Evidence for the Higgs boson's di-tau decay and studies of its CP nature with the ATLAS Experiment

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Seminar at Lund University

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FSP 103 ATLAS
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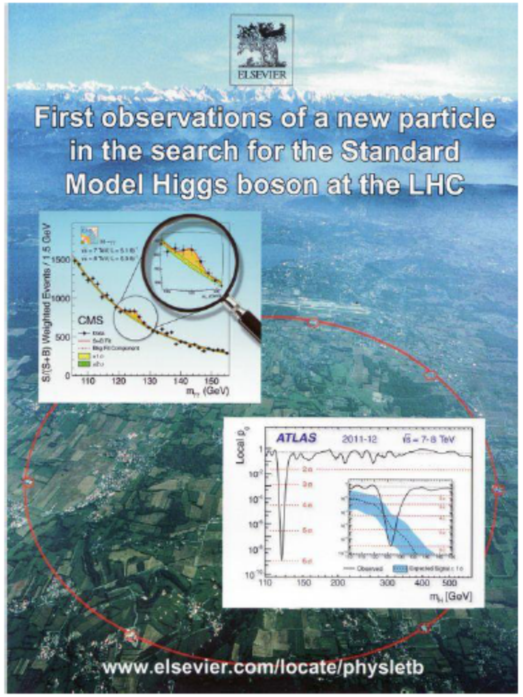
ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

Introduction

- Discovery of the Higgs boson with LHC Run 1 data one of the major scientific results in recent years
  - Observation (>5σ) in bosonic channels, signal strength consistent with SM
  - Evidence (>3σ) for fermionic decays at each of the two experiments, dominated by H→ττ channel
    - CMS H→ττ: 3.2σ (exp. 3.7σ) m_H=125 GeV
    - ATLAS H→ττ: 4.5σ (exp. 3.4σ) m_H=125.36 GeV
  - Statistical combination of ATLAS & CMS:
    - LHC H→ττ: 5.5σ (exp. 5.0σ)



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First Part of this talk!

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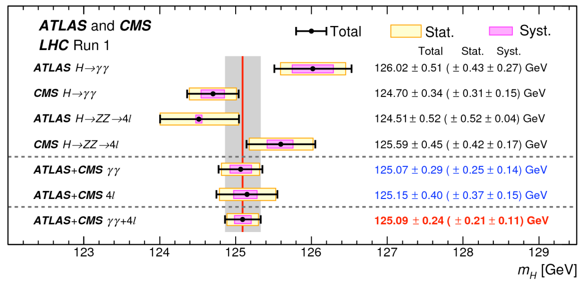
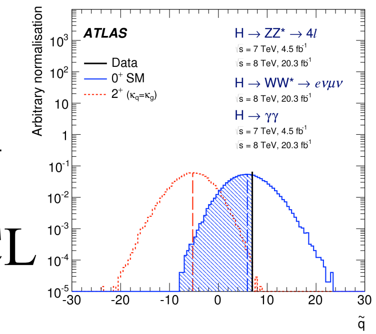
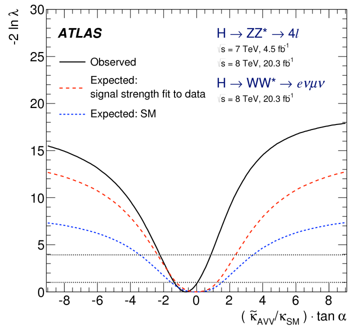
    - LHC $H \rightarrow \tau\tau$: 5.5σ (exp. 5.0σ)

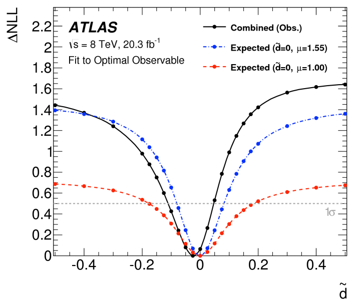
Introduction

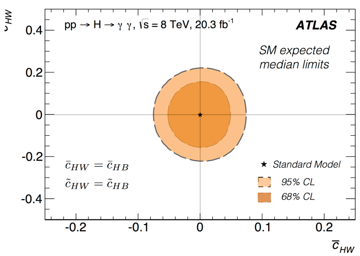
- Is it the Standard Model Higgs boson?
  - Deviations from SM: signal of new physics!
- Several characterisation studies already:
  - Mass: ATLAS+CMS combination m_H=125.09±0.21(stat) ±0.11(syst)
  - Spin/parity: Data compatible with $J^P=0^+$
    - Various 0^-, 2^+ models excluded at >99.9% CL
  - Test CP-violation in H→ZZ and WW
  - Test CP-violation in Vector-Boson Fusion production
  - Differential cross-sections
    - Fit to extract limits on Wilson-coeff. in Effective Field Theory framework











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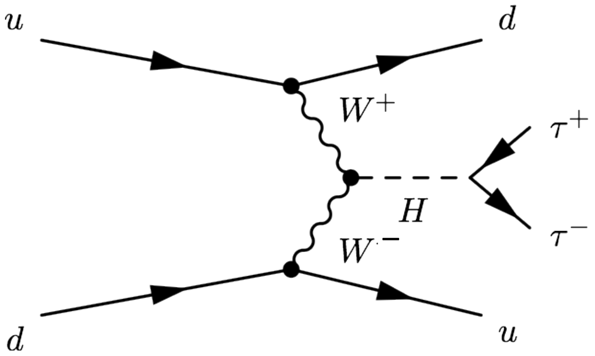
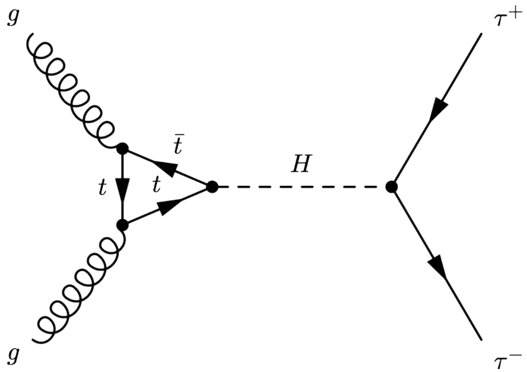
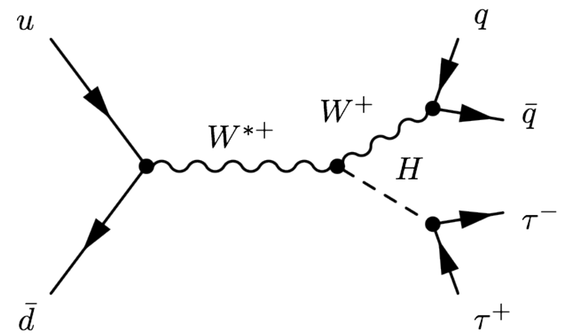
    - Fit to extract limits on Wilson-coefficients in Effective Field Theory

ATLAS Evidence for $H \rightarrow \tau\tau$

JHEP 04 (2015) 117

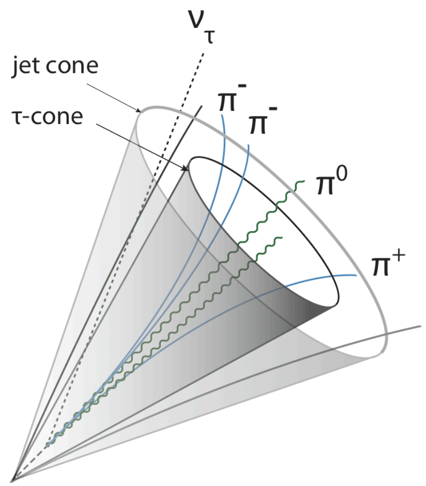


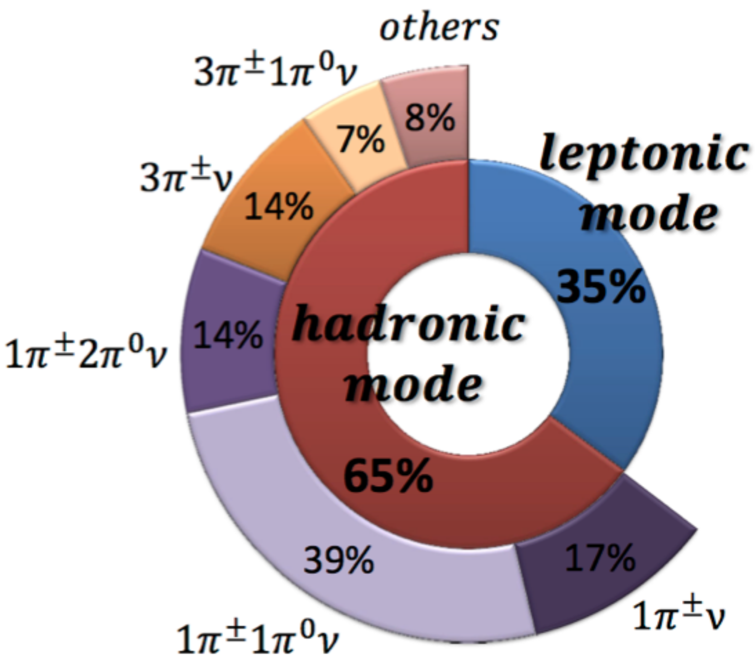




The Tau Lepton

- m_τ=1.777 GeV
- Short life-time: look for tau decay products

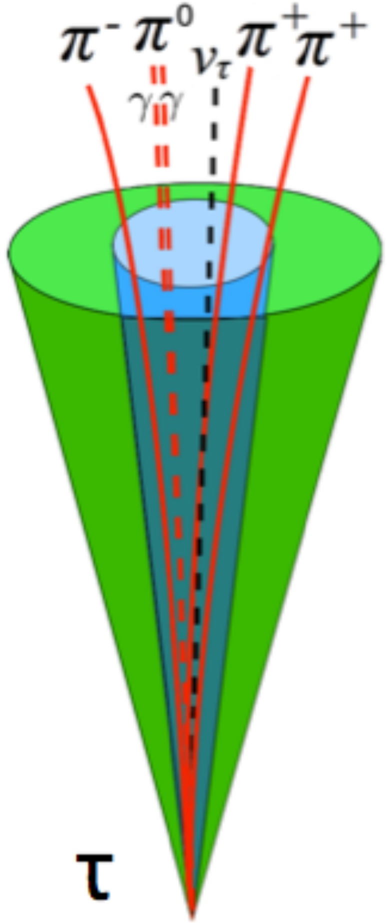




- Tau Reco typically refers to reconstruction of **hadronic** decays
  - Leptonic decays: use same reconstruction as for prompt leptons
- Tau-jet: Reconstructed visible decay products

Tau-Jet Reconstruction*

- Start with a calorimeter jet as *seed*
  - Anti-k_t algorithm, distance parameter R=0.4
  - p_T>10 GeV, $|\eta|<2.5$
- Calculate 4-momentum of tau-jet using only topological clusters within $\Delta R<0.2$ of cluster barycenter
- Associate tracks (p_T>1 GeV) within $\Delta R<0.2$



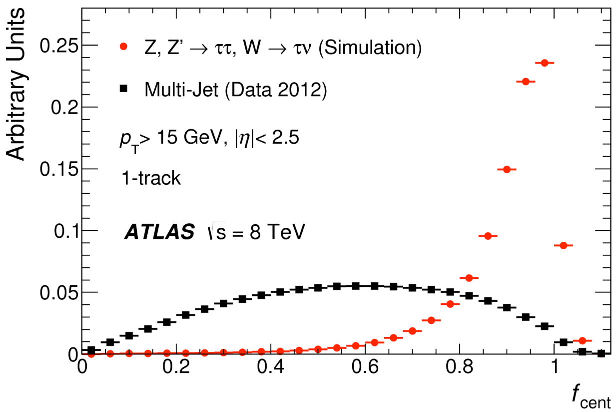
*: Slightly simplified…
See EPJC 75 (2015) 303
for full details

Tau Identification

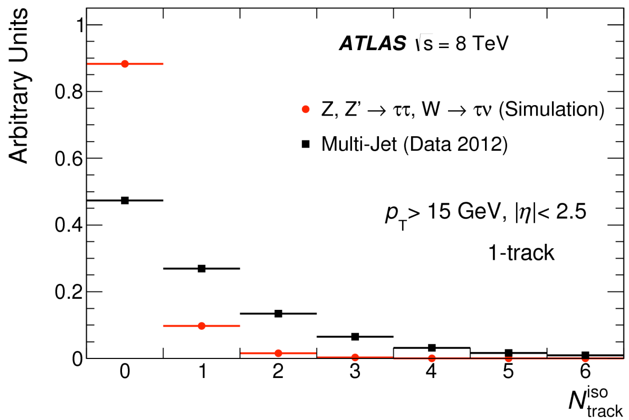
- Problem: Tau-jets look a lot like QCD jets
  - We have a lot of those at the LHC…
  - Requiring 1 or 3 tracks reduces contamination, but not nearly enough to be usable for most analyses
  - Need a more powerful discriminator…

Tau Identification

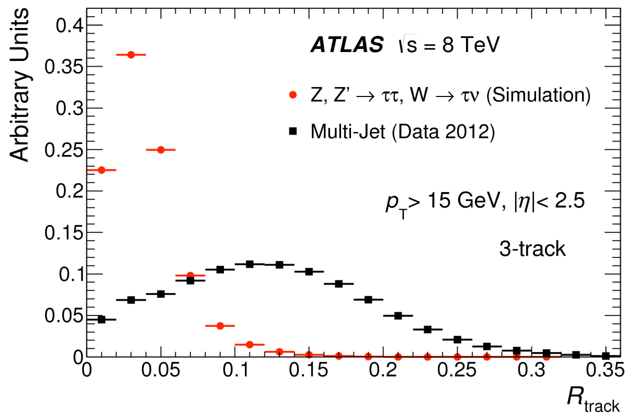
- Problem: Tau-jets look a lot like QCD jets
- Build variables exploiting QCD/tau-jet differences
  - Isolation, Lateral shape, Leading track momentum fraction, Secondary vertex, Invariant mass, and more…



Central Energy Fraction



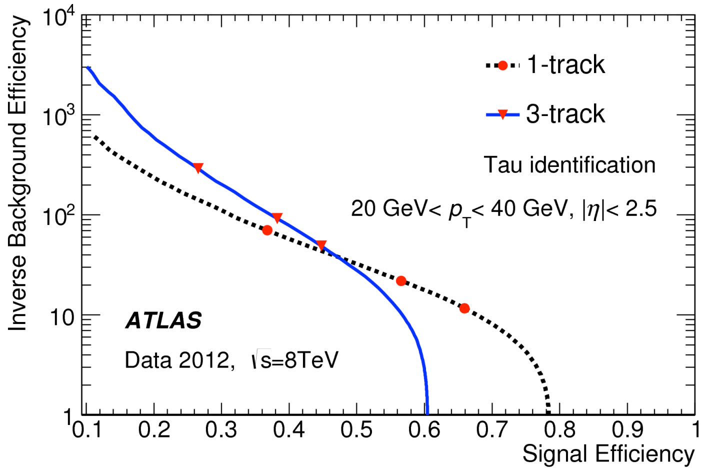
N tracks in isolation region

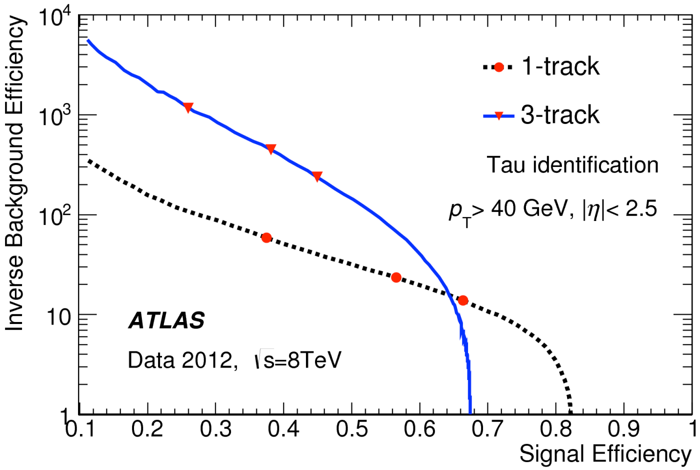


Track Radius

Tau Identification

- Problem: Tau-jets look a lot like QCD jets
- Build variables exploiting QCD/tau-jet differences
- Train Boosted Decision Trees
  - Separately for 1-prong and 3-prong tau-jets
  - Loose/medium/tight working points defined with pT-dependent cut on the BDT score





Tau Identification

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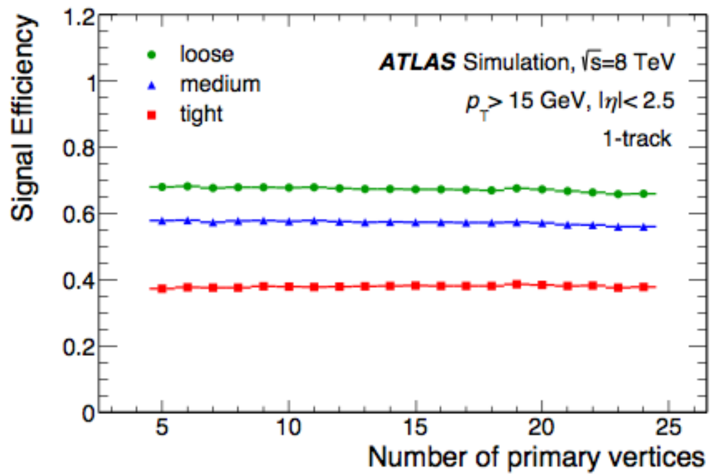
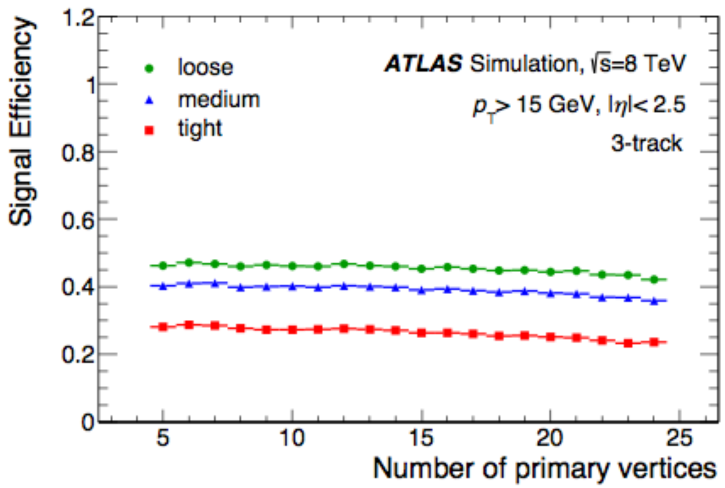
- Train Boosted Decision Trees
- Pile-up corrected input variables → ID is pile-up robust





Tau Identification

- Problem: Tau-jets look a lot like QCD jets
- Build variables exploiting QCD/tau-jet differences
- Train Boosted Decision Trees
- Pile-up corrected input variables → ID is pile-up robust
- Working point used for $H \rightarrow \tau\tau$ analysis yields 55-60% efficiency, and 1-2% jet misidentification probability

The $H \rightarrow \tau\tau$ Analysis

- Does the boson with M_H ~125 GeV decay to τ-lepton pairs?

