THE H TO TAUTAU CHANNEL AT ATLAS

30 Sept 2015

Birmingham Particle Physics Seminar

Kathryn Grimm

Lancaster University

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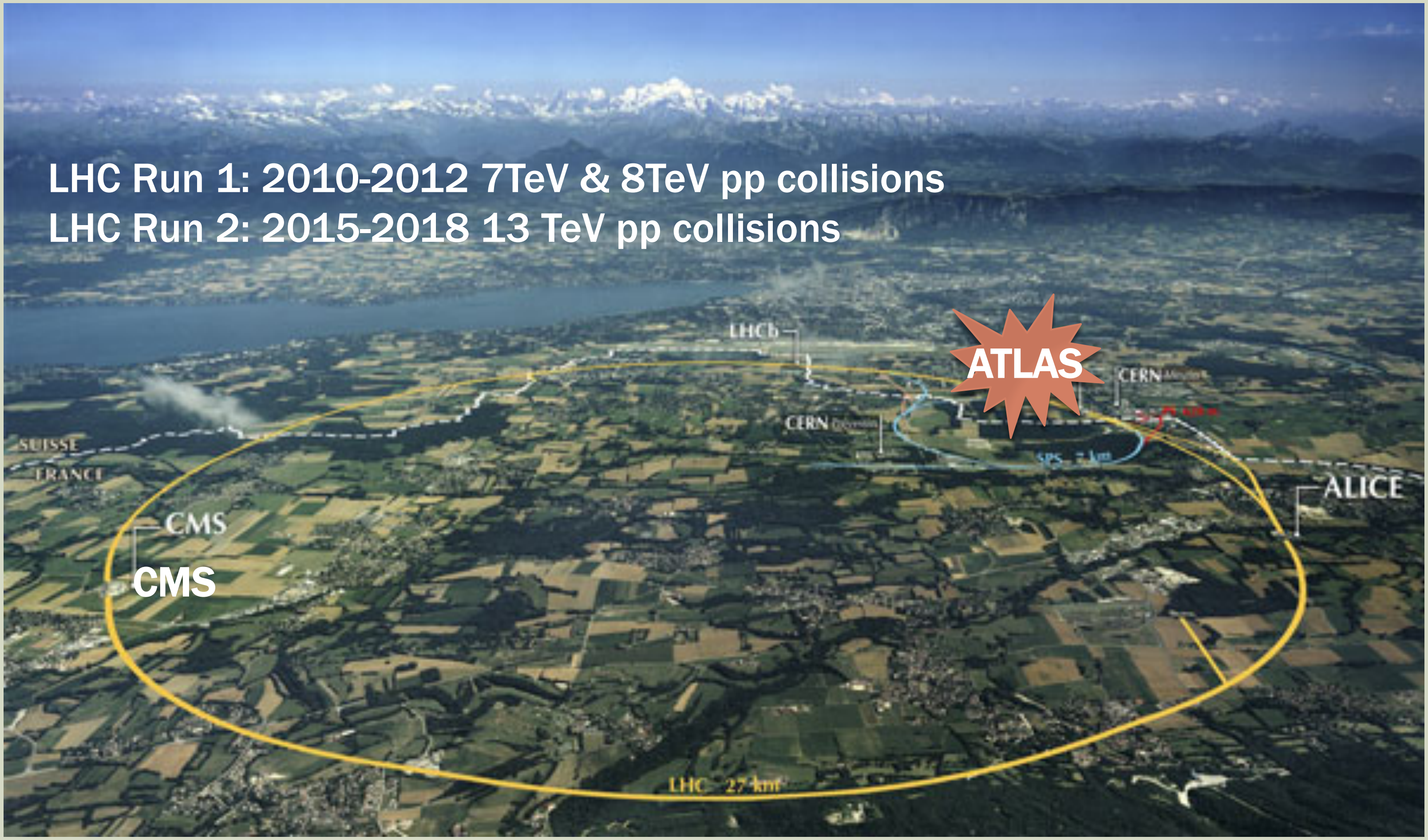
Katy Grimm
Lancaster University

OUTLINE

- Higgs boson searches at the LHC
- The $H \rightarrow \tau\tau$ search at ATLAS in Run 1
- Brief comparison with CMS
- Latest Run 1 Higgs combination
- Prospects for Run 2 and beyond

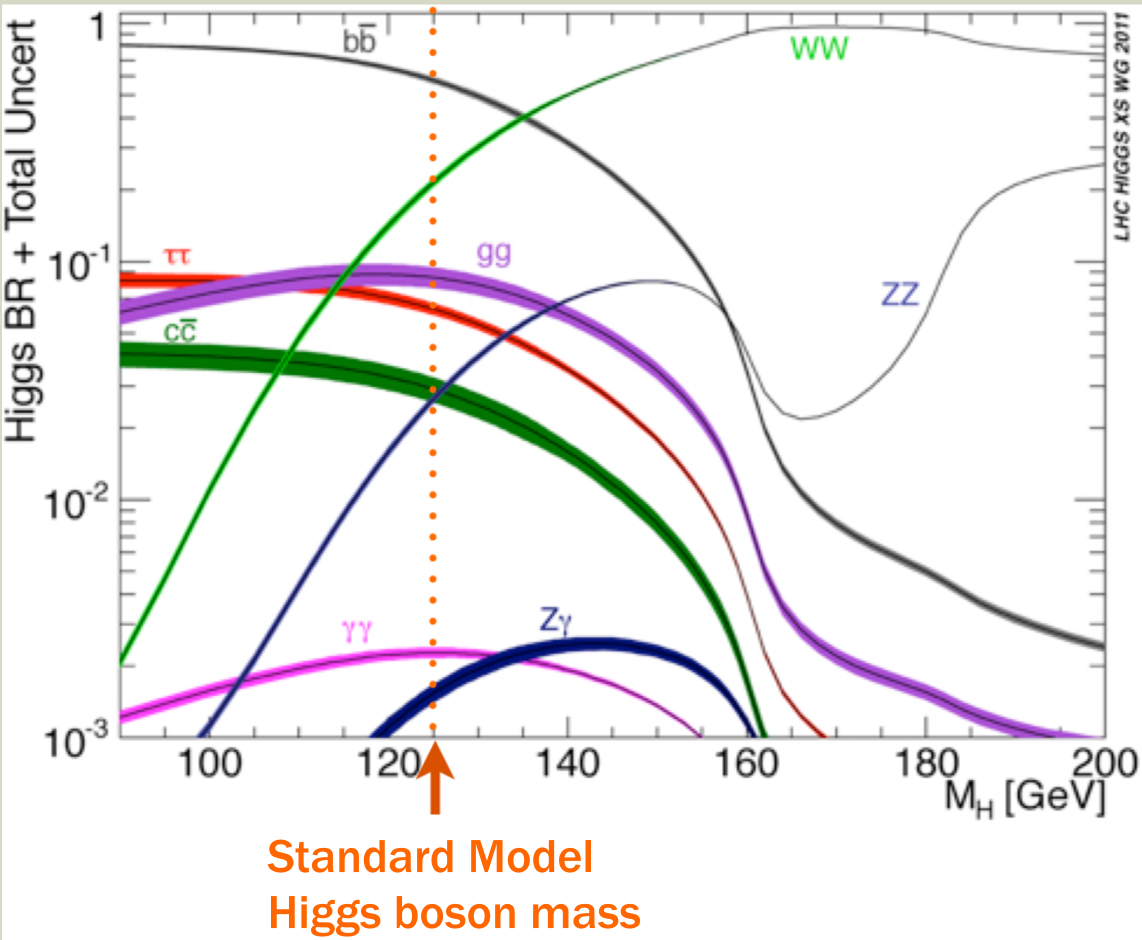
HIGGS SEARCHES AT THE LHC



Photograph: Maximilien Brice

HIGGS SEARCHES AT THE LHC

Higgs Decay Branching Ratios:



- Time line of Higgs evidence:
- $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$
- $H \rightarrow \Upsilon\Upsilon$
- $H \rightarrow WW$
- $H \rightarrow \tau\tau$
- $H \rightarrow bb$

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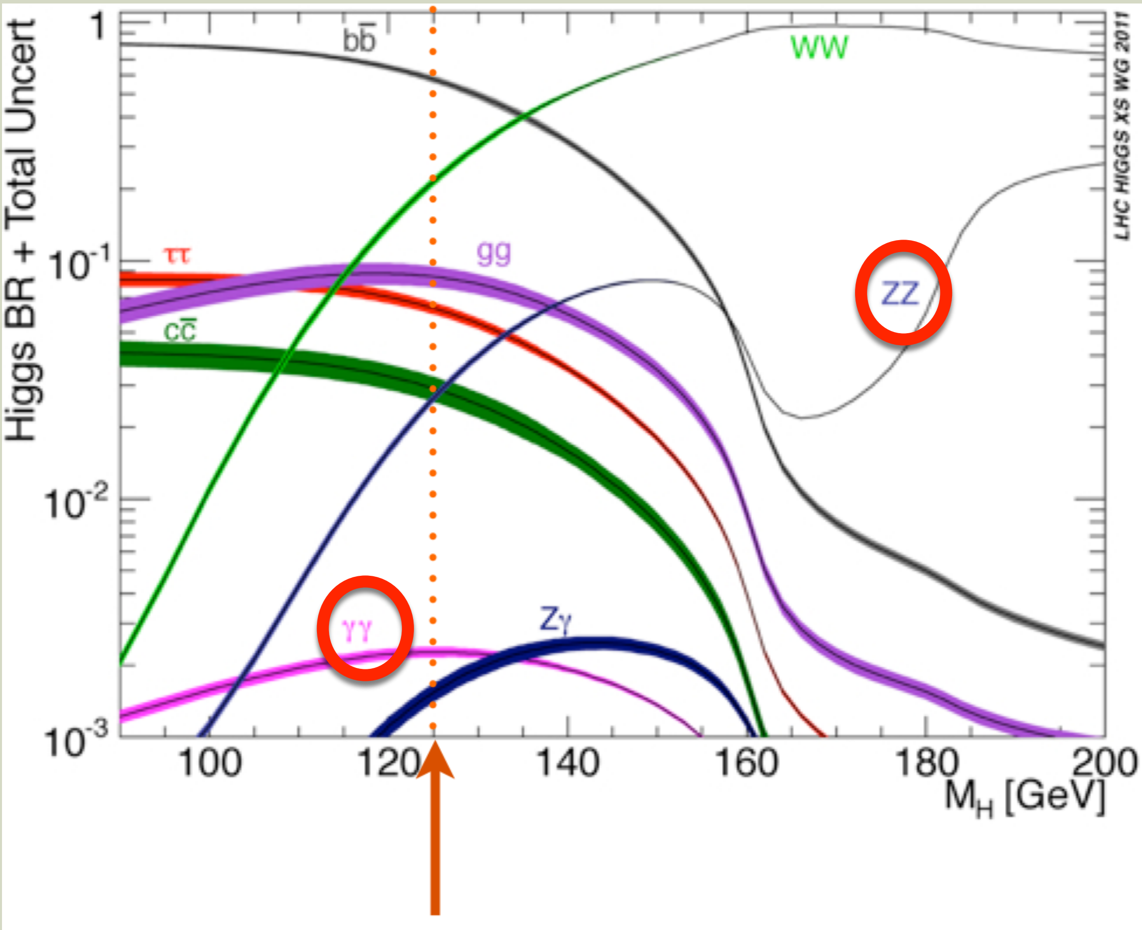

- Time line of Higgs evidence:
- H→ZZ→ℓℓℓℓ
- H→ϒϒ
- H→WW
- H→ττ
- H→bb

4 July 2012!

HIGGS SEARCHES AT THE LHC

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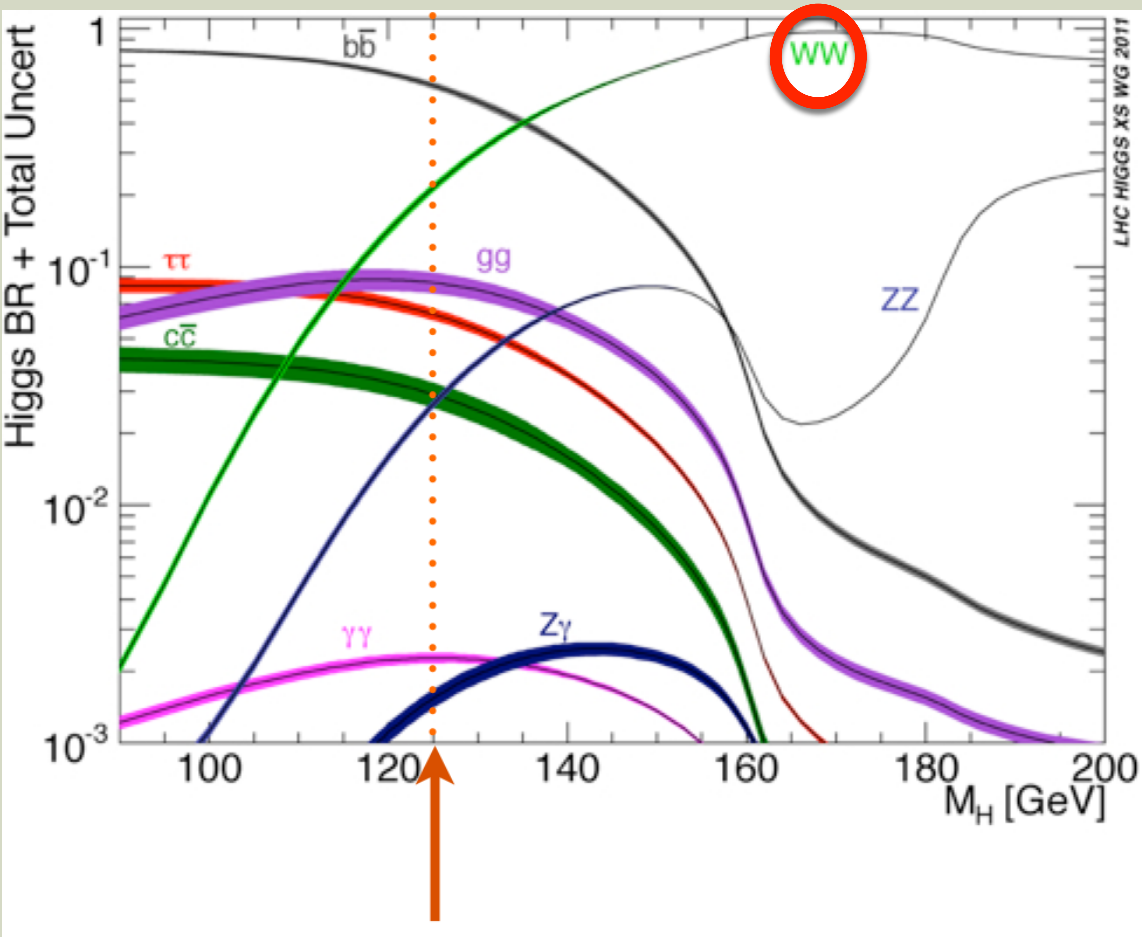

- Time line of Higgs evidence:
- H→ZZ→ℓℓℓℓ
- H→ϒϒ
- H→WW Summer 2012
- H→ττ
- H→bb

