Measurements of fermionic decays of the Standard Model Higgs boson at ATLAS and CMS

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Acknowledgements:
Jessica Liebal - University of Bonn
on behalf of ATLAS collaboration

1st October 2014
Higgs Couplings 2014 - Torino

Overview

- Introduction (KG)
- $H \rightarrow \tau\tau$ (R)
- $H \rightarrow \mu\mu$ (R)
- VH, $H \rightarrow bb$ (KG)
- ttH decays (KG)
- Summary of results (R)

2012 Higgs Discovery

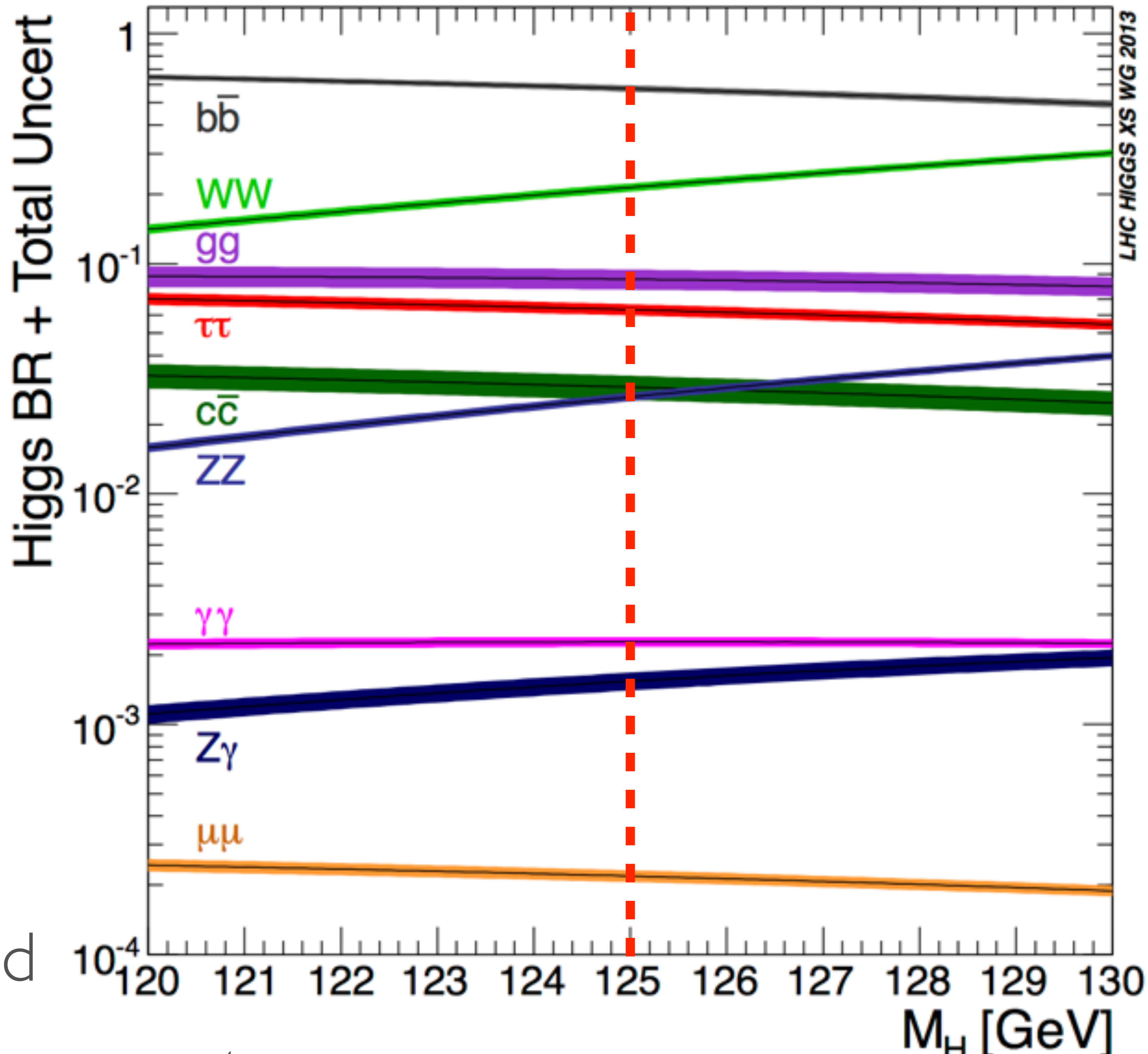
- Higgs boson discovered in **$H \rightarrow ZZ^*$**, **$H \rightarrow \gamma\gamma$** and **$H \rightarrow WW^*$** decay modes
- Mass, **m_H = ~125.6 GeV**
- Quantum numbers, **$J^P = 0^+$**

- ➠ So far, everything consistent with **SM Higgs Boson**
- What about its (direct) coupling to fermions?
  - → *Later results include direct fermion couplings, which is what this talk will discuss*

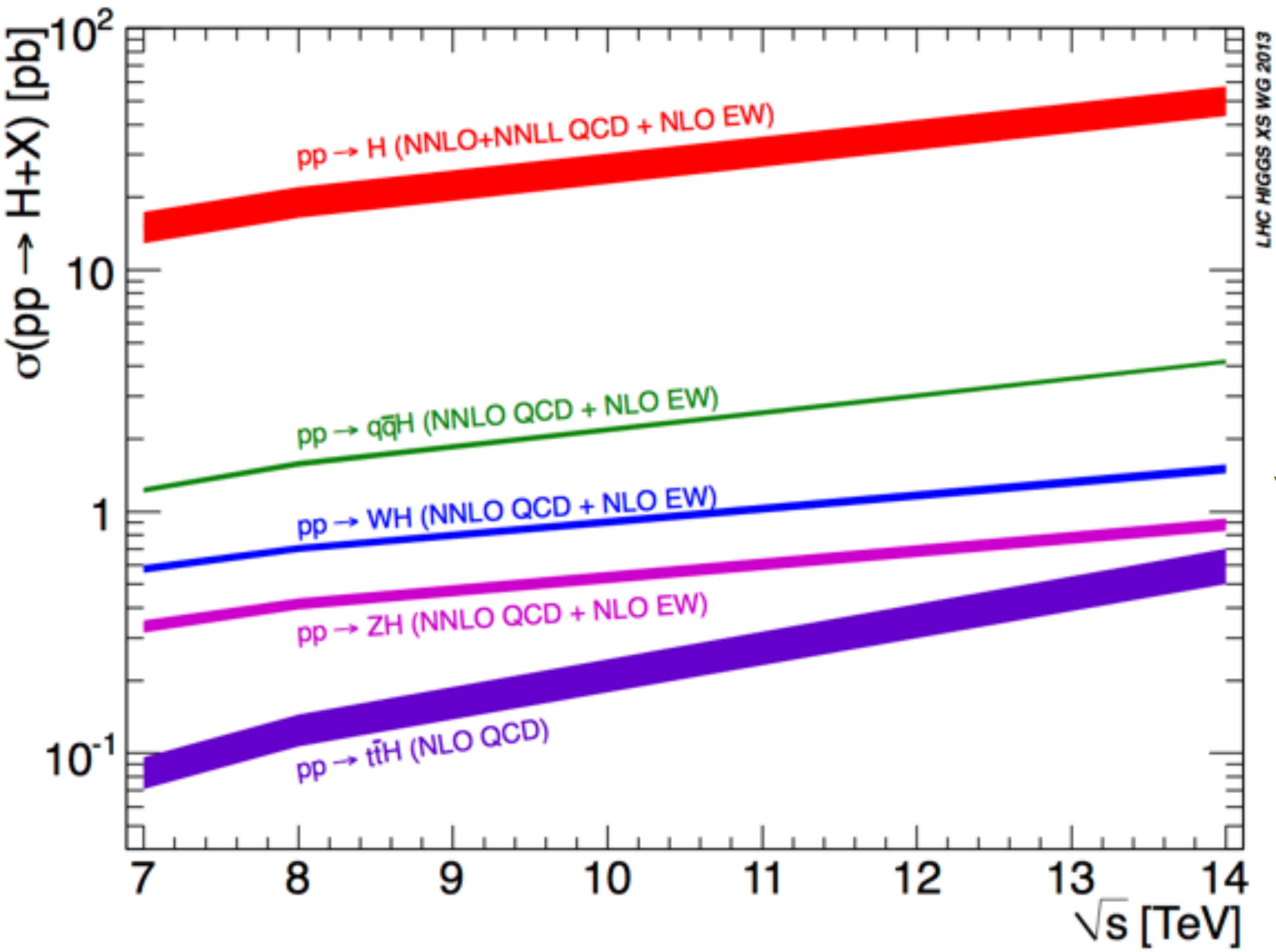
HIGGS DECAY

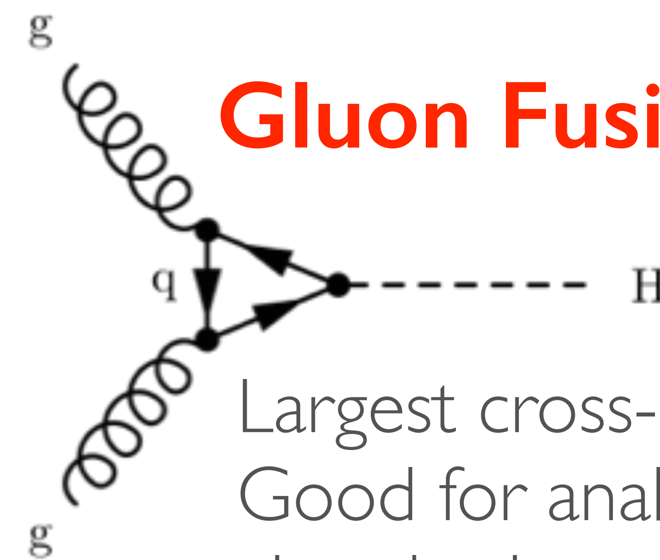
- The most important fermionic decay channels:

1. H→bb
   - Large BR
   - Large background
2. H→**ττ**
   - Moderate BR
   - Better S/B
3. H→μμ
   - Small BR
   - Narrow peak on large DY background



HIGGS PRODUCTION - I

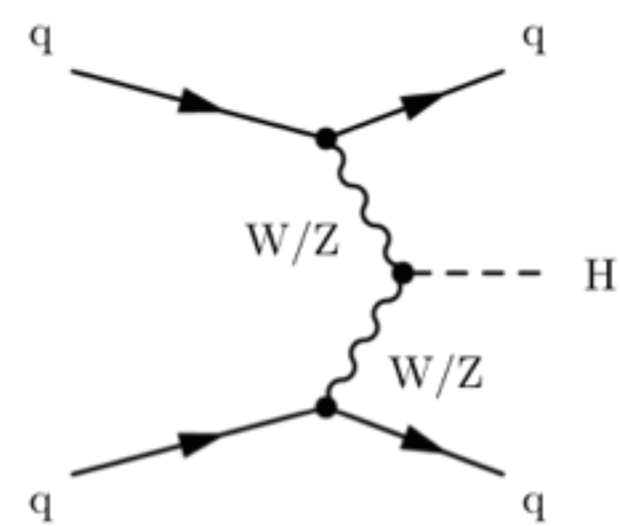




Gluon Fusion (ggF)

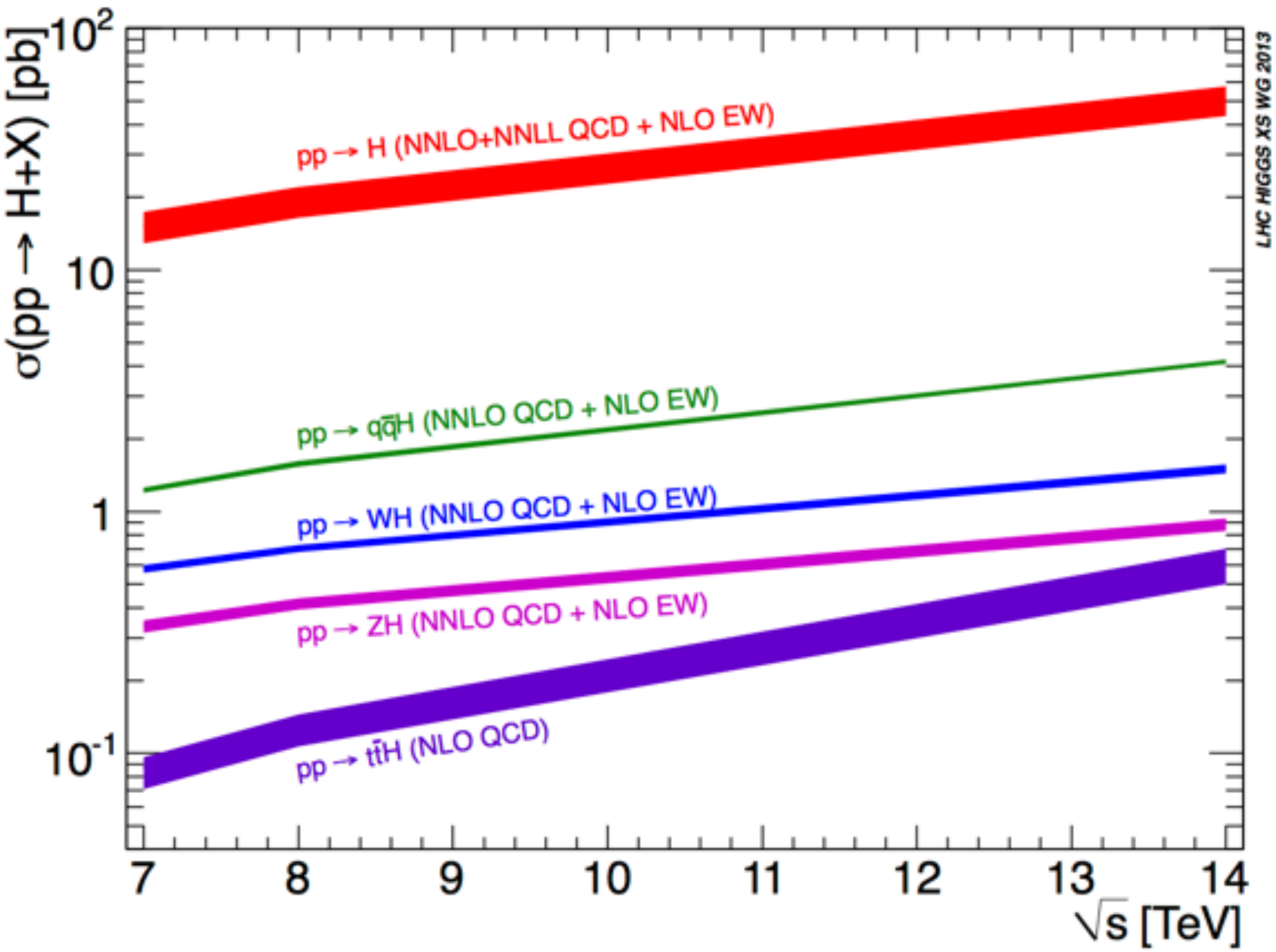
Largest cross-section. Good for analysis with already clean final states

Vector Boson Fusion (VBF)

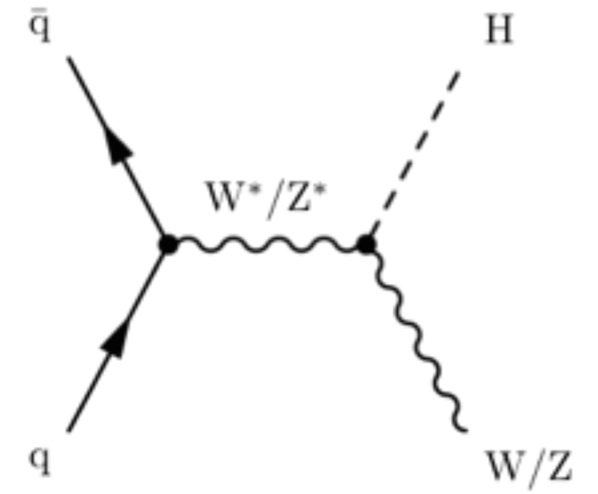


Unique signature with forward jets exploited by e.g. $H\to\tau\tau$

HIGGS PRODUCTION - II

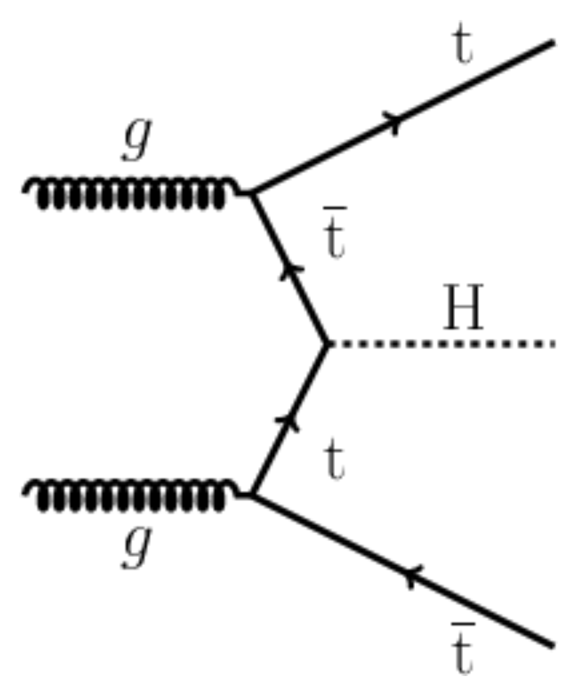


Associate Production (VH)



Unique signature with lepton and neutrino exploited by e.g. H→bb

ttH



Unique signature with tops exploited by various Higgs decay modes

$H \rightarrow \tau\tau$

directly testing the
fermion couplings - 1

arXiv:1401.5041
on JHEP

5 fb^{-1} @7TeV + 20 fb^{-1} @8TeV

ATLAS-CONF-2013-108

20 fb^{-1} @8TeV

7TeV analysis being finalised

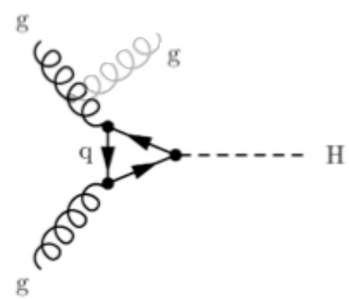
mind the logos
CMS on the left, ATLAS on the right
throughout the rest of the talk

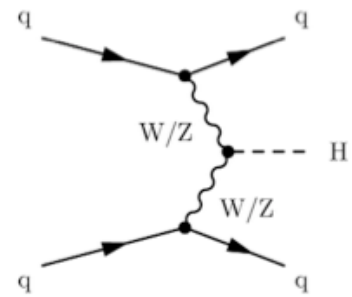
ANALYSIS STRATEGIES

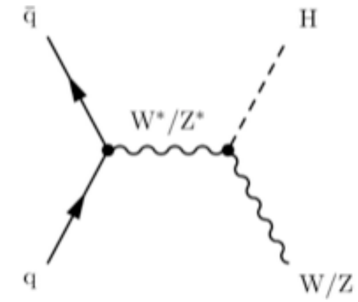
- **search in m_H 90-160 GeV range (not 125 GeV specific)**
- **signal extraction from different discriminators depending on the channel**
  - **$l\tau_h$, $\tau_h\tau_h$, eμ, ZH** di-tau invariant mass **$m_{\tau\tau}$** (SVfit algorithm)
  - **WH** di-tau visible mass
  - **μμ, ee** BDT output
- **all categories are simultaneously fit:**
  - some nuisances are correlated
  - low S/B categories provide in situ calibrations

- **search for the SM-like Higgs at m_H = 125 GeV**
- **loose preselection + signal extraction from a BDT discriminator comprising:**
  - Resonance properties: $m_{\tau\tau}$, $\Delta R_{\tau\tau}$
  - VBF topology: m_{jj}, $\Delta\eta_{jj}$, etc
  - Event activity: Scalar & vector p_T-sum
  - Event topology: m_T, object centralities, $p_T(\tau_1)/p_T(\tau_2)$, etc
- **all categories are simultaneously fit**
  - background normalisations from low S/B sidebands

CATEGORISATION







0/1 jet	2 jet (VBF)	VH

0 jet		1 jet		2 jet (VBF tag)	
low τ p_T	high τ p_T	low boost	high boost	loose	tight
$H \rightarrow \mu\tau_h, e\tau_h, \tau_h\tau_h, e\mu, \mu\mu, ee$					

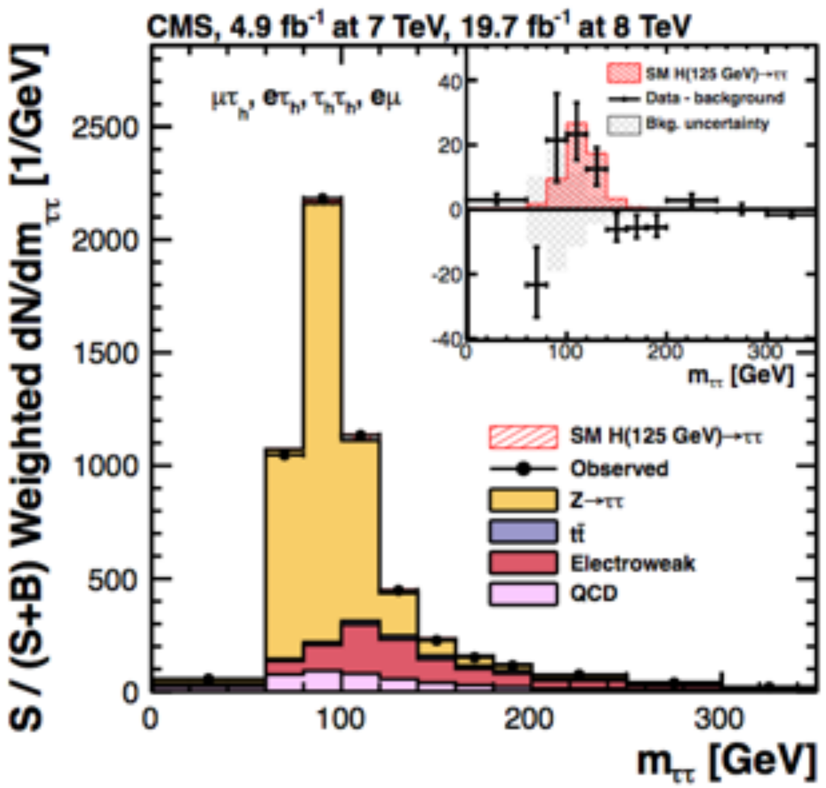
ZH	WH
$Z \rightarrow ee/\mu\mu$ $H \rightarrow \mu\tau_h, e\tau_h, \tau_h\tau_h, e\mu$	$W \rightarrow e\nu_e/\mu\nu_\mu$ $H \rightarrow \mu\tau_h, e\tau_h, \tau_h\tau_h$