- All final states of tau-decays considered
  - $H \rightarrow \tau\tau \rightarrow 2l + 4\nu$ (lep-lep channel; BR=12.4%)
  - $H \rightarrow \tau\tau \rightarrow l + \tau_{had} + 3\nu$ (lep-had channel; BR=45.6%)
  - $H \rightarrow \tau\tau \rightarrow 2\tau_{had} + 2\nu$ (had-had channel; BR=42%)

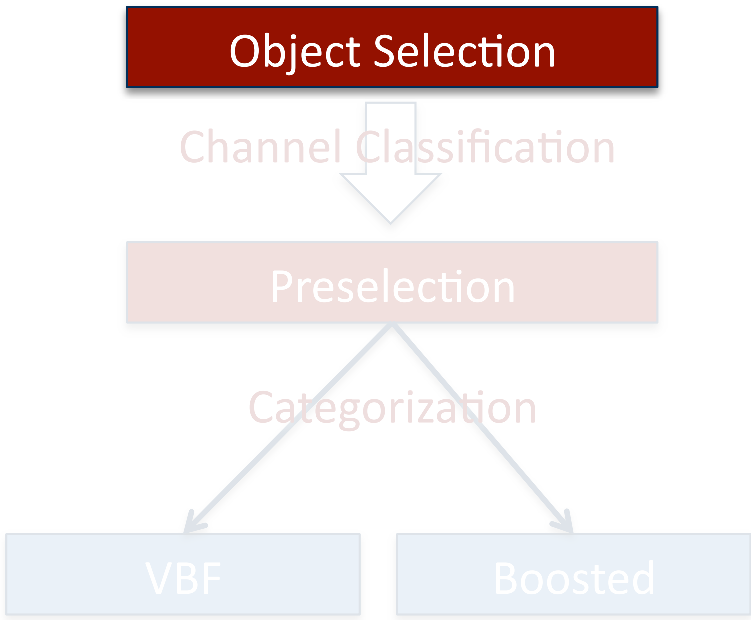
- Main backgrounds: $Z \rightarrow \tau\tau$, Fakes (W+jets, QCD multijet), $Z \rightarrow ll$, top

- Multivariate analysis, based on Boosted Decision Trees, BDTs

- Using all data collected by ATLAS in 2012 (8 TeV, 20.3 fb^{-1}) and 2011 (7 TeV, 4.5 fb^{-1})

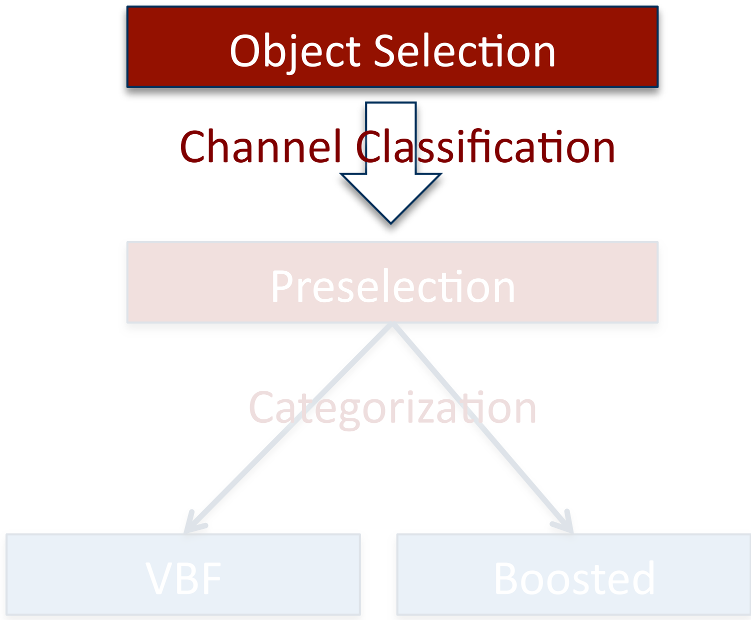
H→ττ – Analysis Concept

- Dataset selected by triggering on electrons, muons or tau-jets
- Reconstruct and identify physics objects according to standard ATLAS procedures



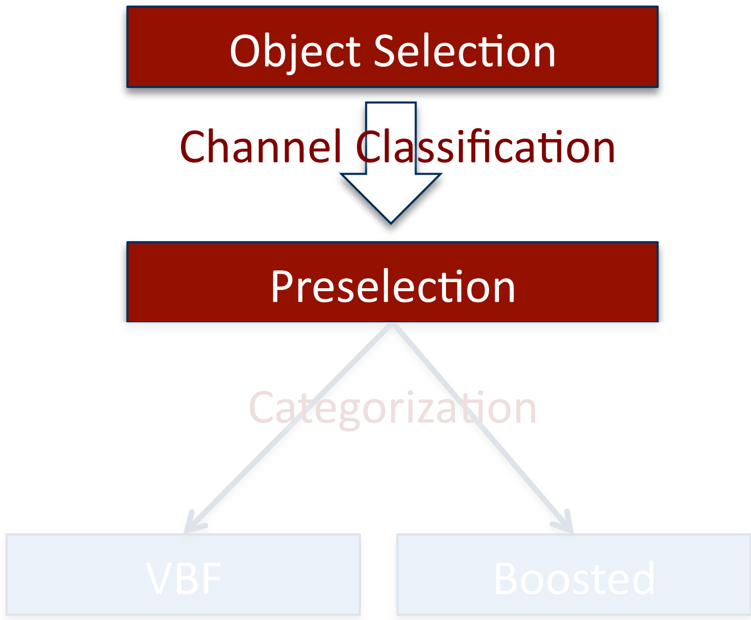
$H\rightarrow\tau\tau$ – Analysis Concept

- Split dataset into 3 orthogonal channels by demanding exactly:
  - 2 light leptons (e, μ) and no tau-jet (lep-lep)
  - 1 light lepton (e, μ) and 1 tau-jet (lep-had)
  - No light lepton (e, μ) and 2 tau-jets (had-had)



H→ττ – Analysis Concept

- Reduce the most "obvious" backgrounds
  - Opposite sign of τ decay products
  - b-jet veto
  - Cuts against Z→ll
- Also cuts to ensure orthogonality with H→WW selection



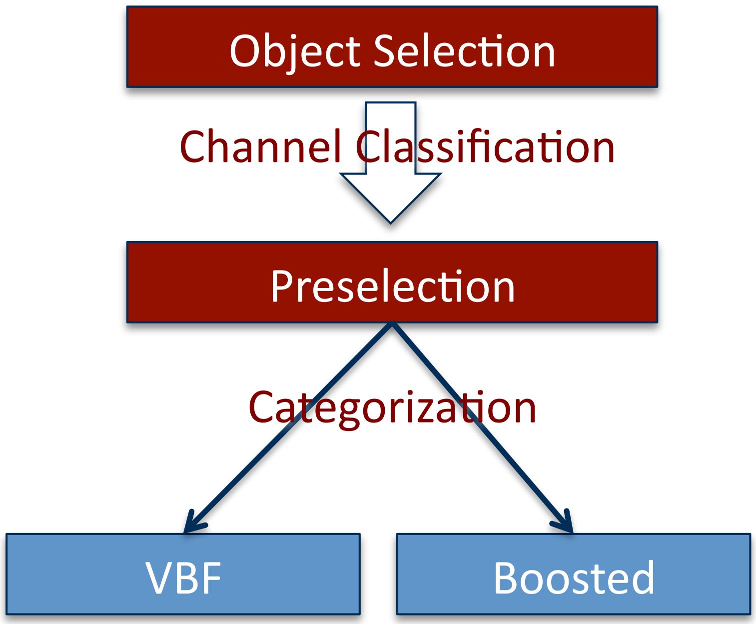
H→ττ – Analysis Concept

- Two categories per channel
  - VBF Category: 2 jets separated in η

    VBF signal fraction: 55-65%

  - Boosted Category: p_T(H)>100 GeV

    ggF signal fraction: 62-67%



Channel	VBF category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_T^{j_1} > 40$ GeV and $p_T^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_T^{j_1} > 50$ GeV and $p_T^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\rm vis} > 40$ GeV
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_T^{j_1} > 50$ GeV and $p_T^{j_2} > 30$ GeV $p_T^{j_2} > 35$ GeV for jets with $\|\eta\| > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	Boosted category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least one jet with $p_T > 40$ GeV
All	Failing the VBF selection $p_T^H > 100$ GeV

H→ττ – Analysis Concept

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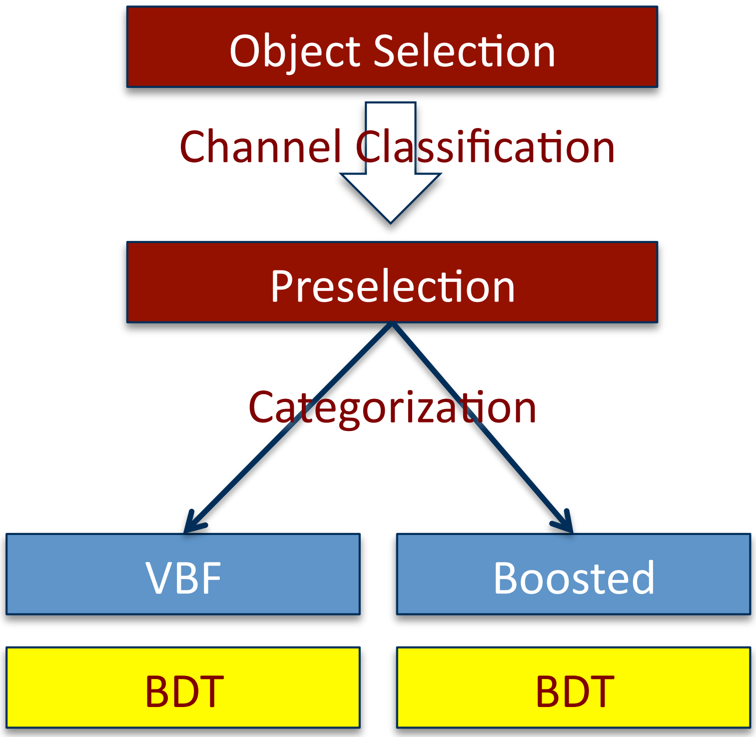
    ggF signal fraction: 62-67%
- Separate BDTs trained in each category



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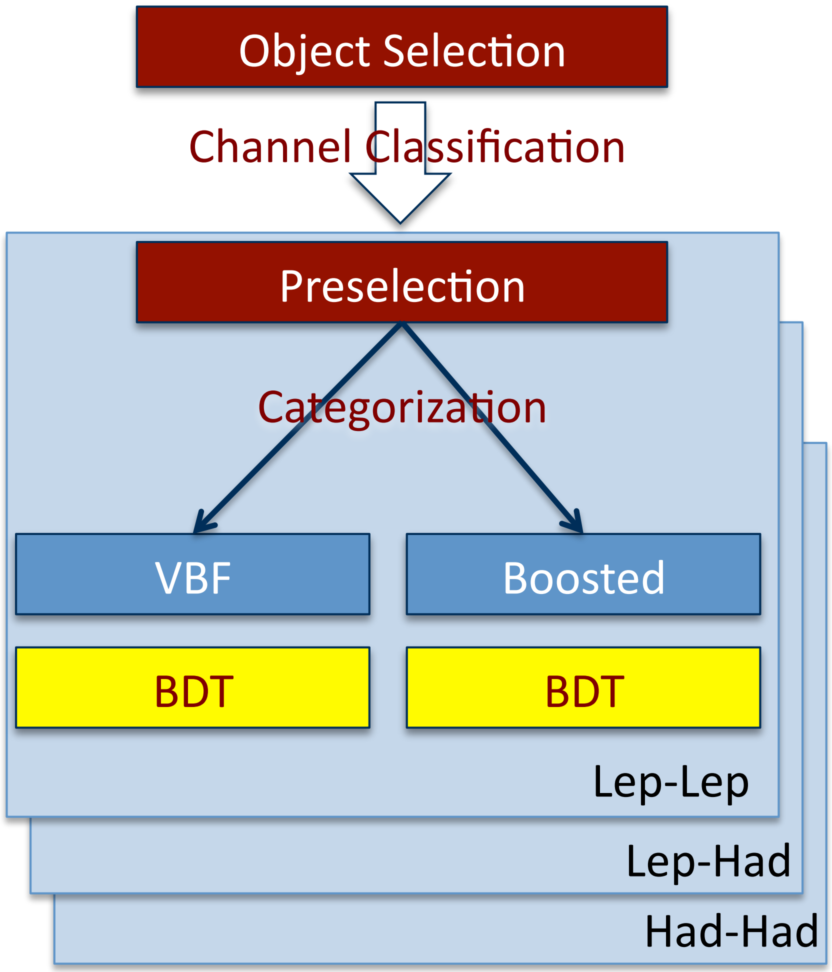
- Separate BDTs trained in each category and each channel
  - Total of 6 different BDTs
  - Use BDTs trained for 8 TeV also on 7 TeV dataset



Boosted Decision Trees

- Decision Tree: Sequential cuts split data into nodes; final nodes (leafs) classify event as signal or background
  - Similar to "classic" cuts – but don't throw away events
  - Each split uses variable that at this node gives best S/B separation when cut on.
  - Separate *training* and *testing* samples

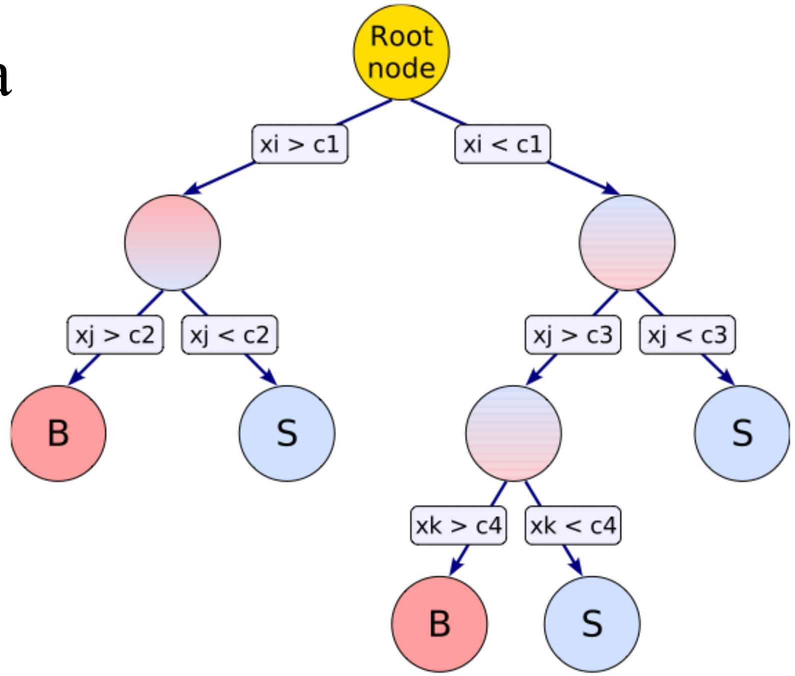
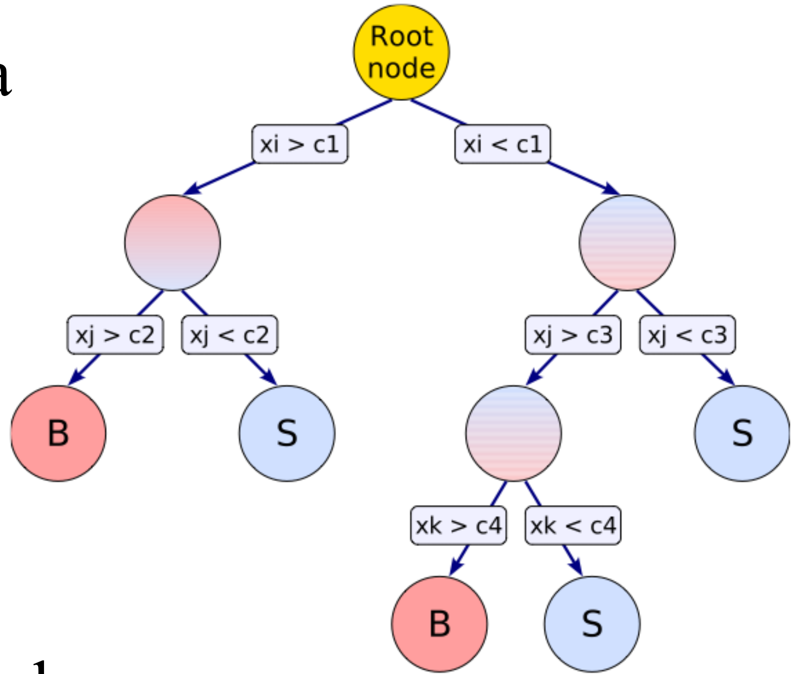


Figure from: A. Hoecker et al CERN-OPEN-2007-007

Boosted Decision Trees



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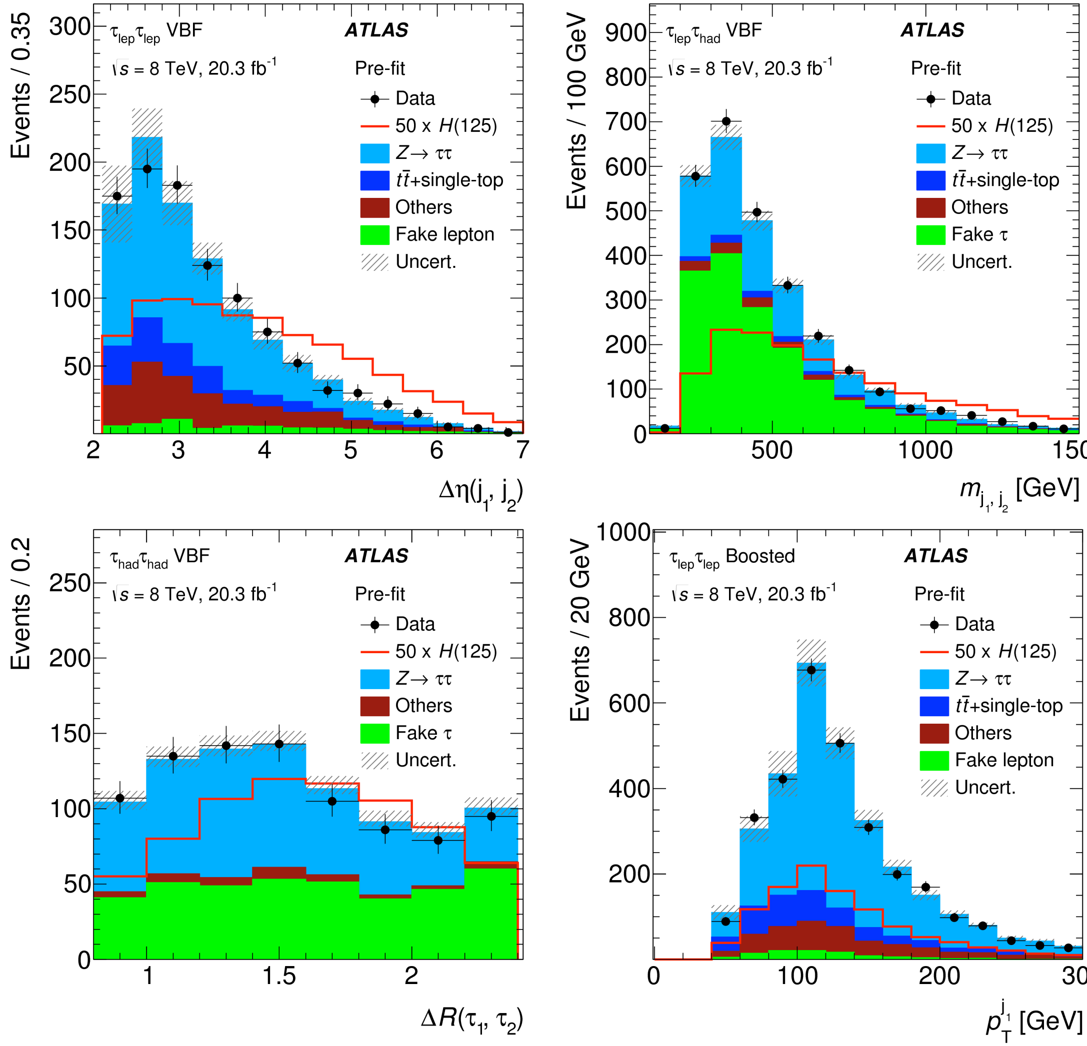
  - Similar to "classic" cuts – but don't throw away events
  - Each split uses variable that at this node gives best S/B separation when cut on.
  - Separate *training* and *testing* samples
- Boosted Decision Trees: Combine a whole "forest" of Decision Trees derived from the same sample, e.g. using different event weights
  - Increases statistical stability → substantial improvement in performance
- Detailed studies of optimal BDT training parameters (Nr trees; min leaf size…) done, in addition to deciding which variables to use

H→ττ – BDT Input Variables

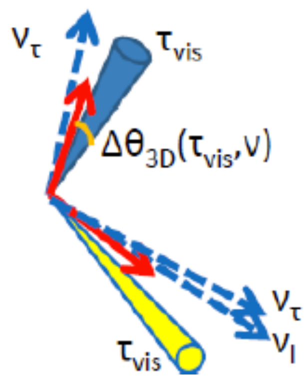
- 6-9 variables used in the BDTs, exploiting:
  - Resonance properties: $m_{\tau\tau}$, $\Delta R_{\tau\tau}$, *etc*
  - Event activity: *scalar & vector* p_T*-sum, etc*
  - Event topology: m_T, $p_T(\tau_1)/p_T(\tau_2)$, *etc*
  - VBF topology: m_{jj}, $\Delta\eta_{jj}$

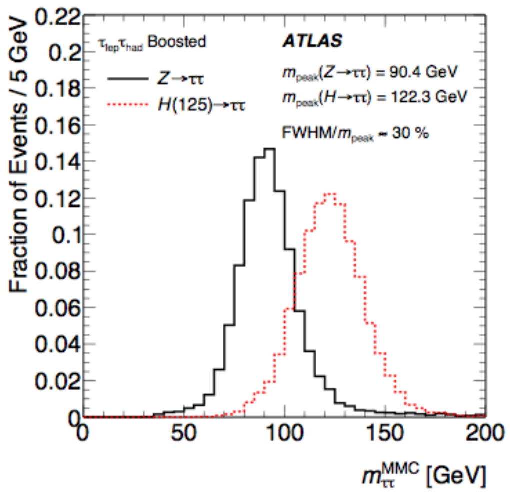


(Pre-fit plots)

Di-tau Mass Reconstruction

- Reconstructing invariant mass of ditau system not straightforward, due to the presence of neutrinos in the tau decay
- Missing Mass Calulator (MMC) to estimate ditau invariant mass A. Elagin et. al. NIM A 654 (2011) 481
- Scan over unknown ν momenta and E_x^{miss} and E_y^{miss}
- Calculate $m_{\tau\tau}$ at each point, then weigh it by its probability, according to E_T^{miss} resolution and tau decay topology
- Mass estimator defined as the most probable value of the scan points
  - E_T^{miss} resolution drives performance of the method.