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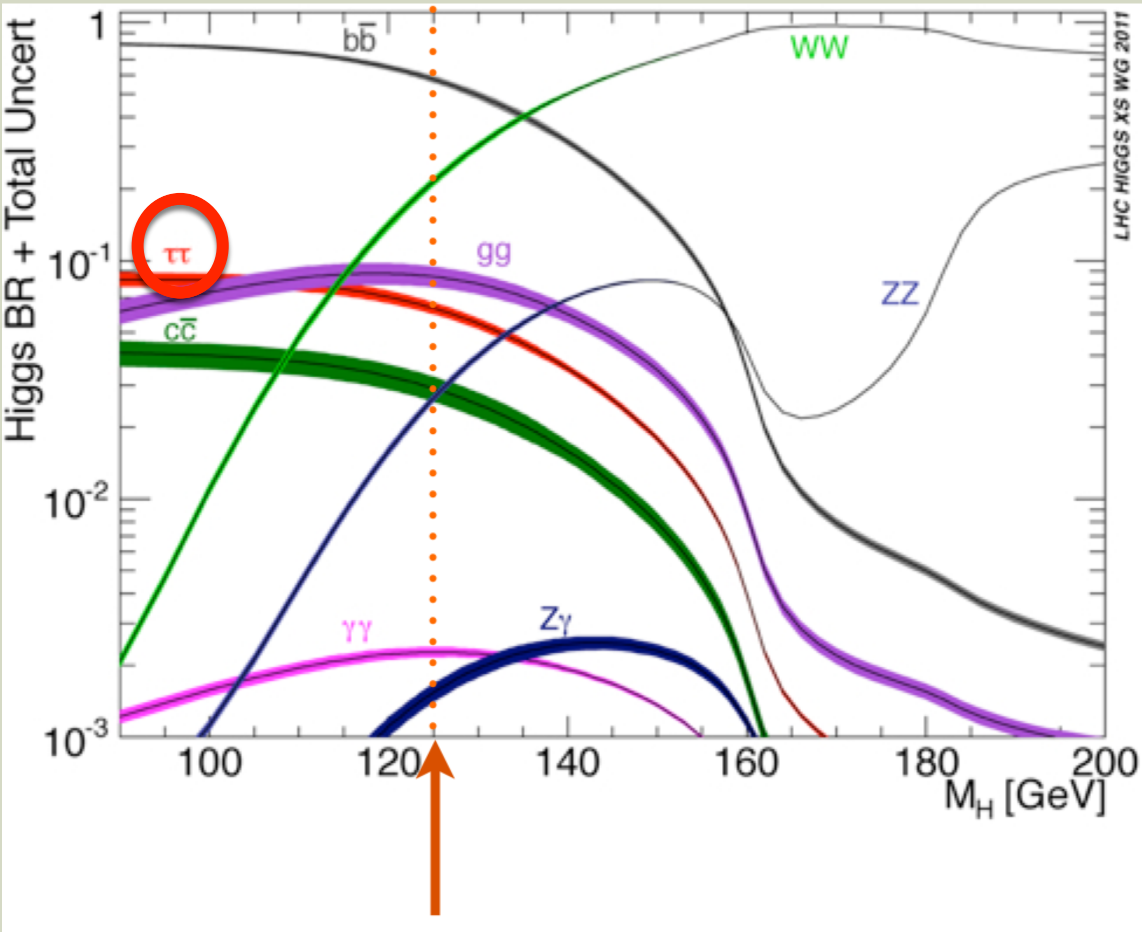

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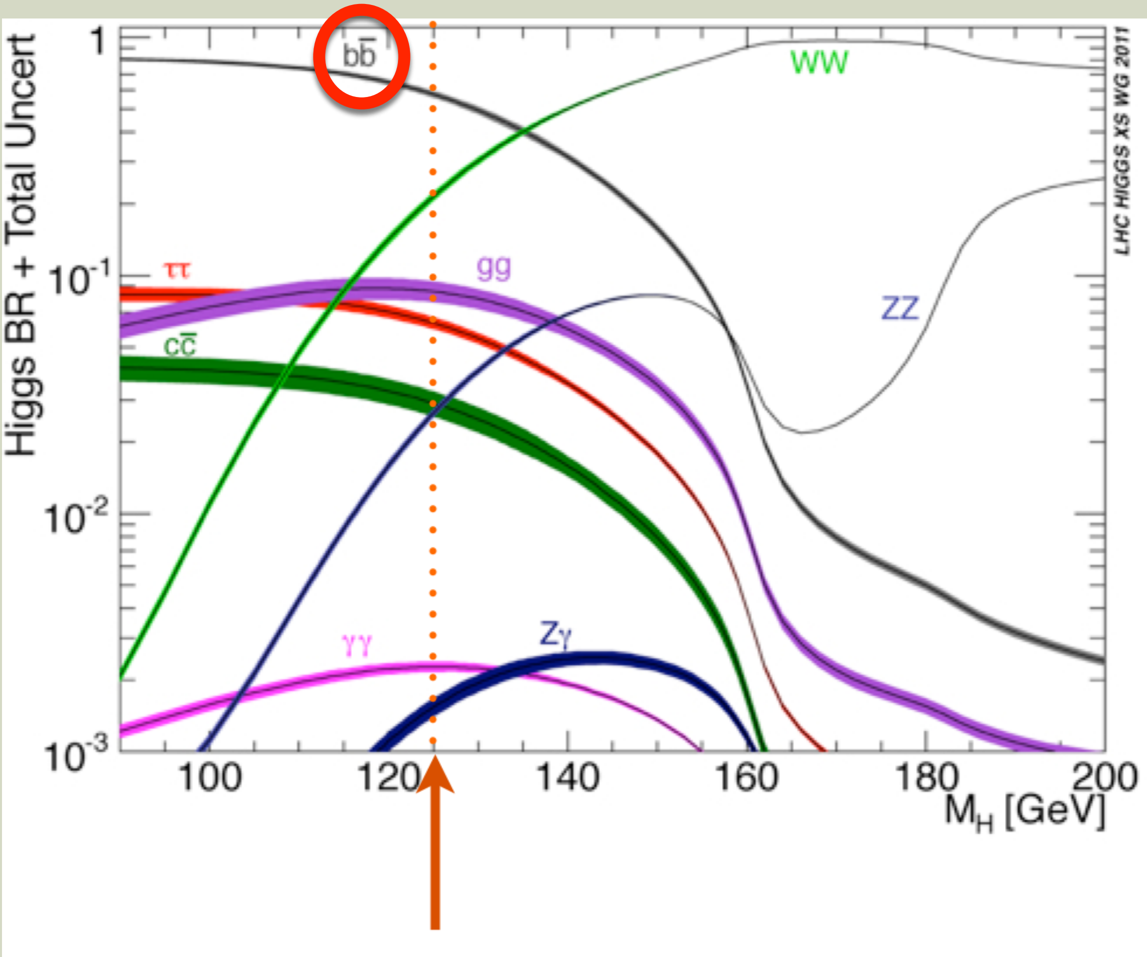
- $H \to \tau\tau$ Fall 2013
- $H \to bb$

HIGGS SEARCHES AT THE LHC

- Higgs Decay Branching Ratios:



- Time line of Higgs evidence:
- H→ZZ→ℓℓℓℓ
- H→ϒϒ
- H→WW
- H→ττ
- H→bb 2 σ in Run 1

TODAY: $H \rightarrow \tau\tau$

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The Higgs boson does a new trick (probably)

Today the ATLAS experiment at CERN announced the strongest evidence so far that the Higgs gives mass to leptons

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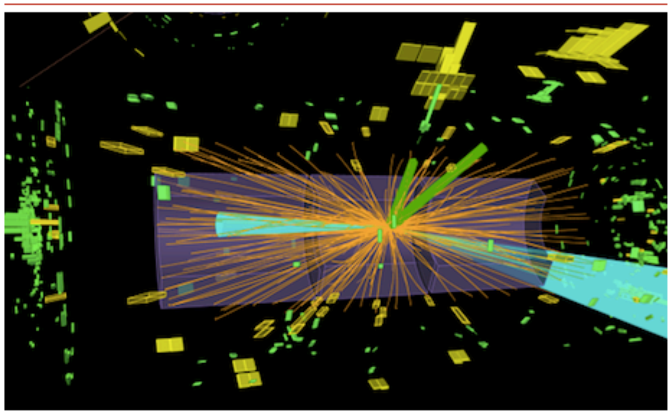

A collision event in the CERN LHC, as measured by the ATLAS detector, looking very much like a Higgs boson decaying to a pair of tau leptons

- Why taus?
- In the SM the Higgs mechanism spontaneously breaks the ElectroWeak gauge symmetry and generates masses for the W and Z gauge bosons as well as for the charged fermions via Yukawa couplings

TODAY: H→ττ

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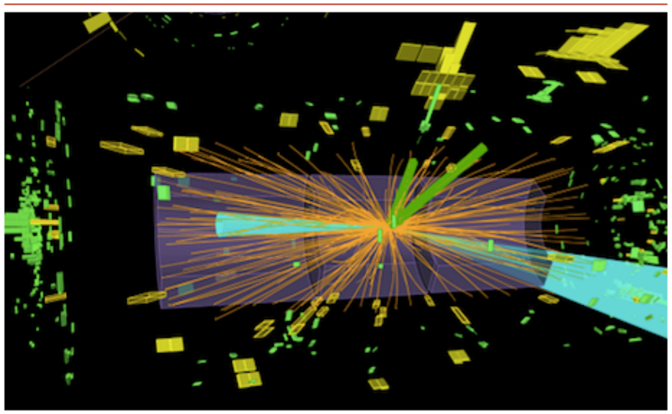

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- Why taus?
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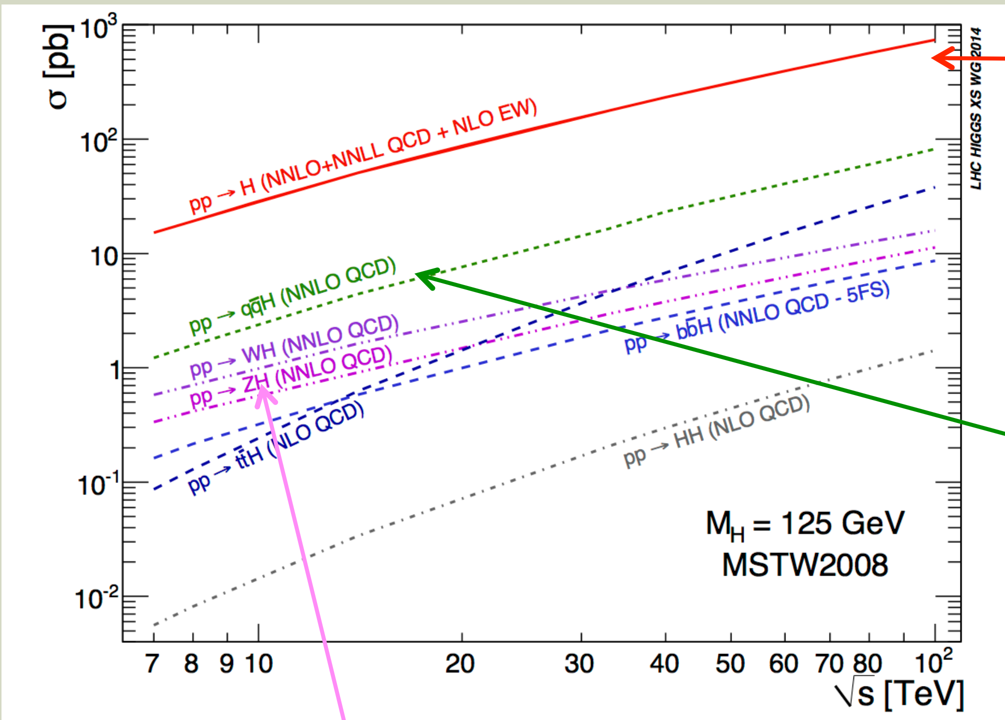
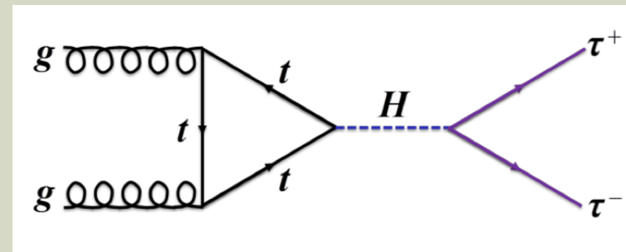
Direct Evidence for the Higgs Decaying to Fermions, and specifically to Leptons

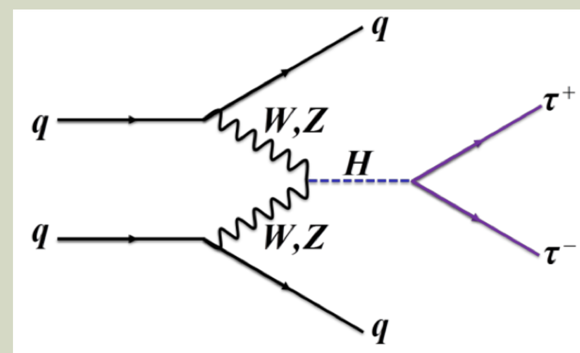
How is the Higgs produced at the LHC?



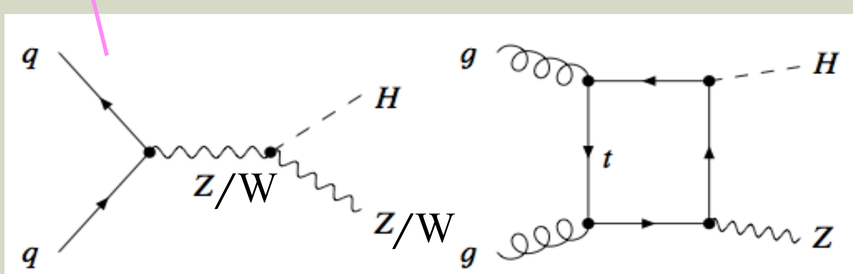
Gluon Fusion



Vector Boson Fusion



Associated Production VH

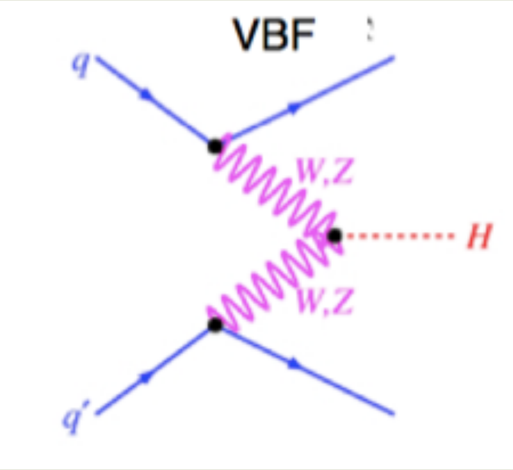


H→ττ at ATLAS: SIGNAL REGION CATEGORIES

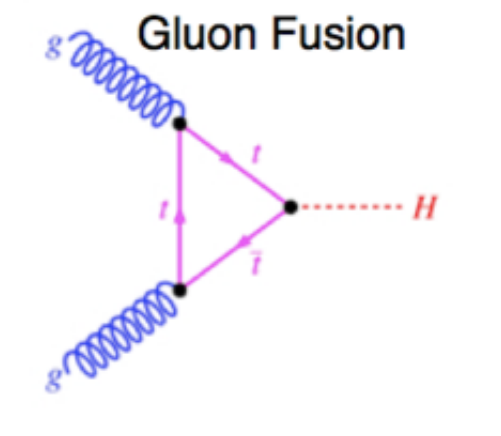
- Take advantage of the unique signature of VBF production!

Select 2 Opposite Charge Taus (or leptons) plus:

Category	Selection	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
VBF	$p_T(j_1) >$ (GeV)	40	50	50
	$p_T(j_2) >$ (GeV)	30	30	30/35
	$\Delta\eta(j_1, j_2) >$	2.2	3.0	2.0
	$b-$jet veto for jet $p_T >$ (GeV)	25	30	-
	$p_T^H >$ (GeV)	-	-	40
Boosted	$p_T(j_1) >$ (GeV)	40	-	-
	$p_T^H >$ (GeV)	100	100	100
	$b-$jet veto for jet $p_T >$ (GeV)	25	30	-