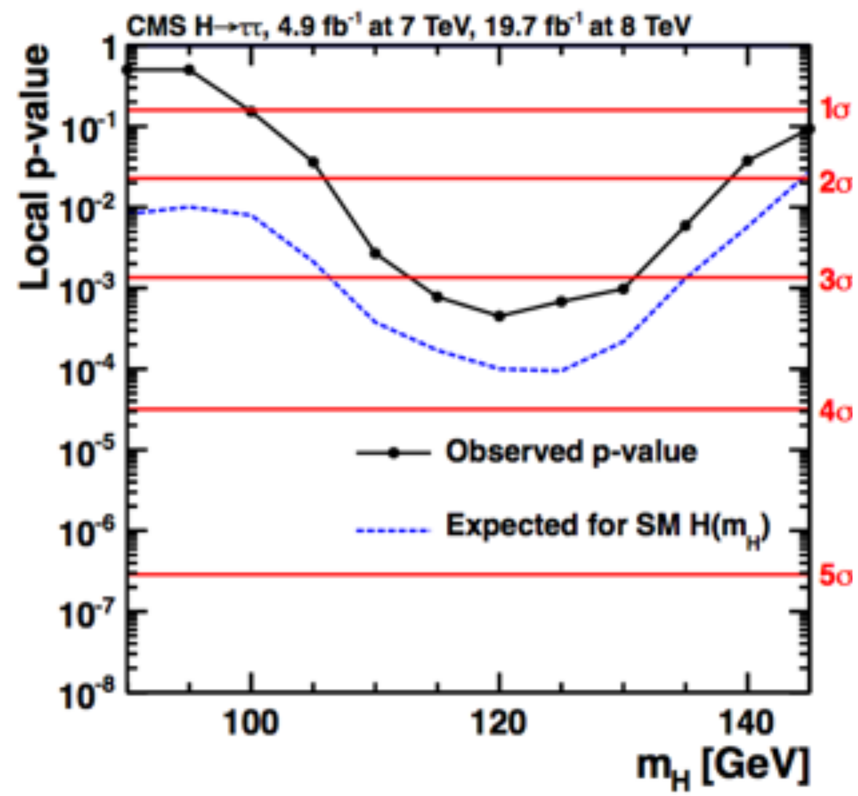
Boosted (Large Higgs p_T)	VBF (VBF tag)
$H \rightarrow \mu\tau_h, e\tau_h, \tau_h\tau_h, e\mu, \mu\mu, ee$	

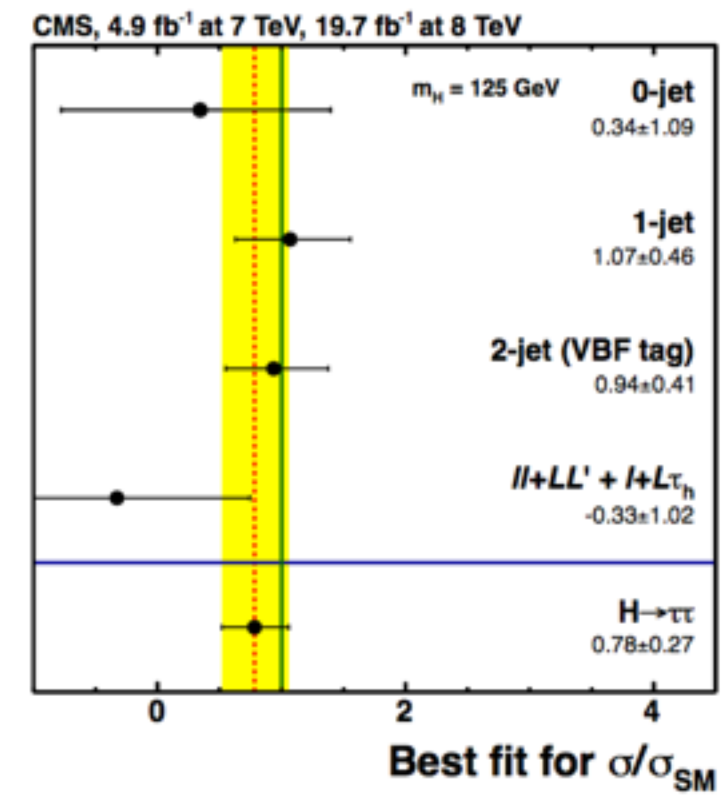
- addresses different Higgs production modes, including VH
- complex uncertainty model
- VBF tight has low ggH contamination

- broad categories definition
- the BDT applied on top of the categories sorts the events by sensitivity

CMS RESULTS





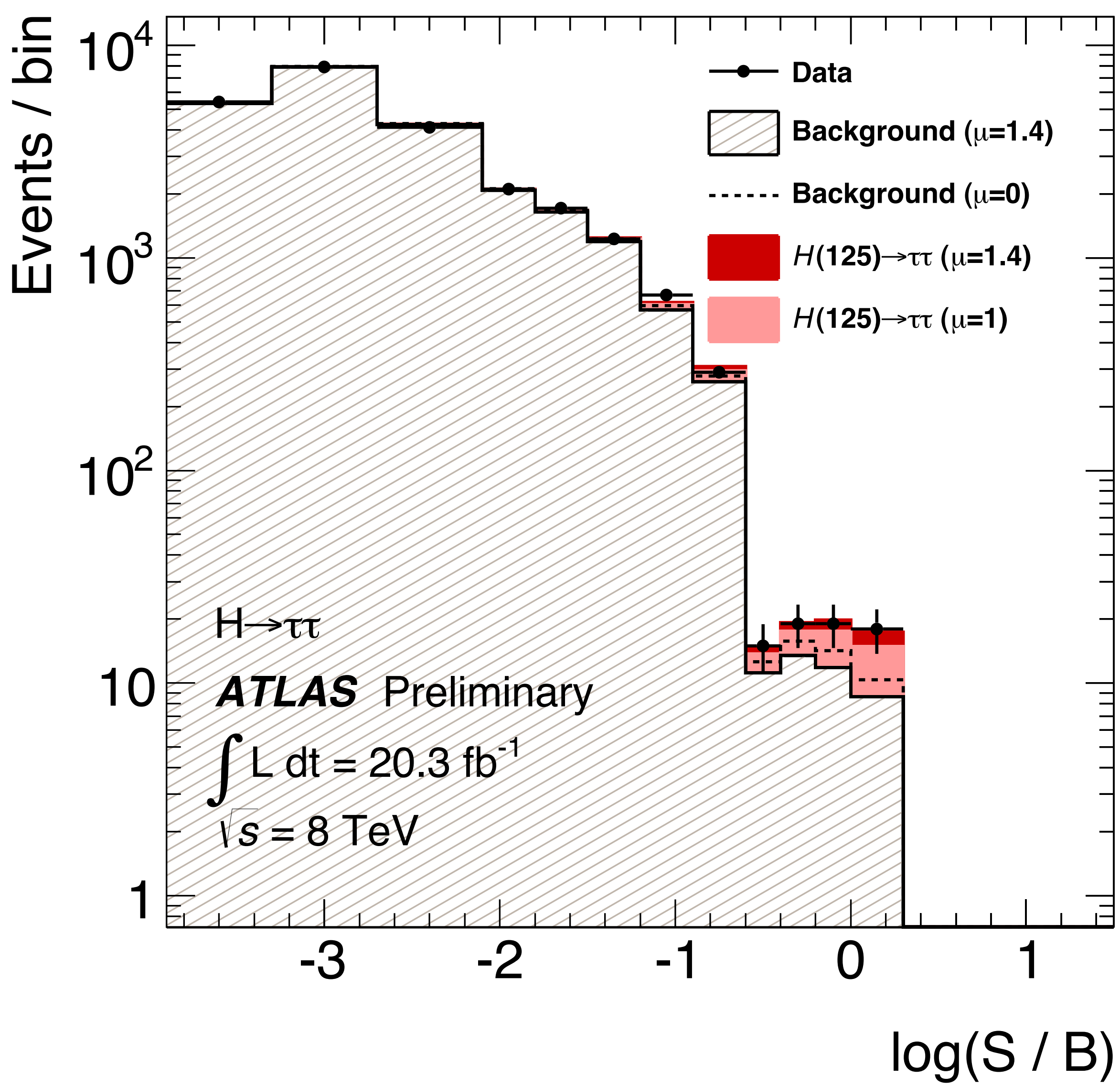


significant excess around m_H 125 GeV

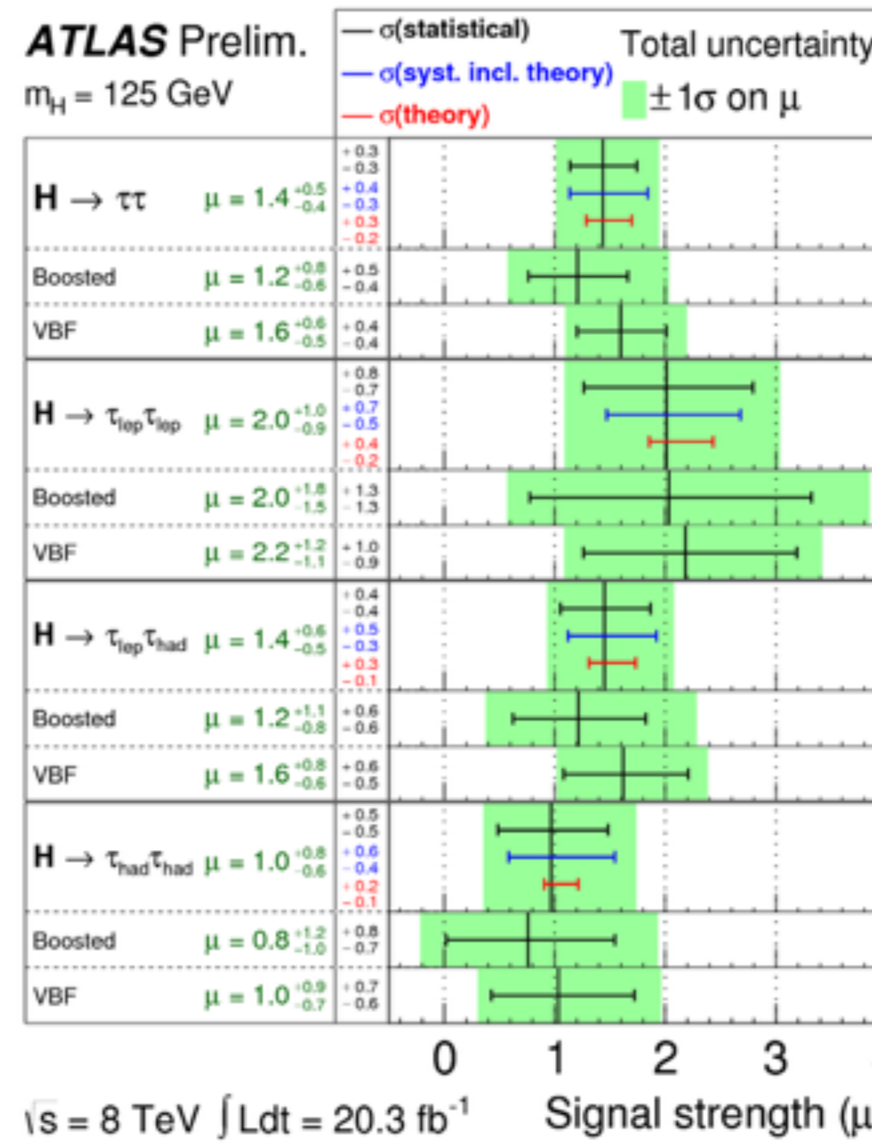
signal strength for m_H = 125 GeV
μ = 0.78 ± 0.27

