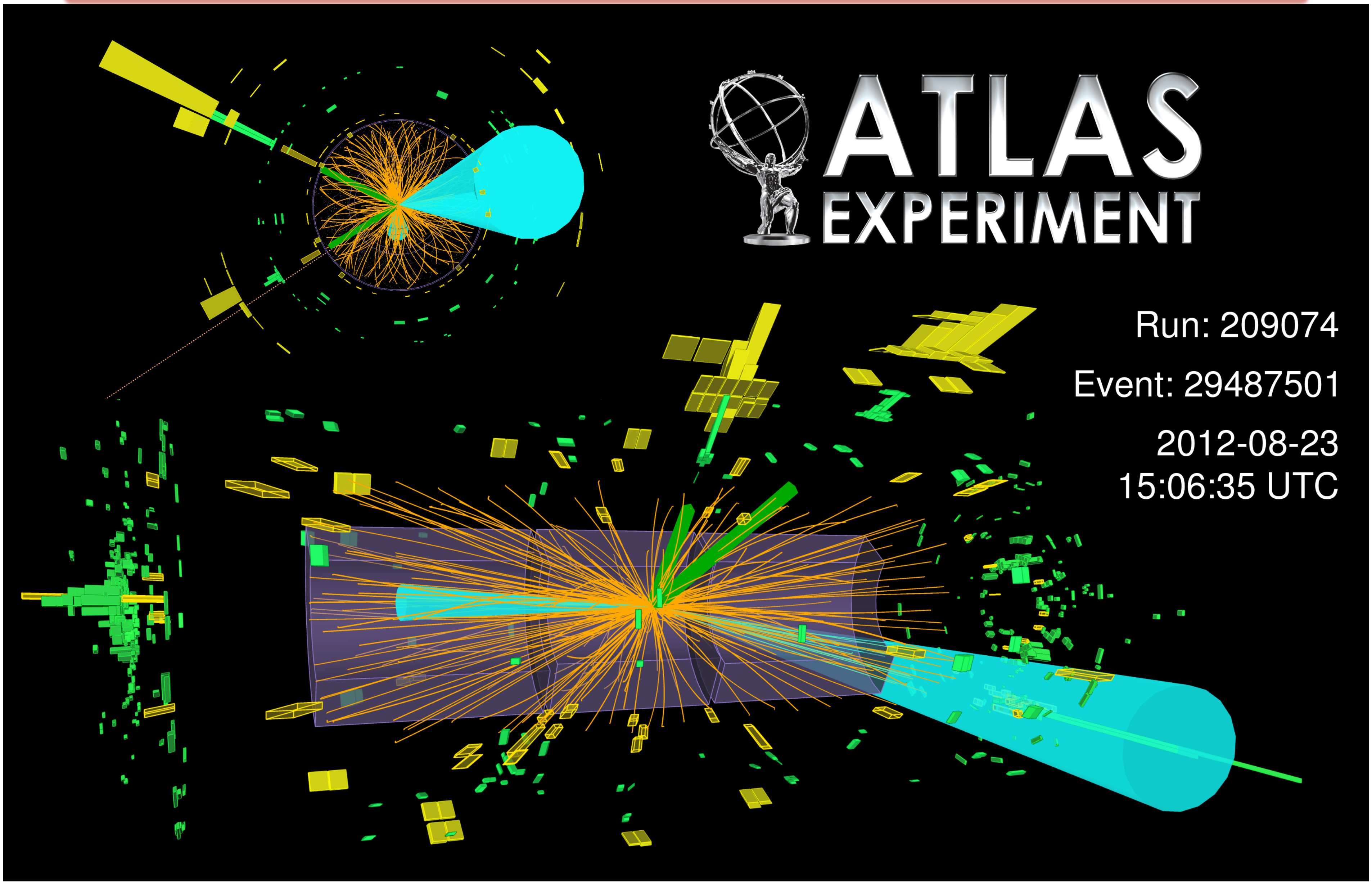
Theory: +0.3/-0.2

$H \rightarrow \tau\tau$ Search: VBF vs Gluon Fusion

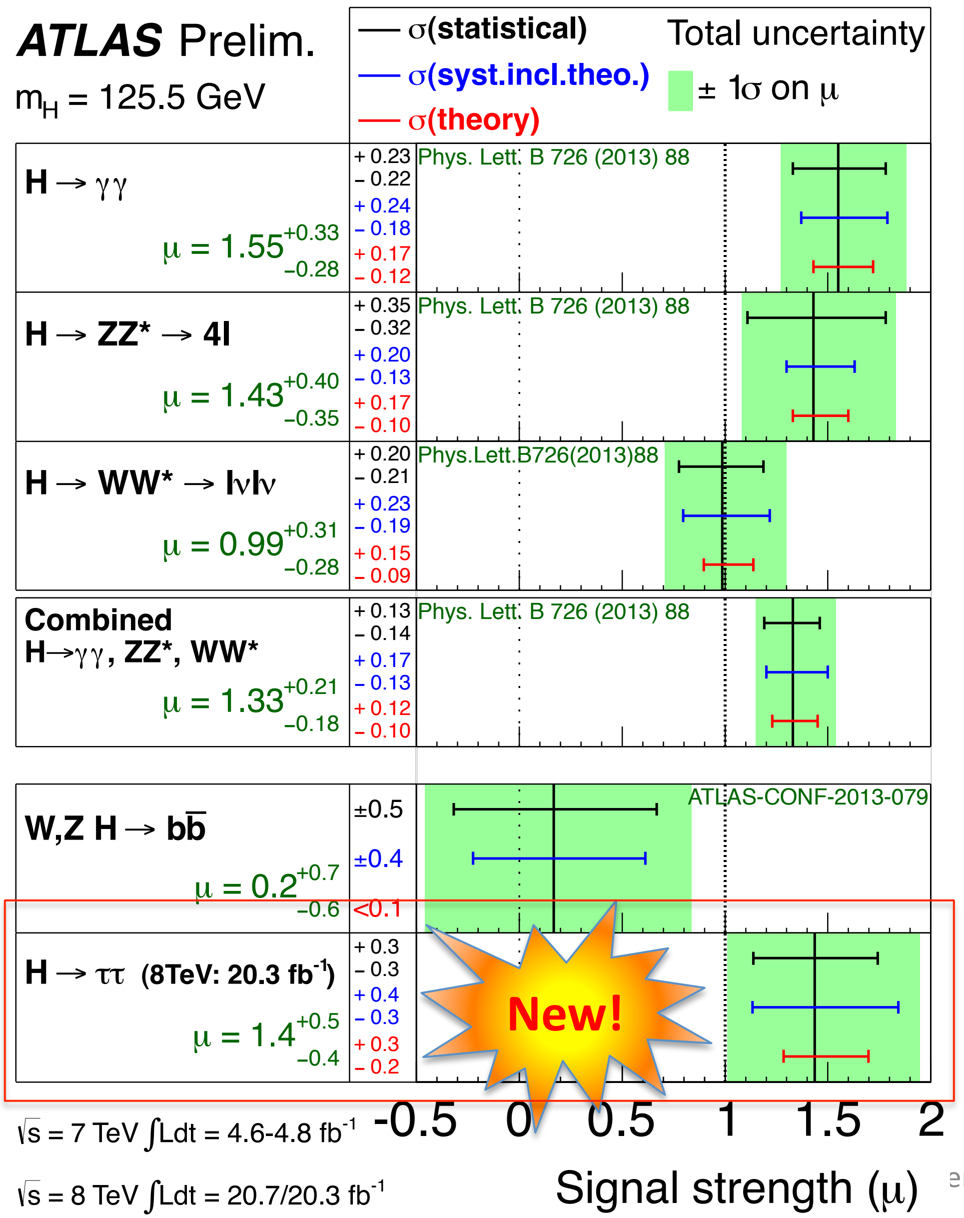


- Results are consistent with SM predictions within 68% contour
- Best fitted values: $\mu_{ggF} \times B/B_{SM} = 1.1^{+1.3}_{-1.1}$; $\mu_{VH+VBF} \times B/B_{SM} = 1.6^{+0.8}_{-0.7}$

H→ττ Candidate Event In Had-Had Channel



Summary



- $H \rightarrow \mu\mu$: no excess over background observed
  - Observed limit: 9.8×SM
  - Expected limit: 8.2×SM
- $H \rightarrow bb$: no excess over background observed
  - Observed limit: 1.4×SM
  - Expected limit: 1.3×SM
- **ATLAS observed 4.1σ evidence for $H \rightarrow \tau\tau$ decays**
- **ATLAS results show that the Higgs boson does not universally couple to fermions (leptons)**