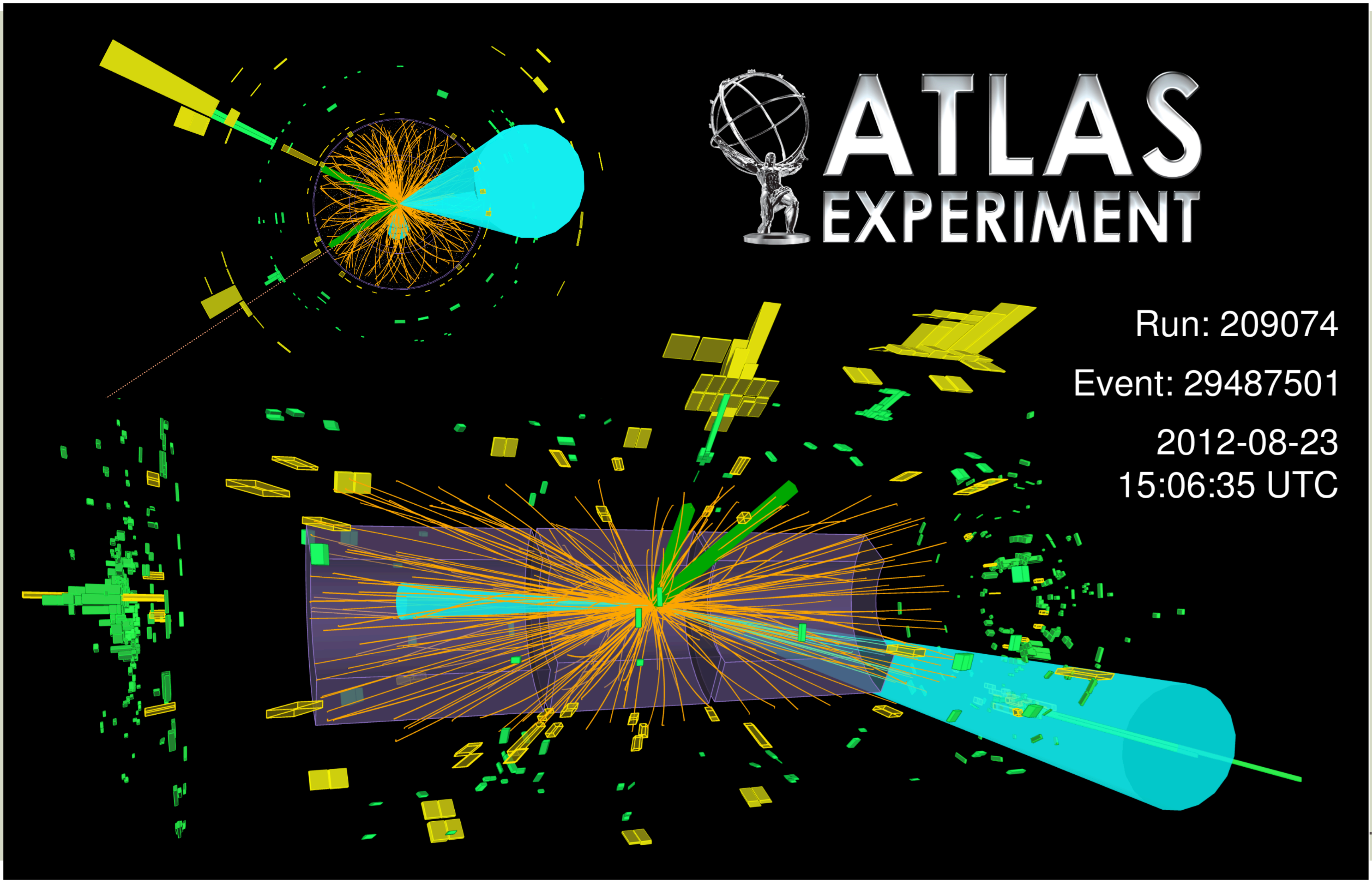


Forward jet signature



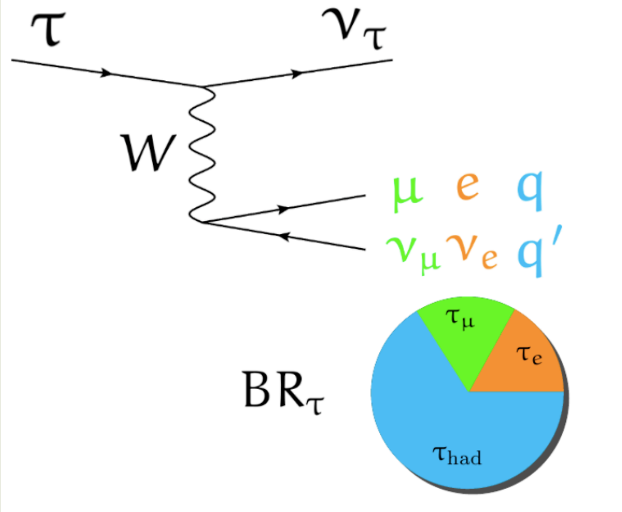
Largest production mode

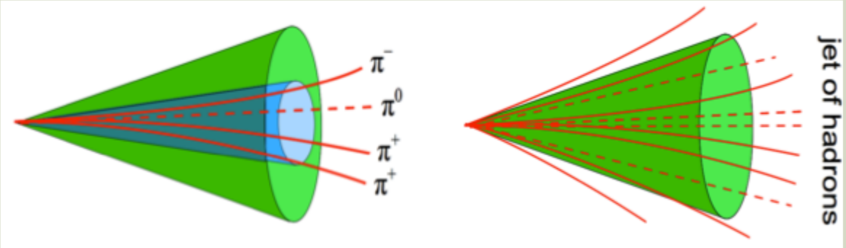
H→ττ CANDIDATE EVENT IN HAD-HAD CHANNEL



TAUS AT ATLAS: RUN 1

- m_τ = 1.78 GeV; Decay length = 87μm
- Decay to Hadrons(65%) or Leptons (35%)
- Hadronic decays are highly collimated and have low track multiplicity– 1 or 3 charged pions
- TauID (and lepton suppression) uses Multivariate Techniques that take advantages of shower-shape and track information





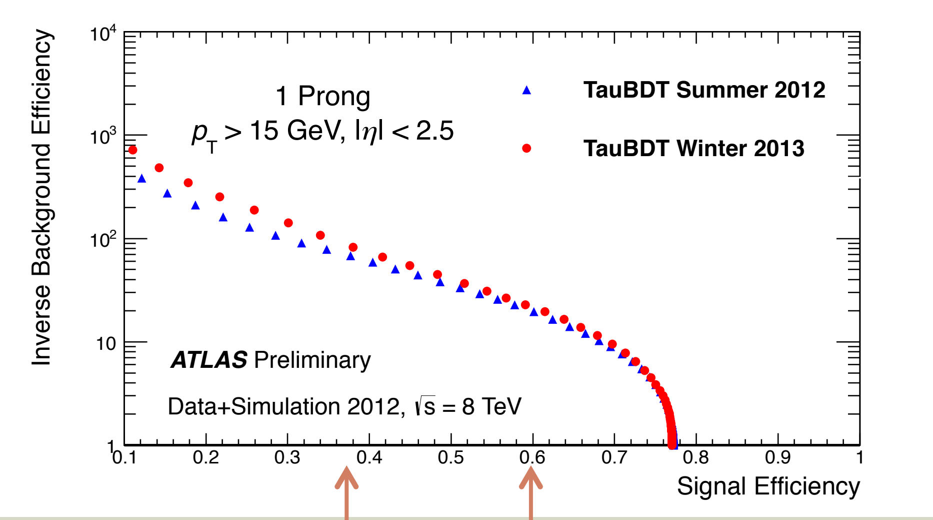
main background: jets of hadrons

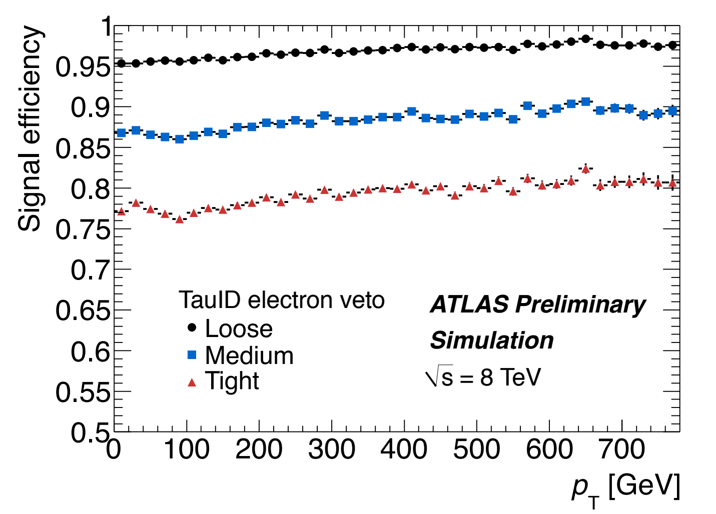
➢ **1 Prong** (BR = 49.5%):
Corresponds mostly to:
$\tau^\pm \to \pi^\pm \nu_\tau$
$\tau^\pm \to \rho^\pm (\to \pi^0 \pi^\pm)\, \nu_\tau$

➢ **3 Prong** (BR = 15.2%):
Corresponds mostly to:
$\tau^\pm \to a_1^\pm (\to \rho^0 \pi^\pm \to 3\pi^\pm)\, \nu_\tau$

TAUS AT ATLAS: RUN 1

- ATLAS uses a BDT to identify taus, based on tracking and shower-shape calorimeter training inputs
- A separate BDT is trained purely for tau electron veto.

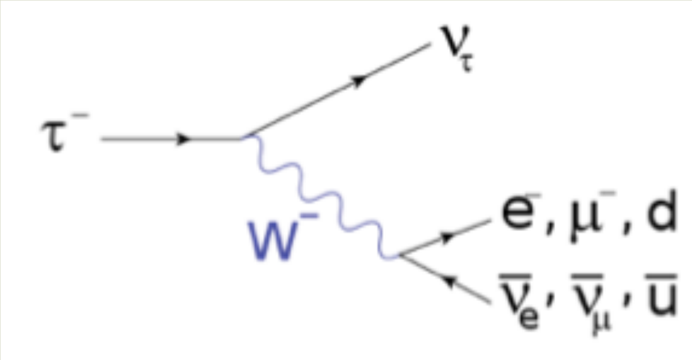




"medium tau" "tight tau"

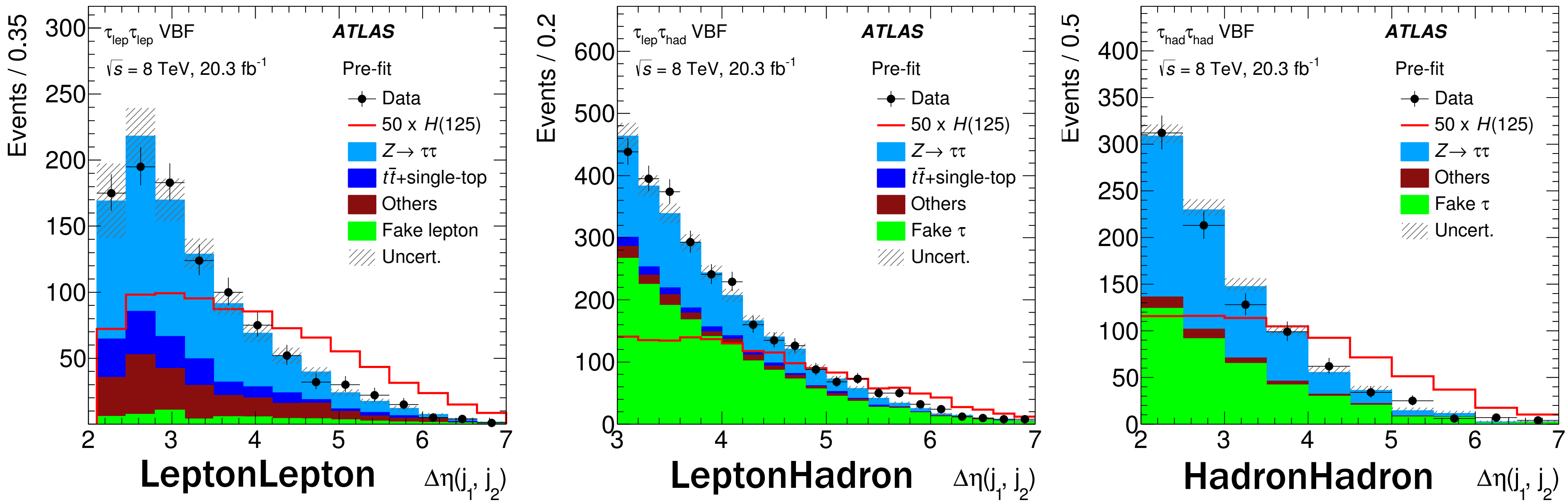
H→ττ at ATLAS

- The H→ττ analysis includes all final states of tau channels:
  - H→ττ →lepton lepton + 4ν, BR = 12.4%
  - H→ττ →lepton hadron + 3ν, BR = 45.6%
  - H→ττ →hadron hadron + 2ν, BR = 42%



- The search uses a Multivariate approach (Boosted Decision Trees)
- The analysis was framed to specifically test for the 125 GeV Standard Model Higgs decaying to taus
- Final sensitivity is determined with a likelihood fit comparing data to μ × [125 GeV SM Higgs signal]

ANALYSIS STRATEGY



- The three channels have different background compositions
- Major background contributions from Z→ττ and "Fake taus". Both are modeled with data.
- The other backgrounds are modeled with Monte Carlo. In the case of ttbar in leplep and lephad, normalization is found in data Control Regions.

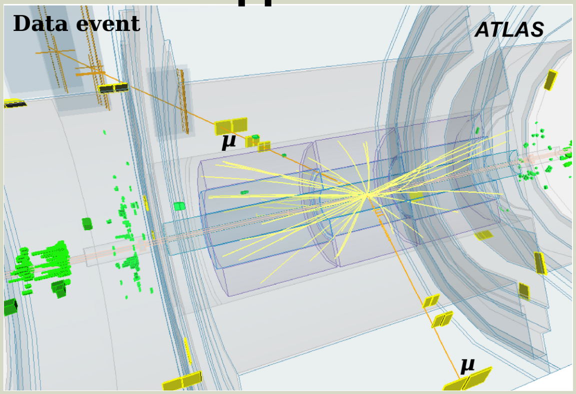
Z→ττ MODELING: EMBEDDING

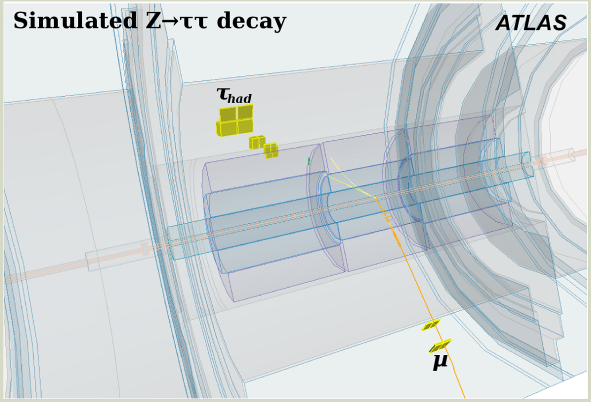
- Embedding:
  - Select Z→ μμ data
  - Replace muons with simulated taus (including spin)

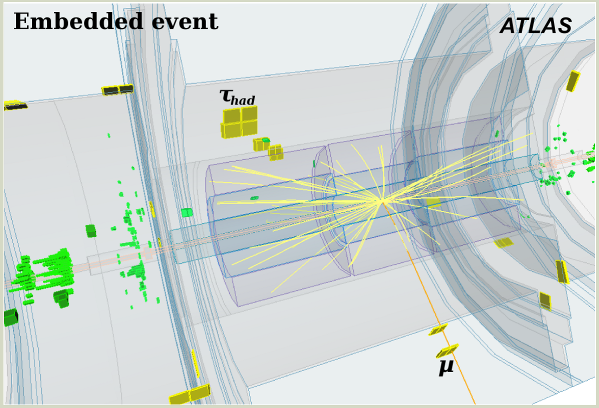
- Z-boson kinematics, jets, MET resolution, pile-up, and VBF/EWK production are directly modeled by data

Z→ μμ data

Embedded Z→ττ event







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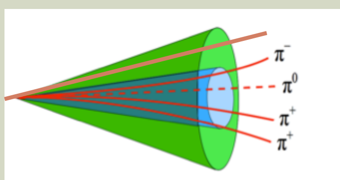
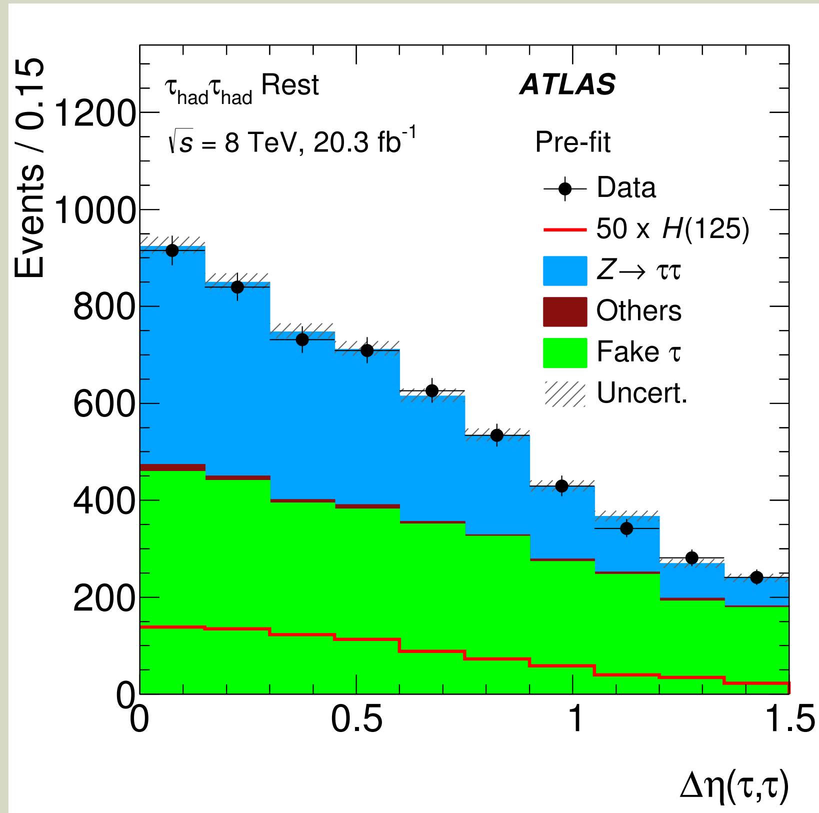
MODELING FAKE TAUS AND MULTIJET BACKGROUND

- Hadron Hadron Channel: Background from jets is made almost entirely of multijet QCD
- Model the Shape of the background with data: taus that fail the isolation and opposite-sign charge requirements



- Normalization: the fit is performed for the distribution of the difference in pseudorapidity between the two hadronic tau candidates, $\Delta\eta(\tau_{had}, \tau_{had})$.