3.7 σ expected 3.2 σ observed
for SM Higgs boson at m_H = 125 GeV

ATLAS Results



significant excess in the sensitive BDT bins
excess evident in all channels

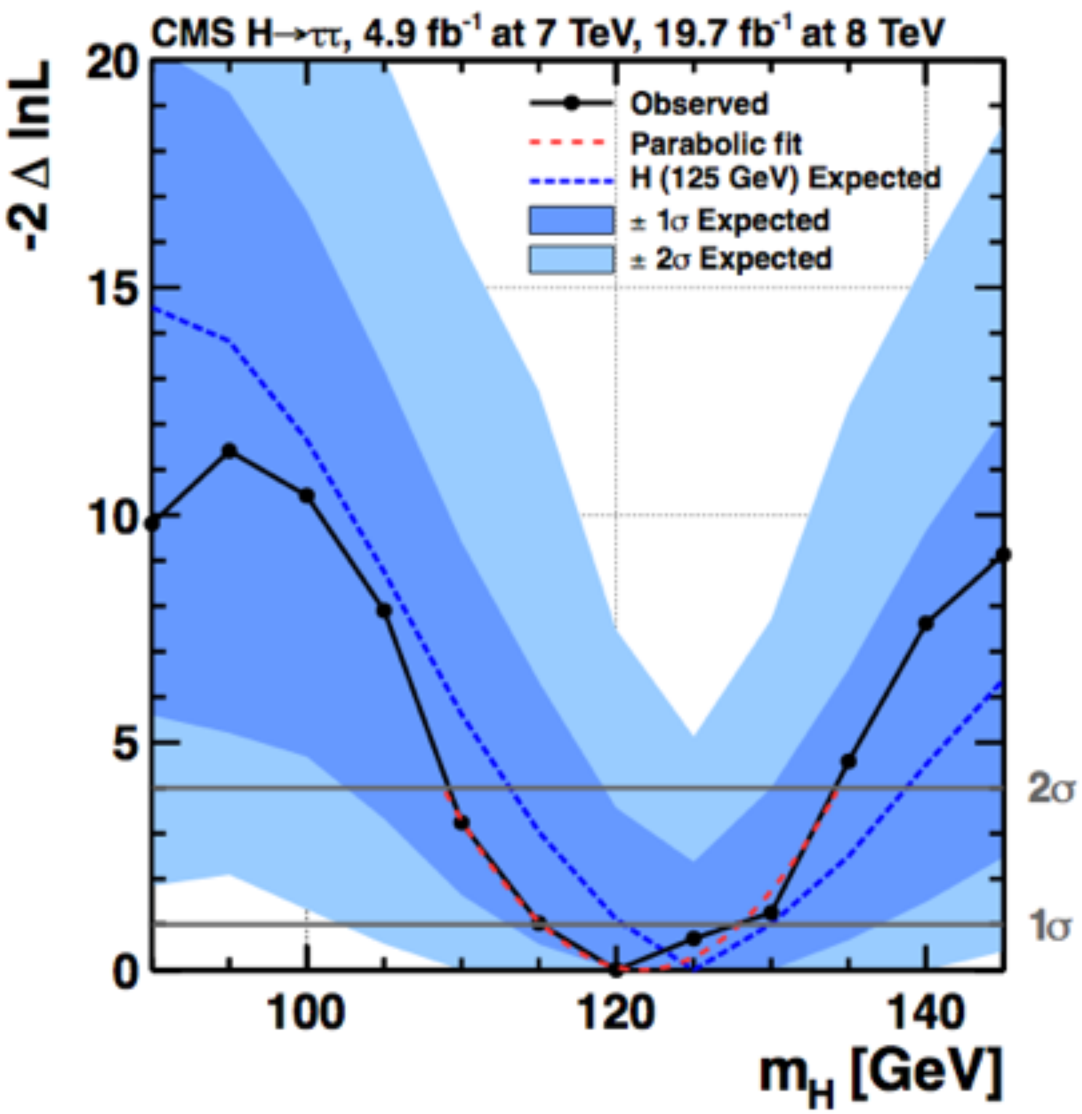


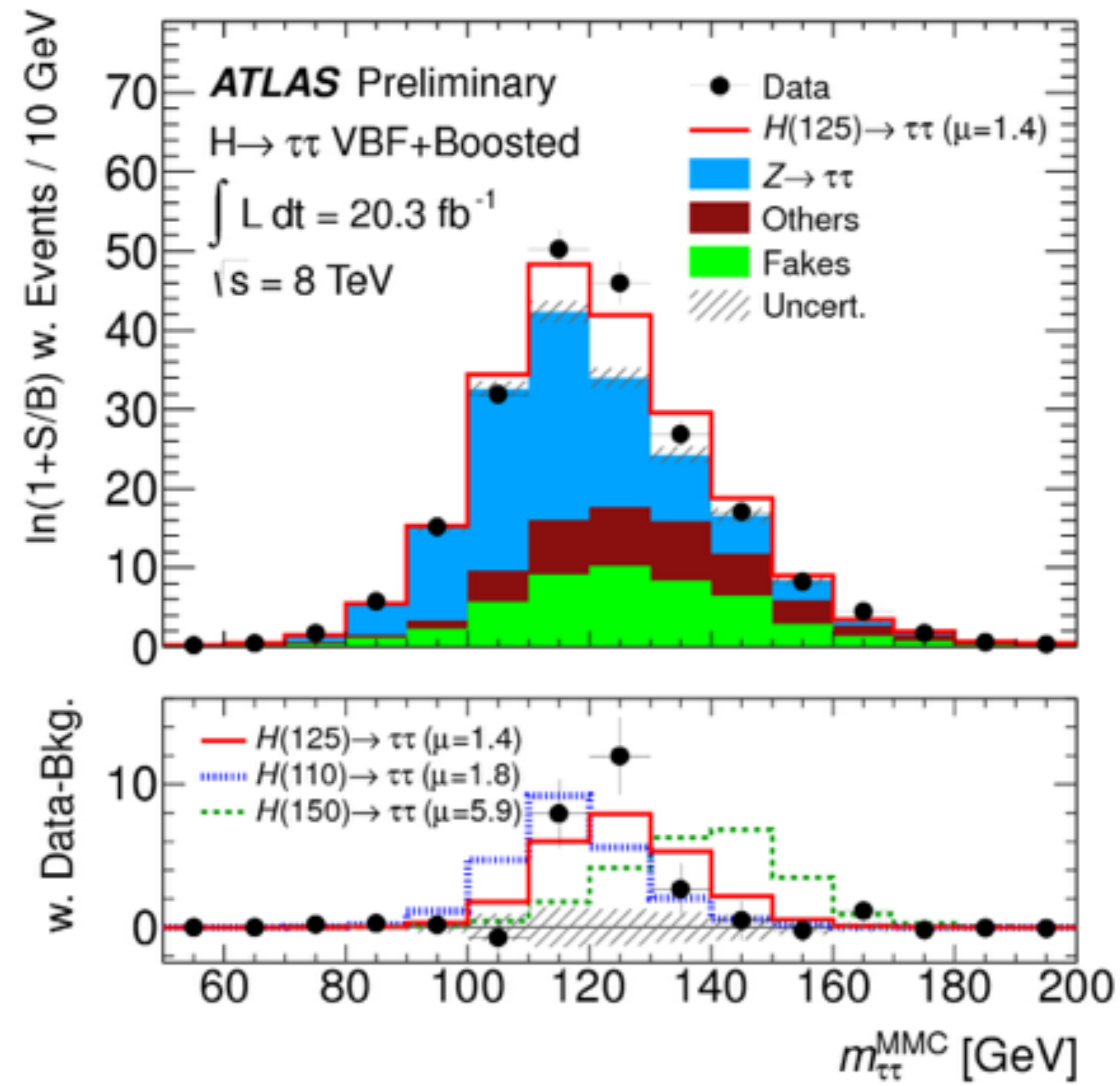
signal strength for m_H = 125 GeV

$\mu = 1.4^{+0.5}_{-0.4}$

3.2 σ expected 4.1 σ observed
for SM Higgs boson at m_H = 125 GeV

Higgs mass compatibility



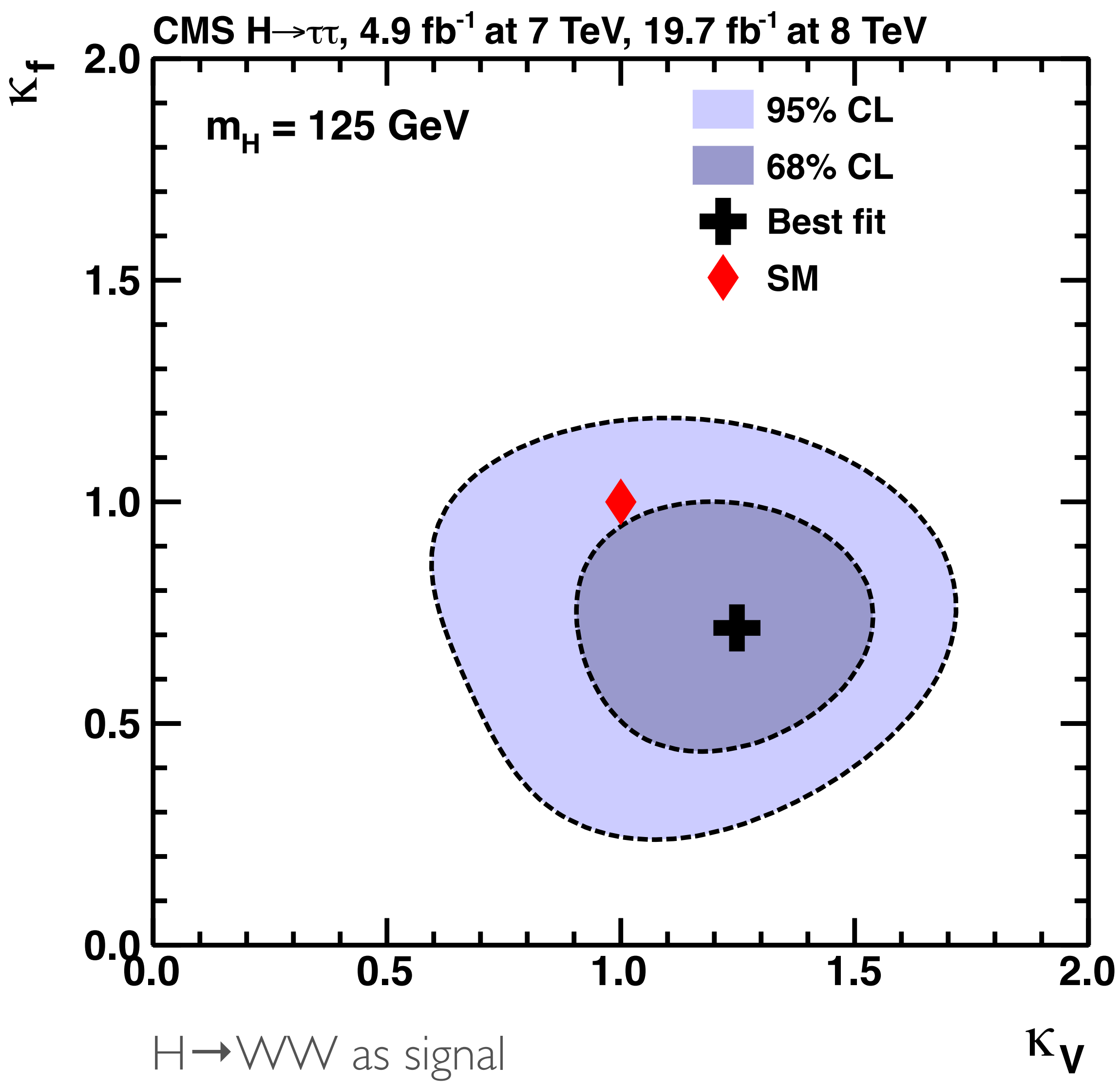


- analysis not 125-specific
- best fit mass 122 ± 7 GeV

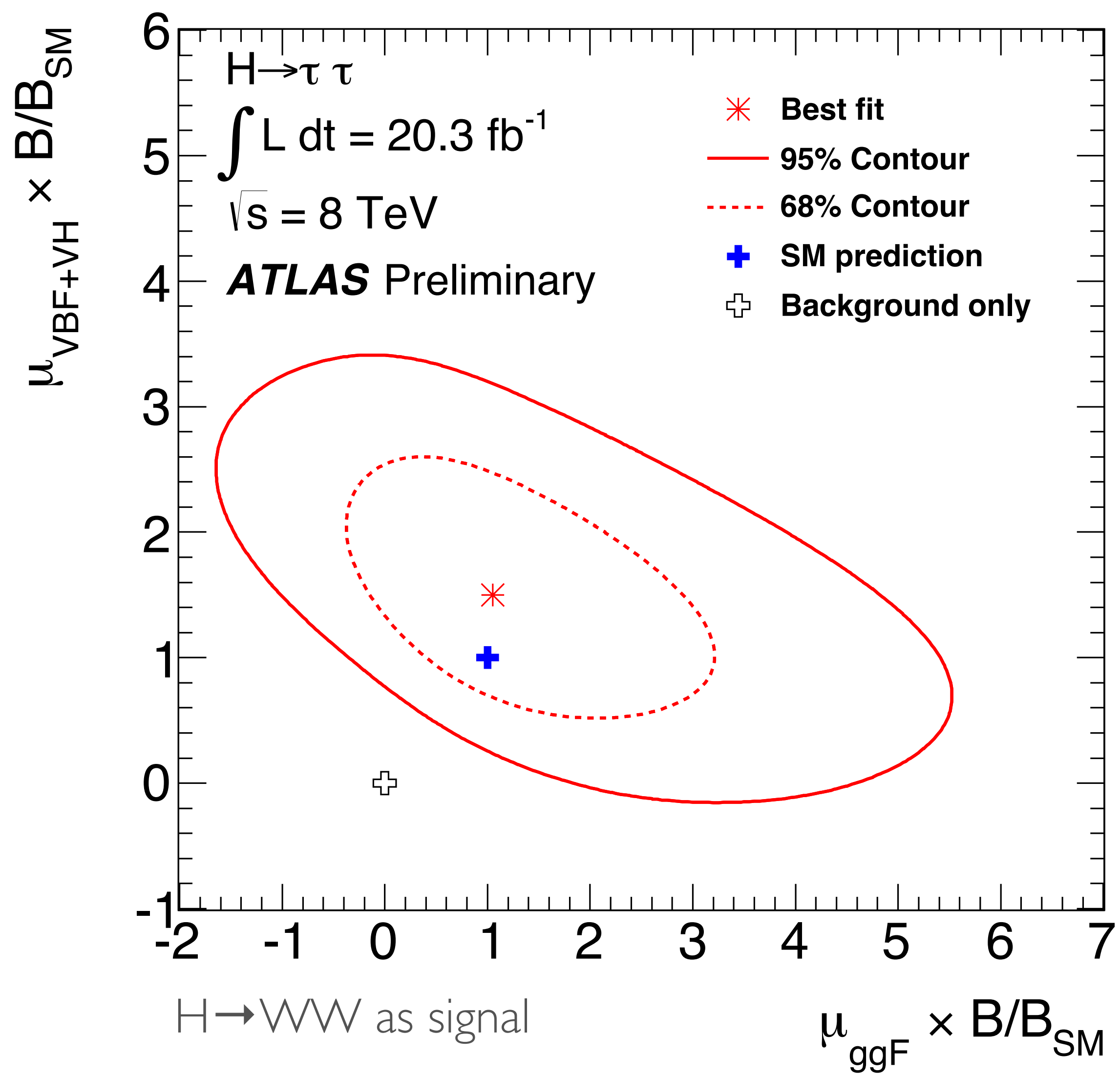
- analysis tuned for m_H = 125 GeV
- low mass discriminating power

compatible with
SM-like Higgs boson at m_H = 125 GeV

HIGGS COUPLINGS



H→WW as signal



H→WW as signal

- strongest constraint to κ_f
- sensitivity driven by VBF

direct constraint on Higgs to fermions coupling

H→μμ

probing the
lepton non-universality

CMS-PAS-HIG-13-007

H→ee also analysed

5 fb^{-1} @7TeV + 20 fb^{-1} @8TeV

Legacy paper - aiming at PLB - being finalised

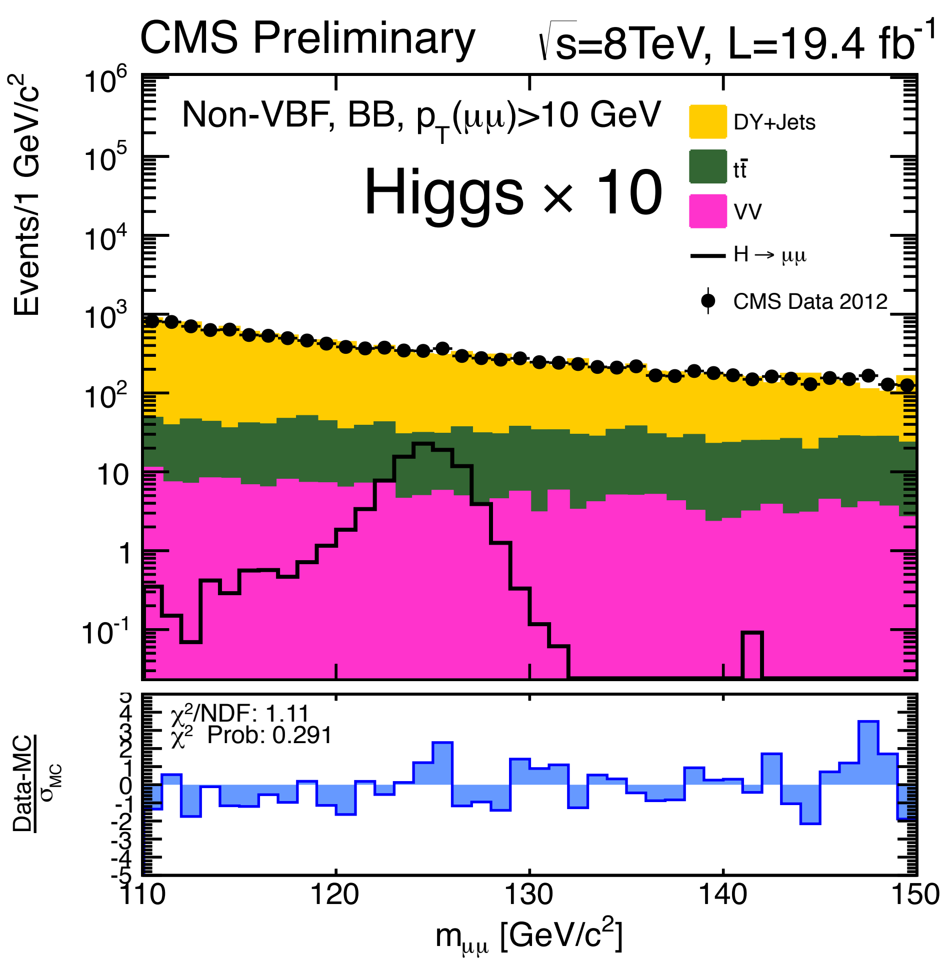
arXiv:1406.7663

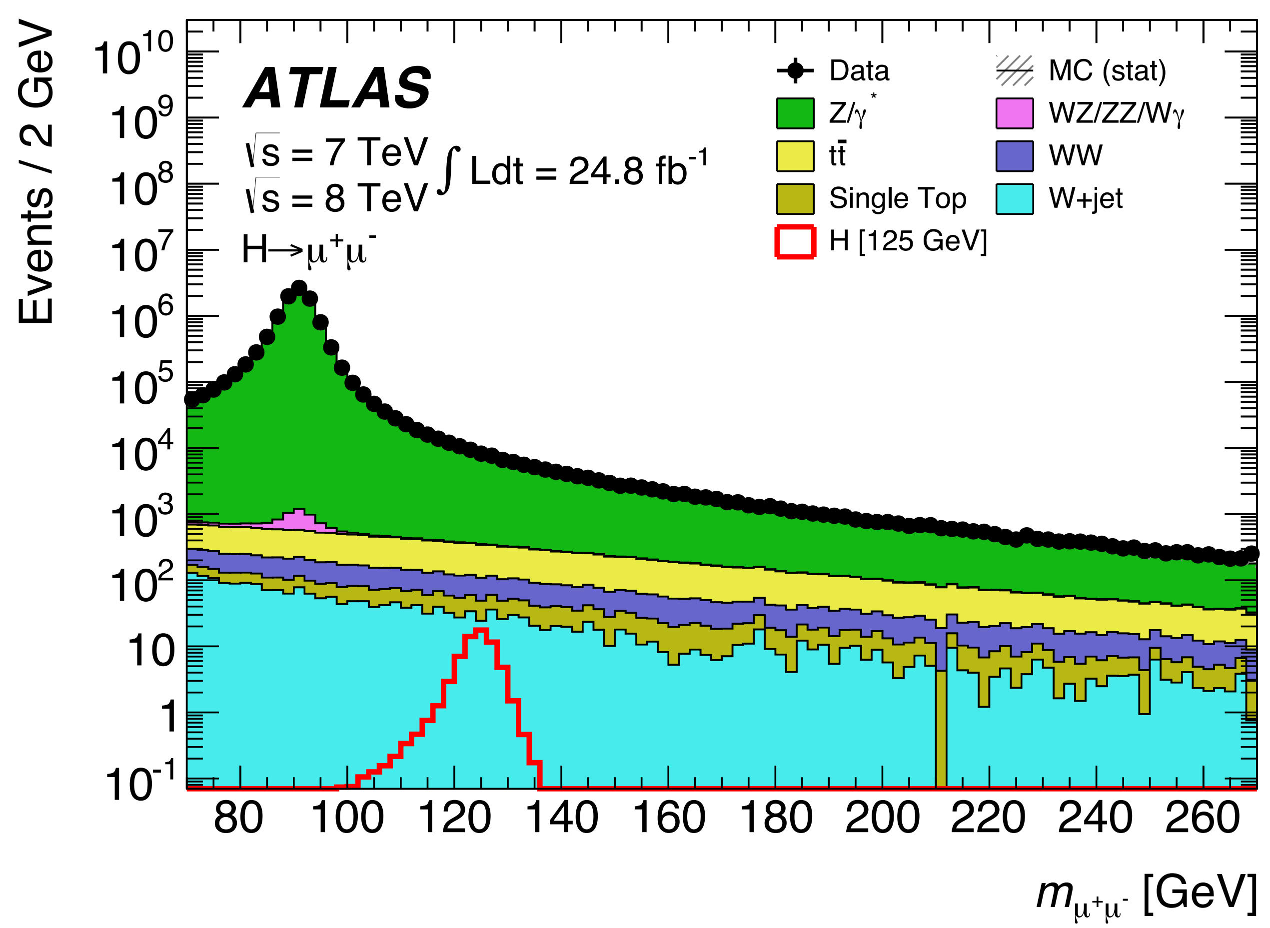
on PLB

5 fb^{-1} @7TeV + 20 fb^{-1} @8TeV

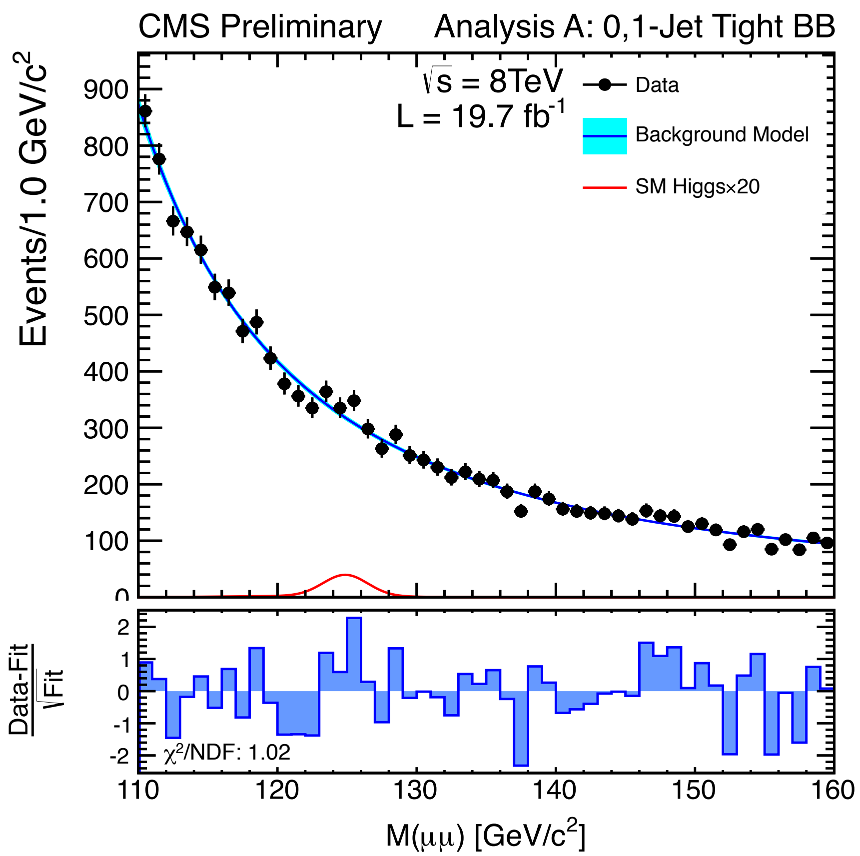
ANALYSIS CHALLENGES

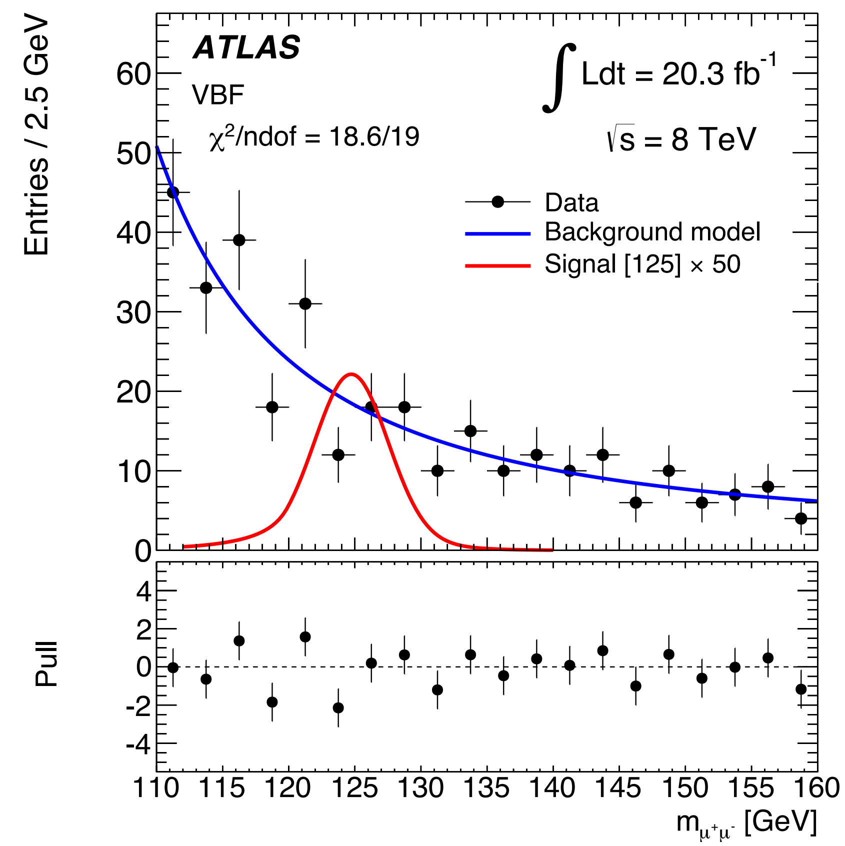
- **very small signal yield**
  - Higgs boson couples with m^2, **μ** is light
- **overwhelming Z/γ*→μμ background**
  - need to master the background modeling
- **categorisation by p_T, endcap - barrel, # of jets**





Results





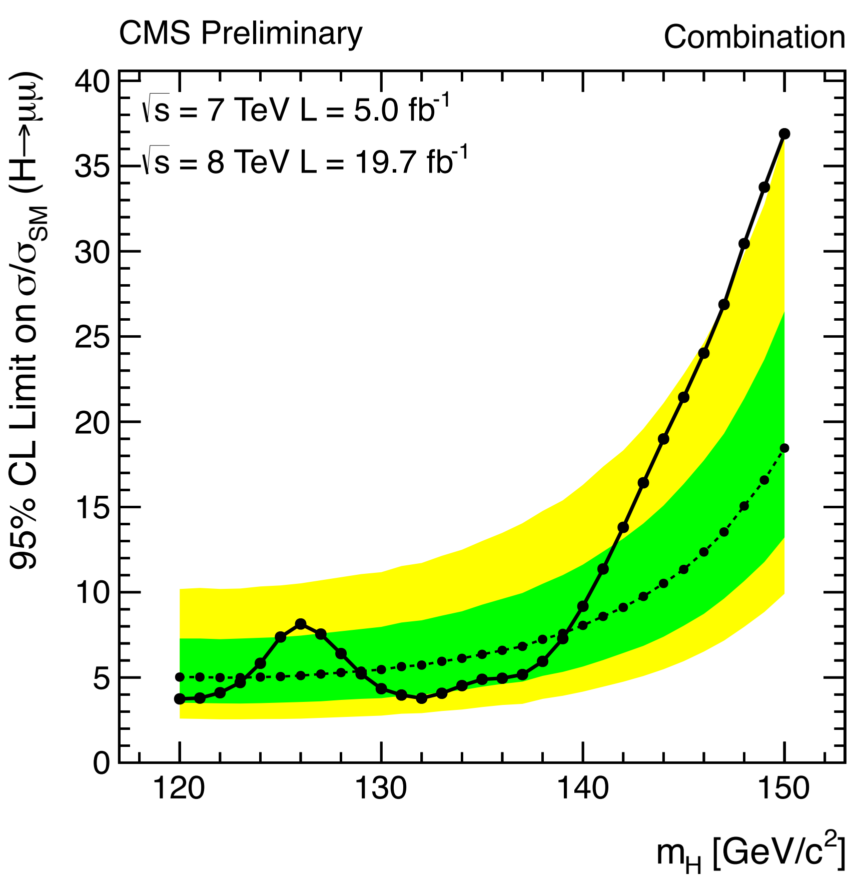
SM Higgs m_H = 125 GeV

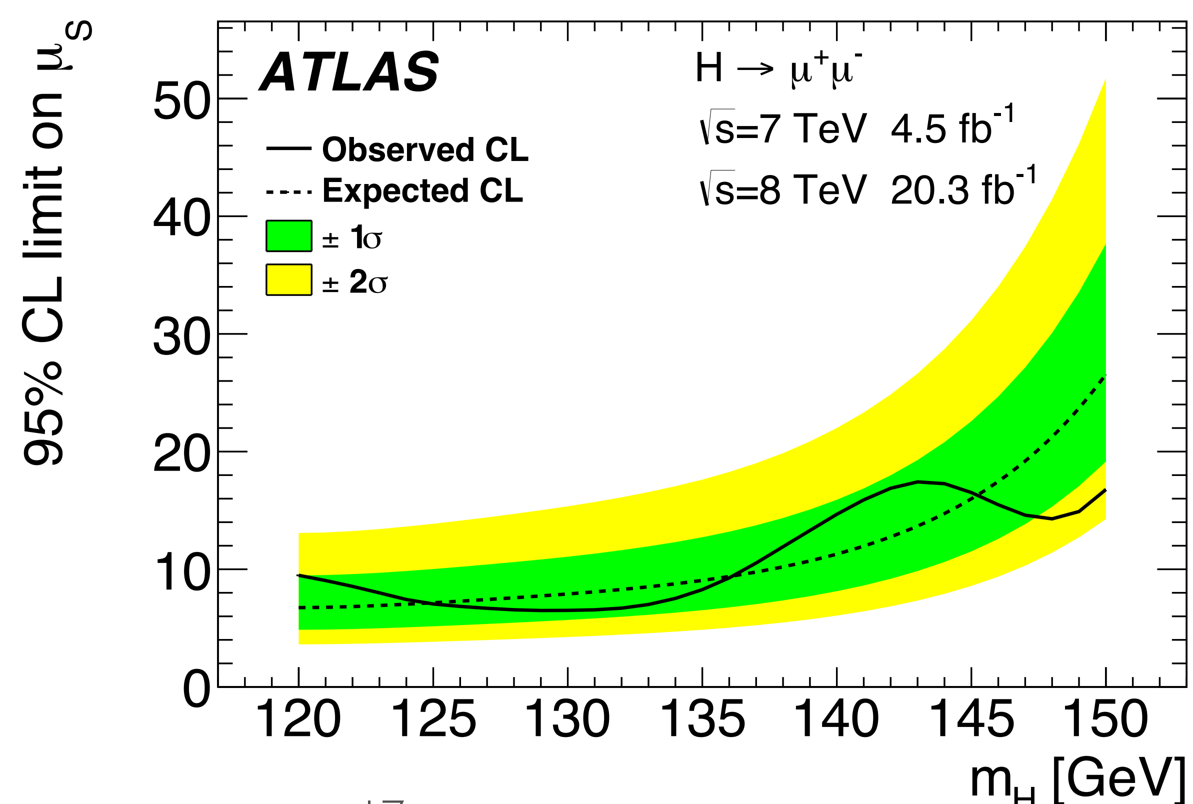
CMS μ/μ_{SM} = 7.4 (5.1)