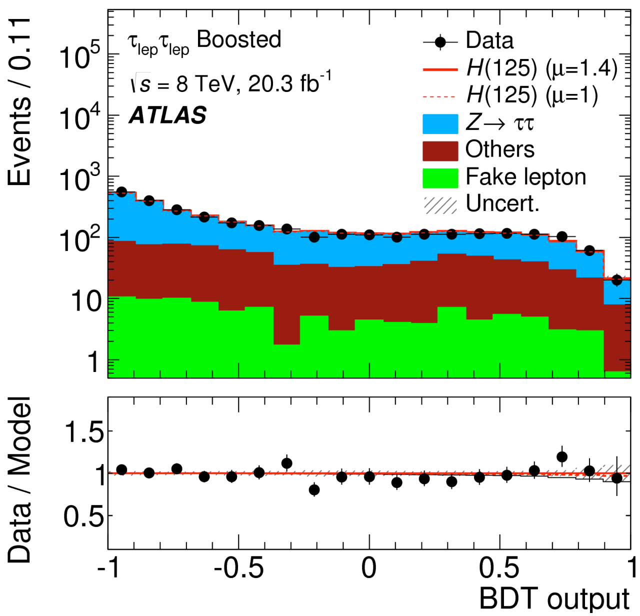




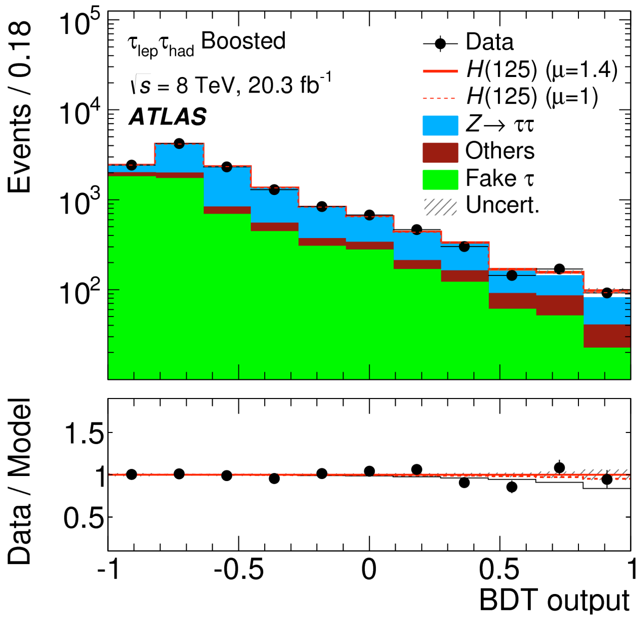
H→ττ

- BDT score distributions in the Boosted category (8 TeV)

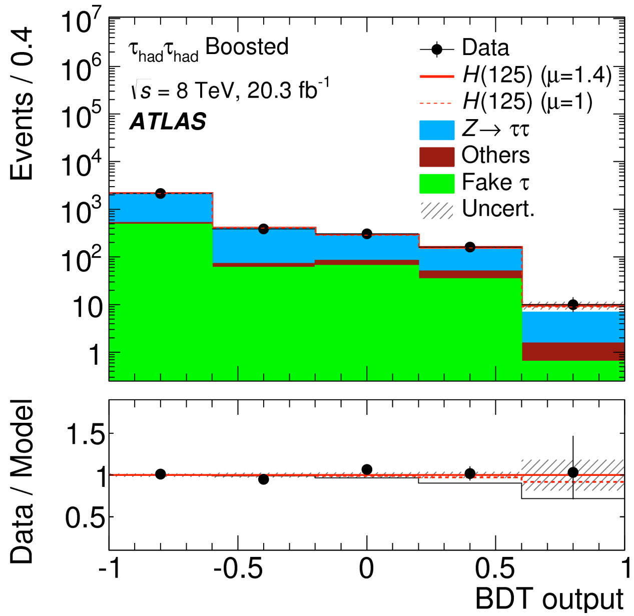
Lep-Lep



Lep-Had



Had-Had

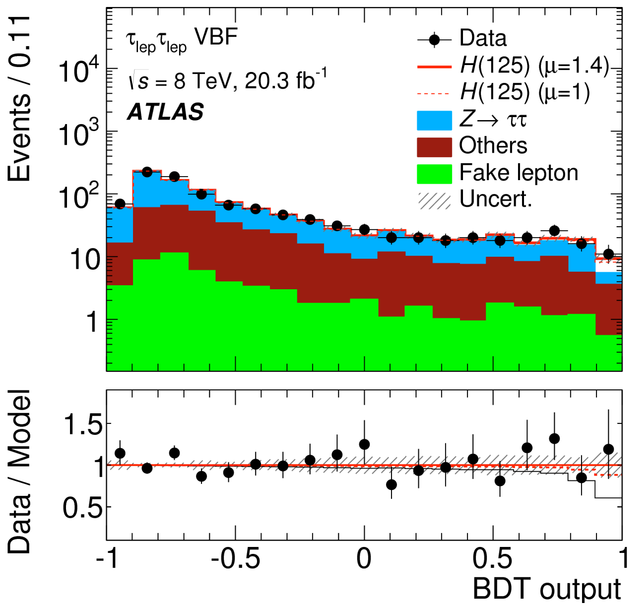


(Post-fit plots)

H→ττ

- BDT score distributions in the VBF category (8 TeV)

Lep-Lep



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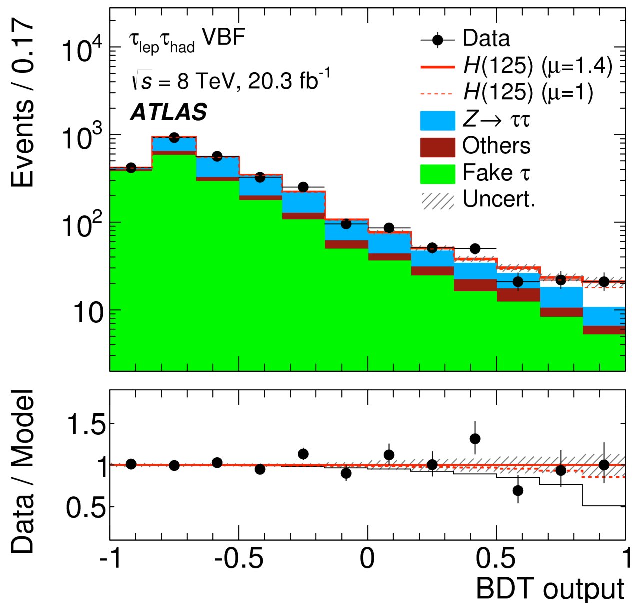

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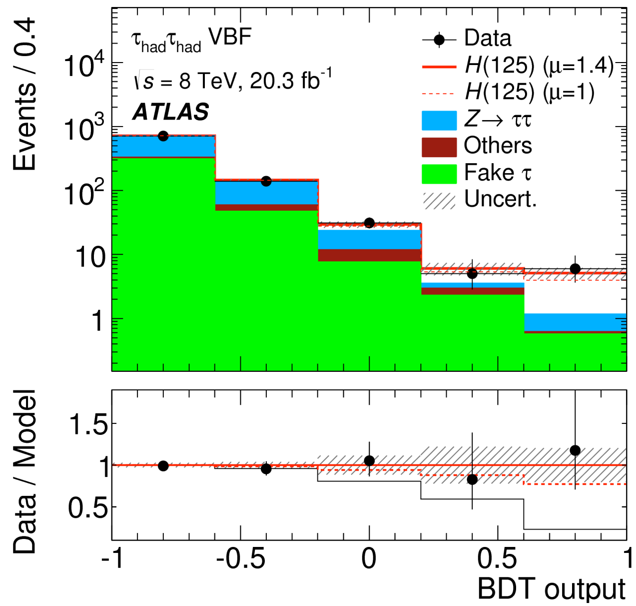
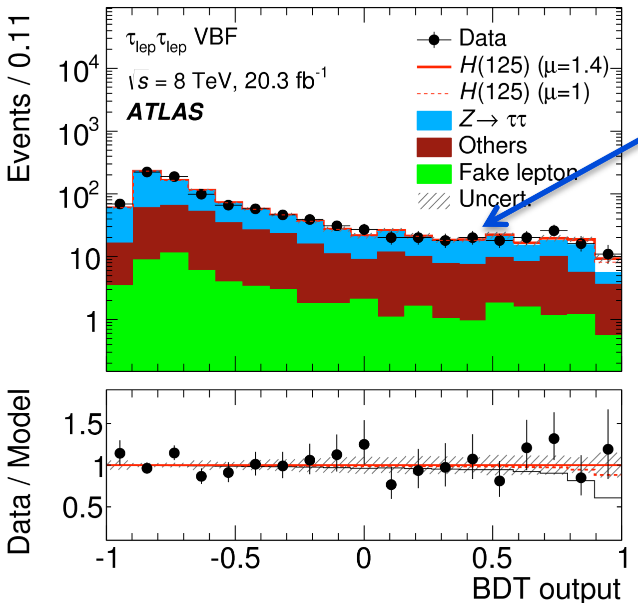


(Post-fit plots)

H→ττ

- Modelling of background processes crucial
  - All major backgrounds either directly estimated from data, or normalized to data in control regions



(Post-fit plot)

Z→ττ:

Obtained from data-driven *"embedding"* procedure:

→ Select Z→μμ events in data

→ Replace μ with a simulated τ

→ τ decayed using TAUOLA; polarization and spin-correlations taken into account

→ Normalization free parameter in the fit

H→ττ

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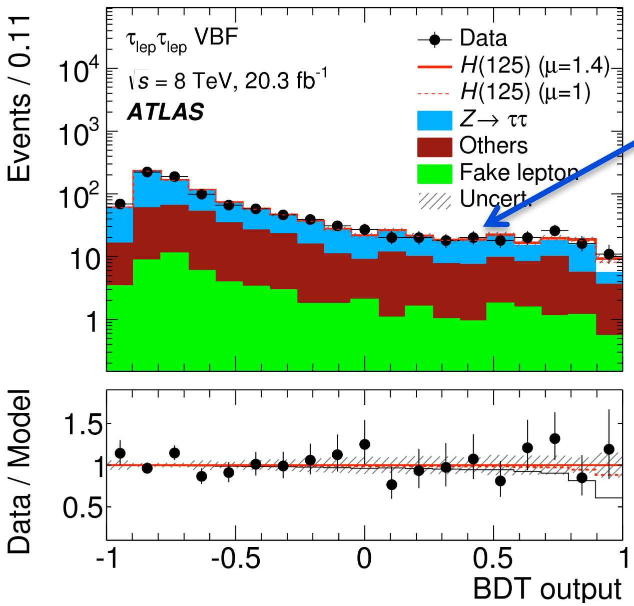
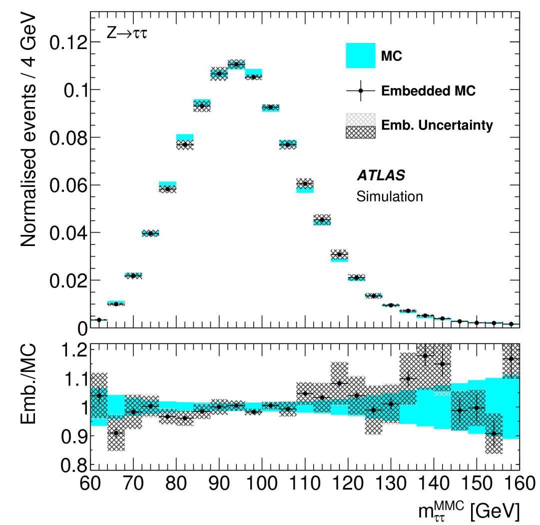
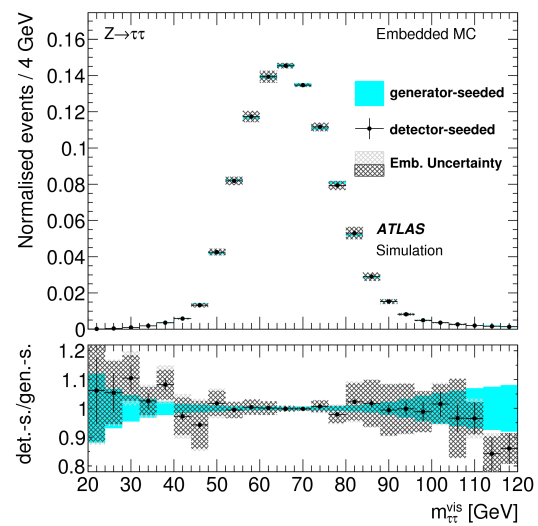


(Post-fit plot)

Z→ττ:

"Embedding" procedure extensively validated
Separate publication describing the method and its validation JINST 10 (2015) P09018





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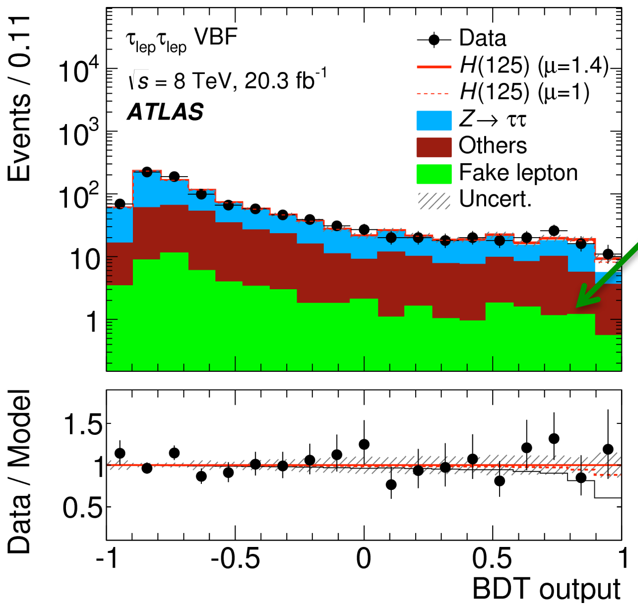

(Post-fit plot)

Fake backgrounds (e.g. W+jets, QCD multijets): Obtained though fully data-driven methods

→ Lep-lep: Template fit in region of inverted lepton isolation.

→ Lep-had: τ_{had} candidates failing ID requirements, multiplied by process-dependent Fake Factors binned in p_T and track multiplicity.

→ Had-had: Invert opposite-sign requirement on two τ_{had} candidates. Normalization from the fit.

H→ττ

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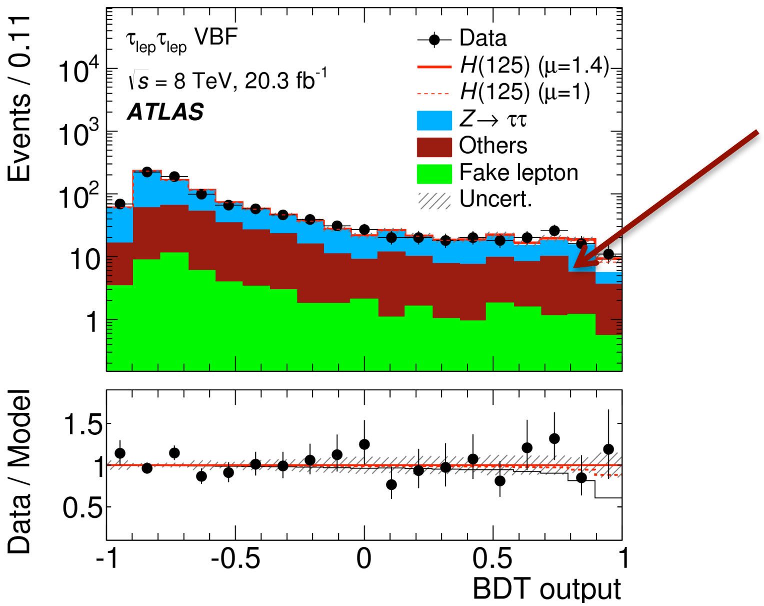


(Post-fit plot)

Other Backgrounds:

→ Top normalized to data in control regions in the leptonic channels

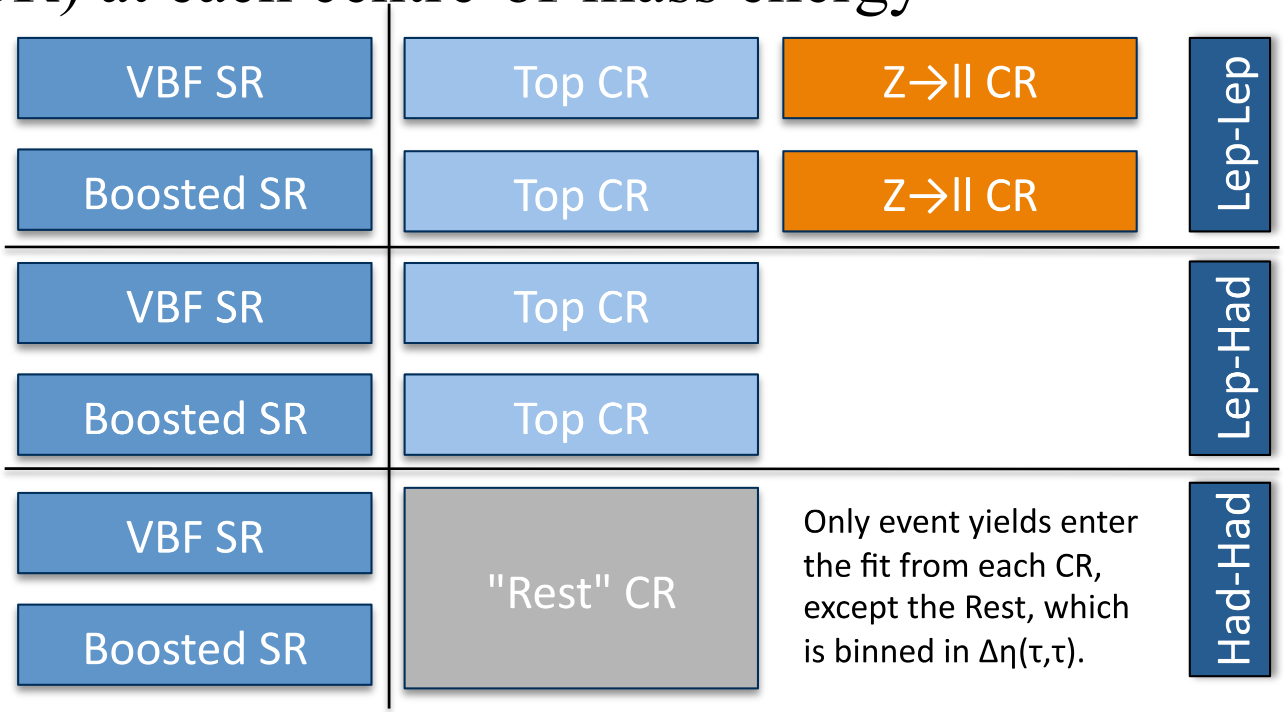
→ Z→ll normalized to data in control region for lep-lep channel

→ Z→ll with lepton misidentified as τ_{had} candidate: scale by mis-ID factors obtained in dedicated tag & probe study

→ Diboson & H→WW: from MC

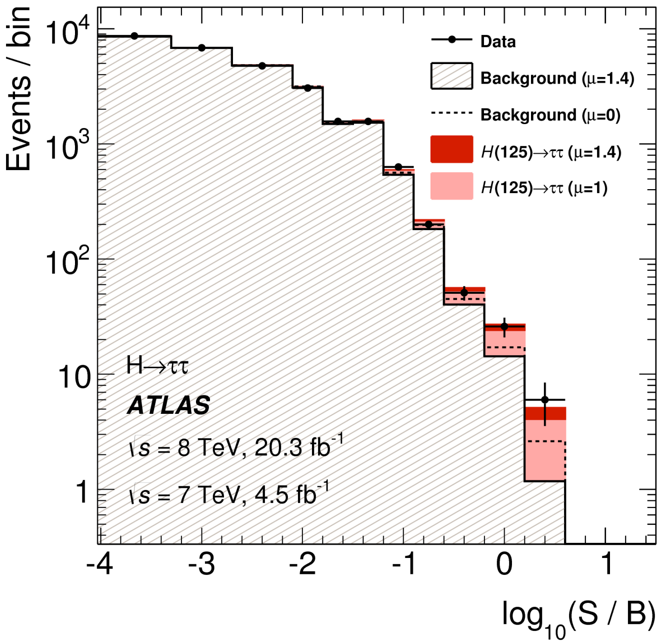
H→ττ

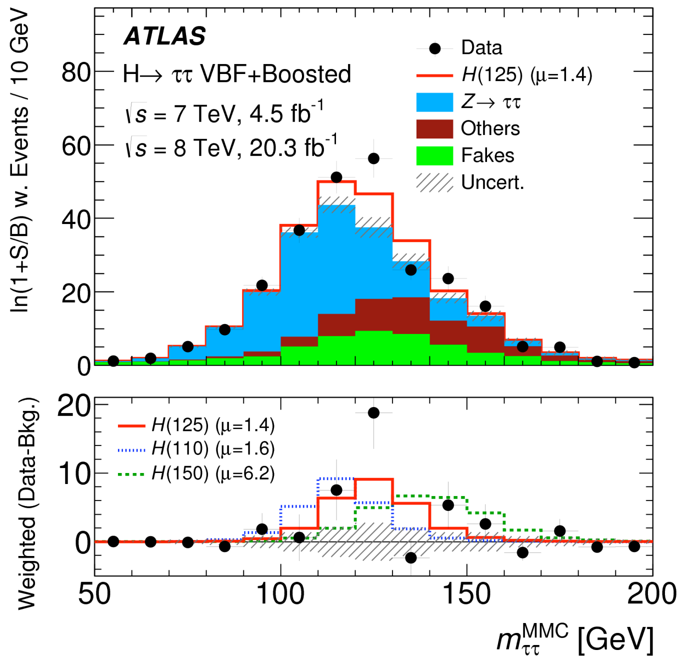
- Modelling of background processes crucial
  - All major backgrounds either directly estimated from data, or normalized to data in control regions
- Signal extracted by fitting BDT shape with signal and background templates, simultaneously in the 6 Signal Regions (SR) + 7 Control Regions (CR) at each centre-of-mass energy