MODELING FAKE TAUS AND MULTIJET BACKGROUND

- LepHad Channel: Background from jets faking hadronic taus = QCD, Z(ℓℓ)+jets, W+jets, ttbar)
  - Model with data events that pass Loose Tau ID but fail Medium ID
  - Use the "Fake factor" method to account for differences according to:

Tau candidate pT

Tau track multiplicity: 1-track vs 3-track tau candidates.

Sources with Quark-dominated jets:

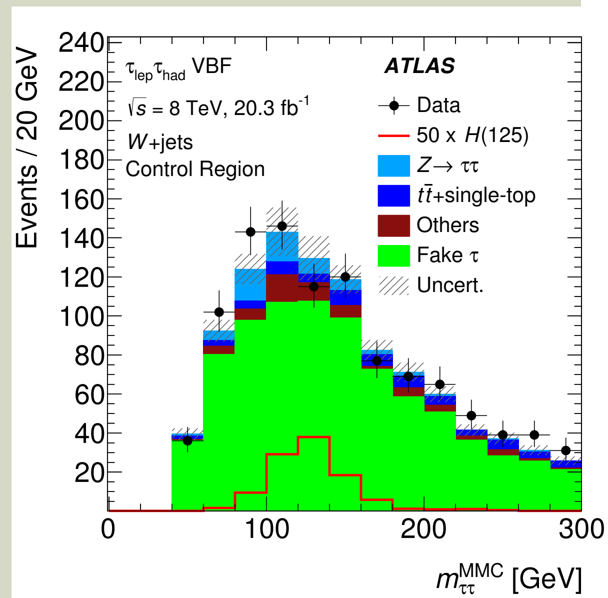
W+jets: mT > 70 GeV

semileptonic ttbar: inverted b-jet veto

Z(ℓℓ)+jets: require 2 leptons w/(80 GeV<m_{ll}<100 GeV)

Sources with Gluon-dominated jets:

QCD: relax lepton selection: Loose requirement

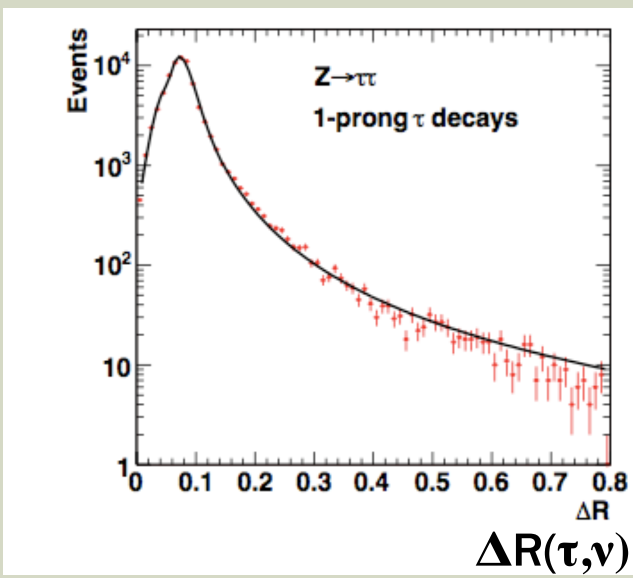


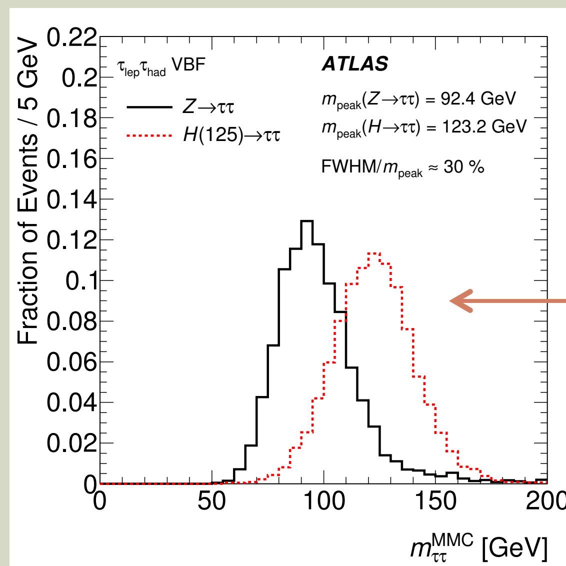
Fake Factor: $\dfrac{N\ \tau_{\text{medium ID}}}{N\ \tau_{\text{loose-but-not-medium ID}}}$

Applied to a sample of data passing selection but with $\tau_{\text{loose-but-not-medium ID}}$

MISSING MASS CALCULATOR

- Good $m_{\tau\tau}$ resolution provides separation between H and $Z \rightarrow \tau\tau$
- Final state neutrinos make invariant mass calculation tricky. Use the **Missing Mass Calculator (MMC)**
  - Find the most probable neutrino momentum based on tau kinematics and Missing Transverse Energy

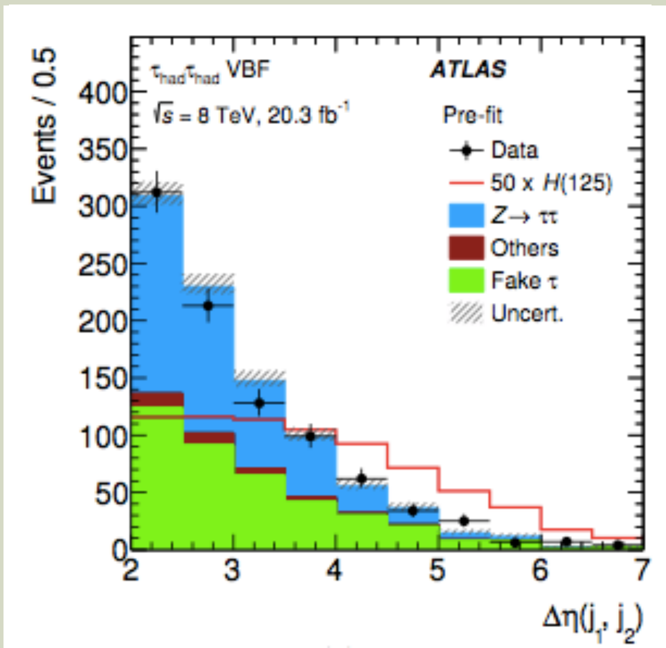


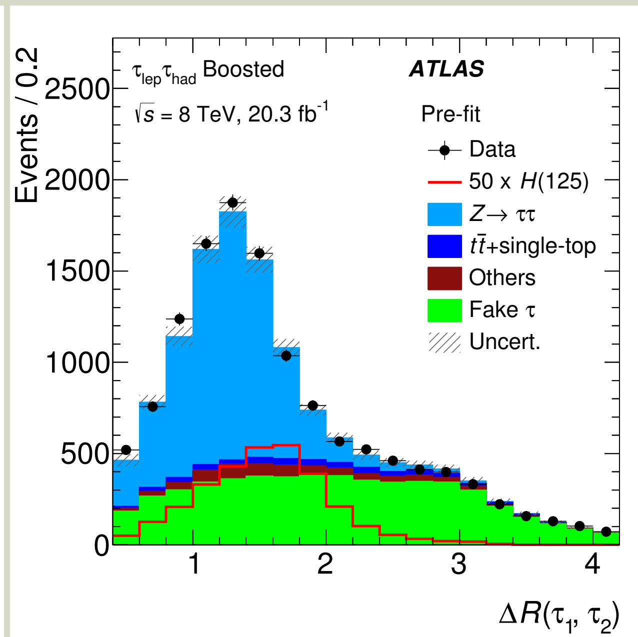


Separation between H and Z

INPUTS TO THE BOOSTED DECISION TREE

- 6 separate BDTs are trained, for each channel and category





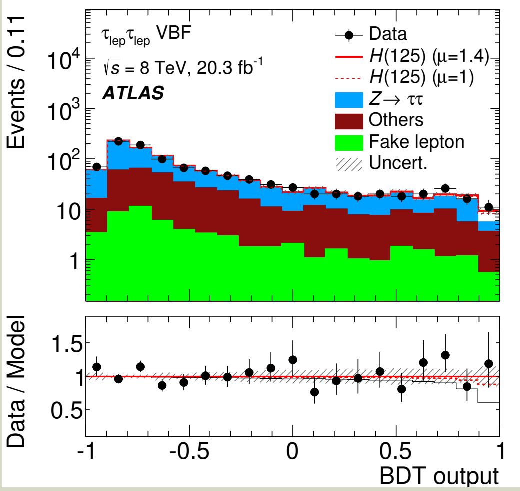
- Hττ Resonance properties: m(ττ), ΔR(ττ)
- VBF topology: m_{jj}, $\Delta\eta_{jj}$, Centrality
- Event activity: sum pT from all objects
- Event topology: m_T, $p_T(\tau_1)/p_T(\tau_2)$

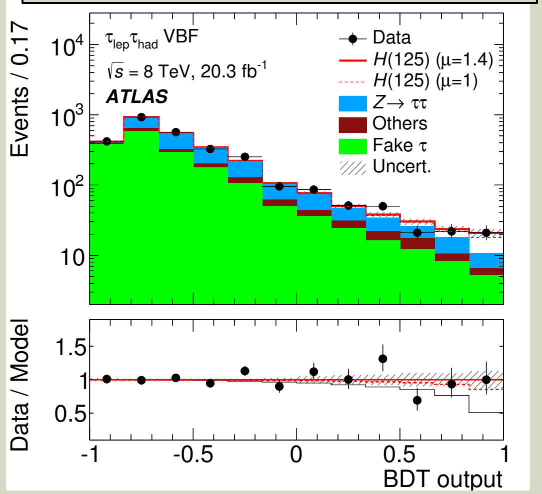
BOOSTED DECISION TREE OUTPUT

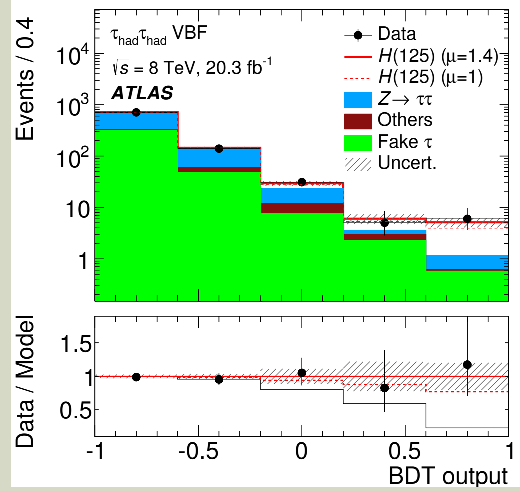
LeptonLepton Channel

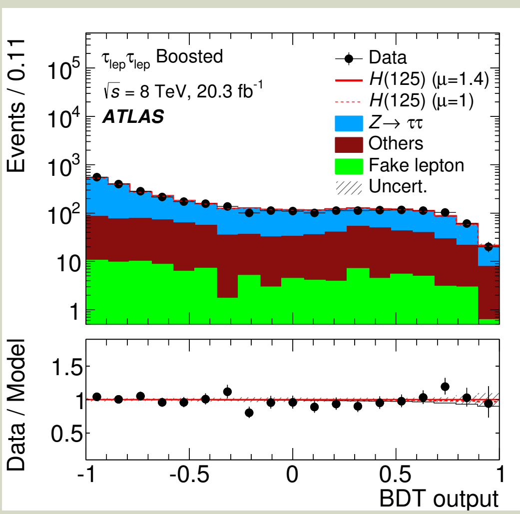
LeptonHadron Channel

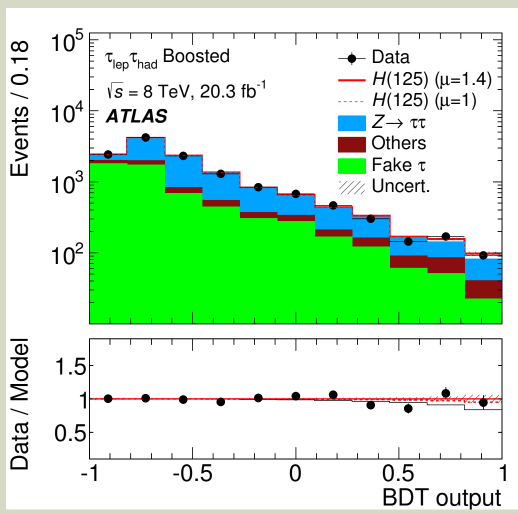
HadronHadron Channel

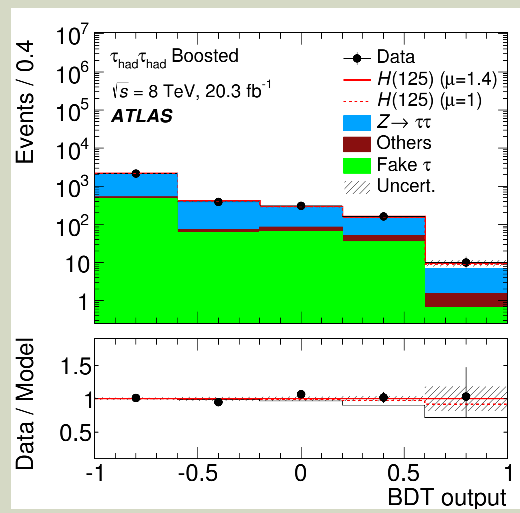










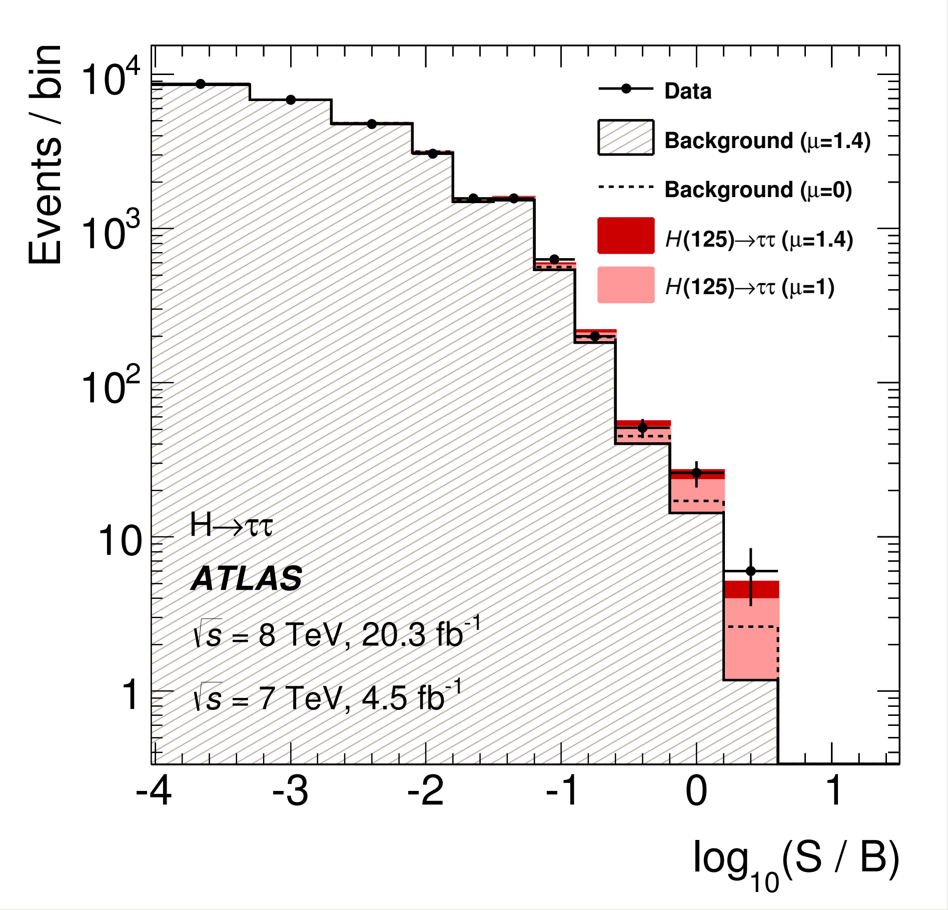


RESULTS

- Visualize the total result:

Calculate the S/B expected in each bin of the BDTs.

Order the bins according to their S/B.