ATLAS μ/μ_{SM} = 7.0 (7.2)

enhanced signal is not observed

lepton universality ruled out





VH, H→bb

directly testing the
fermion couplings - II

arXiv:1320.3687
on PRLD

5 fb^{-1} @7TeV + 19 fb^{-1} @8TeV

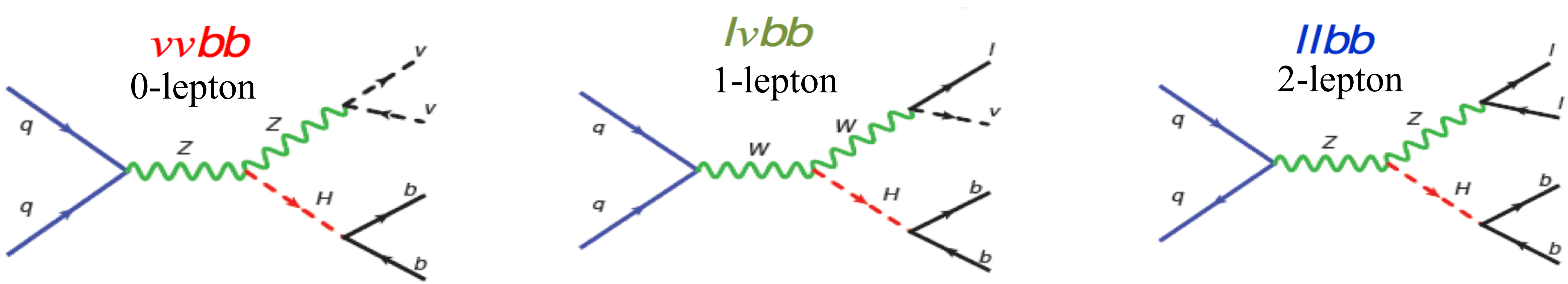
arXiv:1409.6212
submitted to JHEP

5 fb^{-1} @7TeV + 20 fb^{-1} @8TeV

VH, H→bb Overview

- Important for down type quark coupling measurement
- Large BR (~58%), but huge QCD background (B/S ~10^7!)
- Vector boson from associate production provides additional leptons which improve the S/B

- *General analysis strategy (CMS and ATLAS are similar)*
  - Use b-tagging to identify two b-quark initiated jets
  - Categorise analysis based on the vector boson and its decay:



  - Reconstruct di-jet mass of b-tagged jet pair
  - Limit to at most one extra jet
  - Use MVA to optimise analysis and extract signal

VH, H→bb SELECTIONS

0-lepton

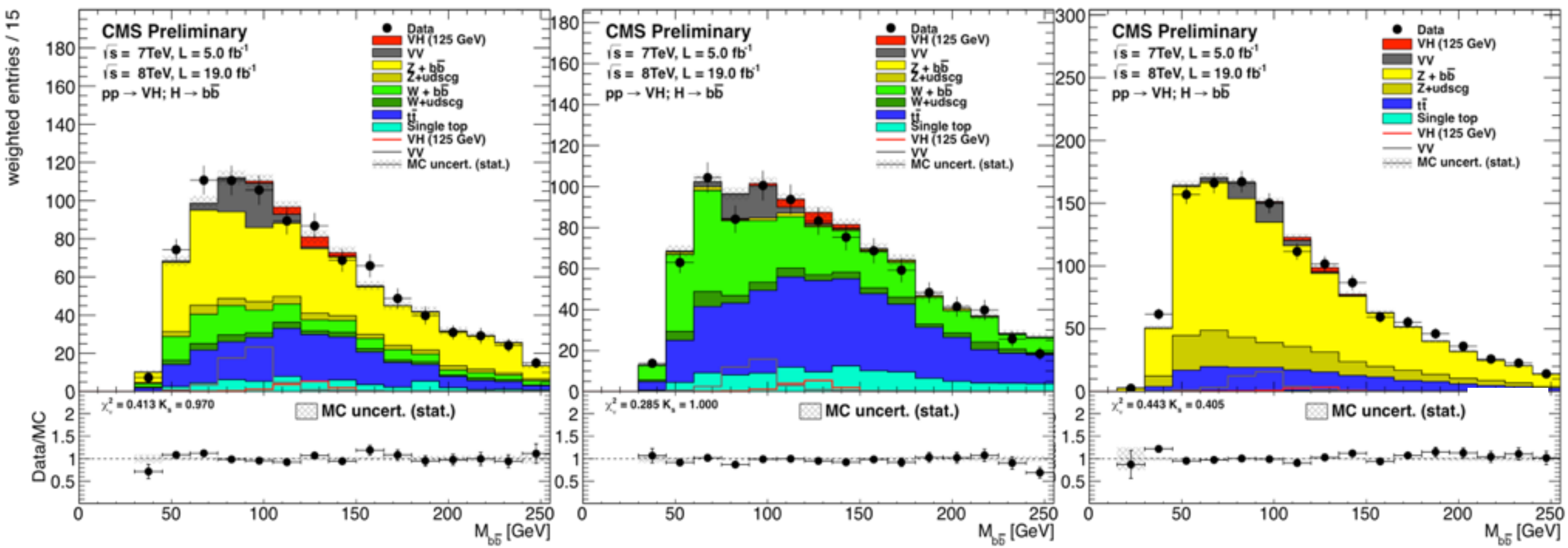
- Require large E_T^{miss} and corresponding p_T^{miss}
- Missing energy and jets are back-to-back

1-lepton

- Require some E_T^{miss}
- Use transverse mass between neutrino and lepton

2-lepton

- Require less E_T^{miss}
- Use invariant mass of the oppositely charged lepton pair

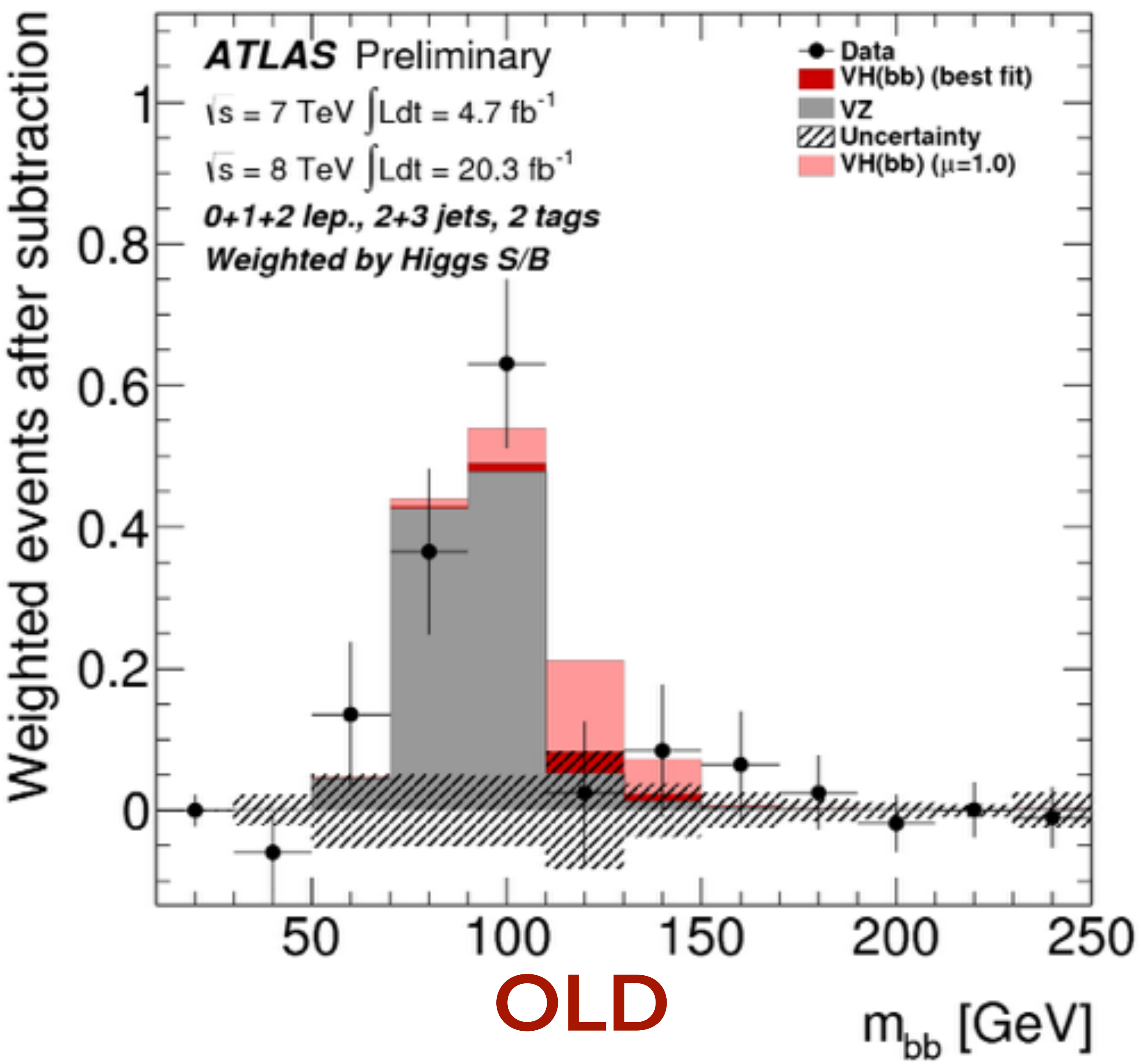


MAJOR BACKGROUNDS

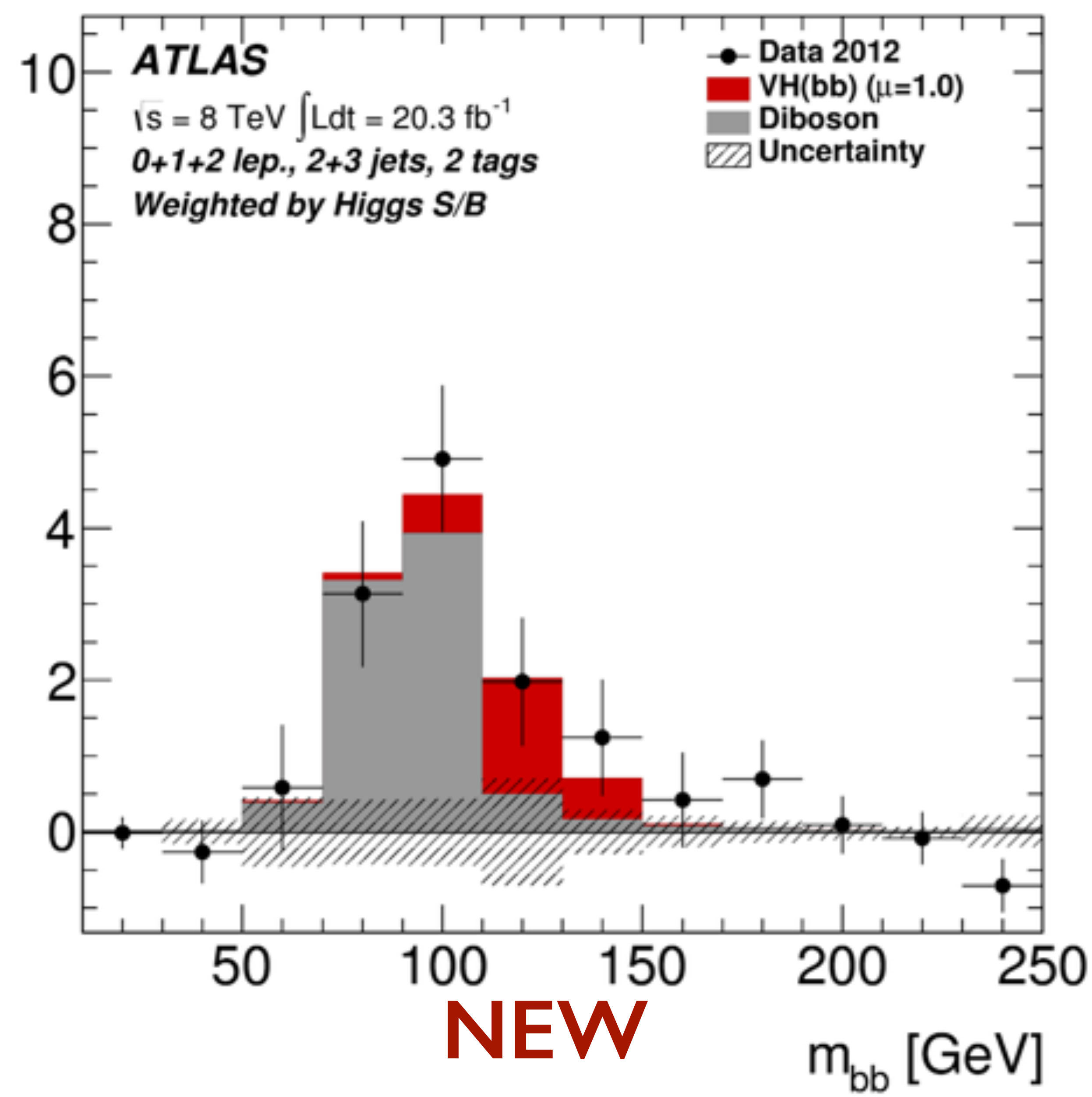
Z+bb, tt | **W+jets, tt** | **Z+bb**

VH, H→bb NEW

- Since last presented results, **ATLAS VH, H→bb** made two major advancements:
  - Continuous b-tagging
  - MVA analysis