ATLAS Evidence for H→ττ

- Excess of data events over the background prediction
  - Excess observed in all three channels
  - **Expected** significance at M_H=125.36 GeV: **3.4σ**
  - **Observed** significance at M_H=125.36 GeV: **4.5σ**
- Consistent with presence of Higgs boson at ~125 GeV

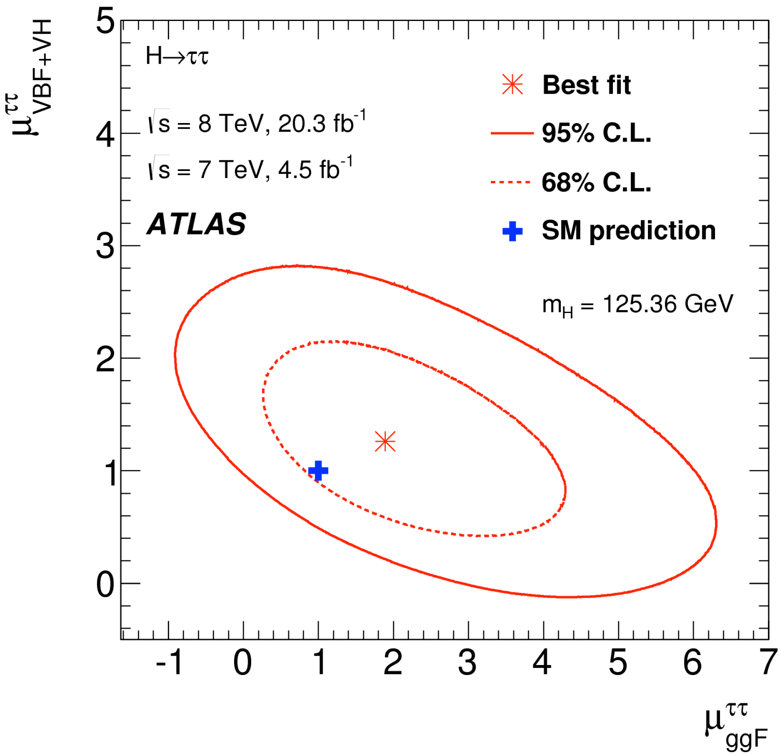


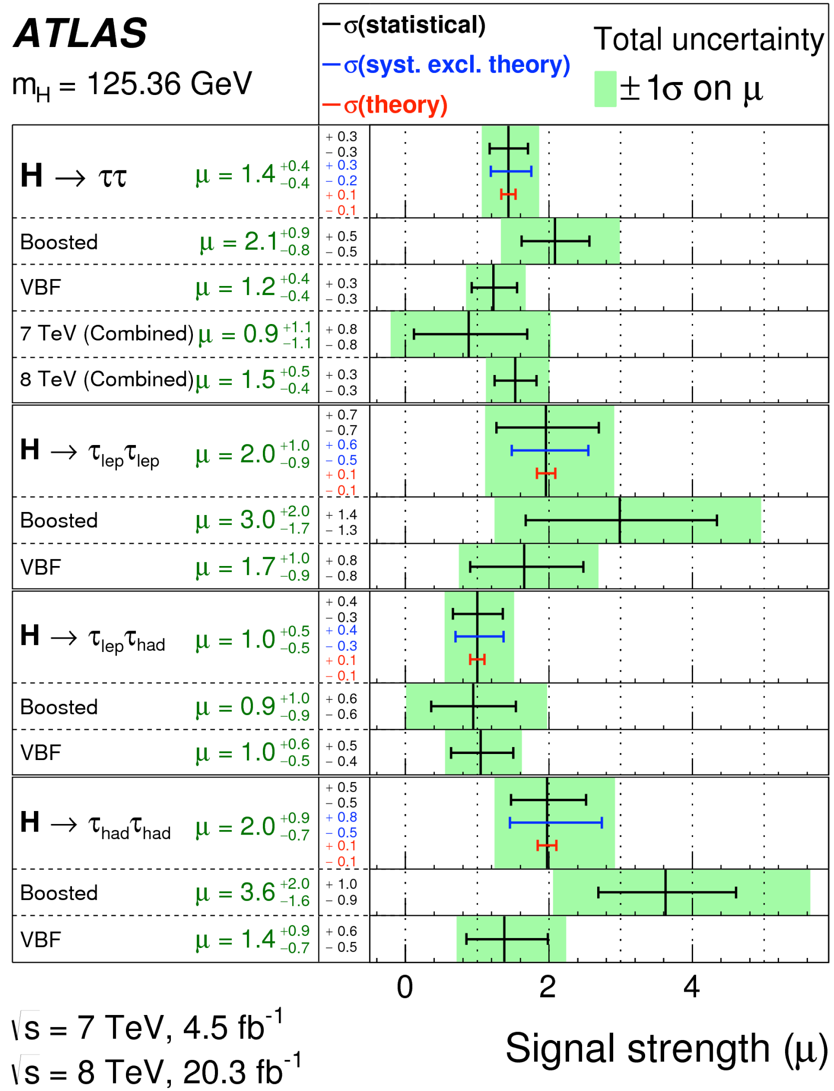


Events weighted by ln(1+S/B) of corresponding bin in BDT score

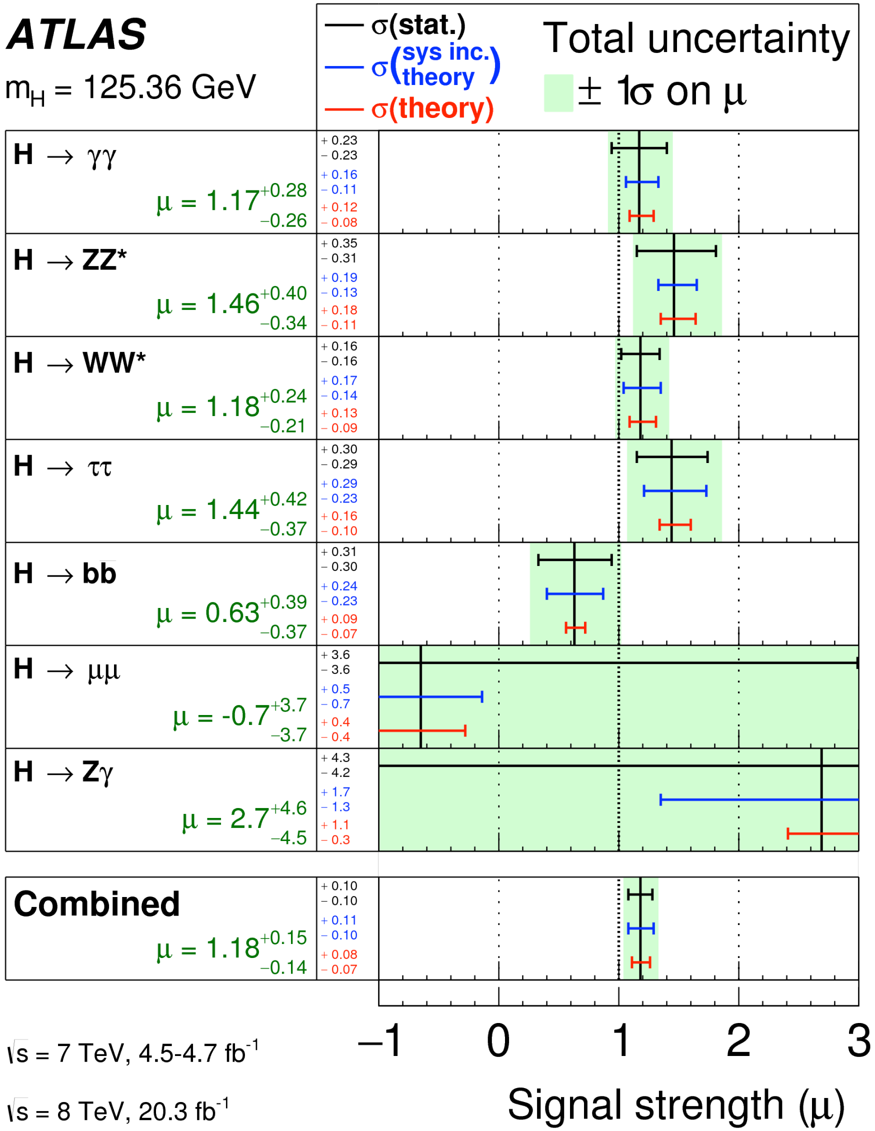
ATLAS Evidence for H→ττ

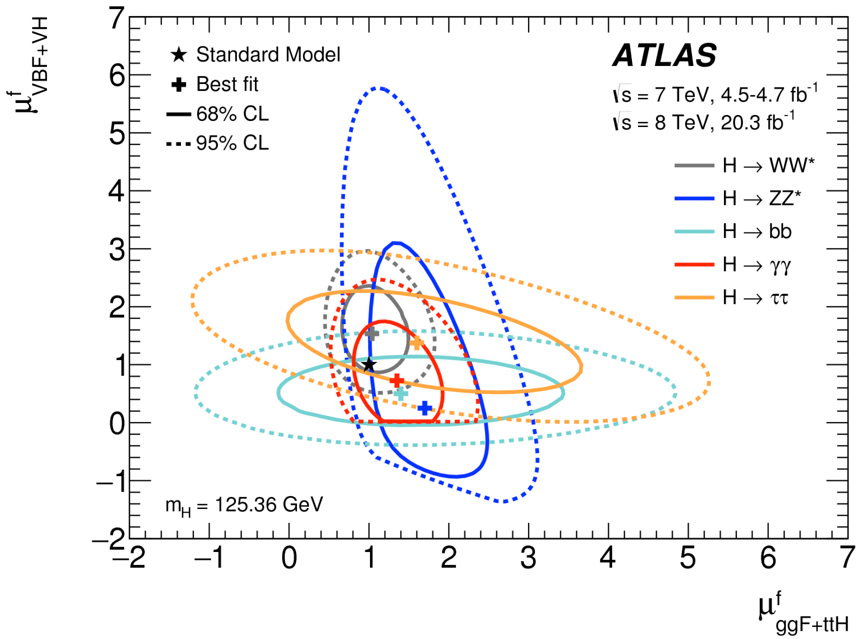
- Measured signal strength:
  $\mu=\sigma_{meas}/\sigma_{SM}=1.4\pm0.4$





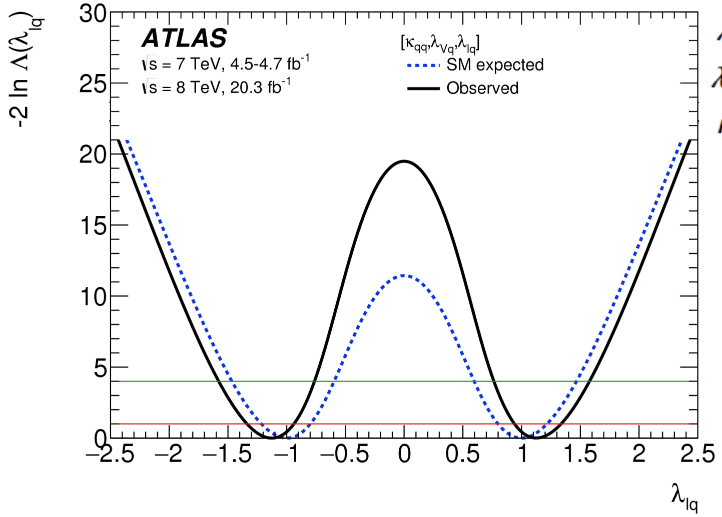
ATLAS Combination



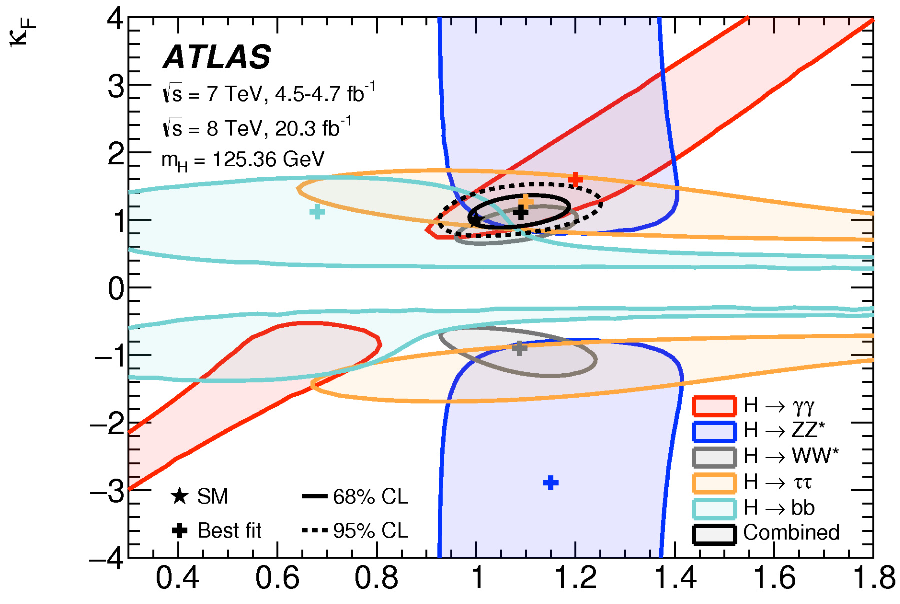


ATLAS Combination

- Results allow us to probe Higgs boson couplings and their ratios
- Use coupling scale factors κ_i (defined such that κ_i=1 for SM) and their ratio $\lambda_{ij}=\kappa_i/\kappa_j$
- Assumptions:
  - zero-width approx.
  - all signals originate from same resonance
  - tensor structure as in SM



$$\lambda_{\ell q} = \kappa_\ell/\kappa_q$$
$$\lambda_{Vq} = \kappa_V/\kappa_q$$
$$\kappa_{qq} = \kappa_q \cdot \kappa_q/\kappa_H$$



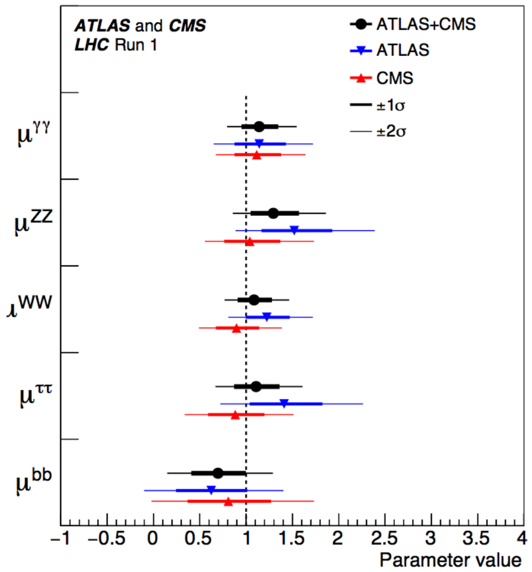
Assume only SM contributions to the total width κV

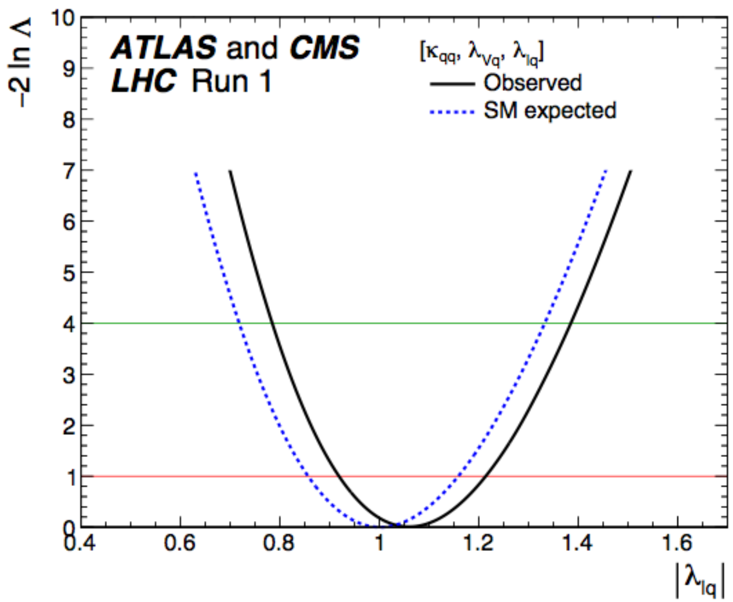
JHEP08(2016)045

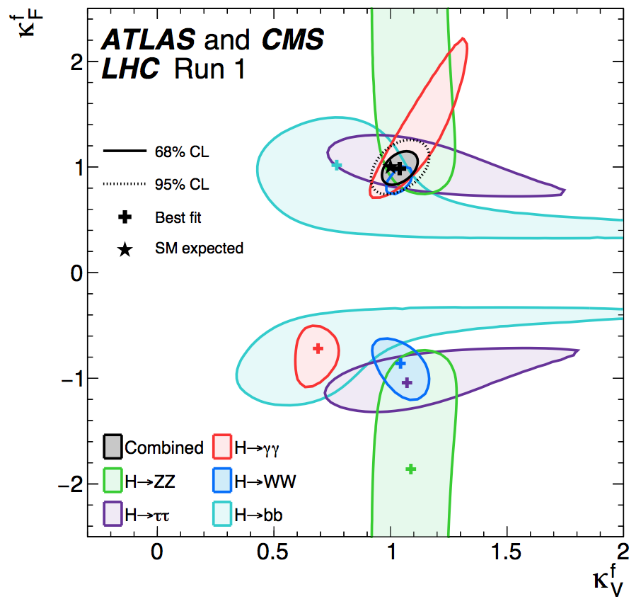
ATLAS+CMS Combination

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Observation!