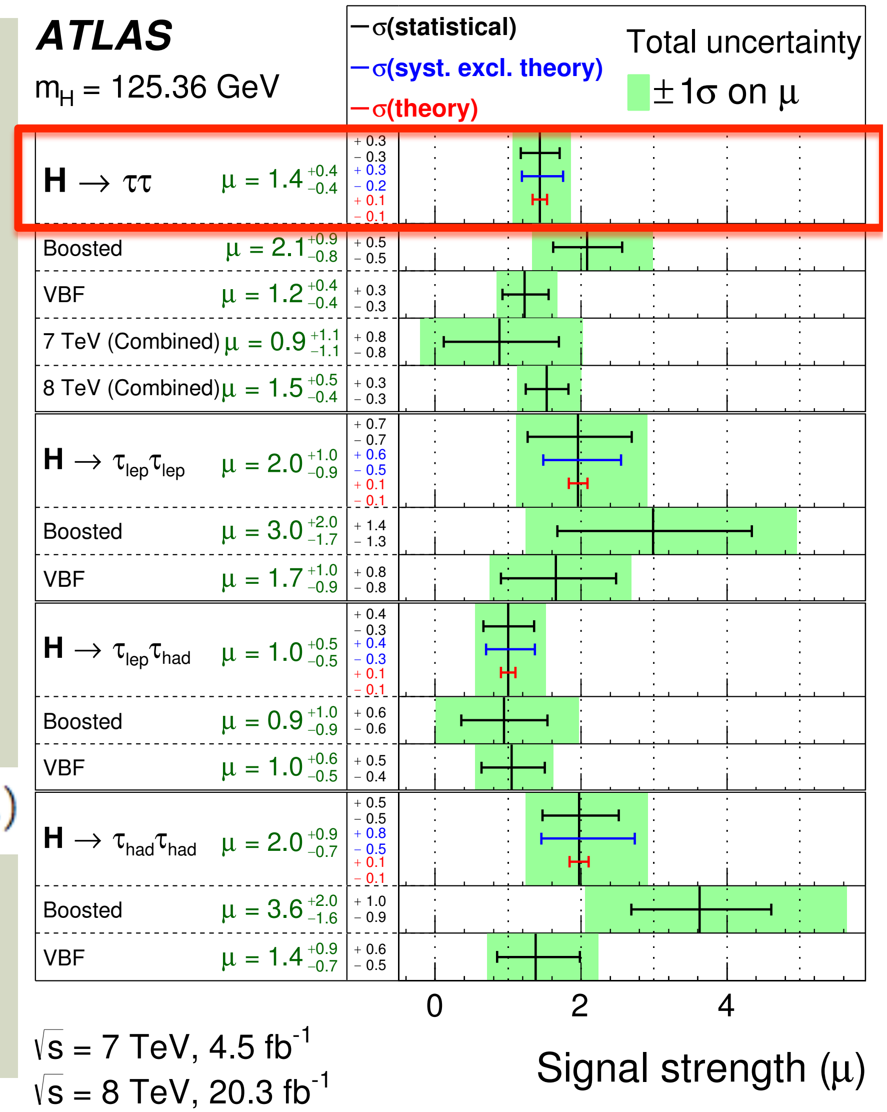
RESULTS

- To determine the signal strength of the analysis, a PDF of each background and predicted signal is made.
- A simultaneous fit is done in all channels to extract the signal strength
  - The backgrounds and signals are allowed to move within their systematic uncertainties
  - The normalizations for many backgrounds are floated

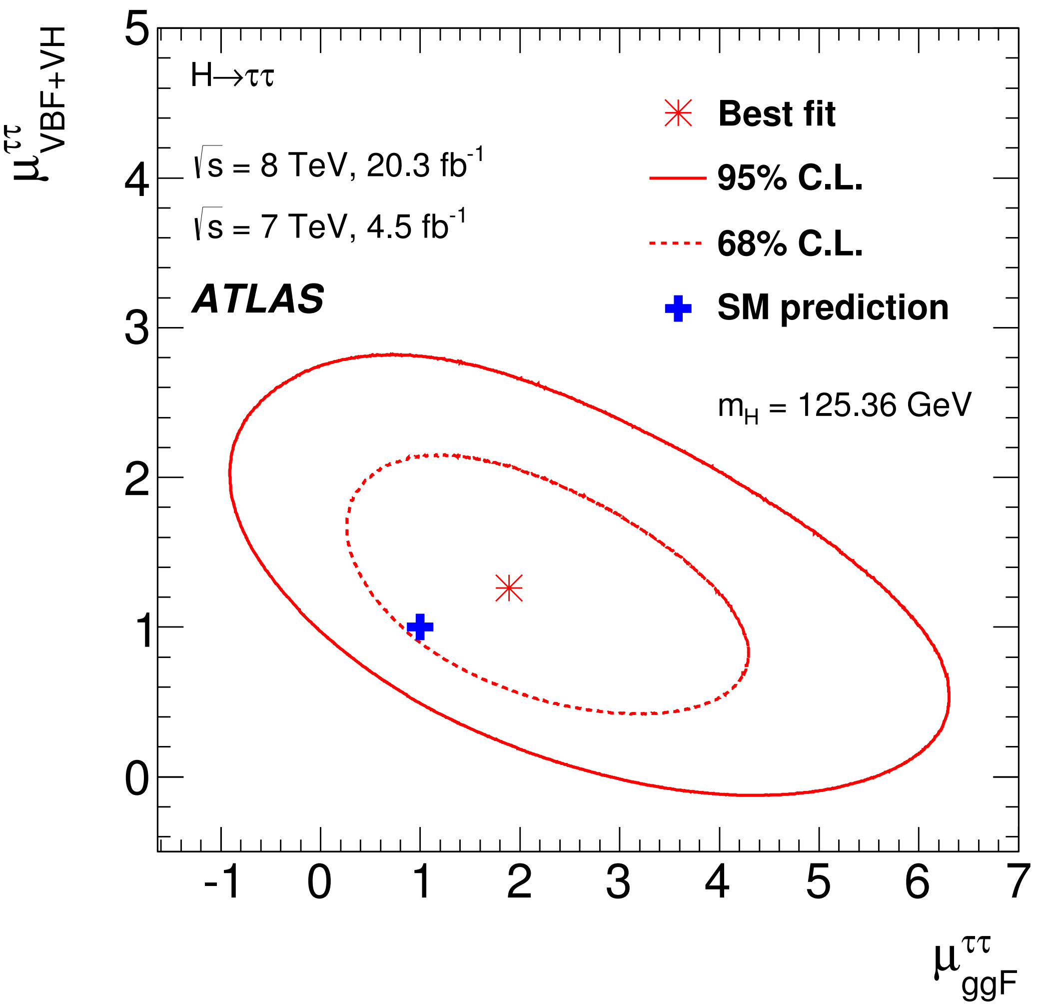
$$\textit{Signal strength } \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$

$$\mu = 1.43\ ^{+0.27}_{-0.26}(\text{stat.})\ ^{+0.32}_{-0.25}(\text{syst.})\ \pm 0.09(\text{theory syst.})$$

The data corresponds to a deviation from the background-only hypothesis at the level 4.5σ (3.4σ expected)



SEPARATION BY HIGGS PRODUCTION

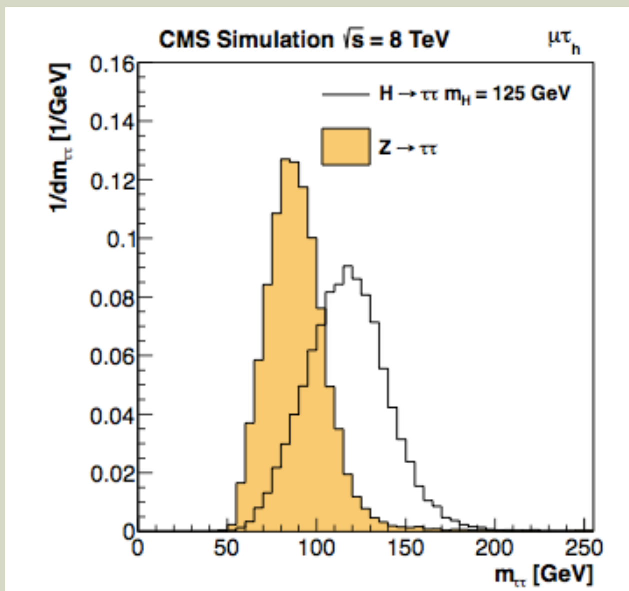


- The $H\rightarrow\tau\tau$ selection is such that a large part of the sensitivity is to H produced via VBF (much more so than other Higgs channels)
- We can separate our sensitivity into the vector-boson-mediated VBF and VH processes gluon-mediated ggF process.

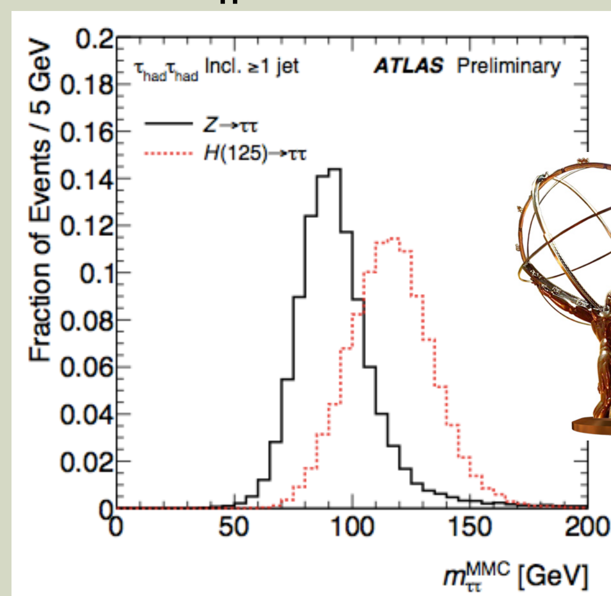
COMPARISON WITH CMS RUN 1 H→ττ

- Evidence for H→ττ at CMS came out at nearly the same time as ATLAS
- CMS does not use a multivariate analysis
- Otherwise, many similarities in the searches

$m_{\tau\tau}$ CMS



$m_{\tau\tau}$ ATLAS



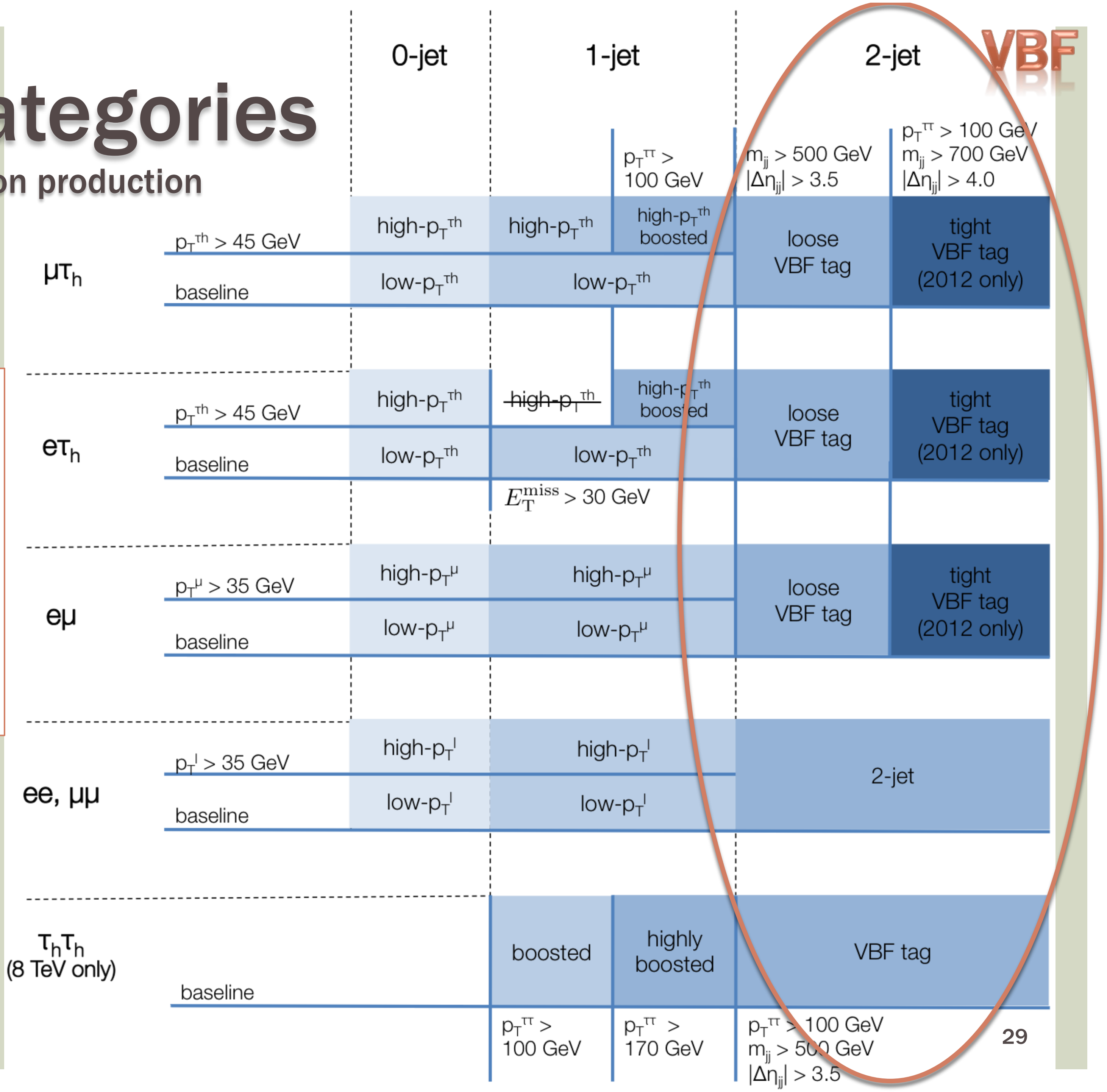
Similar
di-tau
mass resolution

CMS Categories

VBF & GluonFusion production

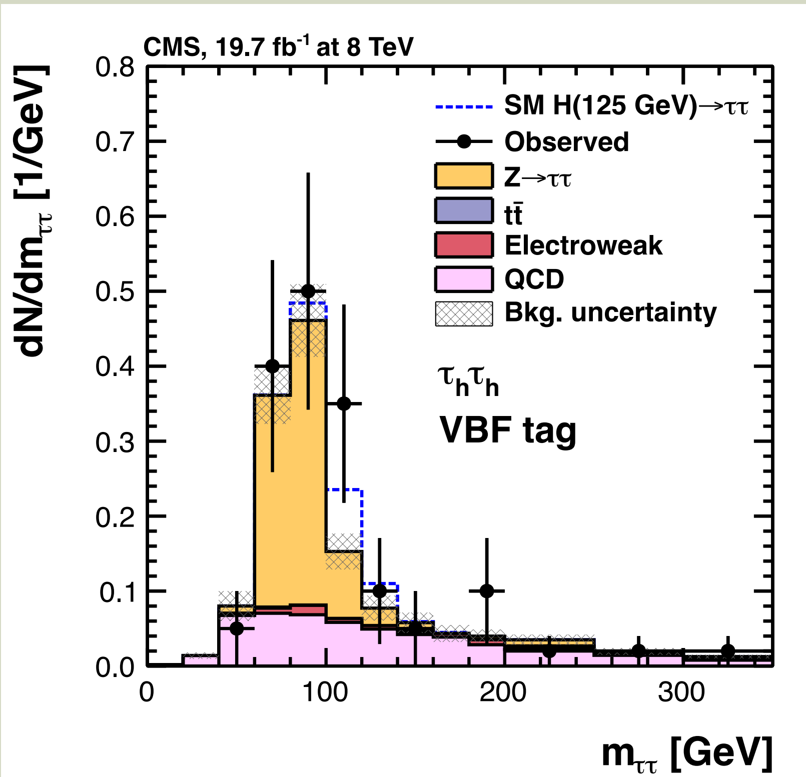
84 categories

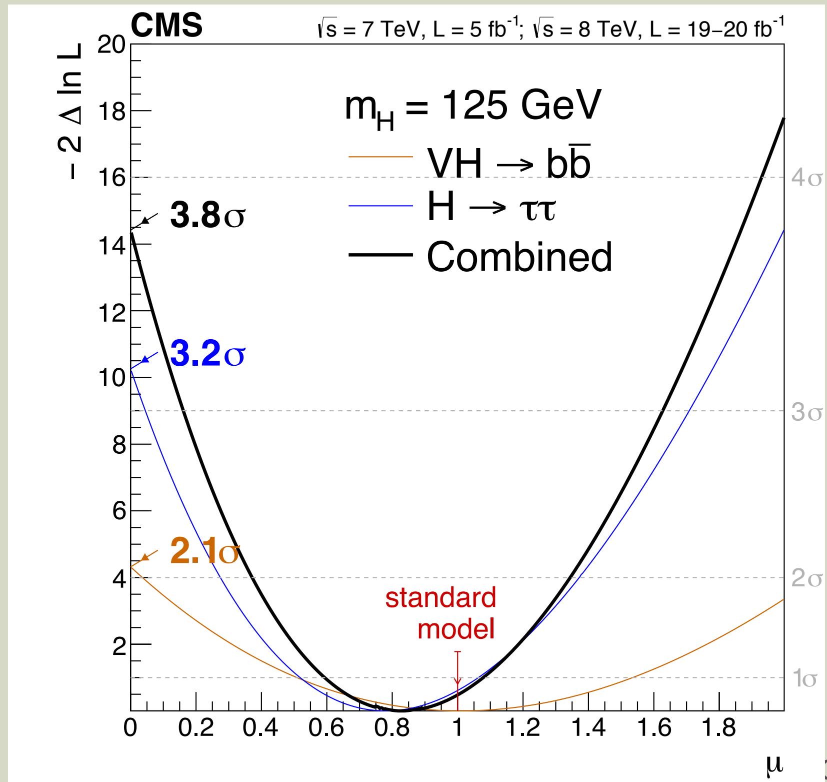
Variables used in cutting:
Jet Multiplicity
DiJet Mass & Separation
DiTau pT
H pT, Tau or lep pT
Central Jet Veto