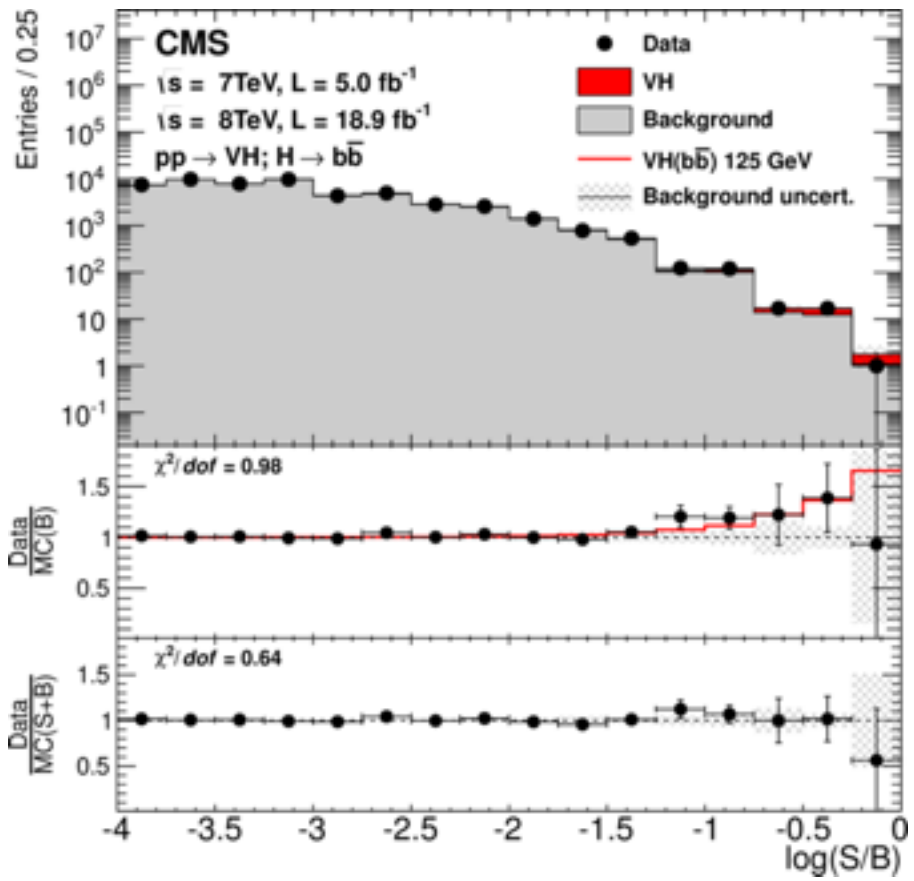


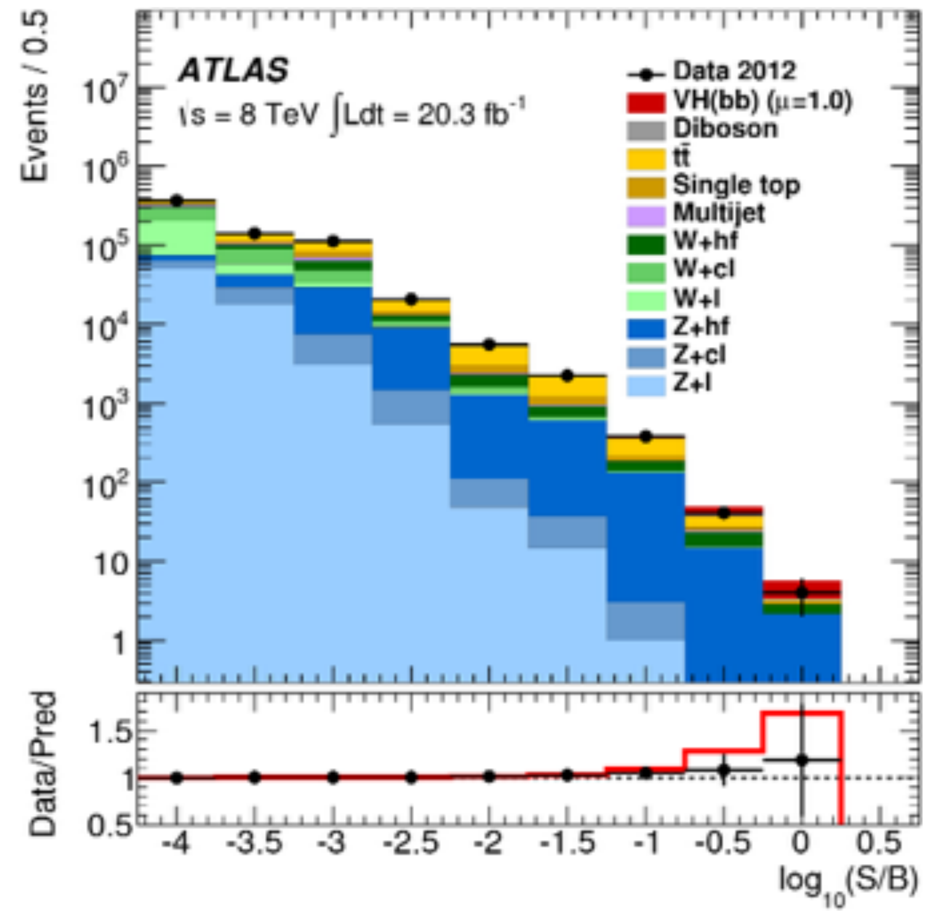
OLD

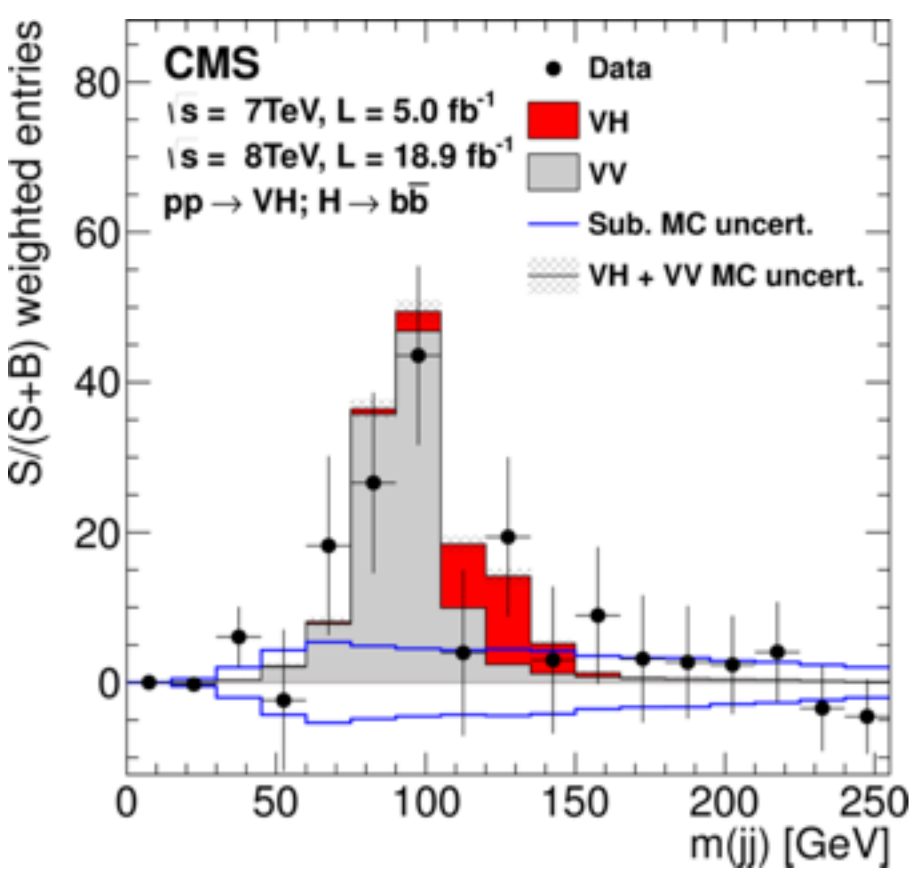


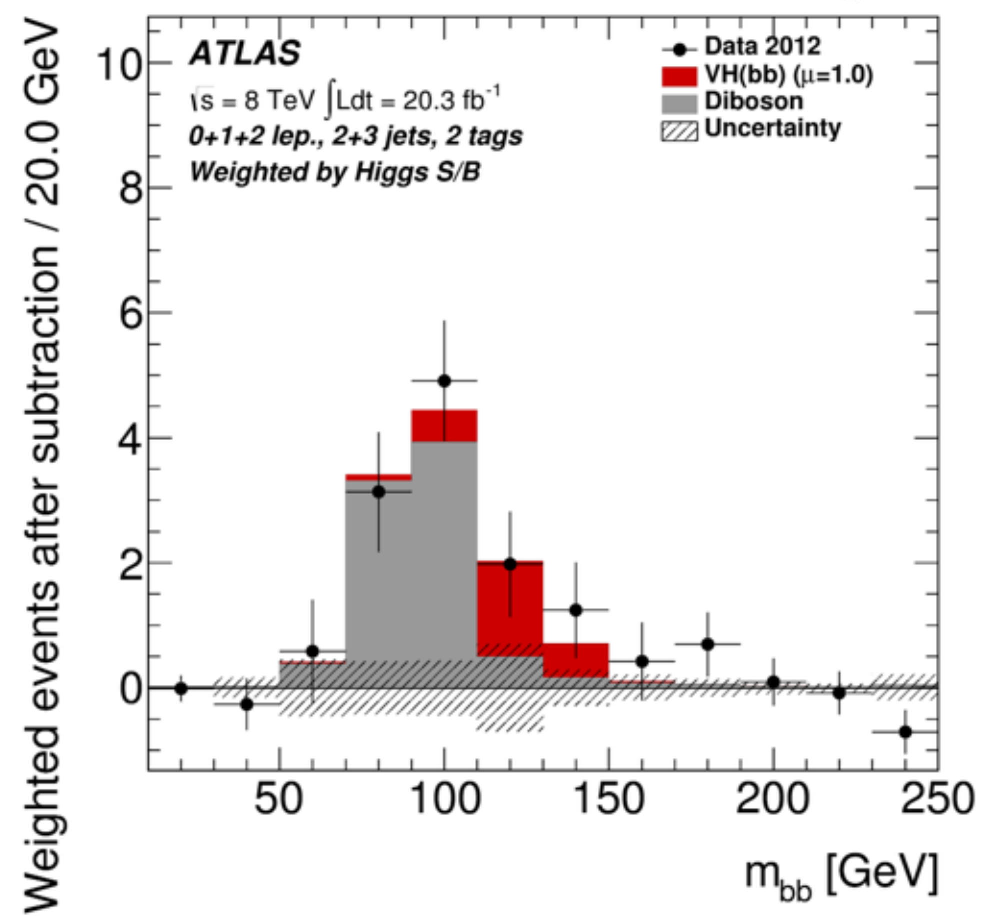
NEW

VH, H→bb Results - I

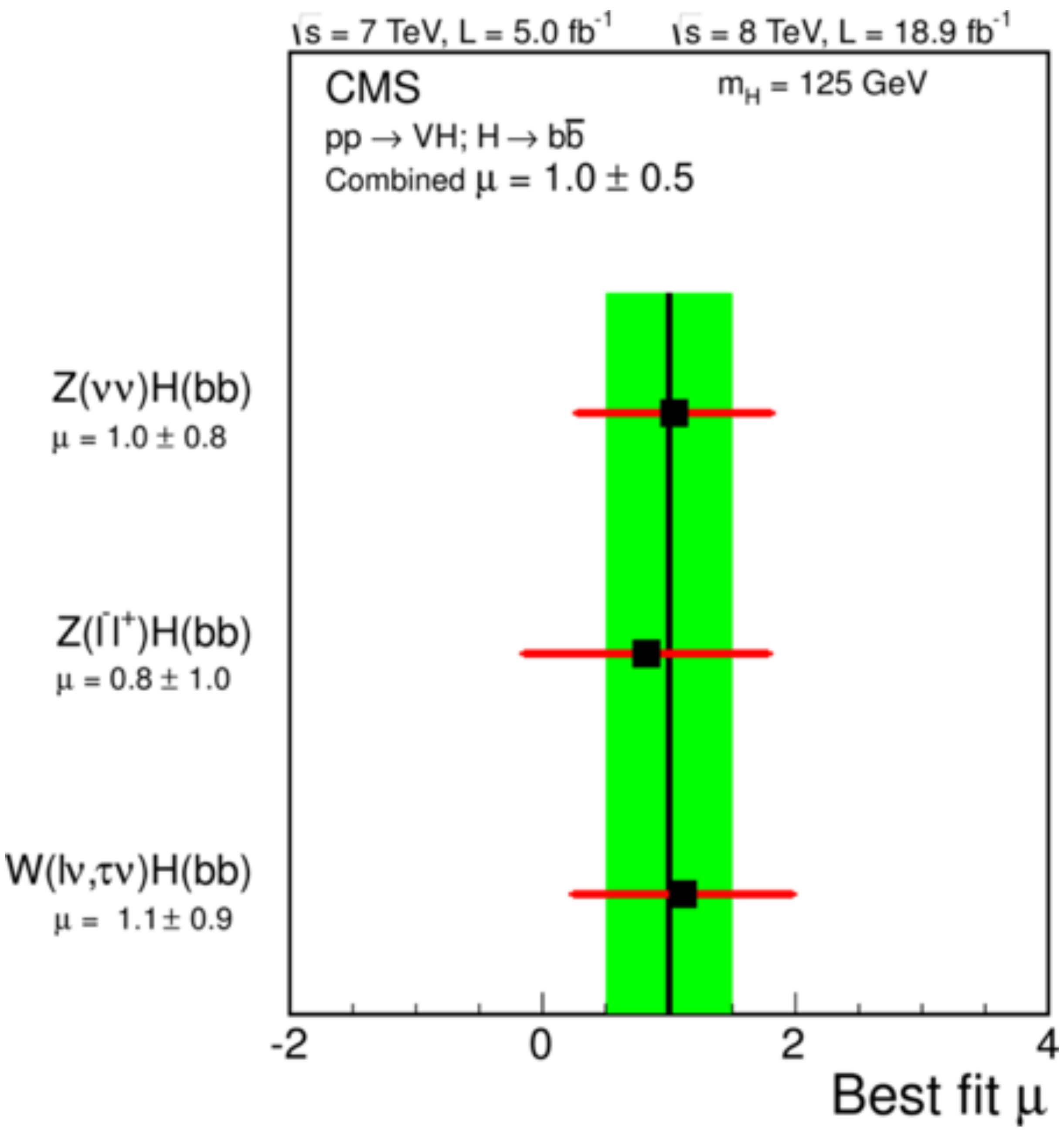


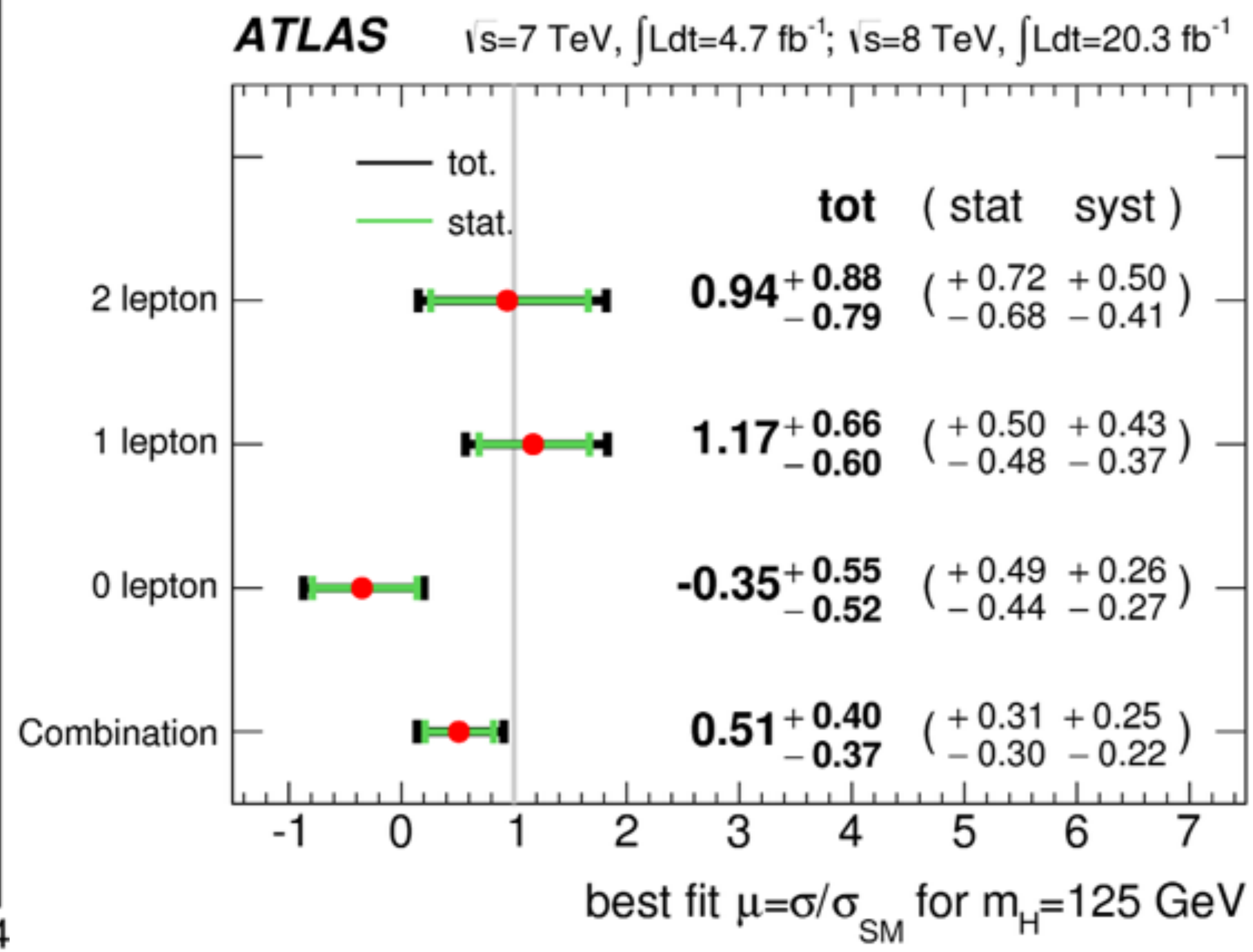




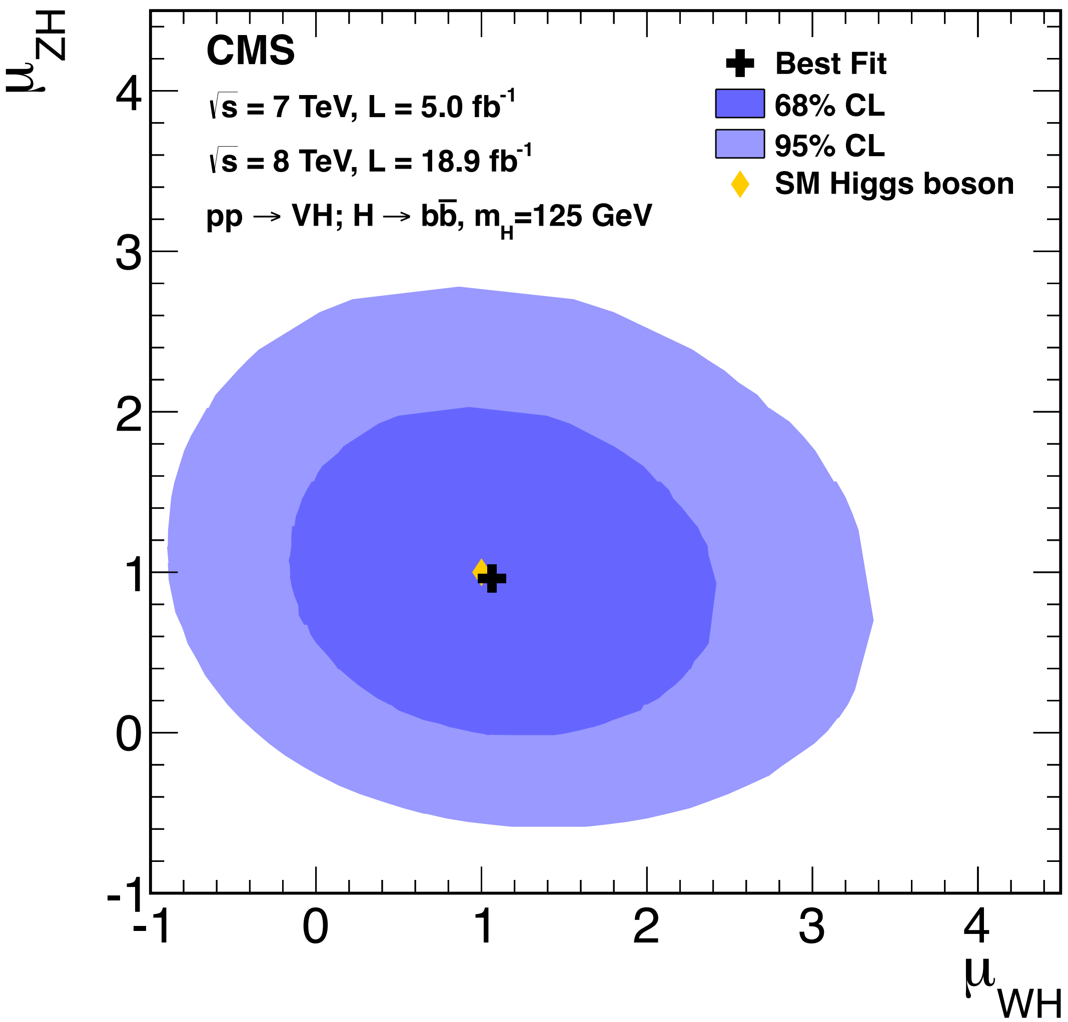


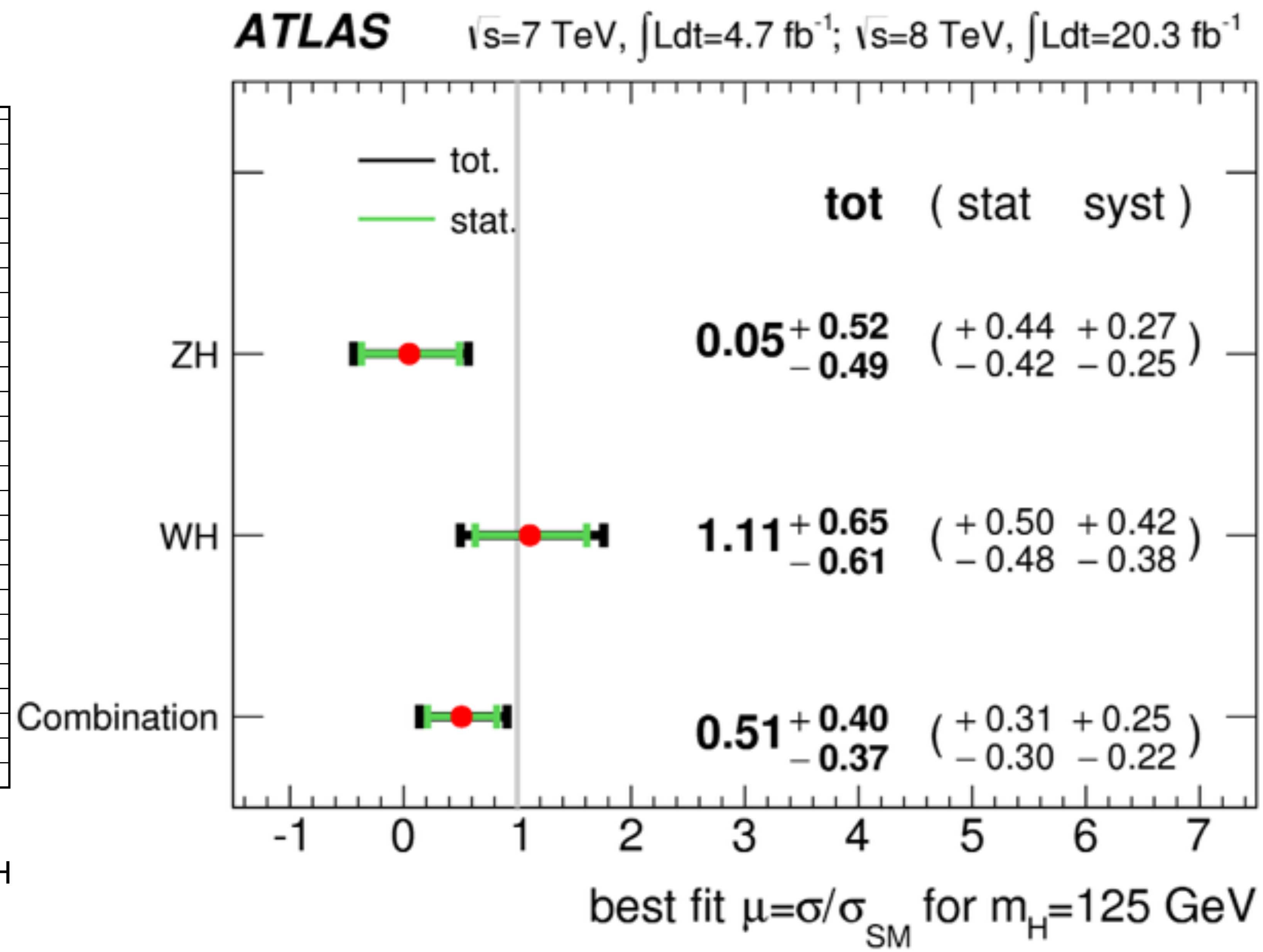
VH, H→bb RESULTS - II





VH, H→bb RESULTS - III





Signal strength, μ:

- ATLAS: $0.51^{+0.40}_{-0.37}$
- CMS: 1.0±0.5

Significance over background observed (expected):

- ATLAS: 1.4σ (2.6σ)
- CMS: 2.1σ (2.1σ)

ttH

directly testing the
fermion couplings - III

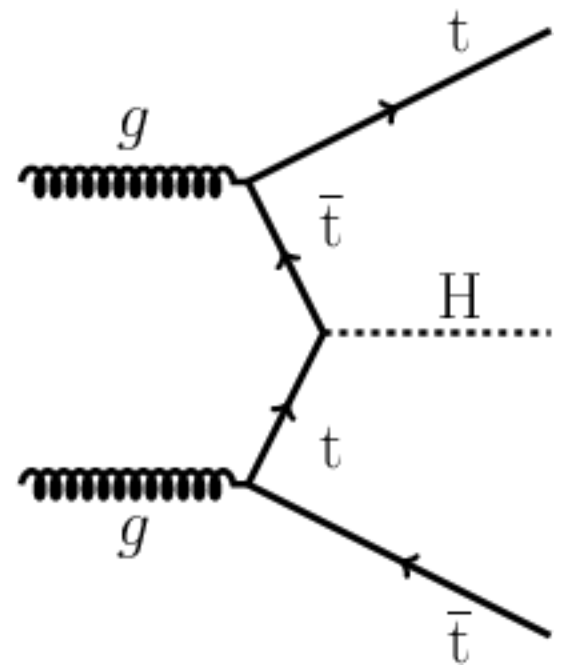
arXiv:1408.1682
on JHEP
5 fb^{-1} @7TeV + 20 fb^{-1} @8TeV

arXiv:1409.3122
sub to PRLB

ATLAS-CONF-2014-011
ATLAS-CONF-2014-043
sub to PRLB

5 fb^{-1} @7TeV + 20 fb^{-1} @8TeV

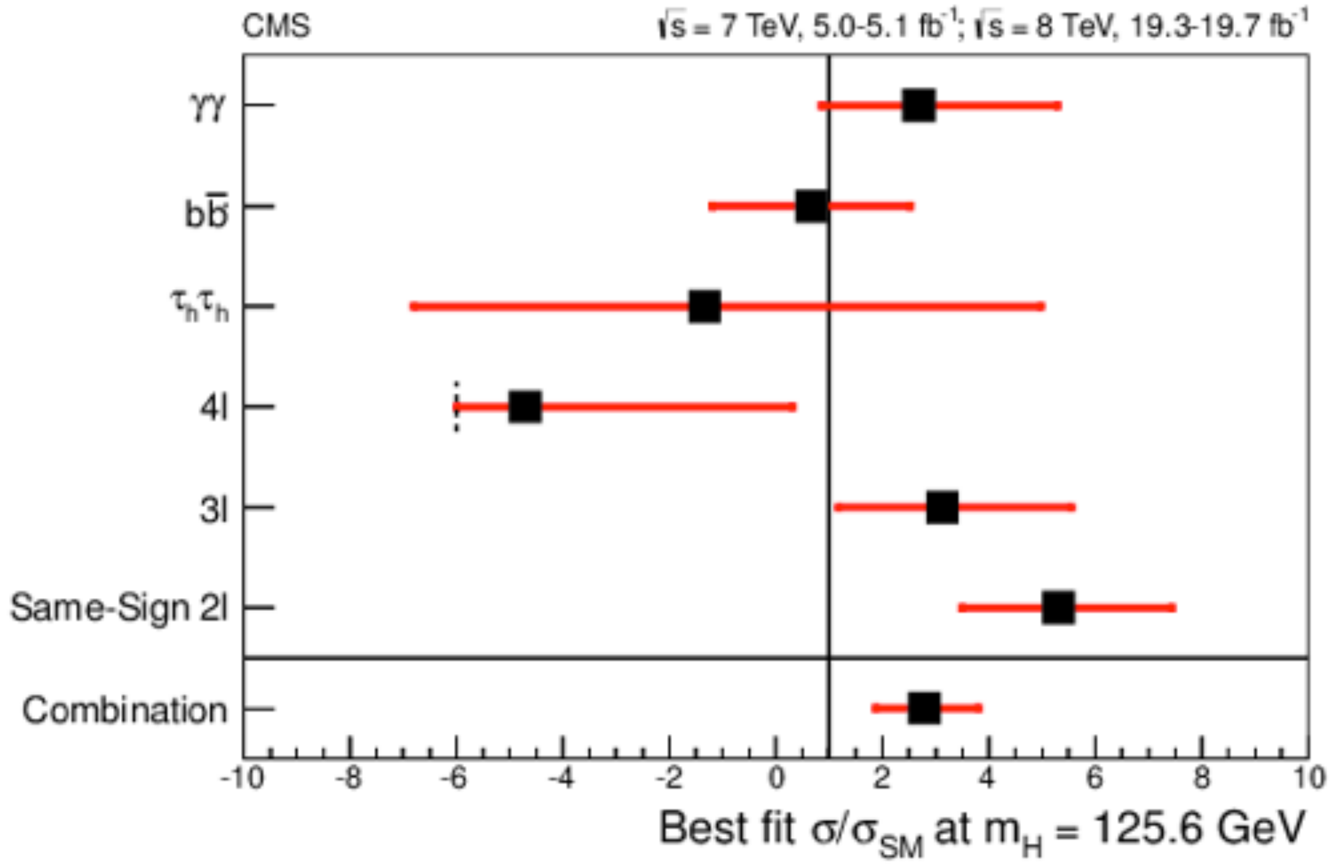
ttH Overview

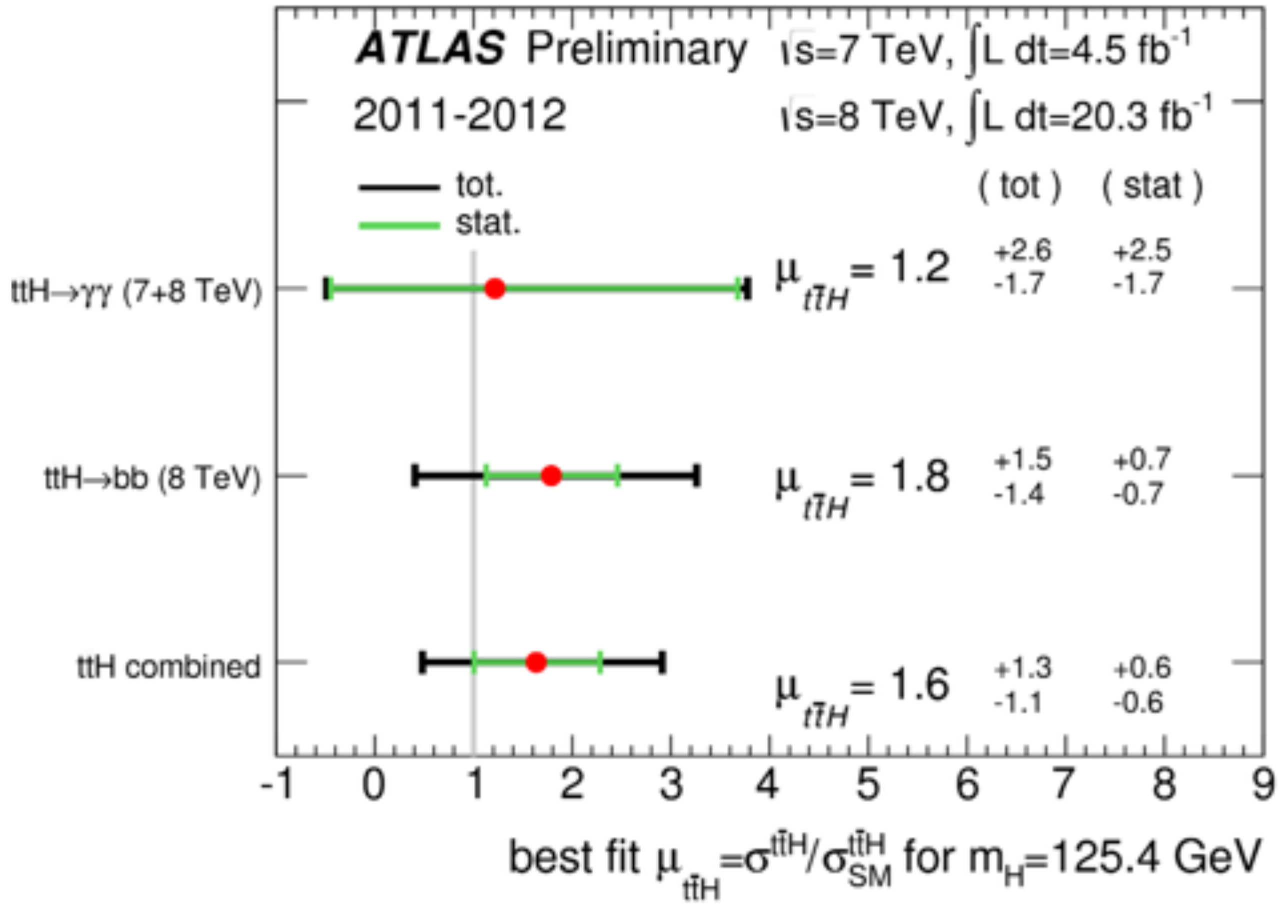


- H→ttbar not kinematically allowed for m_H=125 GeV
- ttH production mode important for direct measurement of top Yukawa coupling