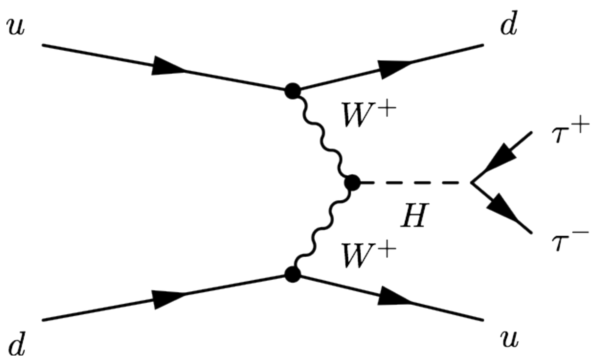






VBF CP Studies

arXiv:1602.04516 (Accepted to EPJC)

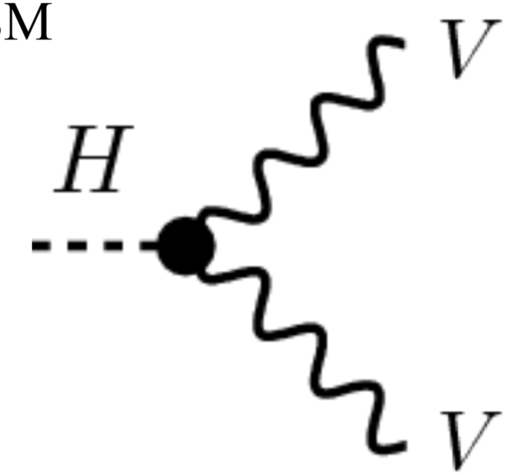


Motivation

- Baryon asymmetry of the universe
- C and CP violation: one of three Sakharov conditions to explain it
- SM: CP violation insufficient (from CKM matrix)

- Discovery of Higgs boson
  → look for CP violation in the Higgs sector
  - Observation of CP violation = Physics beyond the SM

- Test CP invariance in HVV coupling
  - In decay: H→WW and H→ZZ
  - In VBF production: here



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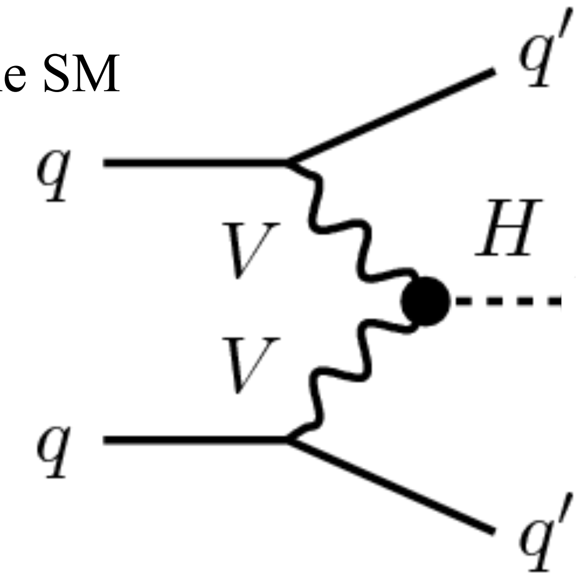

Effective Lagrangian Framework

- Augment SM Lagrangian with CP-violating operators (mass dim. 6) involving Higgs field and EWK gauge bosons:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2} O_{\tilde{B}B} + \frac{f_{\tilde{W}W}}{\Lambda^2} O_{\tilde{W}W} + \frac{f_{\tilde{B}}}{\Lambda^2} O_{\tilde{B}}$$

- Interactions between Higgs and fermions/gluons assumed to be as in SM
- Third operator contributes to CP-violating TGCs; already constrained at LEP → only first two operators considered in this analysis

Effective Lagrangian Framework

- Effective Lagrangian after EW symmetry breaking in the mass basis:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

- Couplings can be parametrised in terms of 2 parameters, $\tilde{d}$ and $\tilde{d}_B$

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}\,.$$

(Relations arising from $SU(2)_{L,IW} x U(1)_Y$ invariance)

Following Phys.Lett.B589:89-102,2004

Effective Lagrangian Framework

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$$\tilde{d} = \tilde{d}_B$$

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$$\tilde{d} = \tilde{d}_B$$

- Couplings become:

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{HAZ} = 0$$

- CP-mixing is parametrised by single parameter $\tilde{d}$

Testing CP Invariance

- General principle: Study a CP-odd variable
  - Mean≠0, asymmetry → CP violation
  - CP invariance → Mean=0, no asymmetry

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \tilde{d} \cdot \mathcal{M}_{\rm CP\text{-}odd} \Longrightarrow |\mathcal{M}|^2 = \boxed{|\mathcal{M}_{\rm SM}|^2} + \boxed{\tilde{d} \cdot 2\,{\rm Re}(\mathcal{M}^*_{\rm SM}\mathcal{M}_{\rm CP\text{-}odd})} + \boxed{\tilde{d}^2 \cdot |\mathcal{M}_{\rm CP\text{-}odd}|^2}$$

- Only CP-odd interference term yields CP-violation
- CP-even terms: affect total cross-section, do not contribute to CP-violation
- Keeping our test general and model-independent:
  - Only use CP-odd observables
  - Do not use (CP-even) rate information

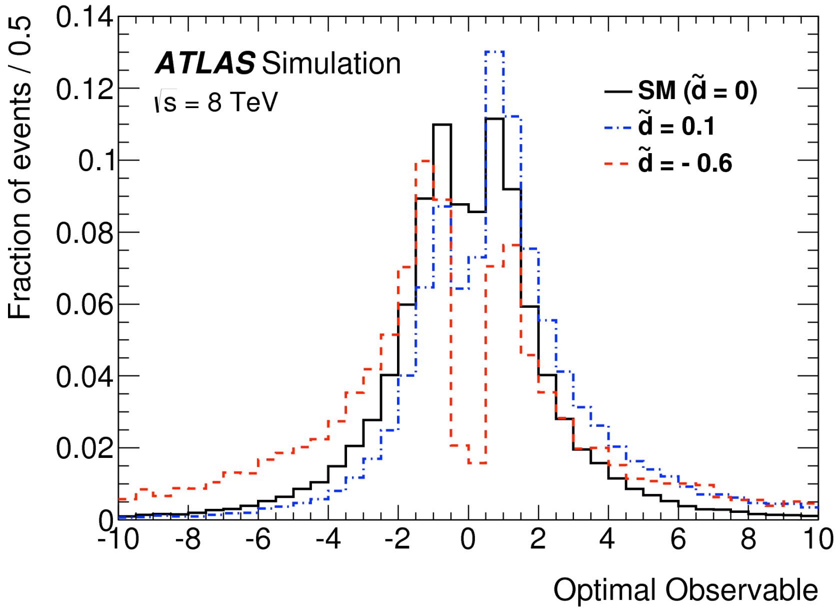
Optimal Observable

- VBF Final State: 7 phase-space variables
- Optimal Observable (OO): combine information into single variable
  - CP-odd observable
  - Highest sensitivity for small values of $\tilde{d}$
- Calculated using ME code from HAWK *Denner et al*, Comput. Phys. Commun. 195 (2015) 161–171
- Input:
  - Reconstructed Higgs 4-vector
  - Tagging Jets 4-vectors

$$OO = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

With the ME for VBF production being:

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d}\cdot\mathcal{M}_{\mathrm{CP\text{-}odd}}$$



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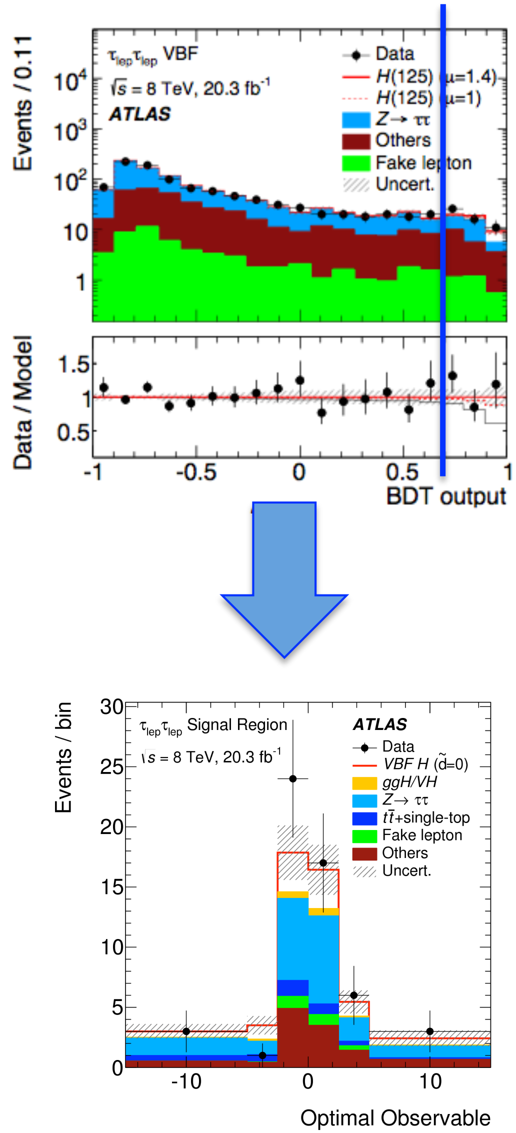
$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d}\cdot\mathcal{M}_{\mathrm{CP\text{-}odd}}$$

First time OO is used in the context of VBF Higgs CP studies

Analysis Strategy

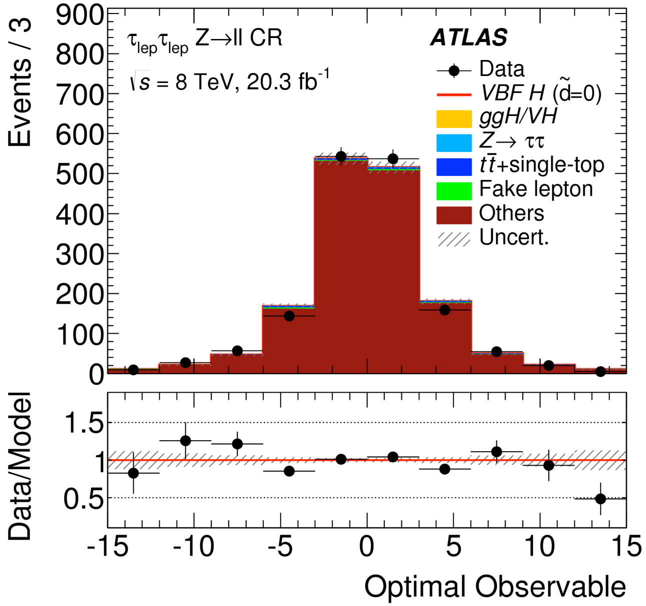
- Independent of decay – use H→ττ channel
  - Large VBF sample
  - Allows reconstruction of H 4-vector
- Build on H→ττ Evidence analysis
  - Use exactly the same background estimation, VBF category definition, BDT and systematics
  - Lep-lep and Lep-had channels; full 8 TeV dataset from Run 1
- Cut on BDT, calculate OO in high-BDT region

BDT-cut efficiency	Signal	Bkg
Lep-had	51%	2.1%
Lep-lep	49%	3.6%

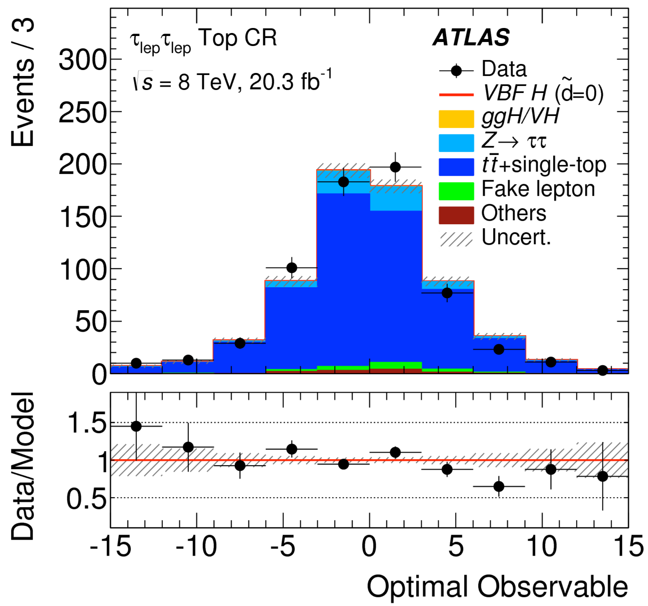


Background Modelling

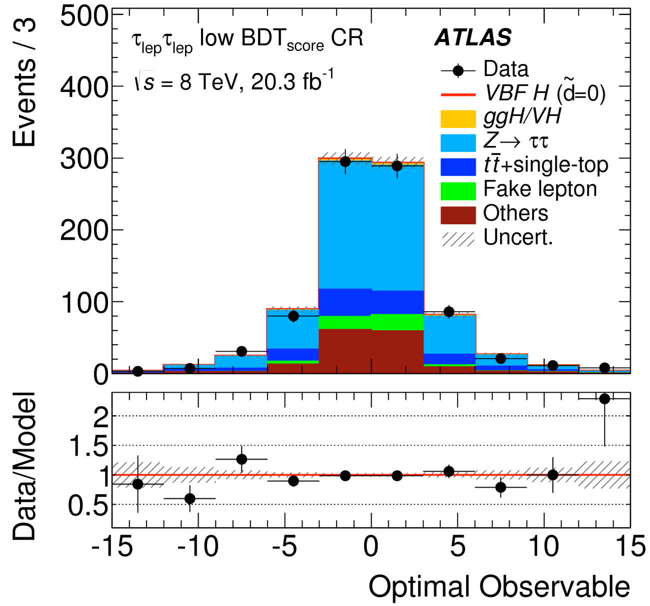
- Data well-described by background predictions
- No asymmetries



$\tau_{lep}\tau_{lep}$ Z Control Region
($80 < m_{ll} < 100$ GeV)

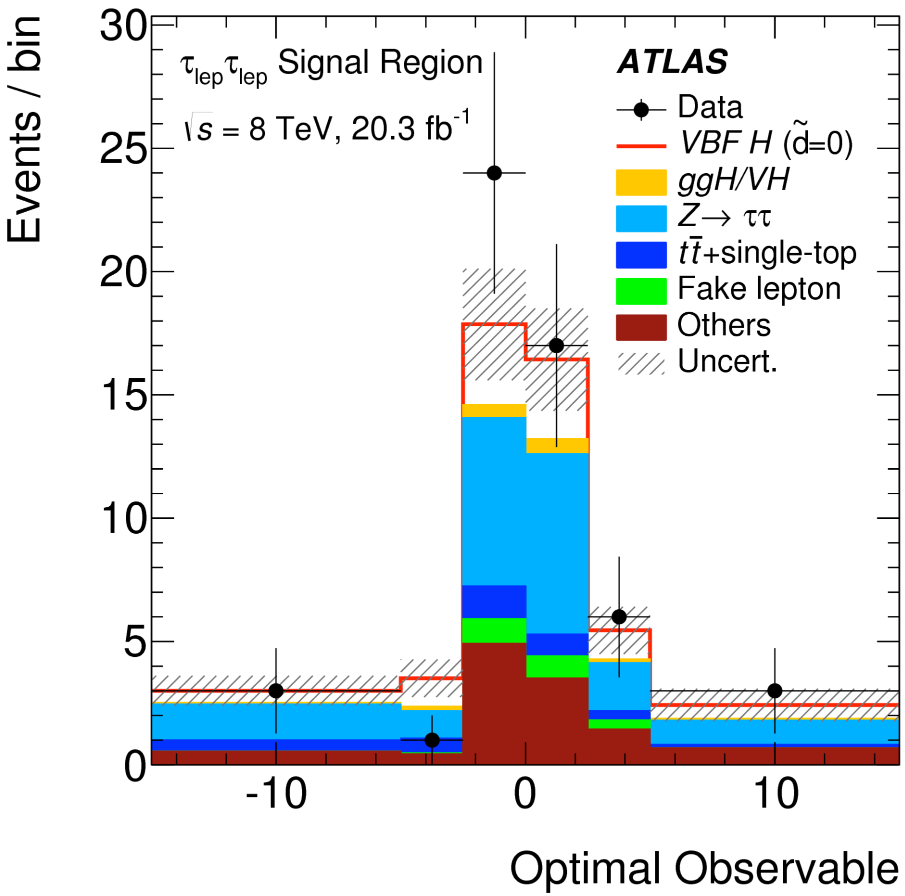


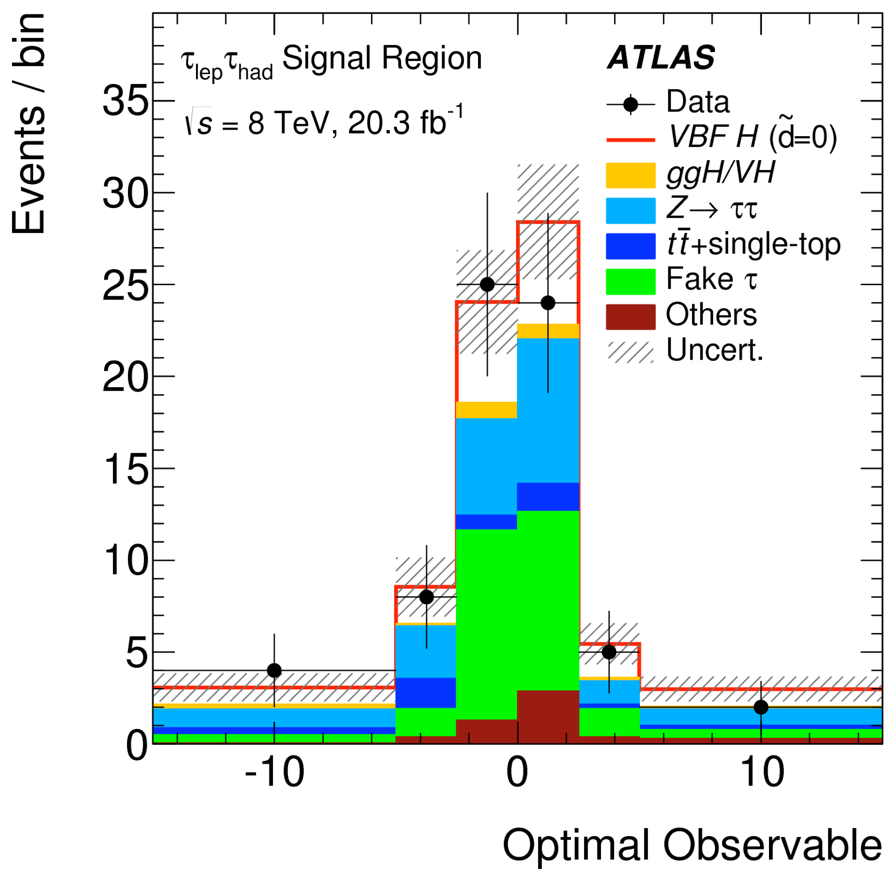
$\tau_{lep}\tau_{lep}$ Top Control Region
(require b-jet)



$\tau_{lep}\tau_{lep}$ low BDT-score
Control Region

Results



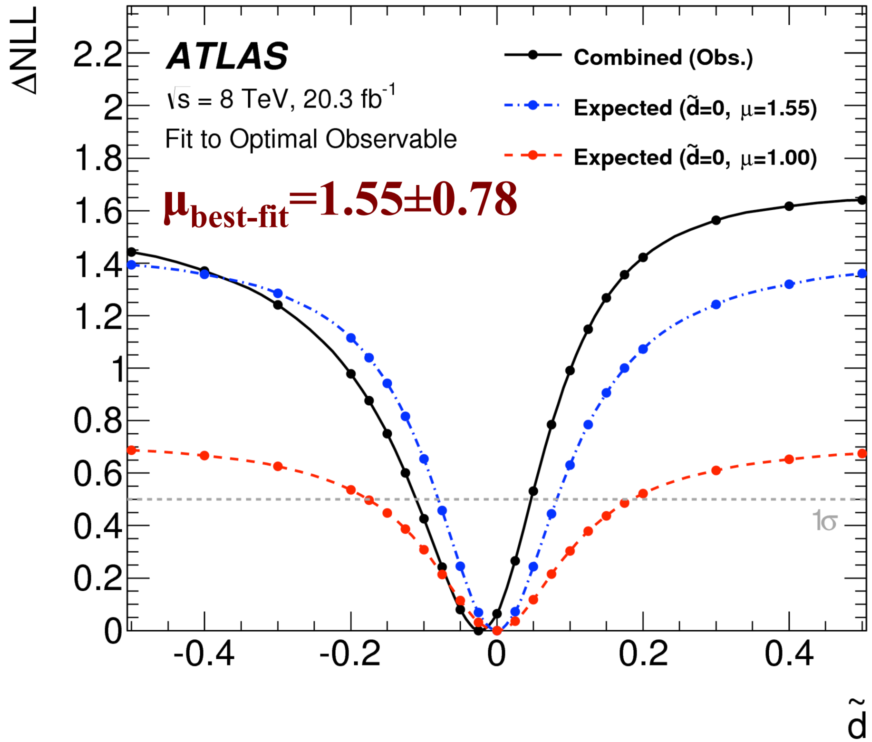


$\langle OO \rangle_{data}$ = 0.3 ± 0.5 **$\langle OO \rangle_{data}$ = -0.3 ± 0.4**

- Mean values consistent with zero: No sign of CP violation

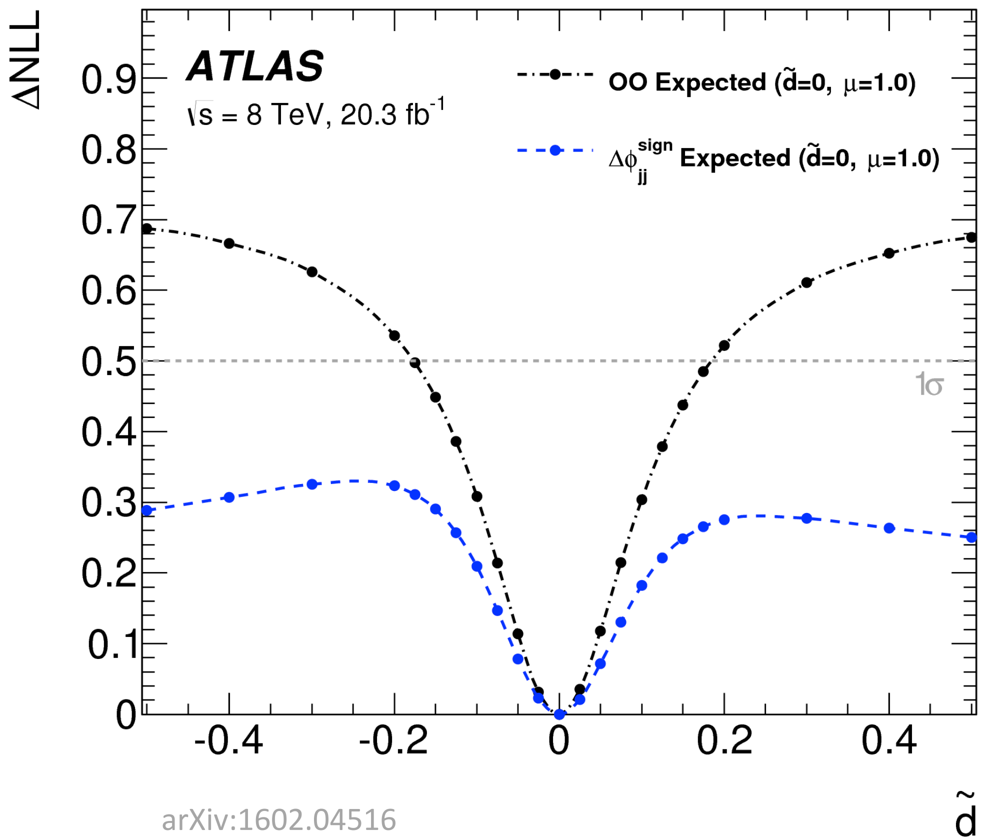
Results

- No sign of CP violation → Fit OO distribution for various $\tilde{d}$ scenaria, to place limits on CP mixing parameter
  - Signal strength $\mu=\sigma_{meas}/\sigma_{SM}$ free parameter
- $\tilde{d}$ values outside [-0.11,0.05] excluded at 68% C.L.
  - This 68% C.L. limit is substantially better than the one from the H→WW/H→ZZ combined CP analysis *ATLAS Collaboration,* Eur. Phys. J. C75 (2015) 476
- No 95% C.L. sensitivity currently – but with more decay channels & Run-2 data, method can be highly competitive