CMS H→ττ RESULTS

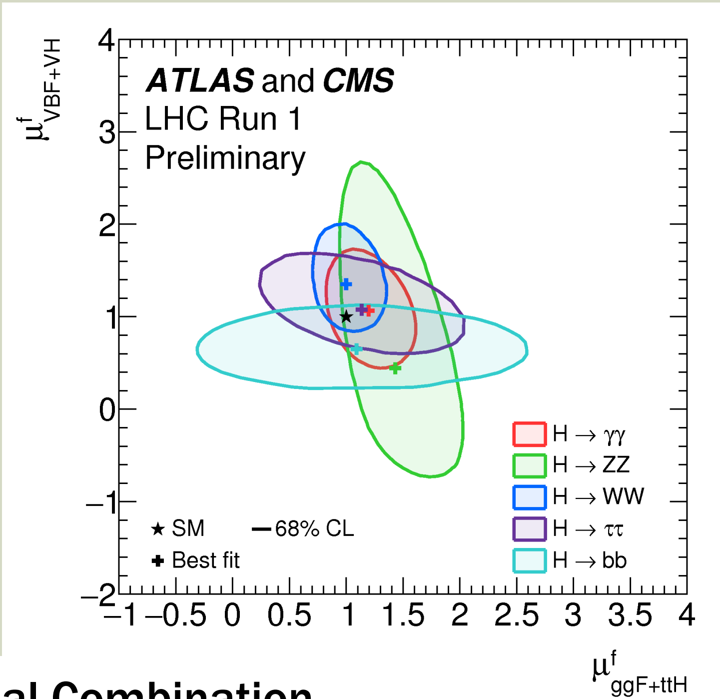
- Evidence at 3.8 standard deviations, when 4.4 are expected.
- The best fit of the observed H→*ττ* signal cross section for *m*H= 125 GeV is 0.78±0.27 times the standard model expectation



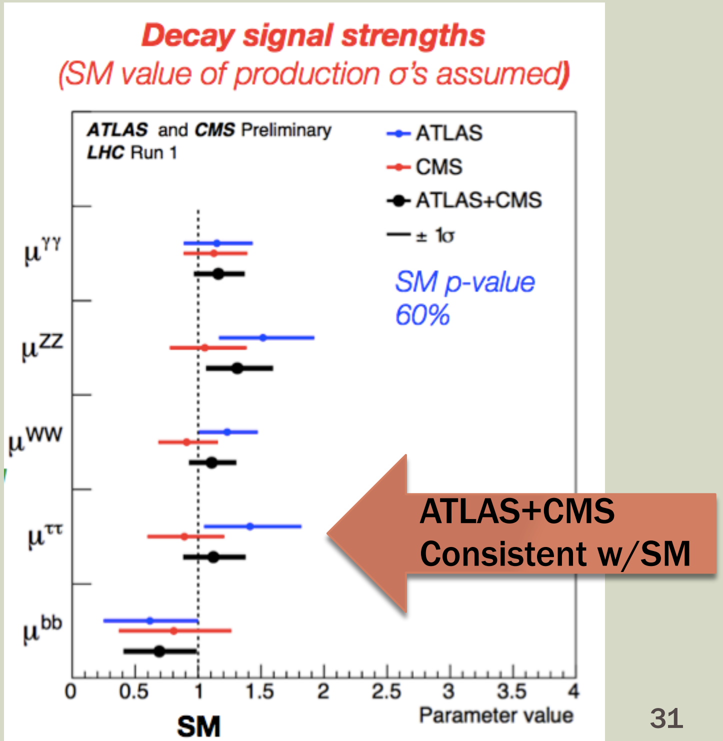


LATEST LHC HIGGS COMBINATION

- Earlier this month the latest CMS+ATLAS Higgs combination was released. Combined measurements from the following channels:
  - $H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$, $H\to\tau\tau$, $VH\to Vbb$, $H\to\mu\mu$, $H\to Z\gamma$, $ttH\to tt(bb, \ell\ell, \gamma\gamma)$



Fit each channel separately:



Total Combination

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\;^{+0.04}_{-0.04}\,(\text{expt})\;^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

LATEST LHC HIGGS COMBINATION

Significance of combined observations

- Comparing likelihood of the best-fit with likelihood assuming μ_{prod}=0 or μ^{decay}=0 we obtain:

Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	5.0
H→bb	2.6	3.7

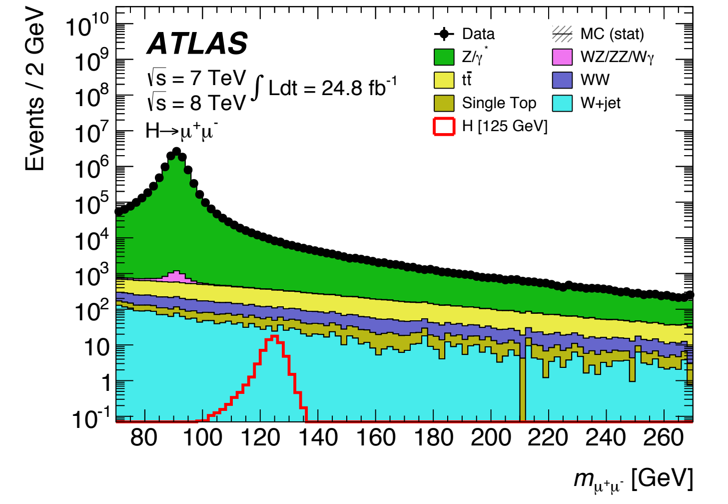
VBF production and H→ττ now established at over 5 σ.
ggF and H→ZZ,γγ,WW already established by each experiment

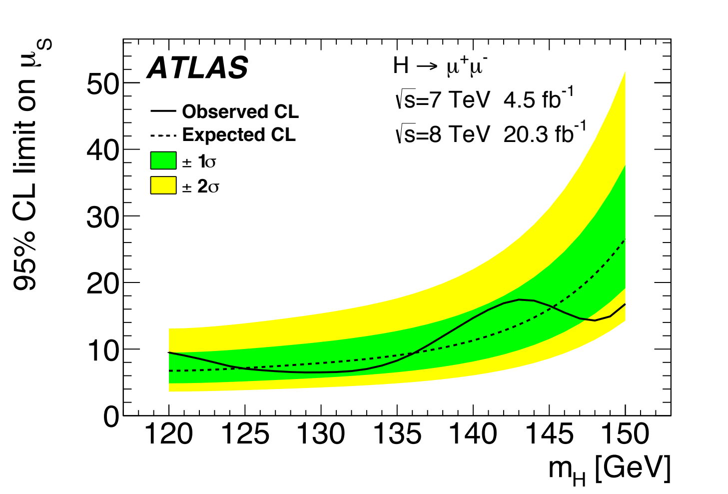
Combining CMS and ATLAS data gives H→ττ evidence at 5.5σ

CERN Seminar
by Wouter Verkeke
21/09/2015

ONE MORE NOTE ON LEPTONS FROM RUN 1

- H→μμ
  - Higgs decaying to muons not seen: Higgs does not couple evenly to all leptons

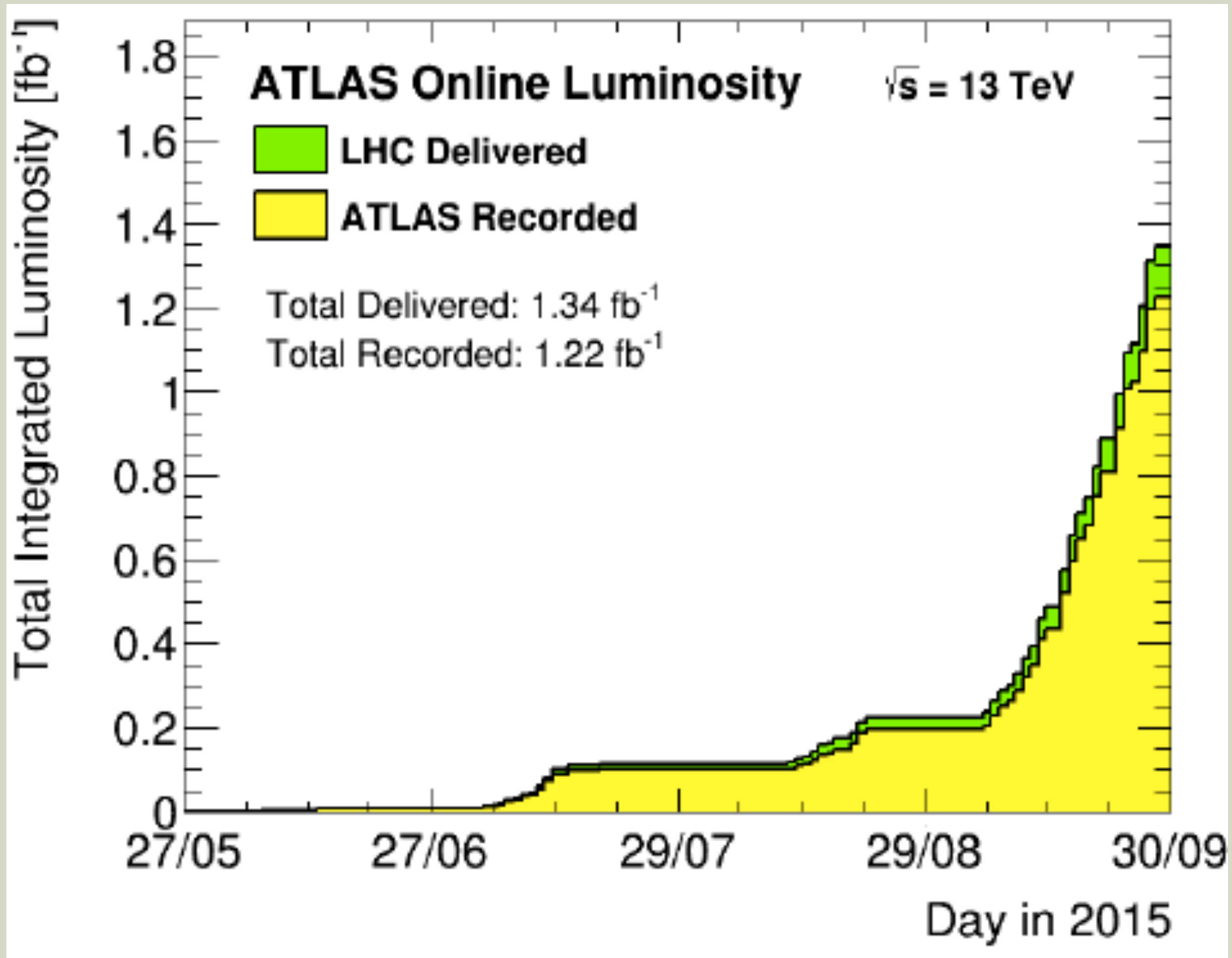




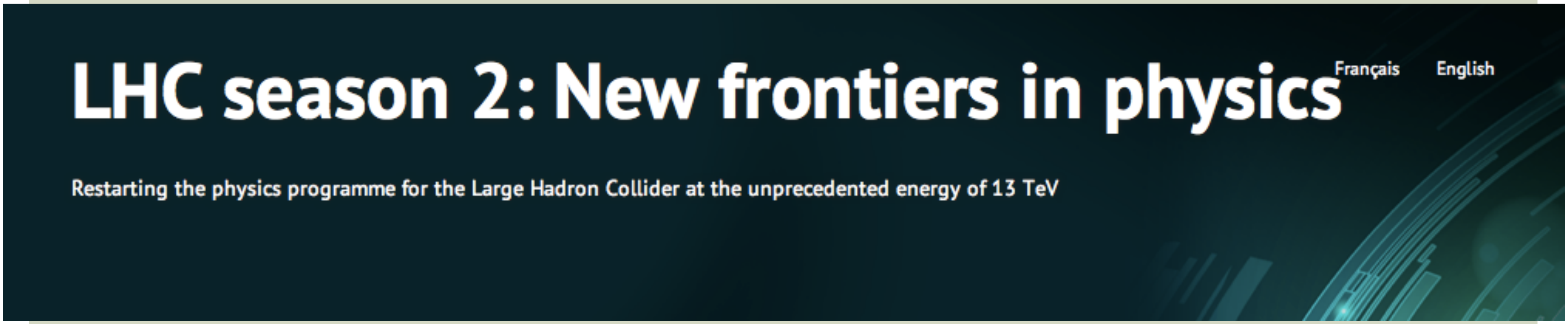
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-07/

AND NOW: RUN 2!

- We have now collected > 1 fb^{-1} of 13 TeV data
- Somewhat slower LHC start than expected, now running well.



H→ττ IN RUN 2



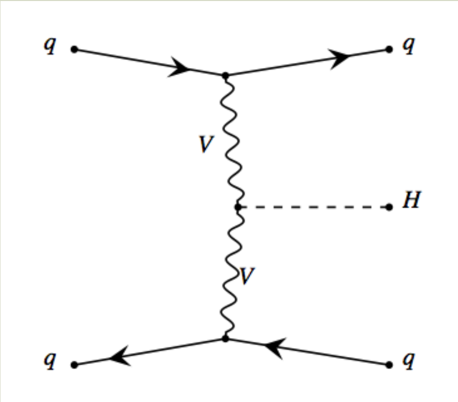
Now that H→ττ has been observed at the 5 sigma level, what are the goals for Run 2?