- **Decay modes of Higgs probed:**
  - ATLAS: $\gamma\gamma$ and **bb**
  - CMS: $\gamma\gamma$, **bb**, $\tau_h\tau_h$, **ZZ** and **WW**

ttH RESULTS





μ $2.8^{+1.0}_{-0.9}$

the observed excess equals

- **3.4σ** in case of SM Bkg only expectation
- **2.0σ** in case of SM Bkg + ttH(125) expectation

μ $1.6^{+1.3}_{-1.1}$

the observed excess equals

- **1.5σ (1.0σ)** in case of SM Bkg only expectation

Evidence of direct top Yukawa coupling

Conclusions

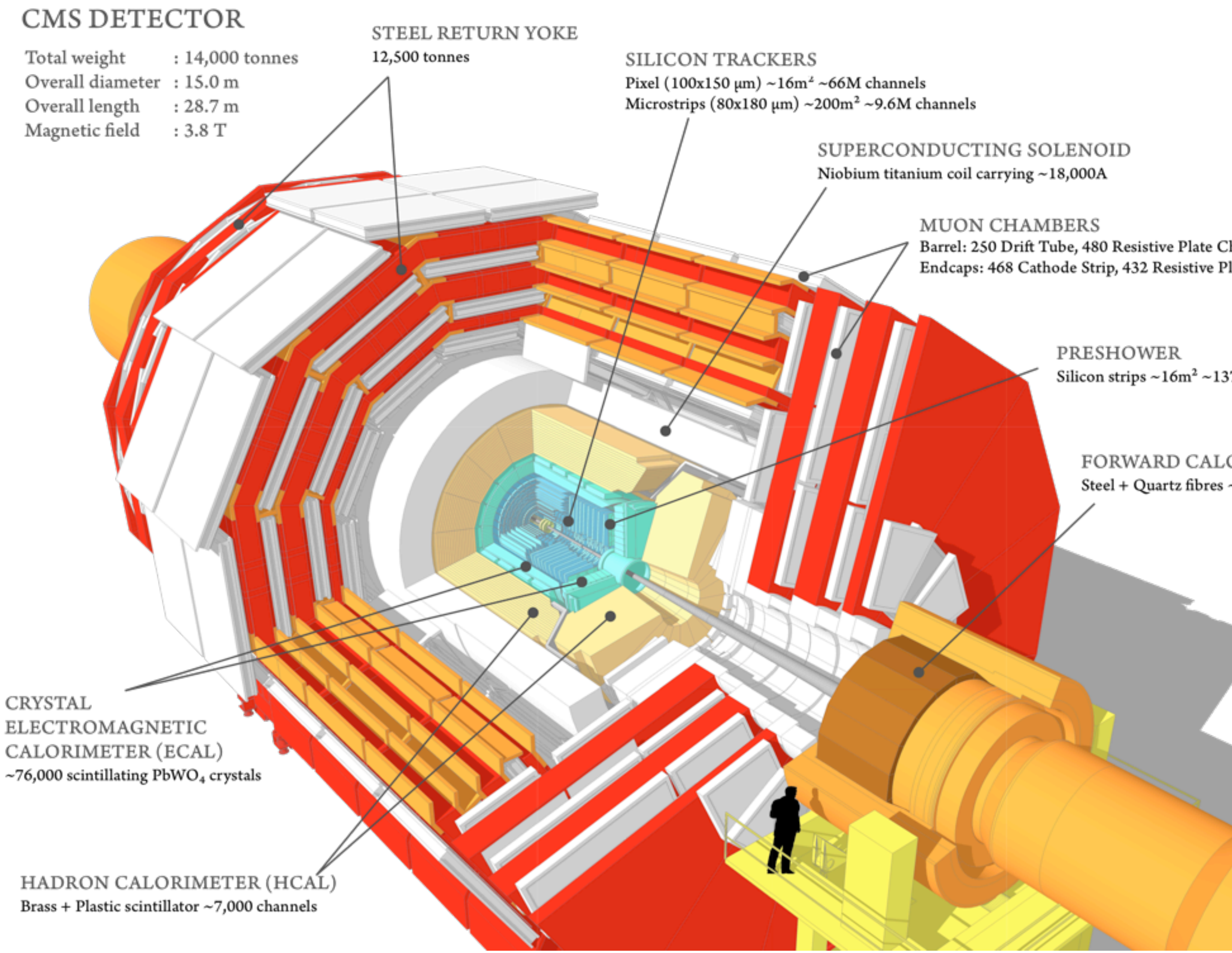
	CMS		Atlas	
	μ	significance / limit	μ	significance / limit
$H\to\tau\tau$	0.8 ± 0.3	3.2 (3.7) σ	$1.4^{+0.5}_{-0.4}$	4.1 (3.2) σ
$VH\to bb$	1.0 ± 0.5	2.1 (2.1) σ	$0.5\ ^{\pm 0.3\ stat}\ _{\pm 0.2\ sys}$	1.4 (2.6) σ
ttH	$2.8^{+1.1}_{-0.9}$	μ/μ_{SM} = 4.3 (1.8)	$1.6^{+1.3}_{-1.1}$	μ/μ_{SM} = 5.6 (3.9)
$H\to\mu\mu$	-	μ/μ_{SM} = 7.4 (5.1)	-	μ/μ_{SM} = 7.0 (7.2)

- **Evidence for H(125) decays into fermions - Hττ and Hbb -**
- **H→μμ results proved the non-universal Higgs coupling to leptons**
- **ttH analyses show strong indication of the direct top Yukawa coupling**
- so far, everything looks compatible with the SM expectations
- precision of most analyses limited by statistics, room for possible deviations from the SM

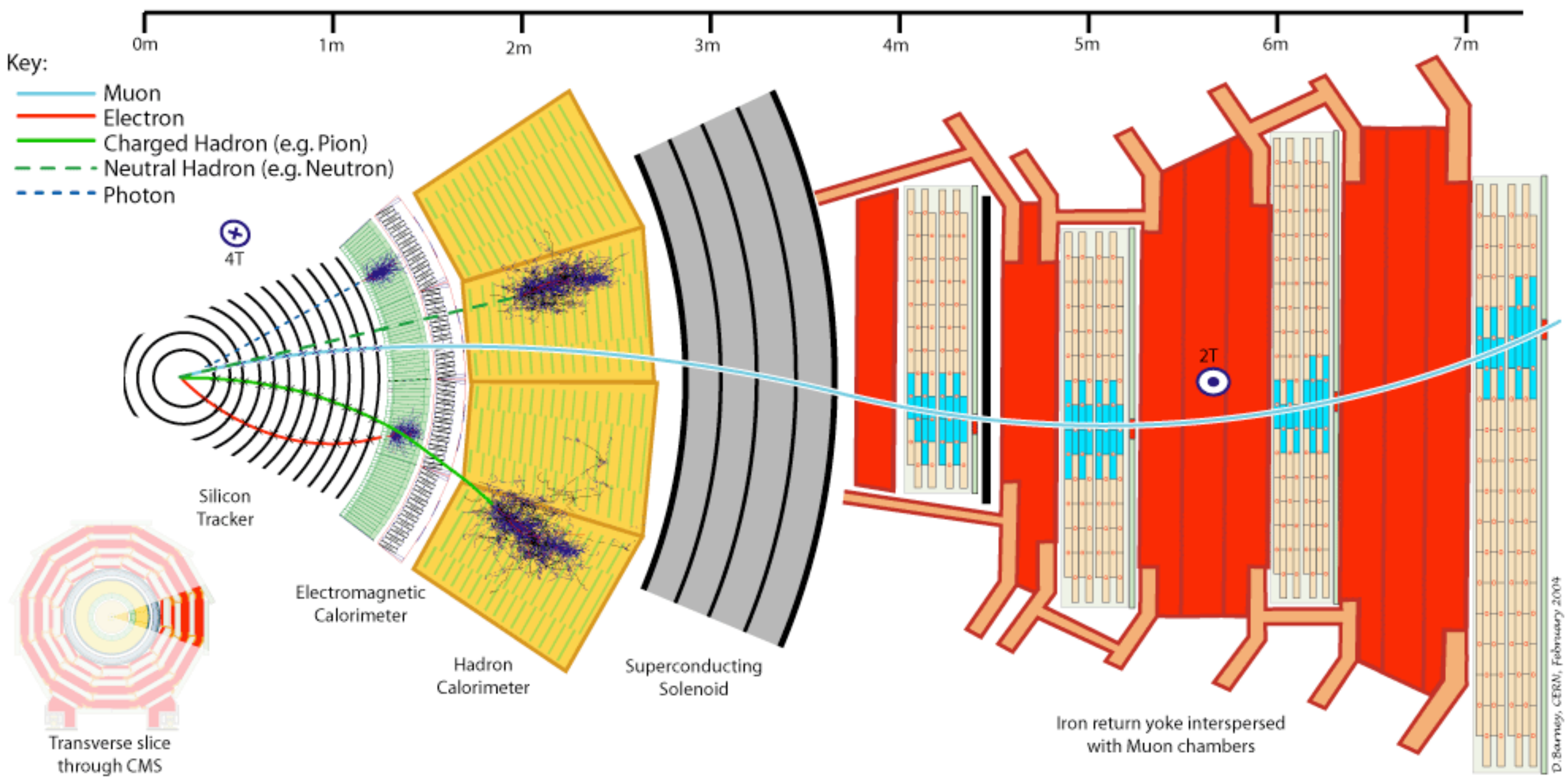
Talks by André David and Hongtao Yang will frame these results in the big picture of Higgs boson's couplings