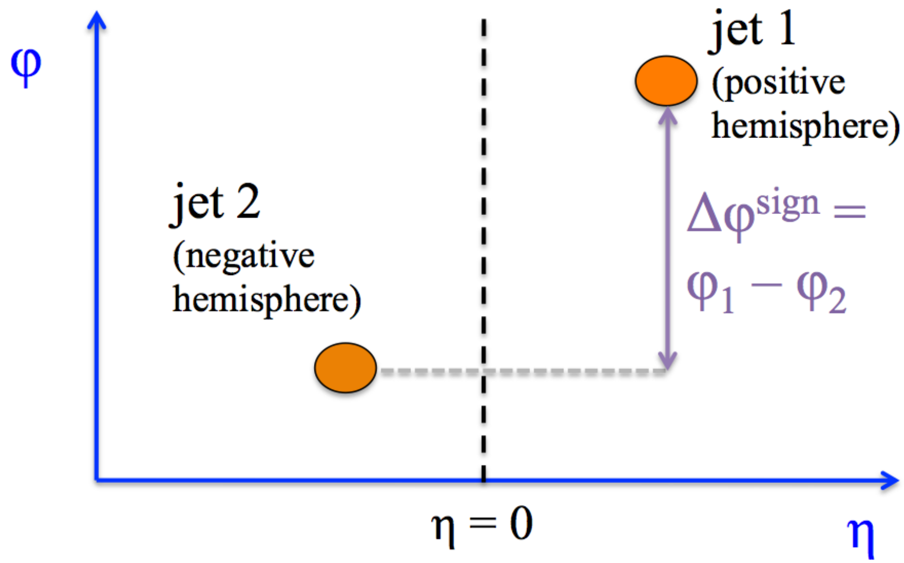


Signed $\Delta\varphi_{jj}$

- Traditional variable for VBF CP studies *Hankele et al,* Phys. Rev. D74 (2006) 095001
- OO performs substantially better



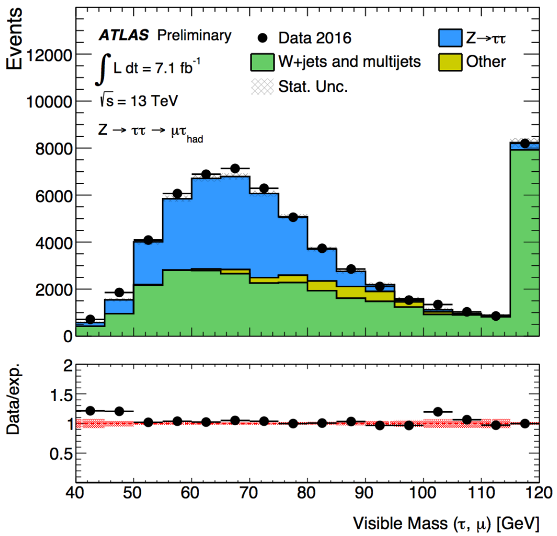
arXiv:1602.04516



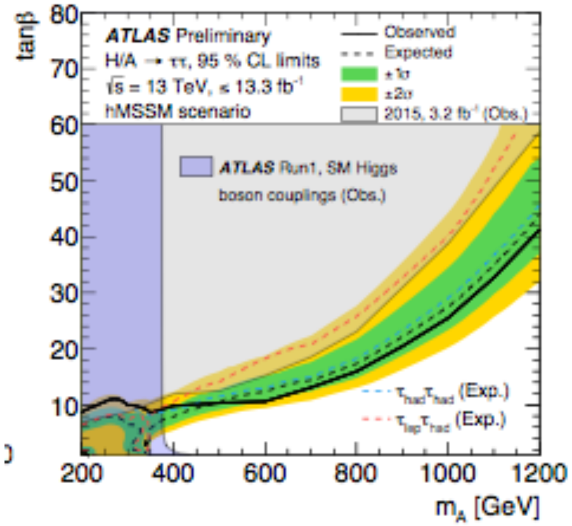
$H \rightarrow \tau\tau$ Outlook

H→ττ in Run 2

- Work is ongoing on SM H→ττ analysis with Run 2 data
  - ATLAS tau-reconstruction demonstrated to perform well
  - Several Run 2 results from searches involving taus

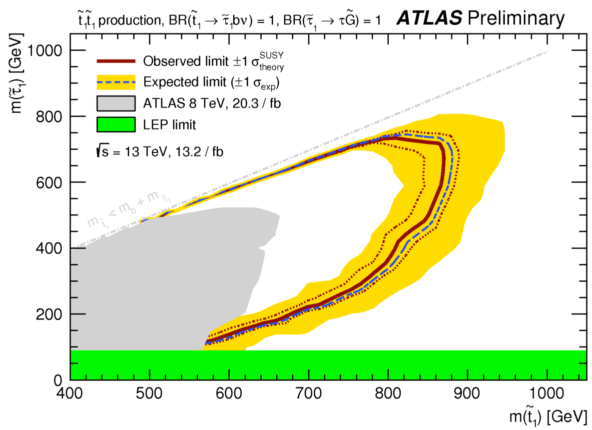


Z→ττ



Heavy MSSM A/H→ττ

ATLAS-CONF-2016-085



Stop→staus

ATLAS-CONF-2016-048

$H \to \tau\tau$ in Run 2

- Work is ongoing on SM $H \to \tau\tau$ analysis with Run 2 data
- With increasing data statistics, many exciting opportunities, beyond observation and signal-strength measurement:

H→ττ in Run 2

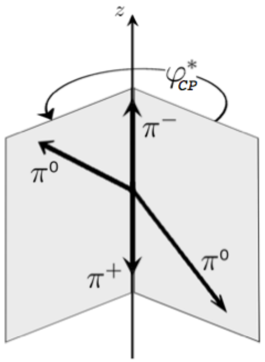
- Work is ongoing on SM H→ττ analysis with Run 2 data
- With increasing data statistics, many exciting opportunities, beyond observation and signal-strength measurement:
  - Test of CP in Higgs-fermions coupling using H→ττ decays

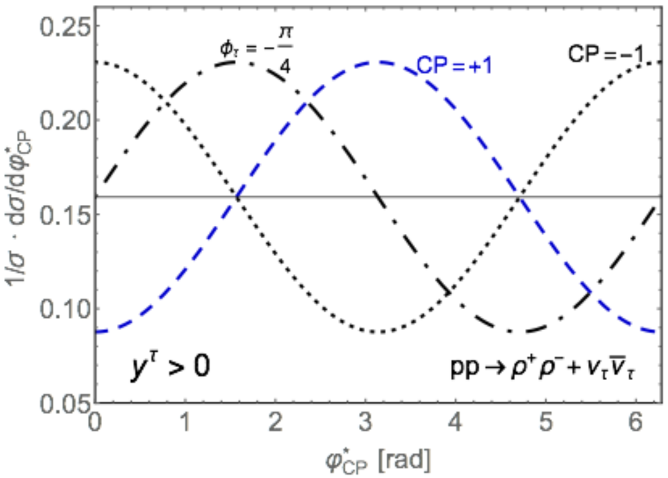
CP-odd fermion couplings appear at tree level in many BSM models.

Use τ transverse spin correlations and angular distributions of τ decay products in the Higgs-boson's rest frame.

Example: K. Desch et al PLB579 (2004) 157-164

For $\tau^\pm \to \rho^\pm \to \pi^\pm \pi^0 \nu$





Figures from
S. Berge et al PRD 92, 096012 (2015)

H→ττ in Run 2

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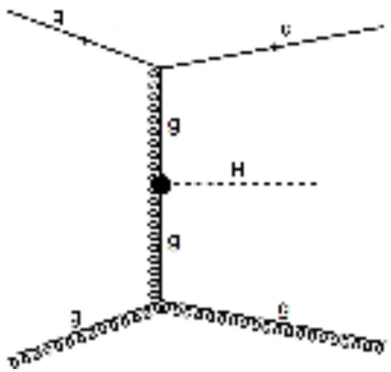
- With increasing data statistics, many exciting opportunities, beyond observation and signal-strength measurement:
  - Test of CP in Higgs-fermions coupling using H→ττ decays
  - Test of CP in effective gluon-Higgs coupling using ggH+2j

Once sufficiently large dataset available:
Can employ similar methodology to that used for VBF studies

Challenge: separate ggH+2j from VBF Higgs events

Preliminary studies demonstrated feasibility of such an analysis. Master Thesis of A. Loesle (U. Freiburg, 2015)



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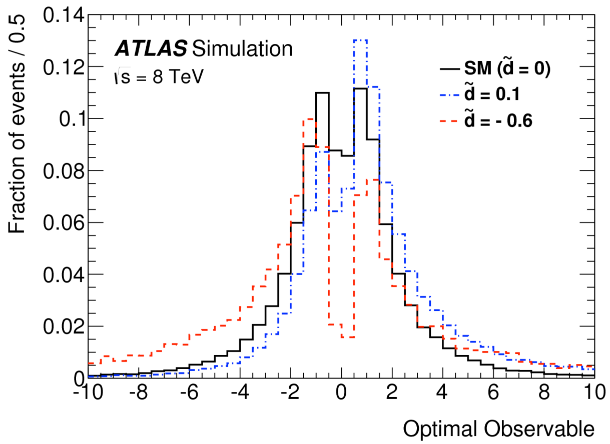
  - Test of CP in Higgs-Vector-boson coupling using VBF

Method has already been demonstrated with Run 1 data

With increased signal statistics, should become highly competitive with e.g. H→WW/ZZ decay studies.
Combination of results should allow even higher sensitivity.



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  - Test of CP in effective gluon-Higgs coupling using ggH+2j
  - Test of CP in Higgs-Vector-boson coupling using VBF
  - Simplified Template Cross-Sections

    Framework for measuring cross sections separated by production mode and kinematic properties (LHC Higgs WG)
    Allows straightforward use of advanced analysis techniques and combination of channels
    Minimises theory dependence

    H→ττ can contribute substantially in VBF and high-p_T(H) regimes!

$H\rightarrow\tau\tau$ in Run 2

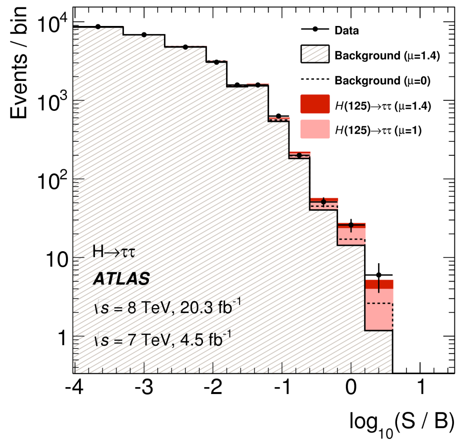
- Work is ongoing on SM $H\rightarrow\tau\tau$ analysis with Run 2 data
- With increasing data statistics, many exciting opportunities, beyond observation and signal-strength measurement:
  - Test of CP in Higgs-fermions coupling using $H\rightarrow\tau\tau$ decays
  - Test of CP in effective gluon-Higgs coupling using ggH+2j
  - Test of CP in Higgs-Vector-boson coupling using VBF
  - Simplified Template Cross-Sections
  - Fiducial & Differential Cross-Sections

Least theory-dependent measurement

$H\rightarrow\tau\tau$: VBF and high-p_T(H) topologies

Summary

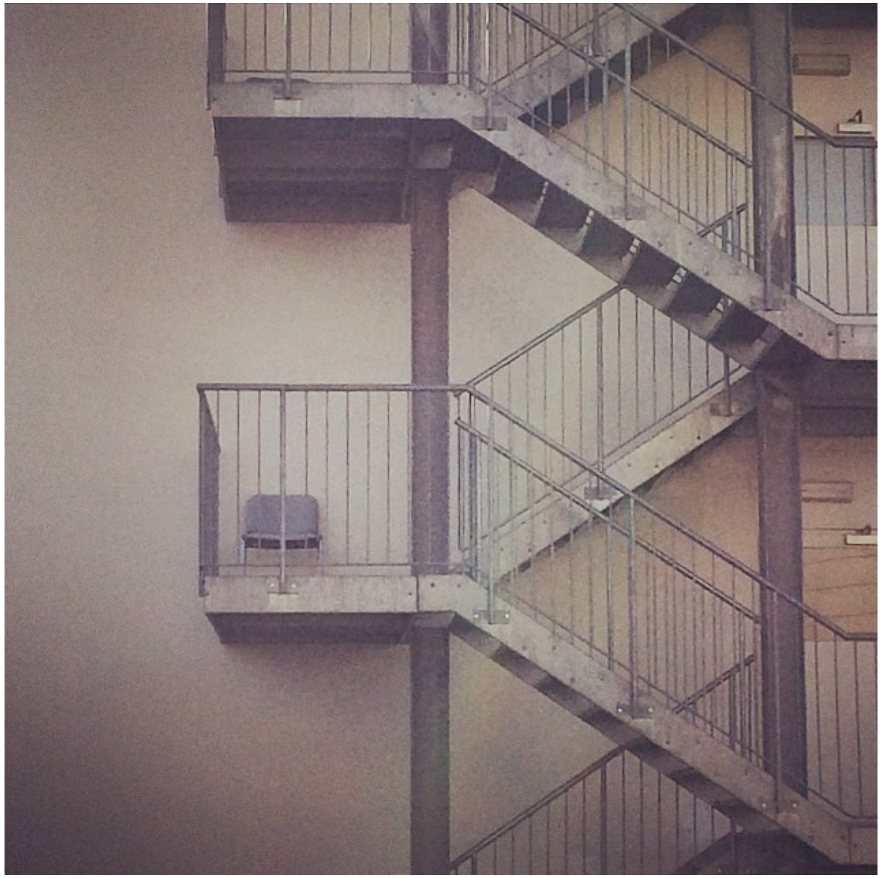
- ATLAS sees evidence of H→ττ decays
  - Observed (expected) significance: **4.5 (3.4) σ**
  - Signal strength $\mu=\sigma_{meas}/\sigma_{SM}=1.4\pm0.4$
- Combination with CMS: **Observation** (5.5σ)



- Used H→ττ to perform first test of CP-invariance in VBF
  - Our method performs substantially better than "traditional" variable
  - **$\tilde{d}$ outside [-0.11,0.05]** excluded at 68% C.L.

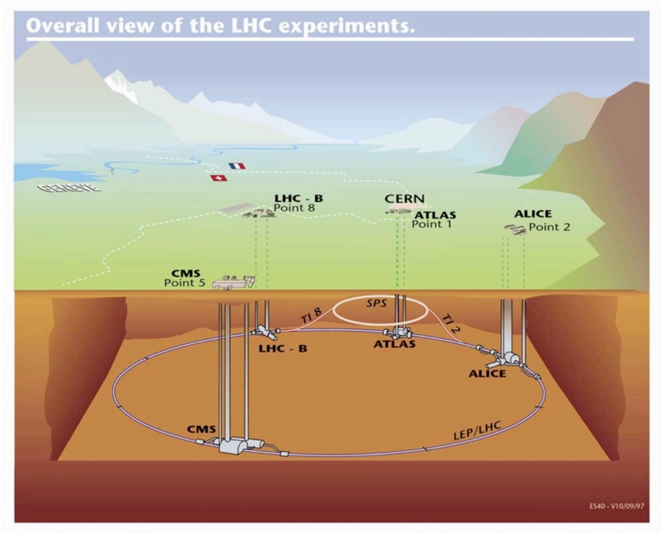
- Many exciting reasons to continue studying H→ττ in Run 2!

Backup Slides



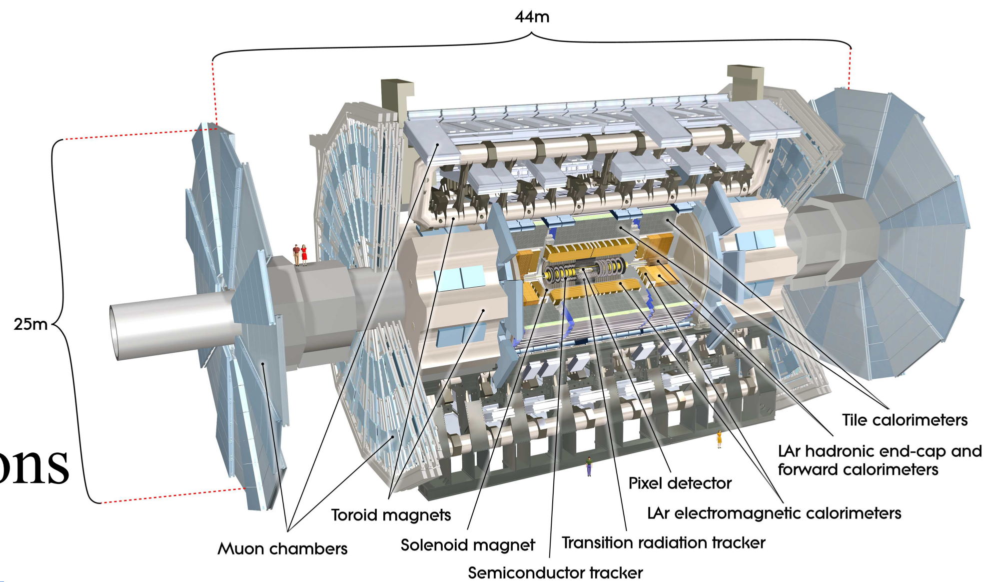
Source: lonelychairsatcern.tumblr.com

LHC & ATLAS



- Large Hadron Collider
  - Circ.: 27km, ~100m underground
  - ~10k superconducting magnets
  - p-p collisions, C.M. Energy:
    7, 8 TeV (Run 1, 2009-13)
    13 TeV (Run 2, 2015-now)

- ATLAS Detector
  - One of two all-purpose LHC detectors
  - Diameter: 25m; Length: 45m; Weight: ~7000 tonnes
  - ~5000 scientists, ~180 institutions from 38 countries



H→ττ Trigger & Preselection Cuts

Trigger	Trigger level thresholds, p_T [GeV]	Analysis level thresholds [GeV]		
		$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Single electron	24	$e\mu$: $p_T^e > 26$, $p_T^\mu > 10$; ee: $p_T^{e1} > 26$, $p_T^{e2} > 15$	$e\tau$: $p_T^e > 26$, $p_T^\tau > 20$	–
Single muon	24	–	$\mu\tau$: $p_T^\mu > 26$, $p_T^\tau > 20$	–
Di-electron	12/12	ee: $p_T^{e1} > 15$, $p_T^{e2} > 15$	–	–
Di-muon	18/8	$\mu\mu$: $p_T^{\mu1} > 20$, $p_T^{\mu2} > 10$	–	–
Electron+muon	12/8	$e\mu$: $p_T^e > 15$, $p_T^\mu > 10$	–	–
Di-τ_{had}	29/20	–	–	$\tau\tau$: $p_T^{\tau1} > 35$, $p_T^{\tau2} > 25$

Lep-Lep

Opposite sign leptons
30<m(l,l)<75 GeV (Same Flavour events)
30<m(l,l)<100 GeV (Diff. Flavour events)
pT(l1)+pT(l2)>35 GeV
MET>40 GeV and MET_{HPTO}>40 GeV (SF)
MET>20 GeV (DF)
0.1<x1,x2<1
$\Delta\varphi$(l,l)<2.5
$m_{coll}(\tau, \tau) < m_Z$ -25 GeV
No b-tagged jets

Lep-Had

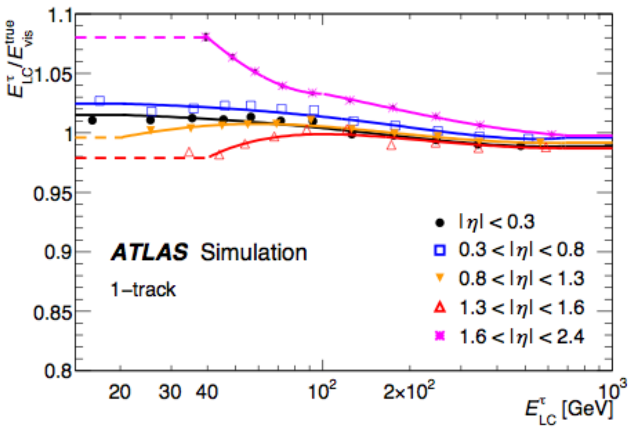
Opposite sign (lepton,τ)
m_T(MET,lepton)<70 GeV
No b-tagged jets