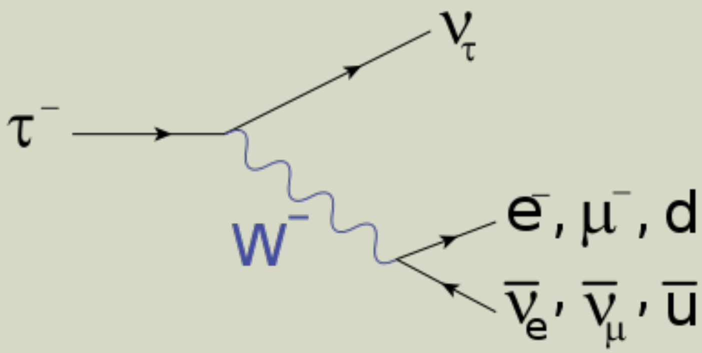
- Precision: H→ττ will be the most sensitive measurement of the H-fermion coupling.
- Properties: CP measurements with H→ττ, develop self-coupling analysis
- New Physics: h→aa → **2**τ2μ, H/A→ττ , H^{+-}→τν, HH→ττbb

HIGGS PROPERTIES MEASUREMENTS: CP-MIXING MEASURED IN H→ττ :

- In the Standard Model the Higgs is Spin 0 CP-even. Evidence for Spin-0 nature has been published.
- The Higgs could yet be a mixture of CP-even & CP-odd.
- In the H→ττ channel the CP can be measured from two sides: Production and Decay angles
- Production: Correlate jet and H decay angles in VBF
- Decay: In Higgs-Fermion coupling CP-even/odd components enter at tree level

Higgs VBF production: HVV vertex

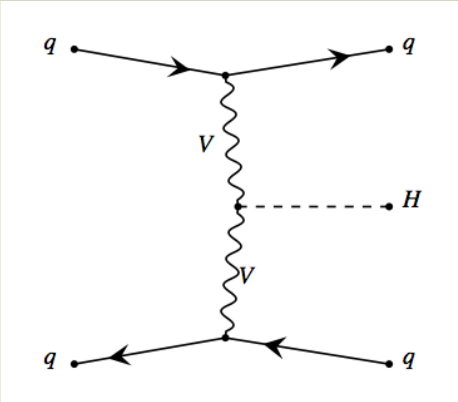


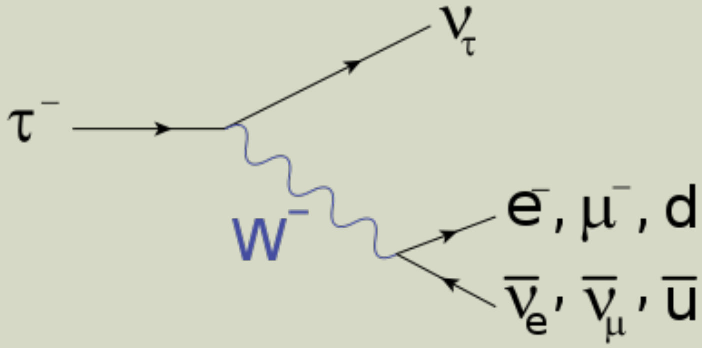


HIGGS PROPERTIES MEASUREMENTS: CP-MIXING MEASURED IN $H\rightarrow\tau\tau$:

- In the Standard Model the Higgs is Spin 0 CP-even. Evidence for Spin-0 H has been published.
- The Higgs could yet be a mixture of CP-even & CP-odd.
- Some theorize: CP-mixing suppressed in H-boson channels (CP odd only enters in loops). H-Fermion could be our portal to see BSM CP-mixing?
- In the $H\rightarrow\tau\tau$ channel the CP can be measured from two sides: Production and Decay angles
- Production: Correlate jet and H decay angles in VBF (H-Boson)
- Decay: In Higgs-Fermion coupling CP-even/odd components enter at tree level

Higgs VBF production: HVV vertex

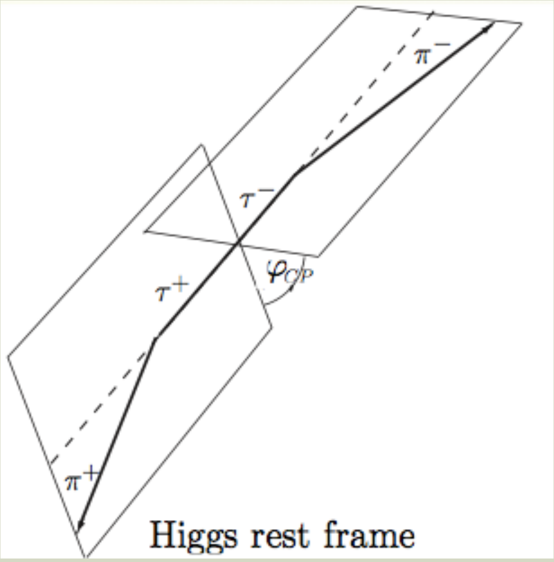




CP-MIXING MEASURED IN H→ττ DECAY:

- In H→ττ decay the spin of the Higgs is correlated to the spin of the tau.
- Measure polar angle distribution of the H-decay products (H-ff vertex) Will allow us to distinguish between CP-even, CP-odd, or CP-mixed states

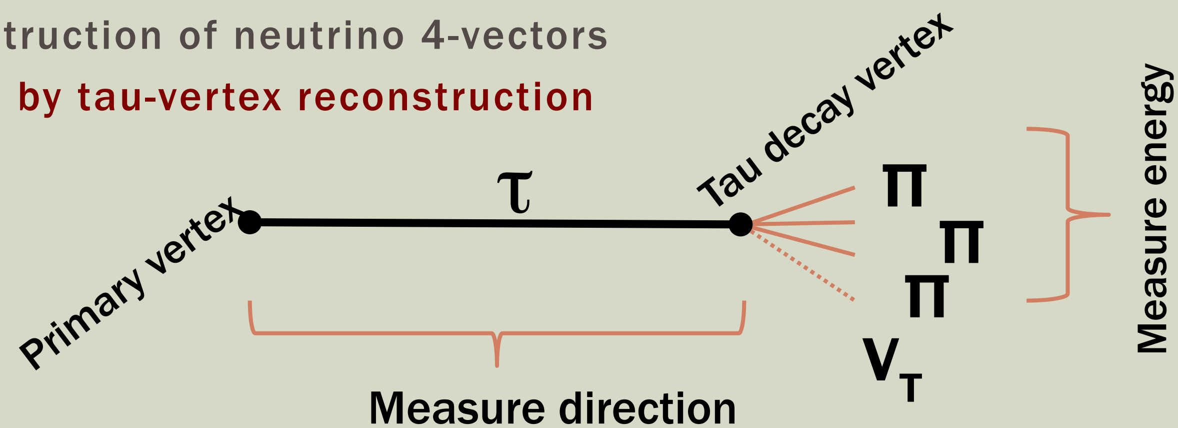
- Two strategies :
  - Via reconstruction of H rest frame: Acoplanarity between decay products in tautau rest frame
    - Requires reconstruction of neutrino 4-vectors
    - Could be helped by tau-vertex reconstruction
  - Via reconstruction of τ impact parameters: Angle between impact parameter vectors in $\pi\pi$ rest frame



CP-MIXING MEASURED IN $H \rightarrow \tau\tau$ DECAY:

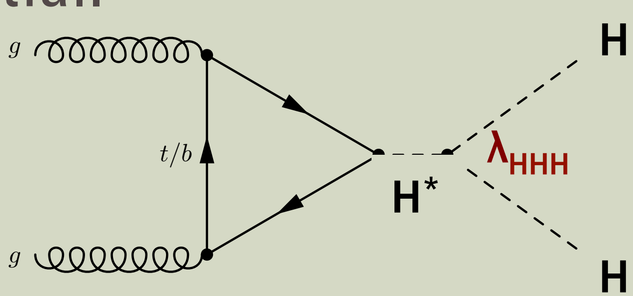
- In $H \rightarrow \tau\tau$ decay the spin of the Higgs is correlated to the spin of the tau.
- Measure polar angle distribution of the H-decay products (H-ff vertex) Will allow us to distinguish between CP-even, CP-odd, or CP-mixed states

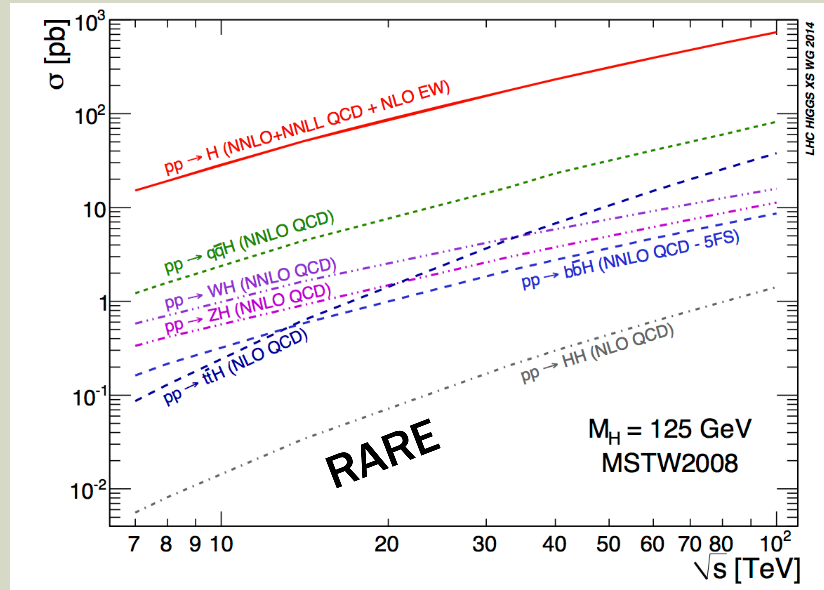
- Two strategies :
  - Via reconstruction of H rest frame: Acoplanarity between decay products in tautau rest frame
    - Requires reconstruction of neutrino 4-vectors
    - Could be helped by tau-vertex reconstruction



HH→ττbb

- The Higgs self-coupling will be an important measurement for Run 2 or 3 that will allow for reconstruction of the Higgs potential.





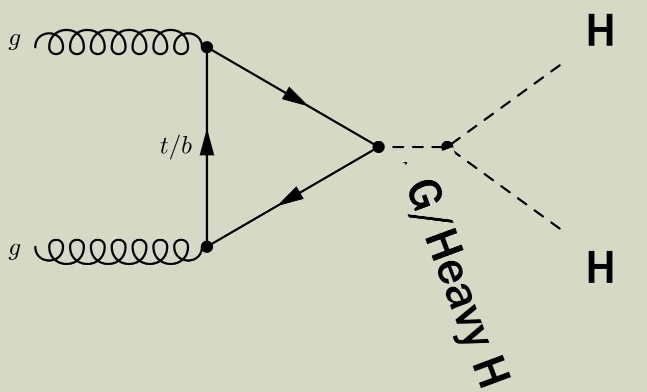
Triple Higgs Coupling

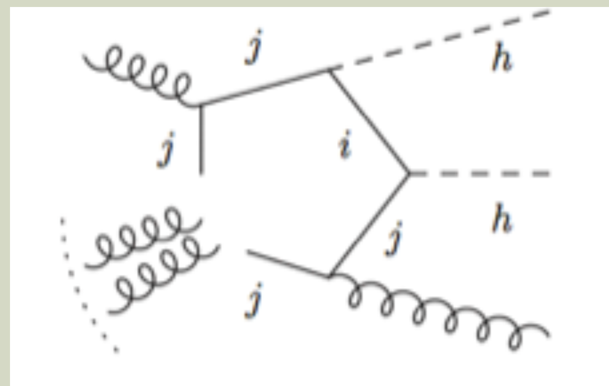
$$\lambda_{HHH} = 6\eta v = \frac{3m_H^2}{v}.$$

← ← Known values

HH→ττbb

- Higgs Pair production is also sensitive to a range of BSM models.





Non-resonant. theories modifying hhtt; composite Higgs, 4th generation models

Resonant enhancement:

- SUSY, H -> hh
- E-dim, G -> hh -> 4b [Gouzevitch et al. 1303.6636]
- Higgs portal [No, Ramsey-Musolf 1310.6035]

MSSM / NMSSM models: mixing effects due to presence of second Higgs doublet can generate 15% to 25% deviations from the Standard Model of λ_{HHH}.

Searches have begun in bbbb, bbgammagamma, bbtautau channel.

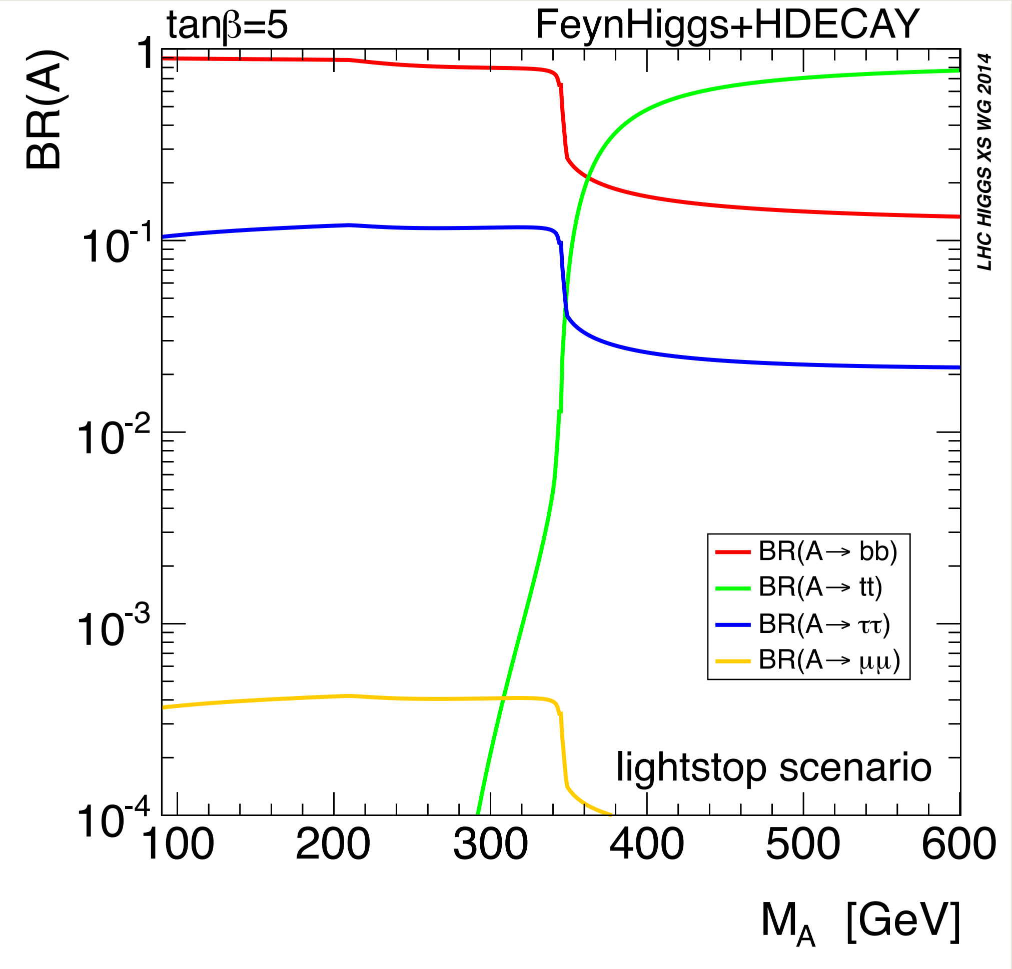
The ττbb is sensitive to a wide mass range compared to the other channels

SUPERSYMMETRY SEARCHES

- In many supersymmetric models Higgs has a high branching ratio

- Active Run 2 searches include:
- A/H → ττ
- nMSSM H→aa→μμττ;
- A->ZH->bbtautau
- H→τμ (LeptonFlavorViolation)

Example susy scenario.



SUMMARY

- $H \rightarrow \tau\tau$ seen at ATLAS and CMS in Run 1.
- New LHC combination gives 5.5σ observation of $H \rightarrow \tau\tau$
- Lots ahead in Run 2
- $H \rightarrow \tau\tau$ will be the best direct measurement of the Higgs to fermion coupling
- Unique CP measurement opportunities
- Lots of places to look for BSM physics

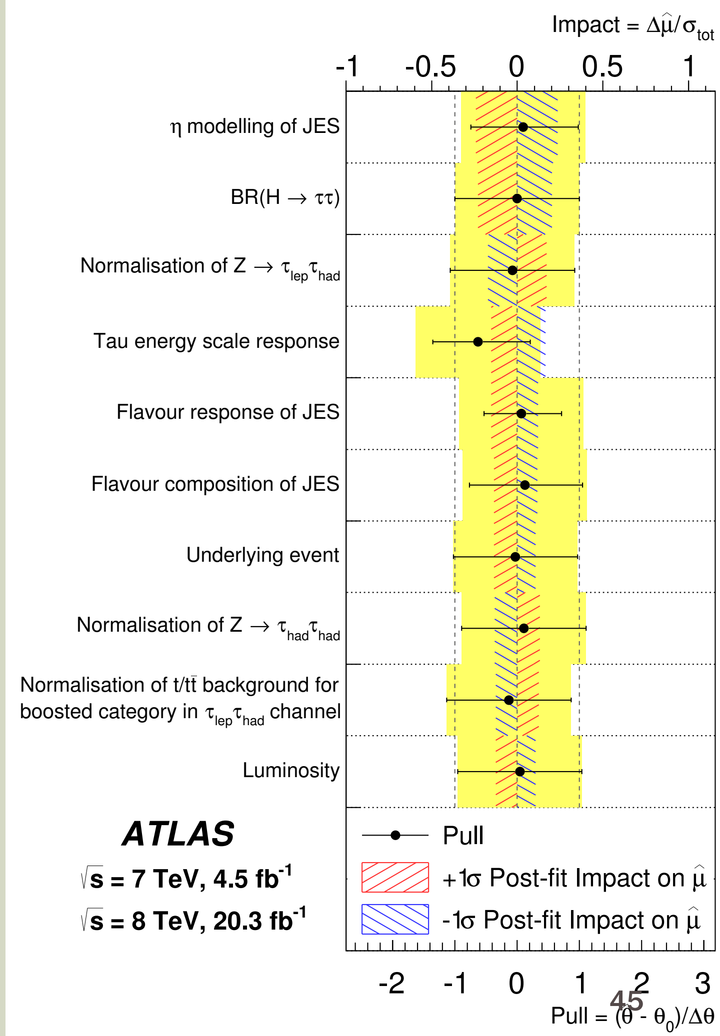
BACKUP

LEADING SYSTEMATIC UNCERTAINTIES

- Determination of Tau Energy Scale
- Normalization of backgrounds
- Theory uncertainties: modeling of underlying event and parton showering