BACKUP

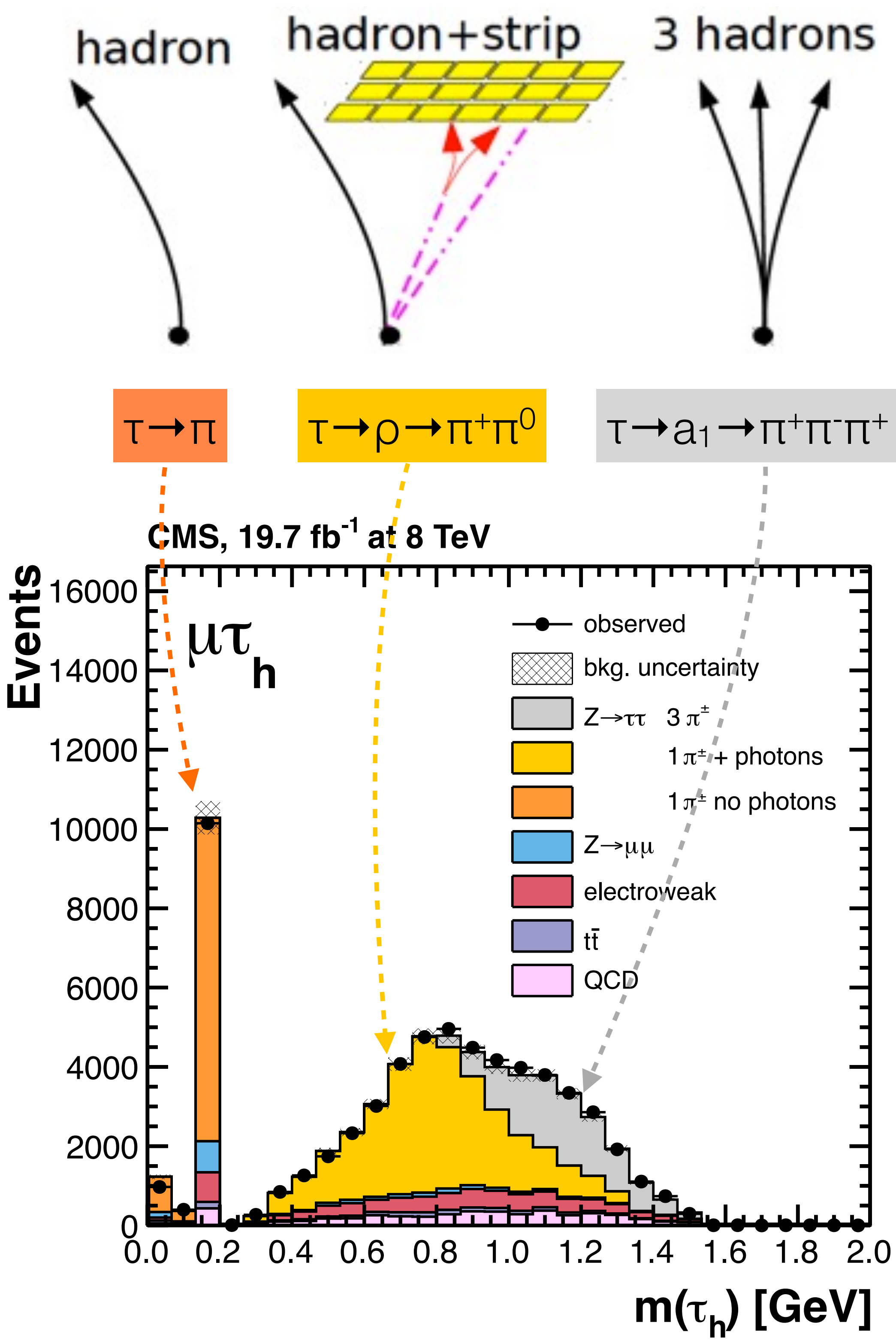
The Compact Muon Solenoid Detector



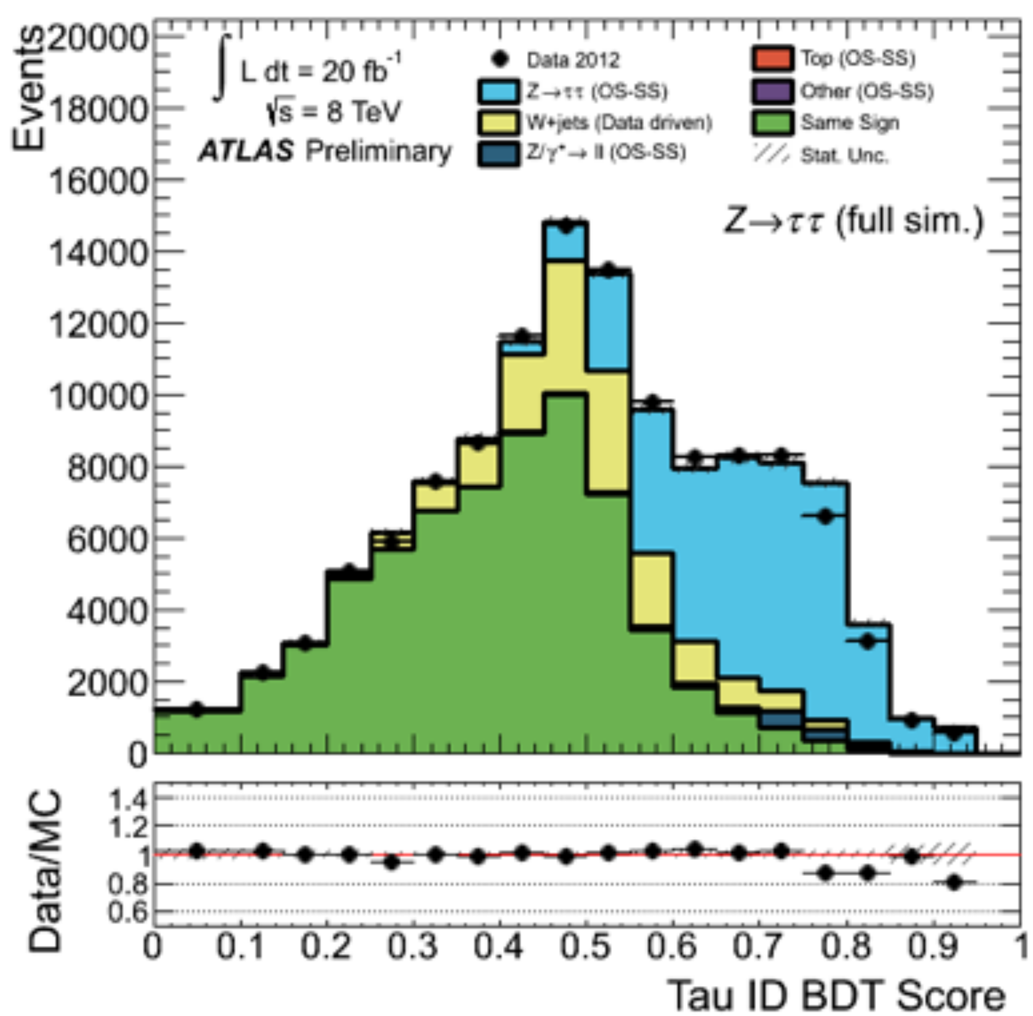
PARTICLE SIGNATURES IN CMS



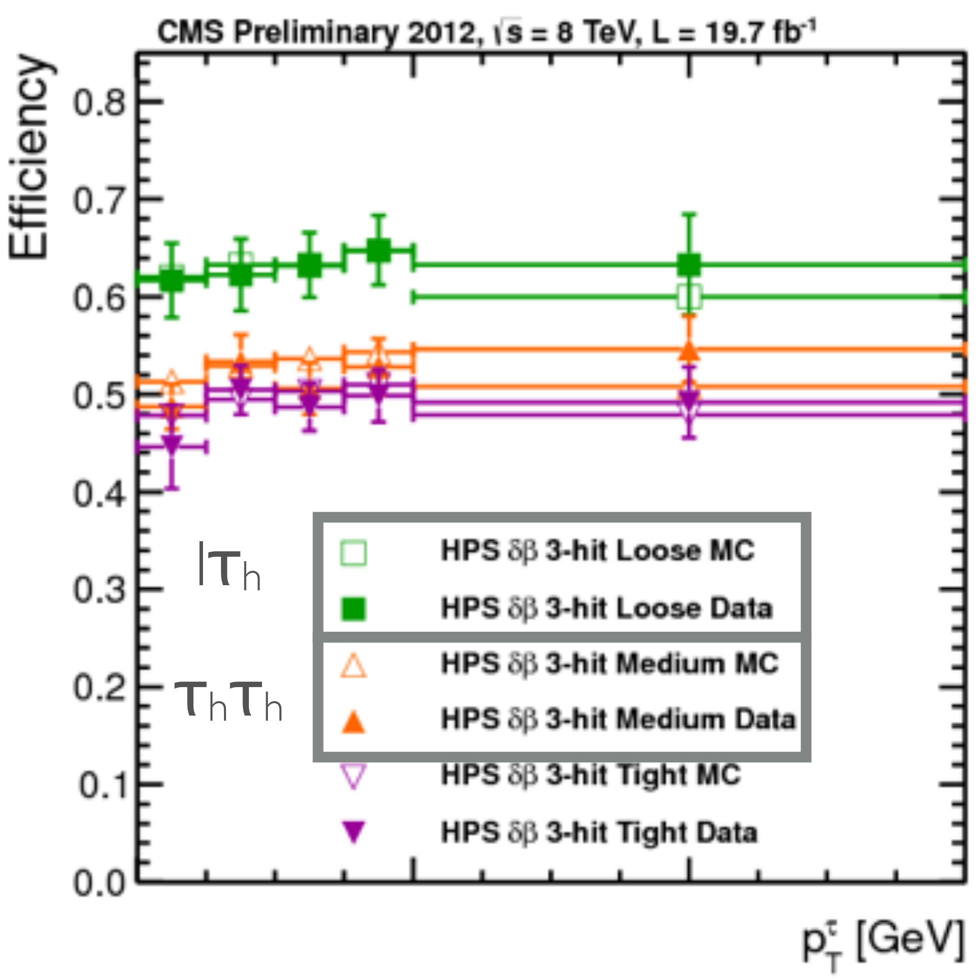
TAU RECONSTRUCTION

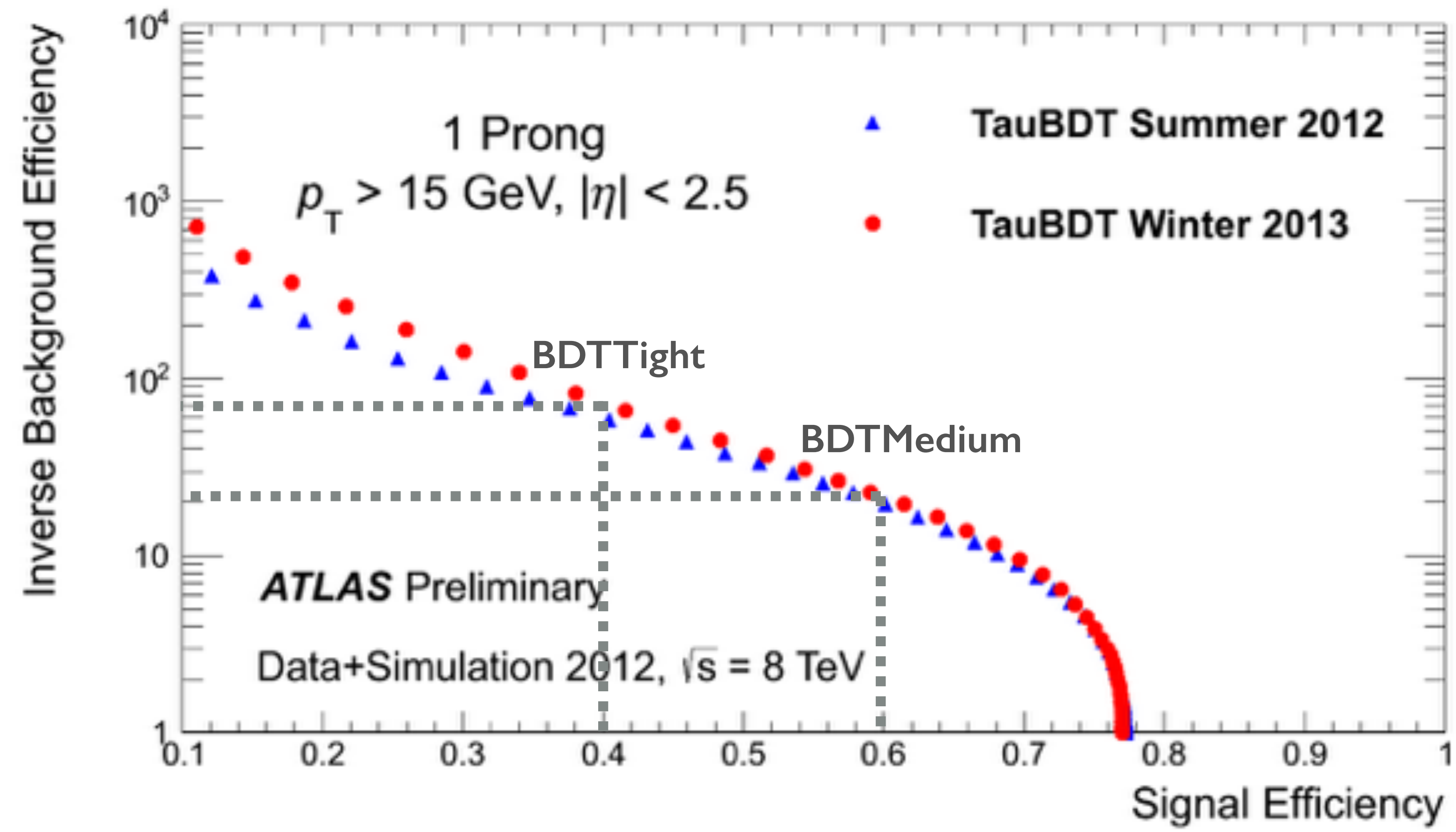


- **CMS**
  - Particle Flow based
- **Atlas**
  - BDT based



TAU RECO PERFORMANCES





- cut based isolation
- anti-lepton discriminators
- fakes 2-4%

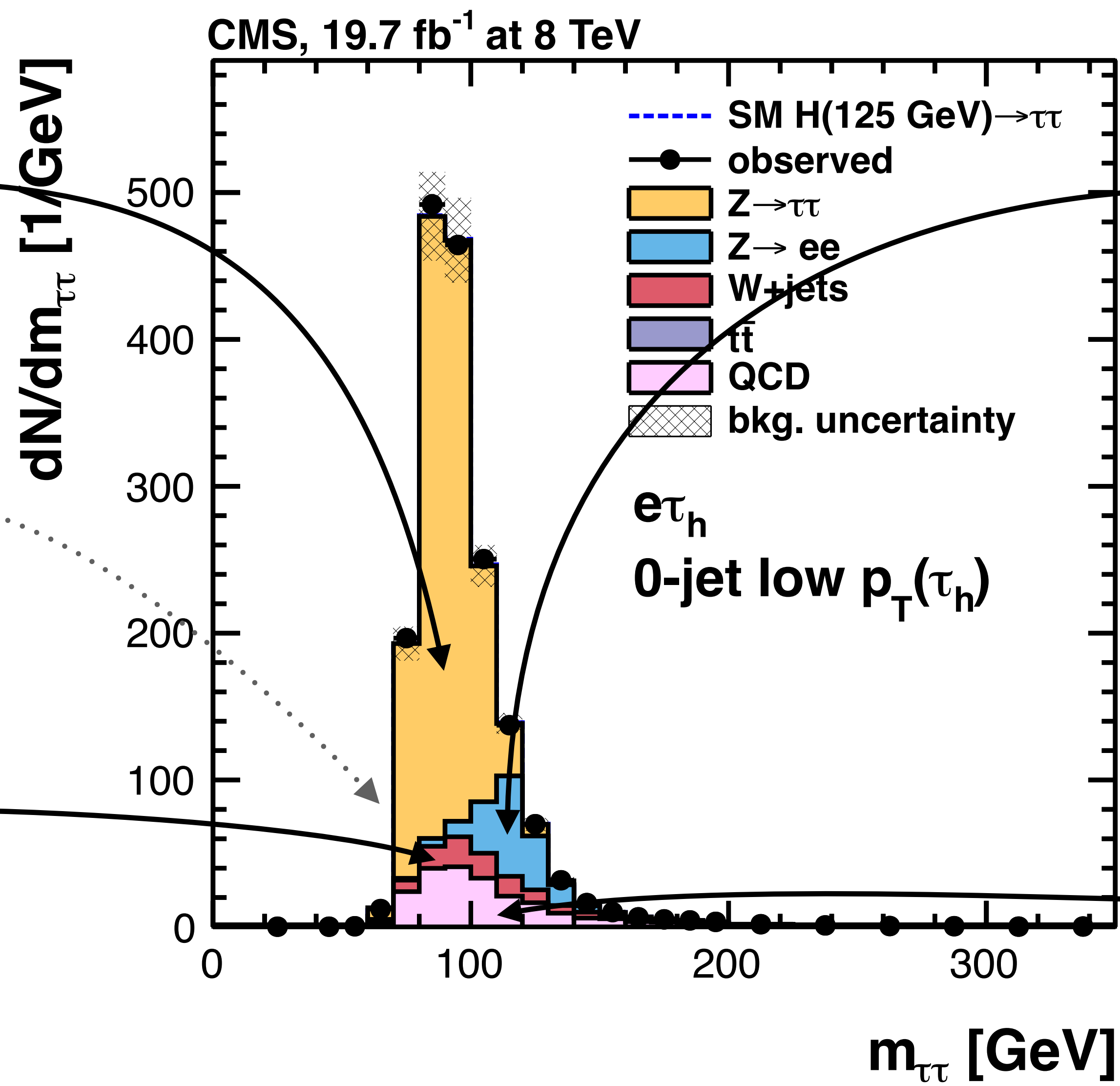
- multivariate BDT
  - isolation
  - narrowness
  - shower shape
  - flight path

BACKGROUND ESTIMATES

$Z \to \tau\tau$
embedded sample
no MET scale and JES unc., since these are data events

$t\bar{t}$
shape MC
norm SF from eμ sideband with ≥1 *b*jet and high MET

W+Jets
shape MC
norm high m_T sideband



$Z \to ee/\mu\mu$
(μτ,eτ channels)
shape MC
norm SF from T&P in data

$Z \to ee/\mu\mu$
(ee/μμ channels)
shape MC
norm Z→ll enriched sideband

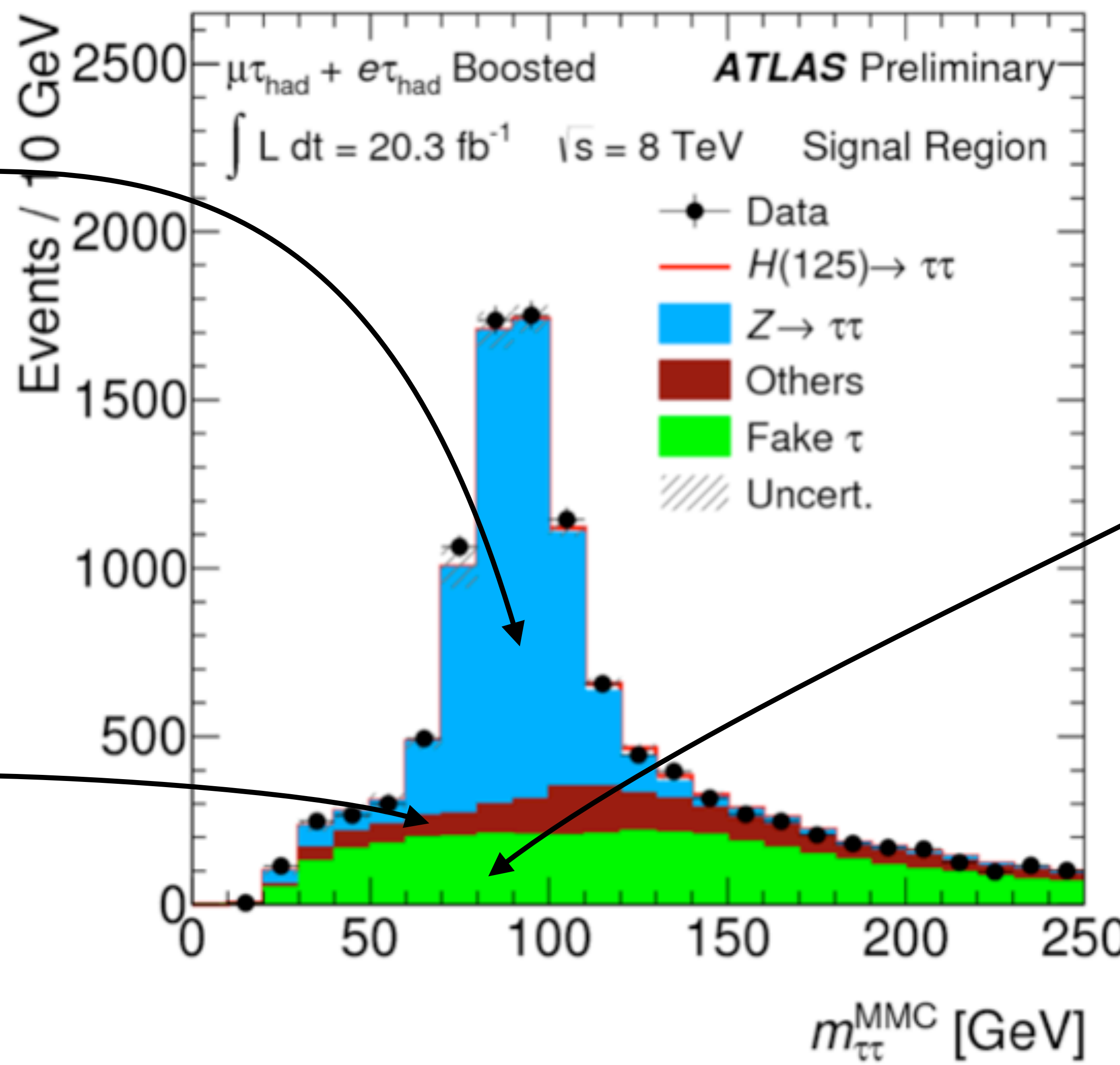
QCD
shape & norm
control regions in data, defined using di-τ charge and isolation

The most relevant backgrounds are derived from data or normalised using data control regions
H\toWW considered as a background

Background estimates

Z→ττ
embedded sample
no MET scale and JES unc., since these are data events

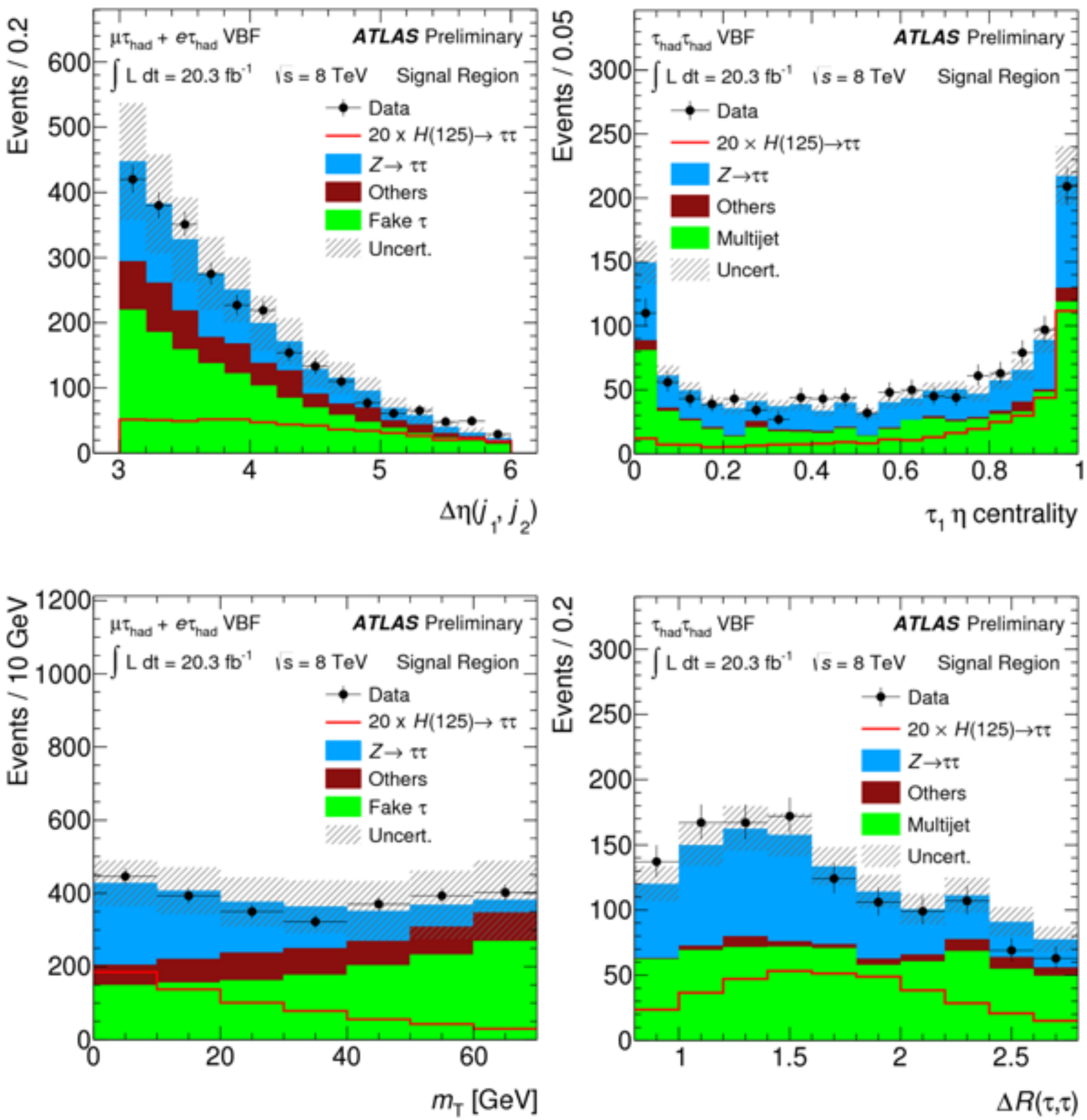
Others
shape MC
norm data sidebands
di-bosons, Z→ll, top



Fakes
modeled by data
QCD, W+Jets, top where a jet fakes a τ_h

The most relevant backgrounds are derived from data or normalised using data control regions
H\toWW considered as a background

BDT Input Variables



Resonance property

- $m(\tau\tau)$, $\Delta R(\tau\tau)$, etc

VBF topology

- m_{jj}, $\Delta\eta_{jj}$, etc

Event activity

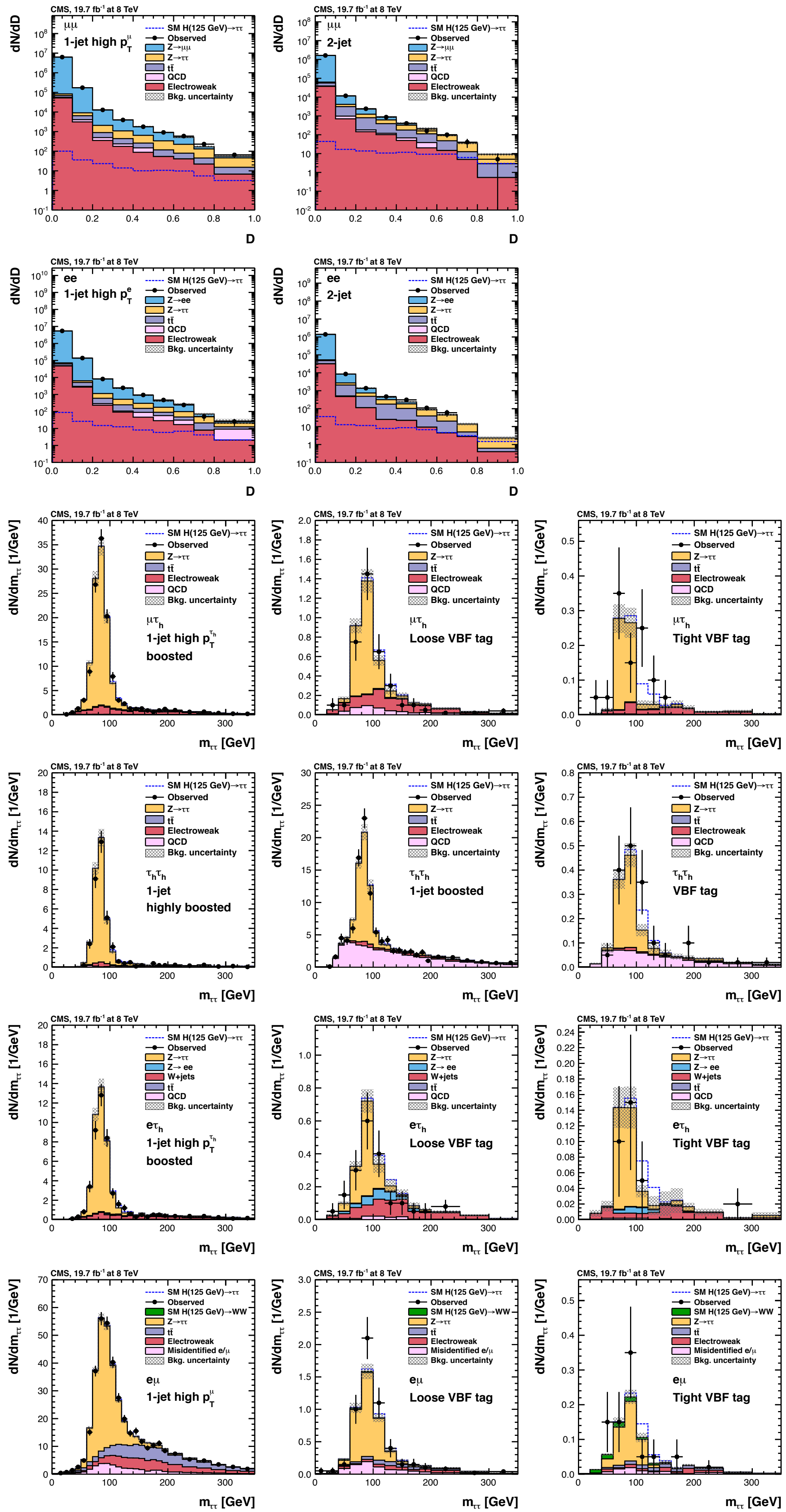
- Scalar & vector p_T-sum

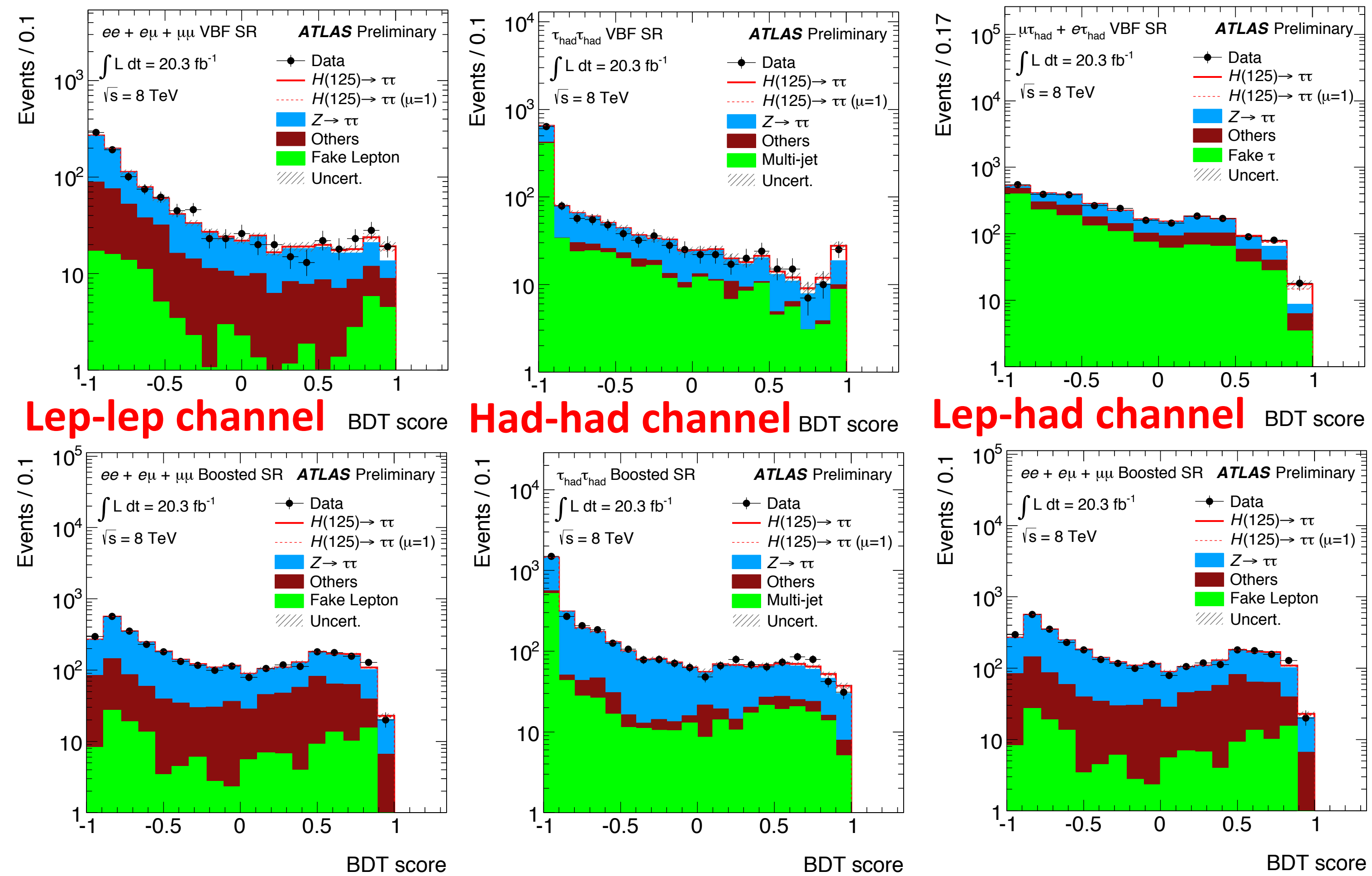
Event topology

- m_T, object centralities, $P_T(\tau_1)/P_T(\tau_2)$, etc

Number of variables

- *VBF:* 7-9
- *Boosted:* 6-9





just a glimpse at (part of) the very many categories and channels that are simultaneously fit to extract the signal