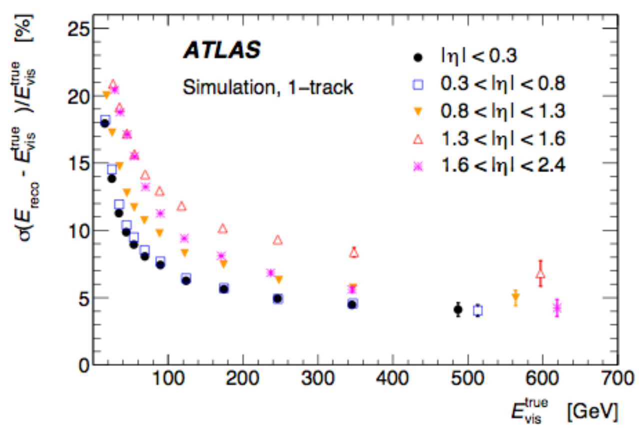
Had-Had

Opposite sign tau-jets
0.8<ΔR(τ,τ)<2.8
Δη(τ,τ)<1.5
MET>20 GeV
MET between taus in φ or
min[Δφ(MET,τ)]<π/2

Tau Energy Scale

- Clusters of seeding jet at local calibration (LC) scale
  - Accounts for non-compensating nature of ATLAS calorimeter and depositions outside clusters and in non-sensitive regions
- On top of this, tau-specific correction factor $E_{LC} \rightarrow E_{\tau\text{-vis}}$ derived using MC
  - Account for specific particle content in taus
  - Additional small corrections for pile-up, and for poorly instrumented regions

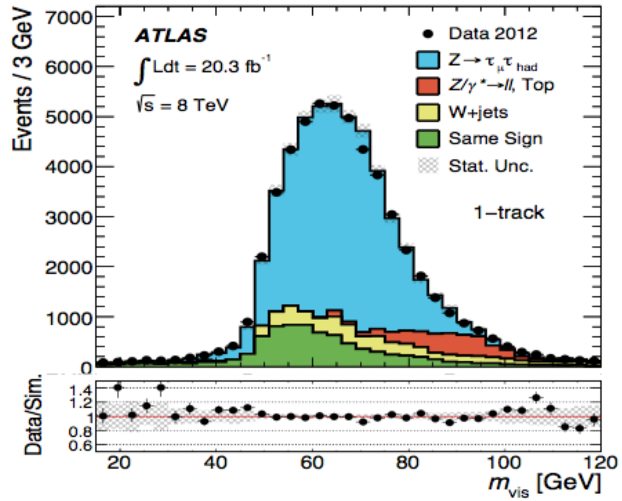




Tau Energy Scale

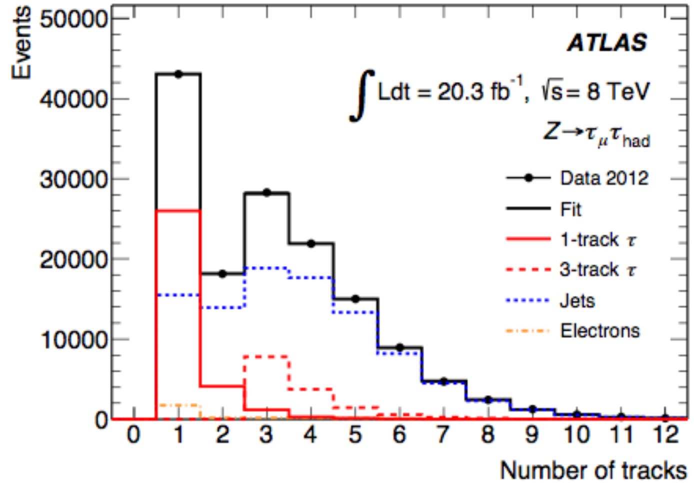
- Uncertainty on TES typically <4%. Two different methods to estimate, giving consistent results
- Single particle response studies (test beam studies, E/p measurements)
  - Use pseudo-experiments to propagate single-particle response uncertainties to reconstructed tau-jet
  - Further uncertainties due to underlying event, detector model, pile-up etc
- In-situ method using $Z \rightarrow \tau\tau$ tag-&-probe
  - Template fits (varying TES)
  - Measure data/MC shift at percent-level

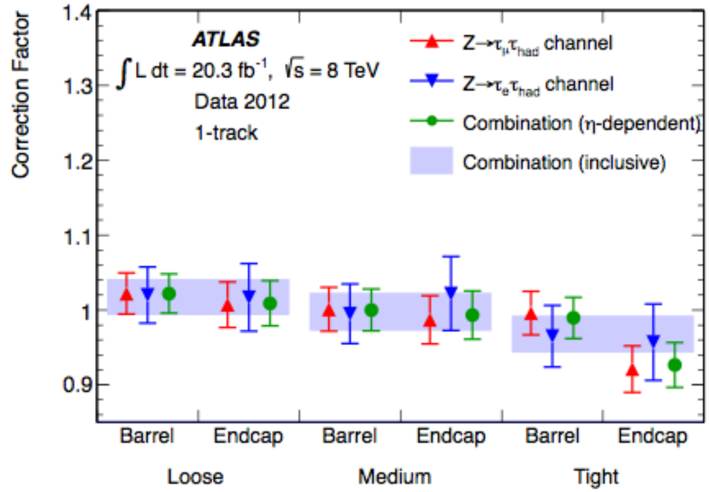
Source	Uncertainty [%]
Response	1.2–2.5
Detector model	0.3–2.5
UE	0.2–2.4
Pile-up	0.5–2.0
Non-closure	0.5–1.2
Shower model	0.0–2.0
Total	1.8–3.9



Tau Identification

- $Z \rightarrow \tau\tau$ tag-&-probe used to measure identification efficiency in data
  - Template fit of extended track multiplicity
- Data/MC correction factors determined
  - In general consistent with 1.0; uncertainties (2-6)% for $p_T > 20$ GeV
- Measurement cross-checked with $W \rightarrow \tau\nu$ and ttbar: consistent results in all channels





Tau ID Variables Definitions

Central energy fraction (f_{cent}): Fraction of transverse energy deposited in the region $\Delta R < 0.1$ with respected to all energy deposited in the region $\Delta R < 0.2$ around the $\tau_{\mathrm{had\text{-}vis}}$ candidate calculated by summing the energy deposited in all cells belonging to TopoClusters with a barycentre in this region, calibrated at the EM energy scale. Biases due to pile-up contributions are removed using a correction based on the number of reconstructed primary vertices in the event.

Leading track momentum fraction (f_{track}): The transverse momentum of the highest-p_{T} charged particle in the core region of the $\tau_{\mathrm{had\text{-}vis}}$ candidate, divided by the transverse energy sum, calibrated at the EM energy scale, deposited in all cells belonging to TopoClusters in the core region. A correction depending on the number of reconstructed primary vertices in the event is applied to this fraction, making the resulting variable pile-up independent.

Track radius (R_{track}): p_{T}-weighted distance of the associated tracks to the $\tau_{\mathrm{had\text{-}vis}}$ direction, using all tracks in the core and isolation regions.

Leading track IP significance ($S_{\mathrm{leadtrack}}$): Transverse impact parameter of the highest-p_{T} track in the core region, calculated with respect to the TV, divided by its estimated uncertainty.

Number of tracks in the isolation region ($N_{\mathrm{track}}^{\mathrm{iso}}$): Number of tracks associated with the $\tau_{\mathrm{had\text{-}vis}}$ in the region $0.2 < \Delta R < 0.4$.

Maximum ΔR (ΔR_{Max}): The maximum ΔR between a track associated with the $\tau_{\mathrm{had\text{-}vis}}$ candidate and the $\tau_{\mathrm{had\text{-}vis}}$ direction. Only tracks in the core region are considered.

Transverse flight path significance ($S_{\mathrm{T}}^{\mathrm{flight}}$): The decay length of the secondary vertex (vertex reconstructed from the tracks associated with the core region of the $\tau_{\mathrm{had\text{-}vis}}$ candidate) in the transverse plane, calculated with respect to the TV, divided by its estimated uncertainty. It is defined only for multi-track $\tau_{\mathrm{had\text{-}vis}}$ candidates.

Track mass (m_{track}): Invariant mass calculated from the sum of the four-momentum of all tracks in the core and isolation regions, assuming a pion mass for each track.

Track-plus-π^0-system mass ($m_{\pi^0+\mathrm{track}}$): Invariant mass of the system composed of the tracks and π^0 mesons in the core region.

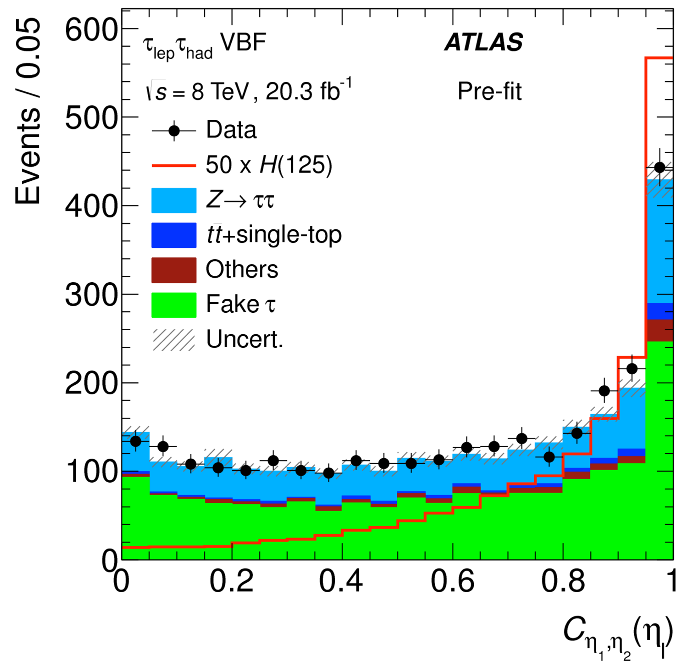
Number of π^0 mesons (N_{π^0}): Number of π^0 mesons reconstructed in the core region.

Ratio of track-plus-π^0-system p_{T} ($p_{\mathrm{T}}^{\pi^0+\mathrm{track}}/p_{\mathrm{T}}$): Ratio of the p_{T} estimated using the track + π^0 information to the calorimeter-only measurement.

From arXiv:1412.7086

H→ττ Variables in BDT

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



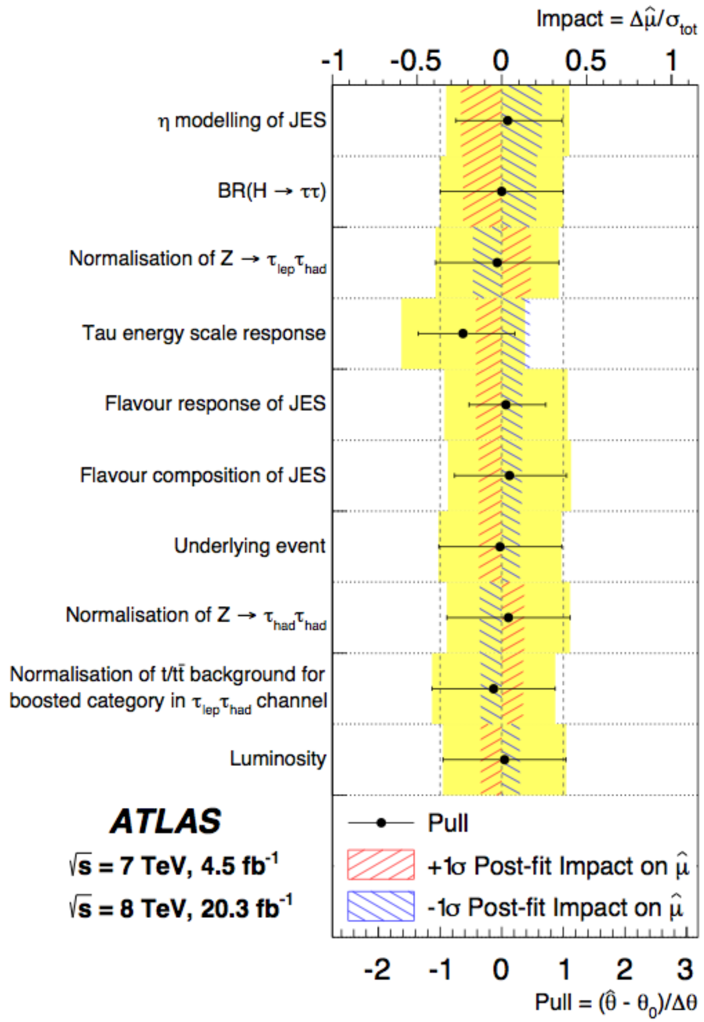
$$C_{\eta_1,\eta_2}(\eta) = \exp\left[\frac{-4}{(\eta_1-\eta_2)^2}\left(\eta - \frac{\eta_1+\eta_2}{2}\right)^2\right]$$

H→ττ Systematics

Source	Relative signal and background variations [%]											
	$\tau_{\rm lep}\tau_{\rm lep}$ VBF		$\tau_{\rm lep}\tau_{\rm lep}$ Boosted		$\tau_{\rm lep}\tau_{\rm had}$ VBF		$\tau_{\rm lep}\tau_{\rm had}$ Boosted		$\tau_{\rm had}\tau_{\rm had}$ VBF		$\tau_{\rm had}\tau_{\rm had}$ Boosted	
	S	B	S	B	S	B	S	B	S	B	S	B
Experimental												
Luminosity	±2.8	±0.1	±2.8	±0.1	±2.8	±0.1	±2.8	±0.1	±2.8	±0.1	±2.8	±0.1
Tau trigger*	–	–	–	–	–	–	–	–	$^{+7.7}_{-8.8}$	< 0.1	$^{+7.8}_{-8.9}$	< 0.1
Tau identification	–	–	–	–	±3.3	±1.2	±3.3	±1.8	±6.6	±3.8	±6.6	±5.1
Lepton ident. and trigger*	$^{+1.4}_{-2.1}$	$^{+1.3}_{-1.7}$	$^{+1.4}_{-2.1}$	$^{+1.1}_{-1.5}$	±1.8	±0.5	±1.8	± 0.8	–	–	–	–
b-tagging	±1.3	±1.6	±1.6	±1.6	< 0.1	±0.2	±0.4	±0.2	–	–	–	–
τ energy scale†	–	–	–	–	±2.4	±1.3	±2.4	±0.9	±2.9	±2.5	±2.9	±2.5
Jet energy scale and resolution†	$^{+8.5}_{-9.1}$	±9.2	$^{+4.7}_{-4.9}$	$^{+3.7}_{-3.0}$	$^{+9.5}_{-8.7}$	±1.0	±3.9	±0.4	$^{+10.1}_{-8.0}$	±0.3	$^{+5.1}_{-6.2}$	±0.2
$E_{\rm T}^{\rm miss}$ soft scale & resolution	$^{+0.0}_{-0.2}$	$^{+0.0}_{-1.2}$	$^{+0.0}_{-0.1}$	$^{+0.0}_{-1.2}$	$^{+0.8}_{-0.3}$	±0.2	±0.4	< 0.1	±0.5	±0.2	±0.1	< 0.1
Background Model												
Modelling of fake backgrounds*†	–	± 1.2	–	±1.2	–	±2.6	–	±2.6	–	±5.2	–	±0.6
Embedding†	–	$^{+3.8}_{-4.3}$	–	$^{+6.0}_{-6.5}$	–	±1.5	–	±1.2	–	±2.2	–	±3.3
$Z \to \ell\ell$ normalisation*	–	± 2.1	–	±0.7	–	–	–	–	–	–	–	–
Theoretical												
Higher-order QCD corrections†	$^{+11.3}_{-9.1}$	±0.2	$^{+19.8}_{-15.3}$	±0.2	$^{+9.7}_{-7.6}$	±0.2	$^{+19.3}_{-14.7}$	±0.2	$^{+10.7}_{-8.2}$	< 0.1	$^{+20.3}_{-15.4}$	< 0.1
UE/PS	± 1.8	< 0.1	± 5.9	< 0.1	±3.8	< 0.1	±2.9	< 0.1	±4.6	< 0.1	±3.8	< 0.1
Generator modelling	±2.3	< 0.1	±1.2	< 0.1	±2.7	< 0.1	±1.3	< 0.1	±2.4	< 0.1	±1.2	< 0.1
EW corrections	±1.1	< 0.1	±0.4	< 0.1	±1.3	< 0.1	±0.4	< 0.1	±1.1	< 0.1	±0.4	< 0.1
PDF†	$^{+4.5}_{-5.8}$	± 0.3	$^{+6.2}_{-8.0}$	± 0.2	$^{+3.9}_{-3.6}$	± 0.2	$^{+6.6}_{-6.1}$	± 0.2	$^{+4.3}_{-4.0}$	± 0.2	$^{+6.3}_{-5.8}$	± 0.1
BR ($H \to \tau\tau$)	± 5.7	–	±5.7	–	±5.7	–	±5.7	–	± 5.7	–	±5.7	–

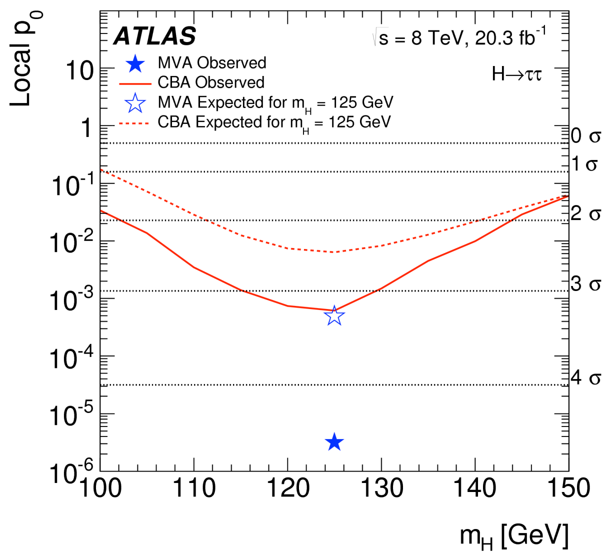
H→ττ Systematics

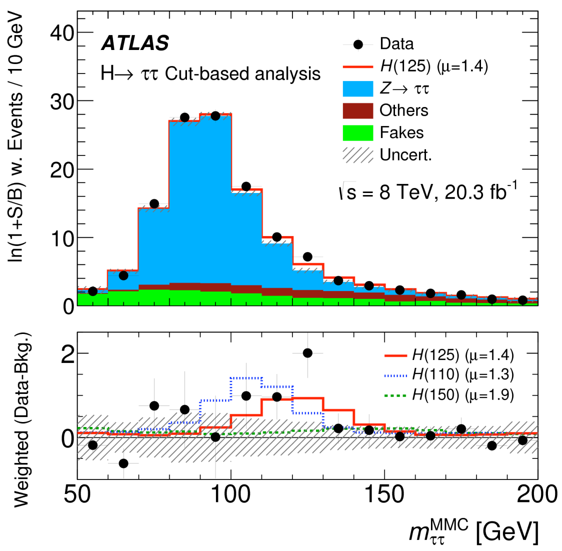
Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR $(H \to \tau\tau)$	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	$^{+0.33}_{-0.26}$
Total	$^{+0.43}_{-0.37}$



Cut-based Cross-check analysis

- BDT-based analysis cross-checked with a cut-based analysis (on 8 TeV only)
- Cut-based analysis gives an observed (expected) significance of 3.2σ (2.5σ)
- Cut-based $\mu_{CBA}=1.43^{+0.55}_{-0.49}$
  - Cut-based result fully compatible with BDT-based analysis: $\Delta\mu<\delta(\Delta\mu)$ for all channels as well as combined results





Cut Based Analysis

Channel	VBF category selection criteria		
$\tau_{lep}\tau_{lep}$	At least two jets with $p_T^{j_1} > 40$ GeV and $p_T^{j_2} > 30$ GeV $\lvert\Delta\eta_{j_1,j_2}\rvert > 3.0$ $m_{j_1,j_2} > 400$ GeV b-jet veto for jets with $p_T > 25$ GeV Jet veto: no additional jet with $p_T > 25$ GeV within $\lvert\eta\rvert < 2.4$		
$\tau_{lep}\tau_{had}$	At least two jets with $p_T^{j_1} > 40$ GeV and $p_T^{j_2} > 30$ GeV $E_T^{miss} >$ 20 GeV $\lvert\Delta\eta_{j_1,j_2}\rvert > 3.0$ and $\eta(j_1)\cdot\eta(j_2) < 0$, $m_{j_1,j_2} > 300$ GeV $p_T^{Total} = \lvert\vec{p}_T^{\ell} + \vec{p}_T^{\tau_{had}} + \vec{p}_T^{j_1} + \vec{p}_T^{j_2} + \vec{E}_T^{miss}\rvert < 30$ GeV b-jet veto for jets with $p_T > 30$ GeV $\min(\eta_{(j_1)},\eta_{(j_2)}) < \eta_{(\ell)},\eta_{(\tau_{had})} < \max(\eta_{(j_1)},\eta_{(j_2)})$		
	VBF tight $m_{j_1,j_2} > 500$ GeV $p_T^H > 100$ GeV $p_T^{\tau_{had}} > 30$ GeV $m_{vis} > 40$ GeV	**VBF loose** Non tight VBF	
$\tau_{had}\tau_{had}$	At least two jets with $p_T^{j_1} > 50$ GeV and $p_T^{j_2} > 30$ GeV $\lvert\Delta\eta(\tau_1,\tau_2)\rvert < 1.5$ $\lvert\Delta\eta_{j_1,j_2}\rvert > 2.6$ and $m_{j_1,j_2} > 250$ GeV $\min(\eta_{(j_1)},\eta_{(j_2)}) < \eta_{(\tau_1)},\eta_{(\tau_2)} < \max(\eta_{(j_1)},\eta_{(j_2)})$		
	VBF high p_T^H $\Delta R(\tau_1,\tau_2) < 1.5$ and $p_T^H > 140$ GeV	**VBF low p_T^H, tight** $\Delta R(\tau_1,\tau_2) > 1.5$ or $p_T^H < 140$ GeV m_{j_1,j_2}[GeV] $> (-250 \cdot \lvert\Delta\eta_{j_1,j_2}\rvert + 1550)$	**VBF low p_T^H, loose** $\Delta R(\tau_1,\tau_2) > 1.5$ or $p_T^H < 140$ GeV m_{j_1,j_2}[GeV] $< (-250 \cdot \lvert\Delta\eta_{j_1,j_2}\rvert + 1550)$