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

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	$^{+0.43}_{-0.37}$



SYSTEMATIC UNCERTAINTIES

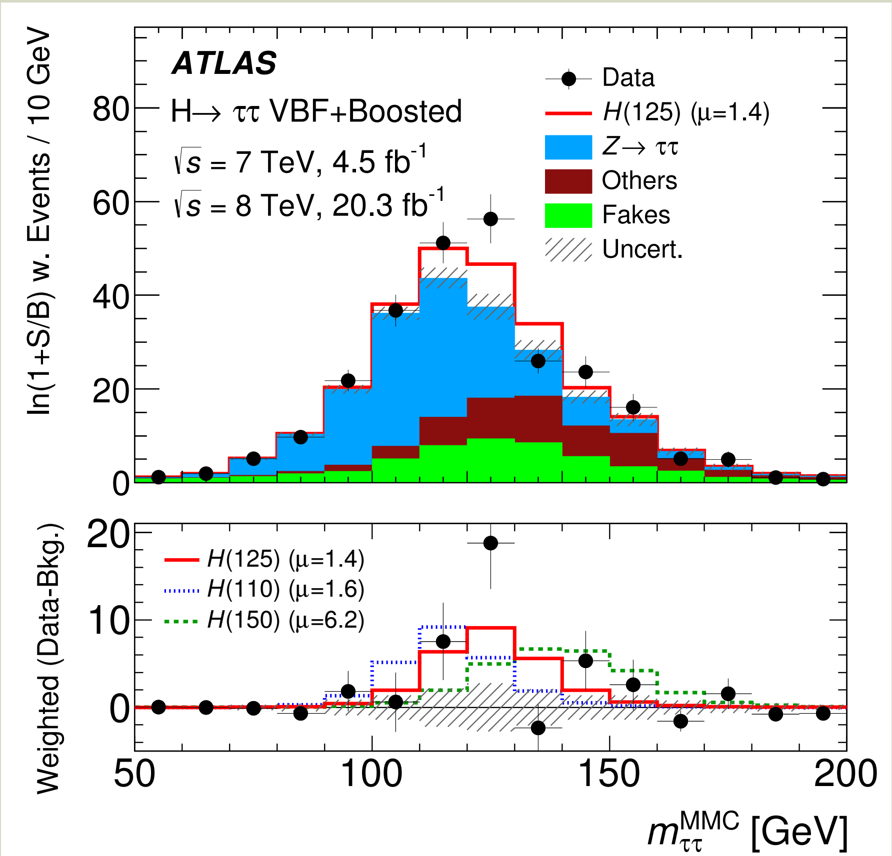
Source	Relative signal and background variations [%]											
	$\tau_{lep}\tau_{lep}$ VBF		$\tau_{lep}\tau_{lep}$ Boosted		$\tau_{lep}\tau_{had}$ VBF		$\tau_{lep}\tau_{had}$ Boosted		$\tau_{had}\tau_{had}$ VBF		$\tau_{had}\tau_{had}$ Boosted	
	S	B	S	B	S	B	S	B	S	B	S	B
Experimental												
Luminosity	± 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_T^{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	–

MC SAMPLES

Signal ($m_H = 125$ GeV)	MC generator	$\sigma \times$BR [pb] $\sqrt{s} = 8$ TeV		
ggF, $H \to \tau\tau$	POWHEG [36–39] + PYTHIA8 [40]	1.22	NNLO+NNLL	[42–47, 78]
VBF, $H \to \tau\tau$	POWHEG + PYTHIA8	0.100	(N)NLO	[51–53, 78]
WH, $H \to \tau\tau$	PYTHIA8	0.0445	NNLO	[56, 78]
ZH, $H \to \tau\tau$	PYTHIA8	0.0262	NNLO	[56, 78]

Background	MC generator	$\sigma \times$BR [pb] $\sqrt{s} = 8$ TeV		
$W(\to \ell\nu)$, $(\ell = e, \mu, \tau)$	ALPGEN [71]+PYTHIA8	36800	NNLO	[79, 80]
$Z/\gamma^*(\to \ell\ell)$, 60 GeV$< m_{\ell\ell} < 2$ TeV	ALPGEN+PYTHIA8	3910	NNLO	[79, 80]
$Z/\gamma^*(\to \ell\ell)$, 10 GeV$< m_{\ell\ell} < 60$ GeV	ALPGEN+HERWIG [81]	13000	NNLO	[79, 80]
VBF $Z/\gamma^*(\to \ell\ell)$	SHERPA [82]	1.1	LO	[82]
$t\bar{t}$	POWHEG + PYTHIA8	$253^\dagger$	NNLO+NNLL	[83–88]
Single top : Wt	POWHEG + PYTHIA8	$22^\dagger$	NNLO	[89]
Single top : s-channel	POWHEG + PYTHIA8	$5.6^\dagger$	NNLO	[90]
Single top : t-channel	AcerMC [74]+PYTHIA6 [67]	$87.8^\dagger$	NNLO	[91]
$q\bar{q} \to WW$	ALPGEN+HERWIG	$54^\dagger$	NLO	[92]
$gg \to WW$	GG2WW [73]+HERWIG	$1.4^\dagger$	NLO	[73]
WZ, ZZ	HERWIG	$30^\dagger$	NLO	[92]
$H \to WW$	same as for $H \to \tau\tau$ signal	$4.7^\dagger$		

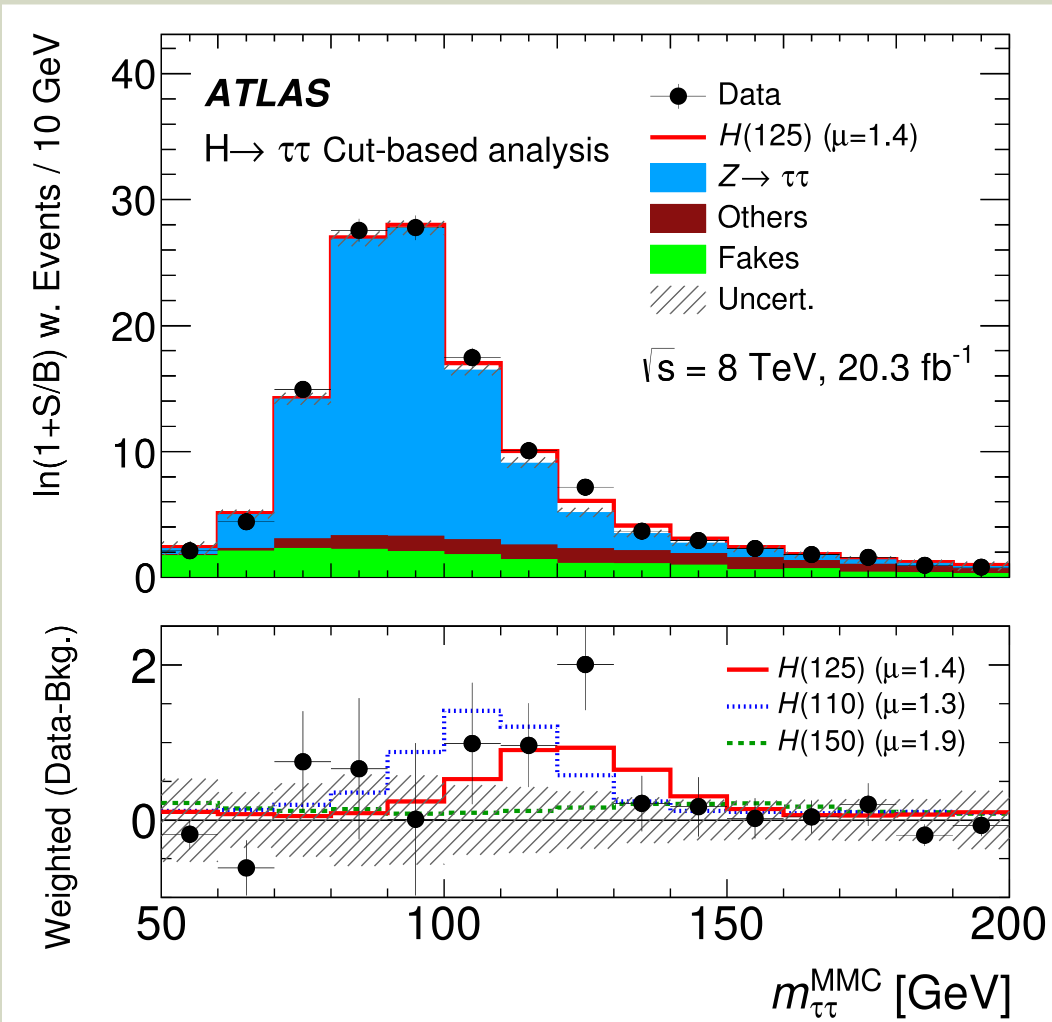
COMPATIBILITY WITH M_H=125 GEV

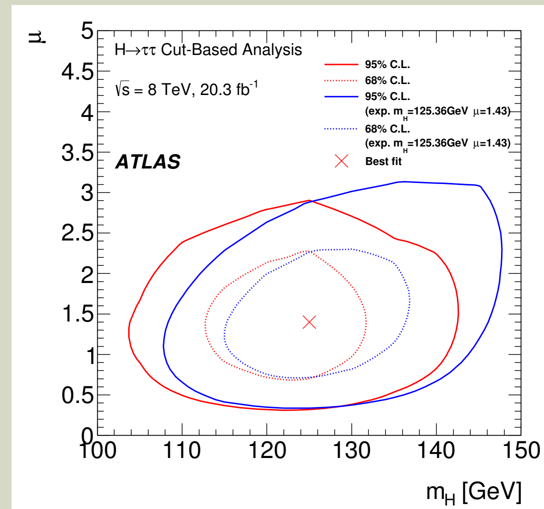


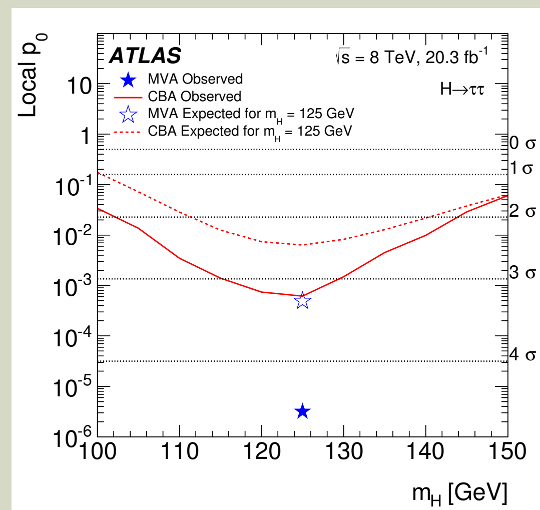
Signals at M_H=110, 125 and 150 GeV are shown at best fit μ; post-fit background normalizations

- This analysis was not designed to measure the H mass. But we can look at how well the excess matches various mass hypotheses
- 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

CUT-BASED CROSS CHECK







YIELDS FOR TOP 3 BDT BINS

LepLep

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
$Z \to \tau\tau$	589 ± 24	9.7 ± 1.0	1.99 ± 0.34	2190 ± 80	33.7 ± 2.3	11.3 ± 1.3
Fake background	57 ± 12	1.2 ± 0.6	0.55 ± 0.35	100 ± 40	2.9 ± 1.3	0.6 ± 0.4
Top	131 ± 19	0.9 ± 0.4	0.89 ± 0.33	380 ± 50	9.8 ± 2.1	4.3 ± 1.0
Others	196 ± 17	3.0 ± 0.4	1.7 ± 0.6	400 ± 40	8.3 ± 1.6	2.6 ± 0.7
ggF: $H \to WW$ ($m_H = 125$ GeV)	2.9 ± 0.8	0.12 ± 0.04	0.11 ± 0.04	7.7 ± 2.3	0.43 ± 0.13	0.24 ± 0.08
VBF: $H \to WW$	3.4 ± 0.4	0.40 ± 0.06	0.38 ± 0.08	1.65 ± 0.18	0.102 ± 0.017	< 0.1
WH : $H \to WW$	< 0.1	< 0.1	< 0.1	0.90 ± 0.10	< 0.1	< 0.1
ZH : $H \to WW$	< 0.1	< 0.1	< 0.1	0.59 ± 0.07	< 0.1	< 0.1
ggF: $H \to \tau\tau$ ($m_H = 125GeV$)	9.8 ± 3.4	0.73 ± 0.26	0.35 ± 0.14	21 ± 8	2.4 ± 0.9	1.3 ± 0.5
VBF: $H \to \tau\tau$	13.3 ± 4.0	2.7 ± 0.7	3.3 ± 0.9	5.5 ± 1.5	0.95 ± 0.26	0.49 ± 0.13
WH : $H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	3.8 ± 1.0	0.44 ± 0.12	0.22 ± 0.06
ZH : $H \to \tau\tau$	0.14 ± 0.04	< 0.1	< 0.1	2.0 ± 0.5	0.21 ± 0.06	0.113 ± 0.031
Total background	980 ± 22	15.4 ± 1.8	5.6 ± 1.4	3080 ± 50	55 ± 4	19.2 ± 2.1
Total signal	24 ± 6	3.5 ± 0.9	3.6 ± 1.0	33 ± 10	4.0 ± 1.2	2.1 ± 0.6
Data	1014	16	11	3095	61	20

LepHad

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	1680 ± 50	8.2 ± 0.9	5.2 ± 0.7	5640 ± 160	51.0 ± 2.5	22.3 ± 1.8
$Z \to \tau\tau$	877 ± 29	7.6 ± 0.9	4.2 ± 0.7	6210 ± 170	57.5 ± 2.8	41.1 ± 3.2
Top	82 ± 15	0.3 ± 0.4	0.5 ± 0.4	380 ± 50	12 ± 4	4.8 ± 1.5
$Z \to \ell\ell(\ell \to \tau_{\text{had}})$	54 ± 26	1.0 ± 0.7	0.30 ± 0.28	200 ± 50	13 ± 4	8.6 ± 3.5
Diboson	63 ± 11	1.0 ± 0.4	0.48 ± 0.20	430 ± 40	9.7 ± 2.2	4.7 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125GeV$)	16 ± 6	1.0 ± 0.4	1.2 ± 0.6	60 ± 20	9.2 ± 3.2	10.1 ± 3.4
VBF: $H \to \tau\tau$	31 ± 8	4.5 ± 1.1	9.1 ± 2.2	16 ± 4	2.5 ± 0.6	2.9 ± 0.7
WH : $H \to \tau\tau$	0.6 ± 0.4	< 0.1	< 0.1	9.1 ± 2.3	1.3 ± 0.4	1.9 ± 0.5
ZH : $H \to \tau\tau$	0.16 ± 0.07	< 0.1	< 0.1	4.6 ± 1.2	0.77 ± 0.20	0.93 ± 0.24
Total background	2760 ± 40	18.1 ± 2.3	10.7 ± 2.7	12860 ± 110	143 ± 6	82 ± 6
Total signal	48 ± 12	5.5 ± 1.3	10.3 ± 2.5	89 ± 26	14 ± 4	16 ± 4
Data	2830	22	21	12952	170	92

YIELDS FOR TOP BDT BINS

HadHad

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	370 ± 18	2.3 ± 0.9	0.57 ± 0.29	645 ± 26	35 ± 4	0.65 ± 0.33
Others	37 ± 5	0.67 ± 0.22	< 0.1	89 ± 11	15.9 ± 2.0	0.92 ± 0.22
$Z \to \tau\tau$	475 ± 16	0.6 ± 0.7	0.6 ± 0.4	2230 ± 70	93 ± 4	5.4 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125GeV$)	8.0 ± 2.7	0.67 ± 0.23	0.53 ± 0.20	21 ± 8	9.1 ± 3.3	1.6 ± 0.6
VBF: $H \to \tau\tau$	12.0 ± 3.1	1.8 ± 0.5	3.4 ± 0.9	6.3 ± 1.6	2.8 ± 0.7	0.52 ± 0.13
$WH : H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	4.0 ± 1.1	1.9 ± 0.5	0.41 ± 0.11
$ZH : H \to \tau\tau$	0.16 ± 0.04	< 0.1	< 0.1	2.4 ± 0.6	1.13 ± 0.30	0.23 ± 0.06
Total background	883 ± 18	3.6 ± 1.3	1.2 ± 1.0	2960 ± 50	143 ± 6	7.0 ± 1.8
Total signal	20 ± 5	2.5 ± 0.6	3.9 ± 1.0	34 ± 10	15 ± 4	2.7 ± 0.8
Data	892	5	6	3020	161	10