Channel	Boosted category selection criteria	
$\tau_{lep}\tau_{lep}$	Exclude events passing the VBF selection $p_T^H > 100$ GeV b-jet veto for jets with $p_T > 25$ GeV	
$\tau_{lep}\tau_{had}$	Exclude events passing the VBF selection $E_T^{miss} > 20$ GeV $p_T^H > 100$ GeV $p_T(\tau_{had}) > 30$ GeV b-jet veto for jets with $p_T > 30$ GeV	
$\tau_{had}\tau_{had}$	Exclude events passing the VBF selection $\Delta\eta(\tau_1,\tau_2) < 1.5$ $p_T^H > 100$ GeV	
	Boosted high p_T^H $\Delta R(\tau_1,\tau_2) < 1.5$ and $p_T^H > 140$ GeV	**Boosted low p_T^H** $\Delta R(\tau_1,\tau_2) > 1.5$ or $p_T^H < 140$ GeV

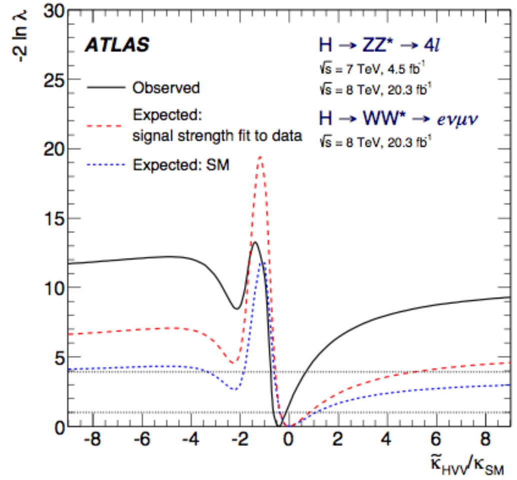
$\tau_{lep}\tau_{lep}$	VBF	Boosted
Total signal	11 ± 4	38 ± 13
Total background	130 ± 7	3400 ± 64
Data	152	3428

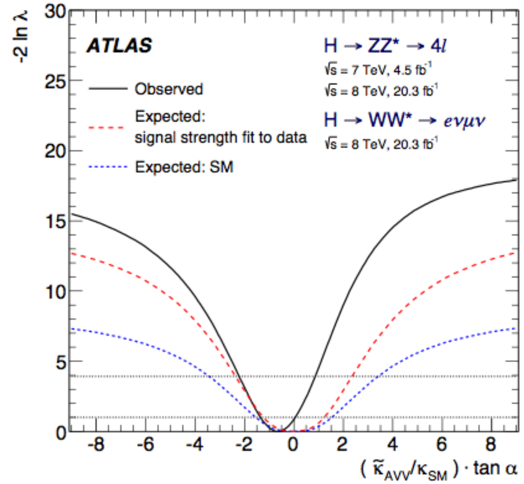
$\tau_{lep}\tau_{had}$	Tight VBF	Loose VBF	Boosted
Signal	8.8 ± 3	17 ± 6	52 ± 17
Background	52 ± 4	398 ± 17	4399 ± 73
Data	62	407	4435

$\tau_{had}\tau_{had}$	VBF high p_T^H	VBF low p_T^H		Boosted	
		tight	loose	high p_T^H	low p_T^H
Signal	5.7 ± 1.9	5.2 ± 1.9	3.7 ± 1.3	17 ± 6	20 ± 7
Background	59 ± 4	86 ± 5	156 ± 7	1155 ± 28	2130 ± 41
Data	65	94	157	1204	2121

Spin/Parity with Bosonic Channels

- Spin: studies done with H→γγ, H→ZZ and H→WW
  - Data compatible with $J^P=0^+$ (SM)
  - Have excluded specific 0^- and 2^+ models at >99.9% CL
- Investigation of tensor structure of HVV vertex (with H→ZZ and H→WW)
  - Matrix Element-based discriminating variables (H→ZZ) or BDT (H→WW)
  - Regions outside of $-0.73 < \tilde{\kappa}_{HVV}/\kappa_{SM} < 0.63$ and $-2.18 < (\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha < 0.83$ intervals excluded at 95% CL

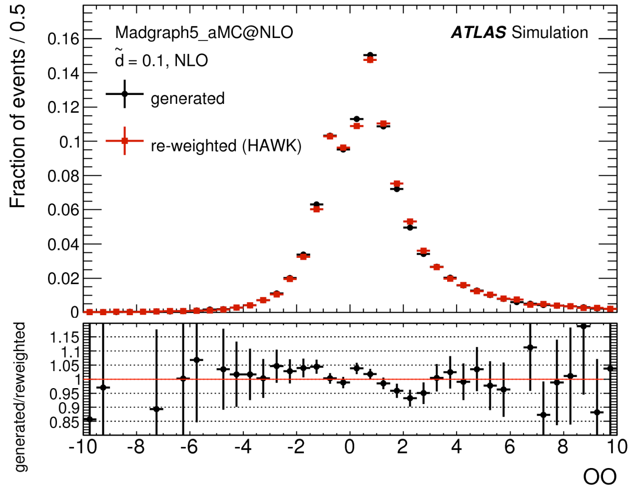


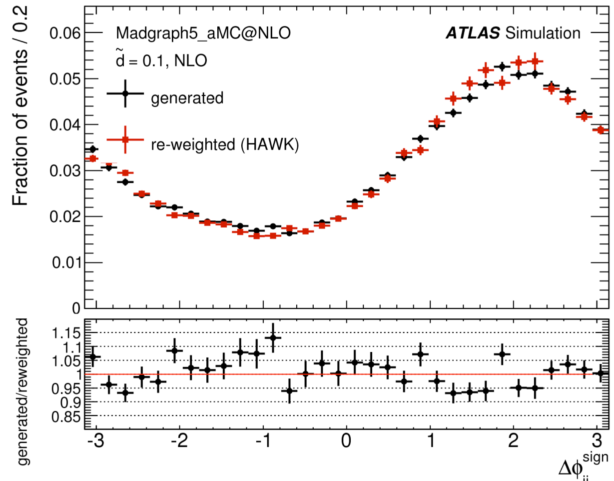


Tested Hypothesis	$p^{alt}_{exp,\mu=1}$	$p^{alt}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{alt}_{obs}	Obs. CL_s (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125GeV)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125GeV)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

Signal Reweighting

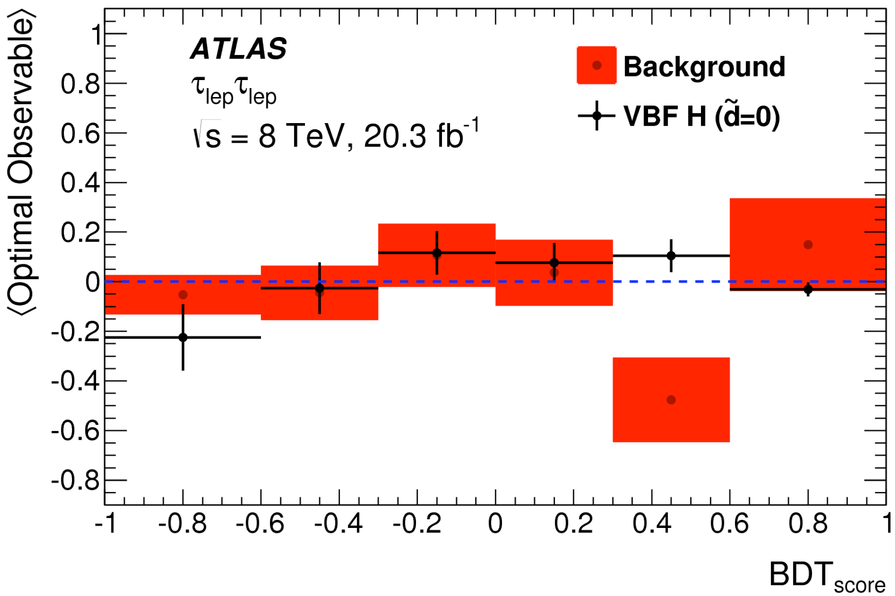
- No full-simulation MC samples for $\tilde{d} \neq 0$ $\rightarrow$ reweight SM samples
- MEs from HAWK 2.0
- Approximation for NLO reweighting: Use appropriate ME at LO for 2→2+H or 2→3+H process, taking into account ingoing and outgoing parton flavours
  - Reweighting has been validated at NLO using MG5_aMC@NLO
- Small difference in closure test applied as systematic uncertainty

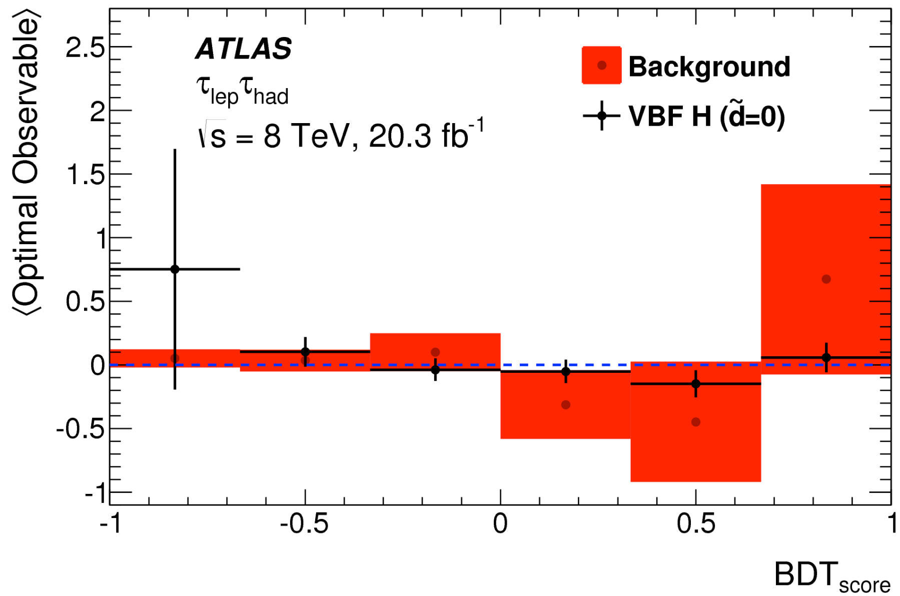




All figures from arXiv:1602.04516

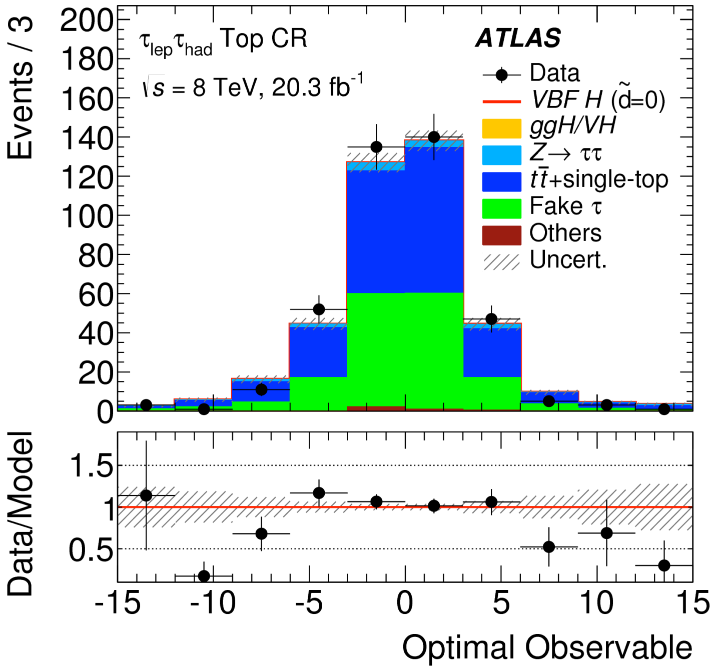
<OO> vs BDT

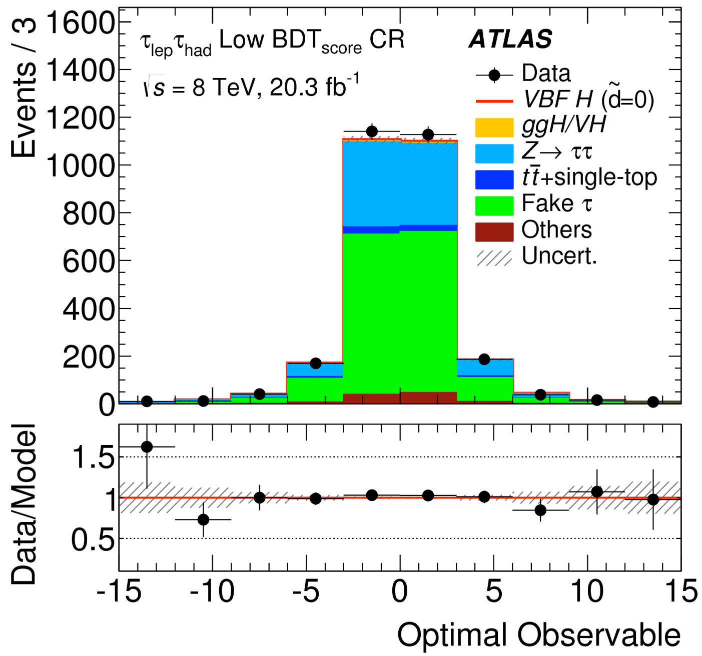




All figures from arXiv:1602.04516

Bkg Modelling



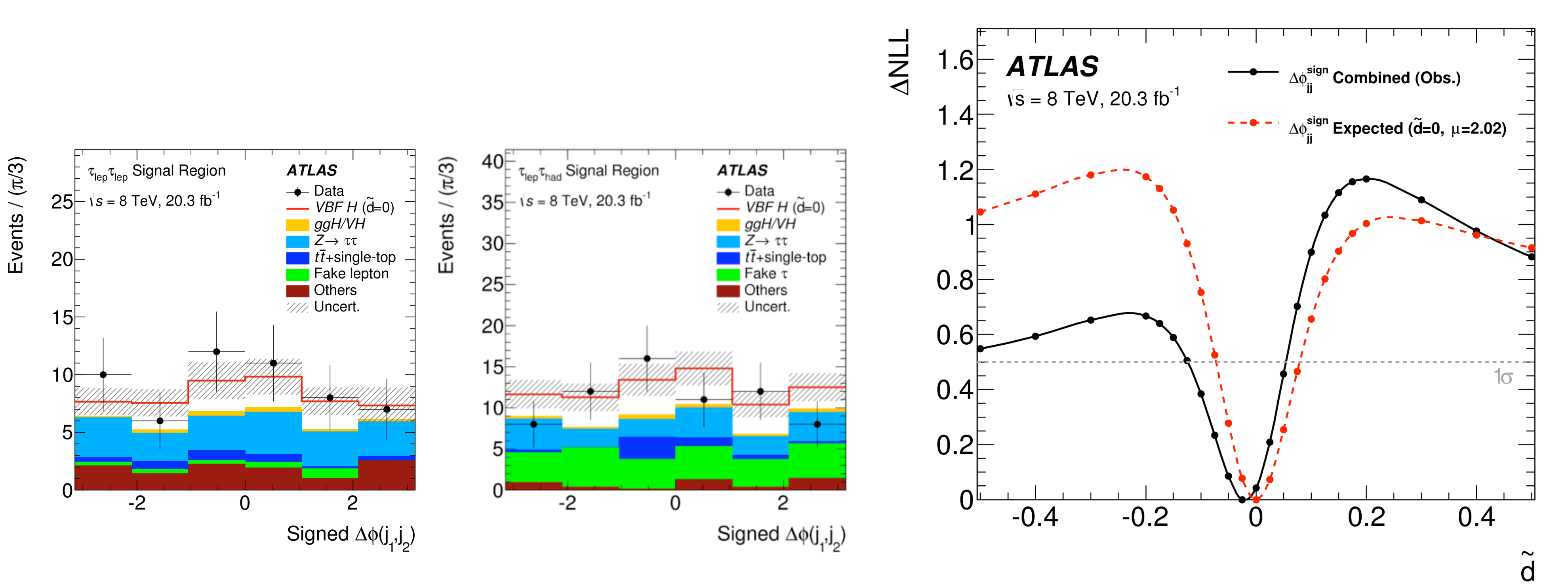


Semileptonic Channel:
Top CR (invert b-veto)
Low-BDT CR

All figures from arXiv:1602.04516

Signed $\Delta\varphi_{jj}$

- Traditional variable for VBF CP studies *Hankele et al,* Phys. Rev. D74 (2006) 095001
- OO performs substantially better



All figures from arXiv:1602.04516

EFT in more detail

- Augment SM Lagrangian by $SU(2)_{L,IW} x U(1)_{Y}$ invariant CP-violating dim-6 operators involving Higgs field and EWK gauge bosons

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2} \mathcal{O}_{\tilde{B}B} + \frac{f_{\tilde{W}W}}{\Lambda^2} \mathcal{O}_{\tilde{W}W} + \frac{f_{\tilde{B}}}{\Lambda^2} \mathcal{O}_{\tilde{B}}$$

with

$$\mathcal{O}_{\tilde{B}B} = \Phi^{+} \hat{\tilde{B}}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \qquad \mathcal{O}_{\tilde{W}W} = \Phi^{+} \hat{\tilde{W}}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{\tilde{B}} = (D_\mu \Phi)^{+} \hat{\tilde{B}}^{\mu\nu} D_\nu \Phi$$

$$D_\mu = \partial_\mu + \tfrac{\mathrm{i}}{2} g' B_\mu + \mathrm{i} g \tfrac{\sigma_a}{2} W^a_\mu, \; \tilde{V}_{\mu\nu} \; (V = B, W^a)$$

$$\tilde{V}_{\mu\nu} = \tfrac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma} \qquad \hat{B}_{\mu\nu} + \hat{W}_{\mu\nu} = \mathrm{i} \tfrac{g'}{2} B_{\mu\nu} + \mathrm{i} \tfrac{g}{2} \sigma^a W^a_{\mu\nu}.$$

Third operator contributes to CP-violating TGCs; already constrained at LEP
→ only first two considered in this analysis

EFT in more detail

- After EW symmetry breaking in mass basis ($W^{\pm}$, Z, photon A, Higgs boson):

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

Two independent parameters:

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}\,.$$

Given by Wilson coefficients and Λ

$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} \qquad \tilde{d}_B = -\frac{m_W^2}{\Lambda^2}\tan^2\theta_W f_{\tilde{B}B}$$

Contributions from W^+W^-, ZZ, gZ, gg fusion not distinguishable experimentally

→ arbitrary choice

$$\tilde{d} = \tilde{d}_B$$

Coupings become:

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{HAZ} = 0$$

Optimal Observable

- In principle highest sensitivity for maximum likelihood (ML) fit to multidimensional phase-space

$$\vec{\Phi} = (\Phi_1, \ldots, \Phi_n)$$ (VBF H 6+1 phase space observables)

- Requires many simulated events for binned ML fit, and other practical problems

$$d\sigma(\vec{\Phi}) = d\sigma_0 + \eta \cdot d\sigma_1 + \eta^2 \cdot d\sigma_2 \qquad \mathcal{L} = \prod_{i=1}^{N_{data}} d\sigma_i$$

$$\log \mathcal{L} = \sum_{i=1}^{N_{data}} \log\left(d\sigma_0 + \eta \cdot d\sigma_1 + \eta^2 \cdot d\sigma_2\right)$$

$$\frac{d \log \mathcal{L}}{d\eta} = \sum_{i=1}^{N_{data}} \frac{d\sigma_1 + \eta \cdot \sigma_2}{d\sigma_0 + \eta \cdot d\sigma_1 + \eta^2 \cdot d\sigma_2} = 0$$

$$\sum_{i=1}^{N_{data}} \frac{O_1 + \eta \cdot O_2}{1 + \eta \cdot O_1 + \eta^2 \cdot O_2} = 0$$

- Same sensitivity in fit to 1-dim. optimal observable distributions

$$O_1 = \frac{d\sigma_1}{d\sigma_0}$$

$$O_2 = \frac{d\sigma_2}{d\sigma_0}$$

- Neglecting squared term in ME (or assuming $\tilde{d}$ small):

$$O := \frac{d\sigma_{nonSM}}{d\sigma_{SM}} \simeq \frac{2\,\Re(\mathcal{M}^*_{SM}\,\mathcal{M}_{CPodd})}{|\mathcal{M}_{SM}|^2}$$

Optimal Observable – Some References: Development & Examples

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