Systematic Uncertainties

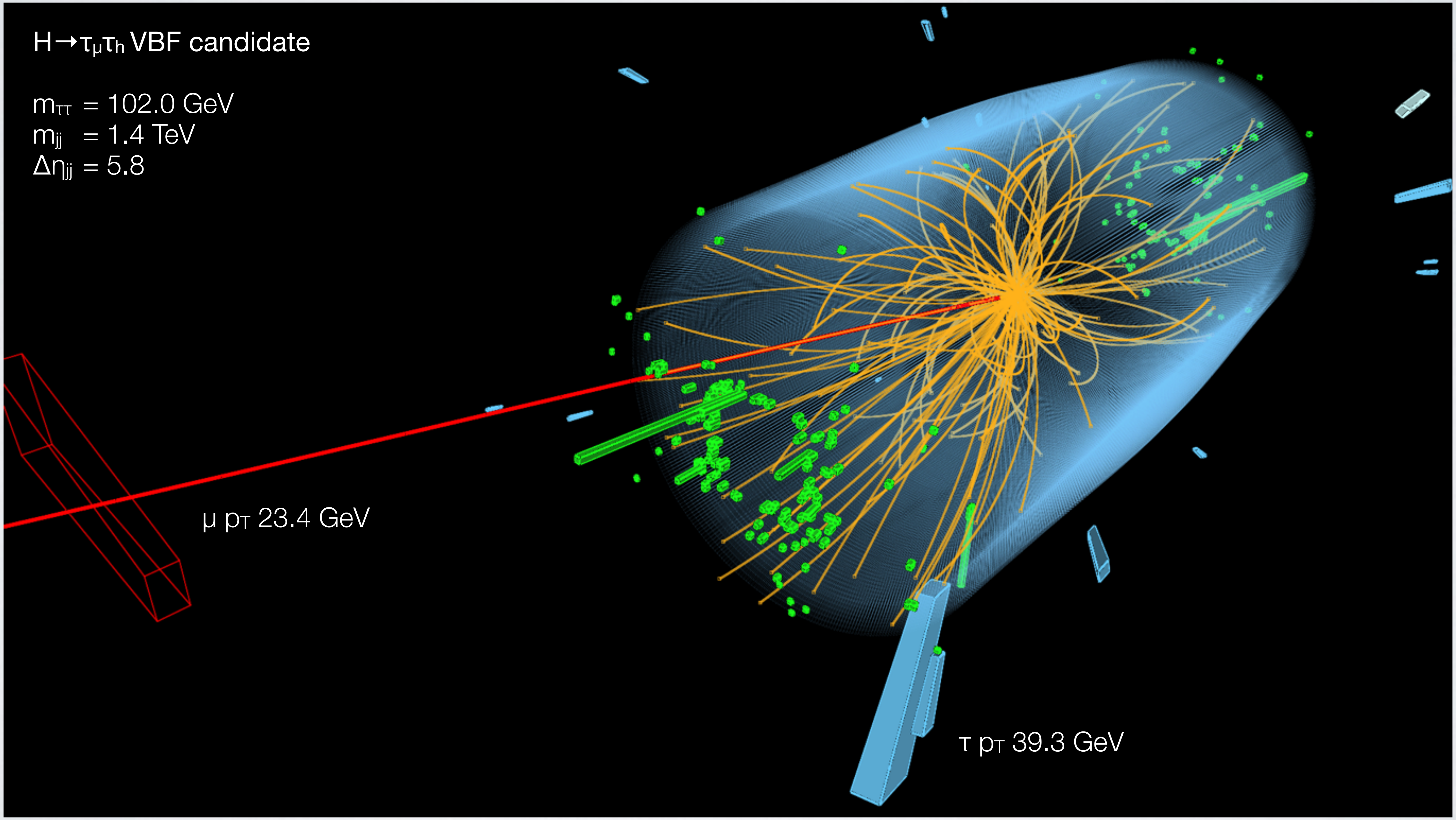
Uncertainty	Affected processes	Change in acceptance
Tau energy scale	signal & sim. backgrounds	1–29%
Tau ID (& trigger)	signal & sim. backgrounds	6–19%
e misidentified as τ_h	$Z \to ee$	20–74%
μ misidentified as τ_h	$Z \to \mu\mu$	30%
Jet misidentified as τ_h	Z + jets	20–80%
Electron ID & trigger	signal & sim. backgrounds	2–6%
Muon ID & trigger	signal & sim. backgrounds	2–4%
Electron energy scale	signal & sim. backgrounds	up to 13%
Jet energy scale	signal & sim. backgrounds	up to 20%
E_T^{miss} scale	signal & sim. backgrounds	1–12%
$\epsilon_{b\text{-tag}}$ b jets	signal & sim. backgrounds	up to 8%
$\epsilon_{b\text{-tag}}$ light-flavoured jets	signal & sim. backgrounds	1–3%
Norm. Z production	Z	3%
$Z \to \tau\tau$ category	$Z \to \tau\tau$	2–14%
Norm. W + jets	W + jets	10–100%
Norm. $t\bar{t}$	$t\bar{t}$	8–35%
Norm. diboson	diboson	6–45%
Norm. QCD multijet	QCD multijet	6–70%
Shape QCD multijet	QCD multijet	shape only
Norm. reducible background	Reducible bkg.	15–30%
Shape reducible background	Reducible bkg.	shape only
Luminosity 7 TeV (8 TeV)	signal & sim. backgrounds	2.2% (2.6%)
PDF (qq)	signal & sim. backgrounds	4–5%
PDF (gg)	signal & sim. backgrounds	10%
Norm. ZZ/WZ	ZZ/WZ	4–8%
Norm. $t\bar{t}$ + Z	$t\bar{t}$ + Z	50%
Scale variation	signal	3–41%
Underlying event & parton shower	signal	2–10%
Limited number of events	all	shape only

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

different final discriminators are differently affected by the systematics

H→ττ

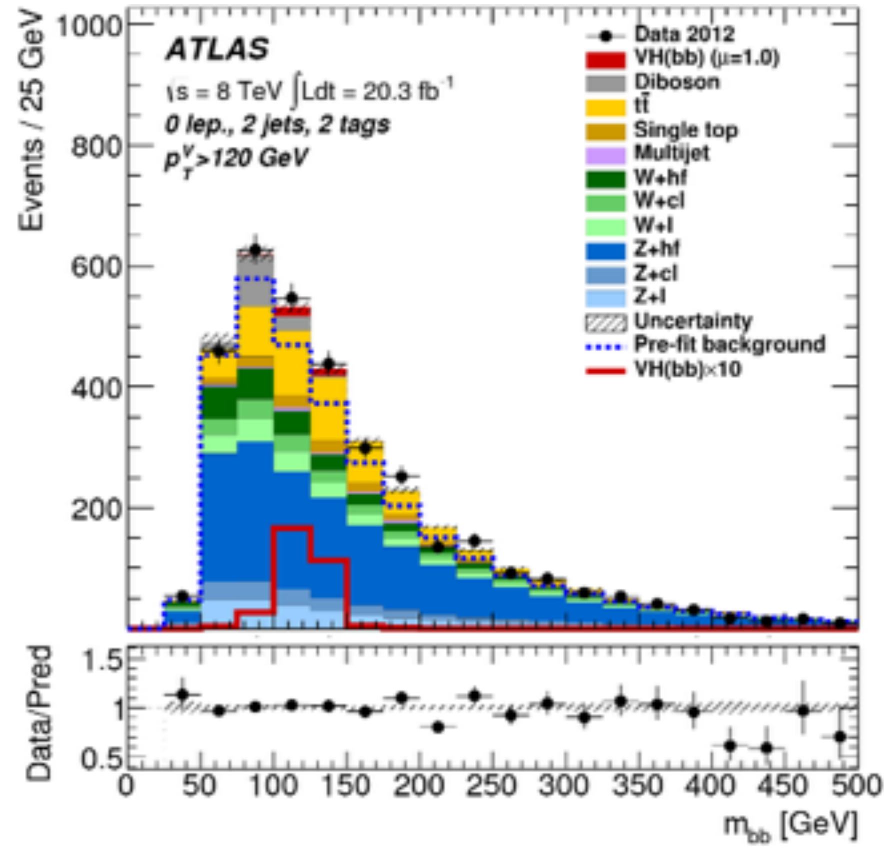
CMS EVENT DISPLAY

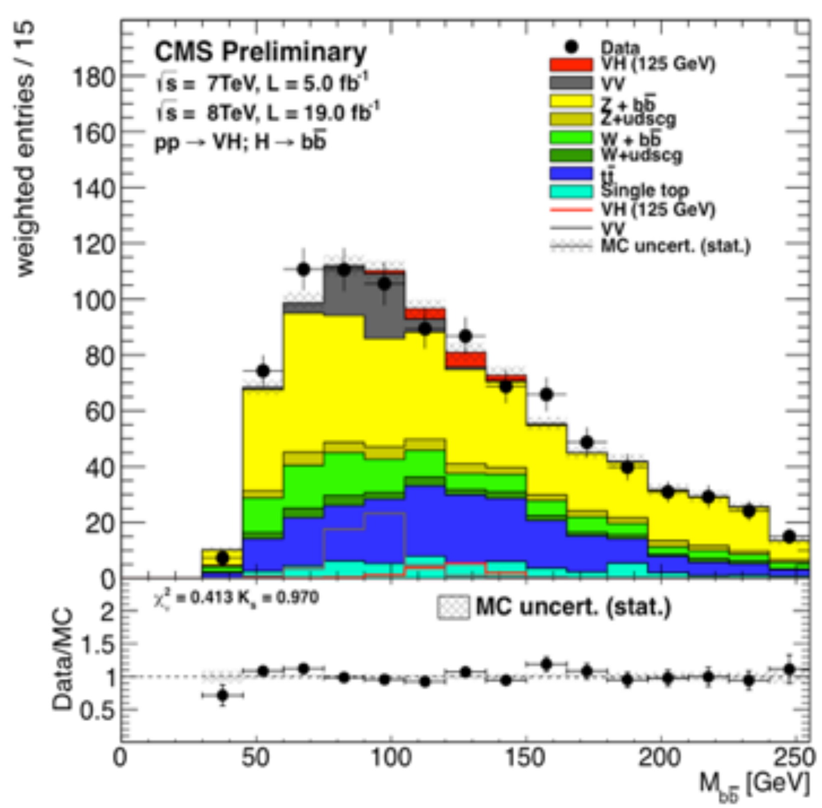


VH, H→bb BACKGROUNDS

ATLAS

- Multijet
  - Data-driven
- Z+jets, W+jets, ttbar
  - Initial from MC
  - Normalisation & shape constrained in global fit
  - Dedicated background CR included in fit
- Diboson, Single top
  - From MC

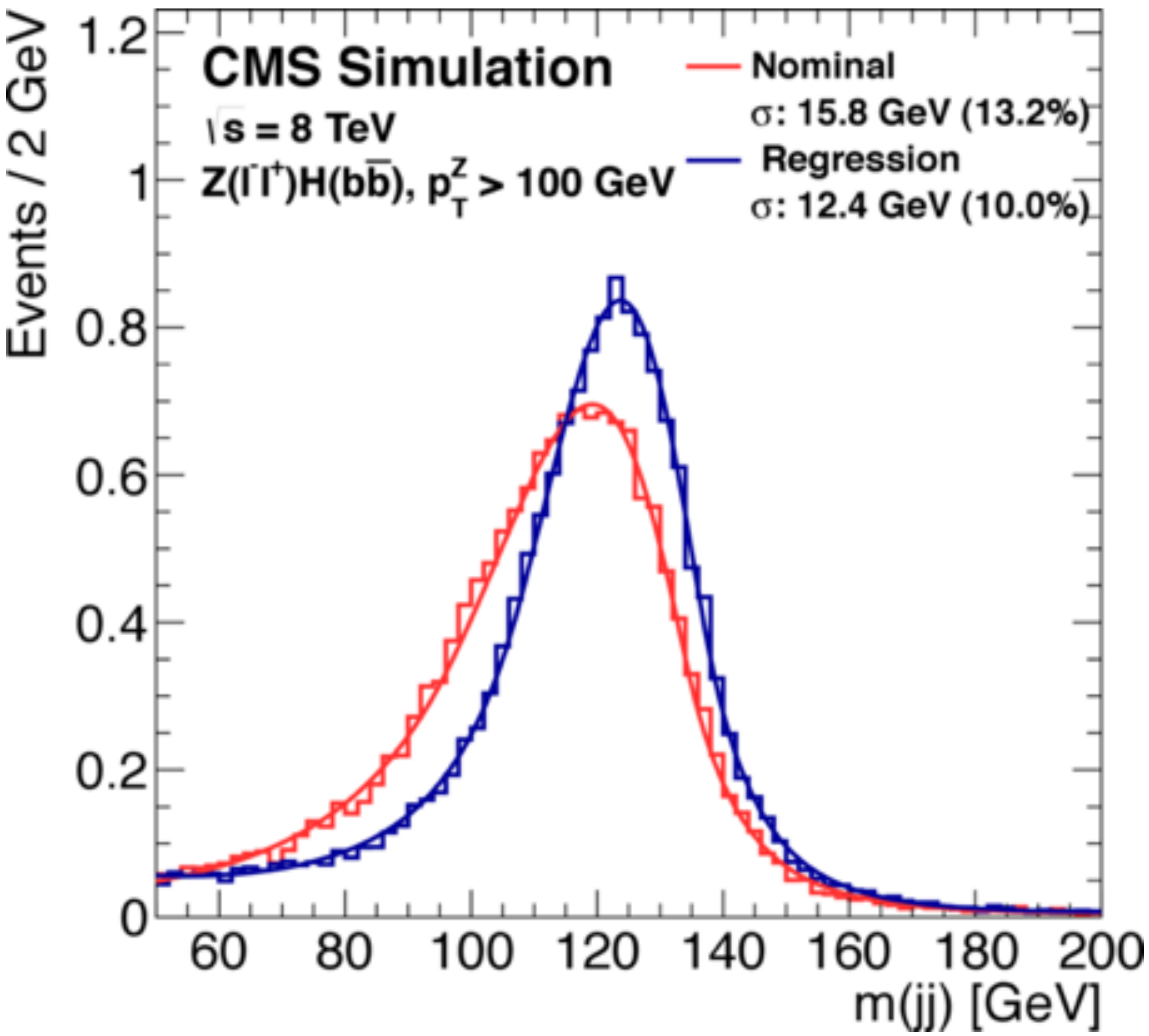




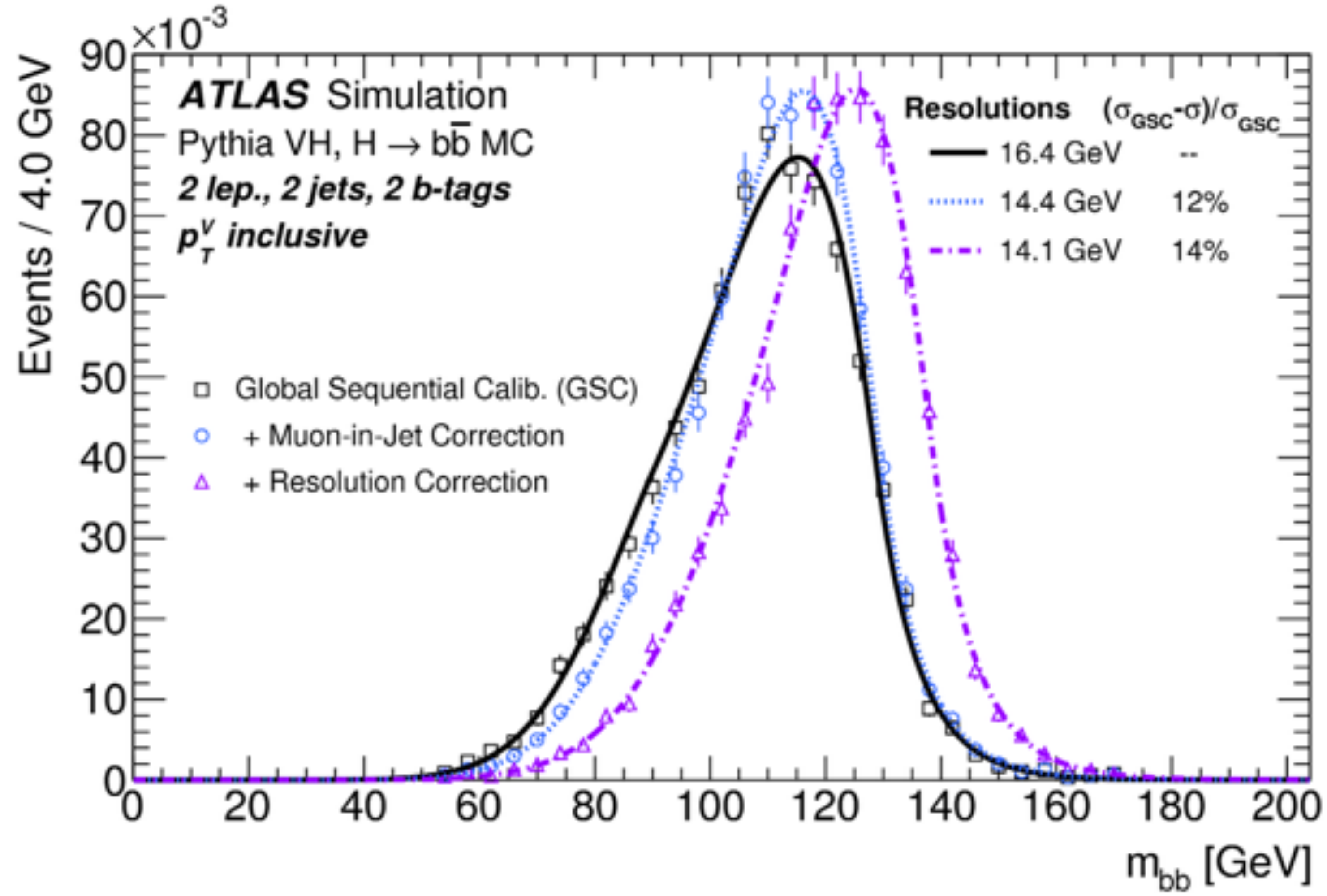
CMS

- QCD
  - Data-driven
- Z+jets, W+jets, ttbar, Diboson, Single top
  - Shape from MC
  - Normalised to CR in data

VH, H→bb MASS



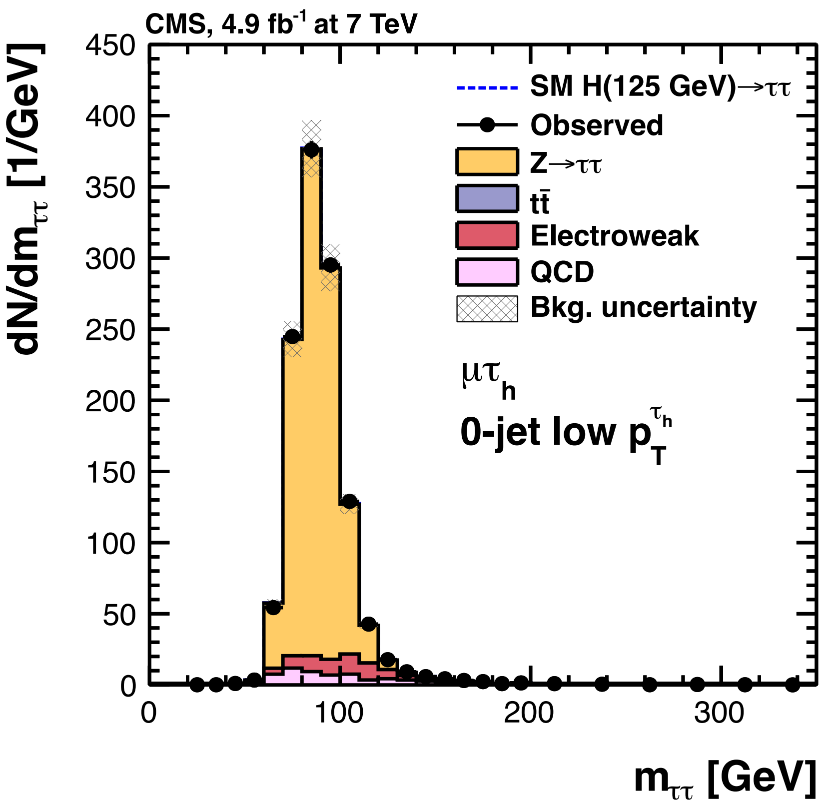
CMS Simulation
√s = 8 TeV
Z(l⁻l⁺)H(bb̄), p_T^Z > 100 GeV
Nominal
σ: 15.8 GeV (13.2%)
Regression
σ: 12.4 GeV (10.0%)
Events / 2 GeV
m(jj) [GeV]



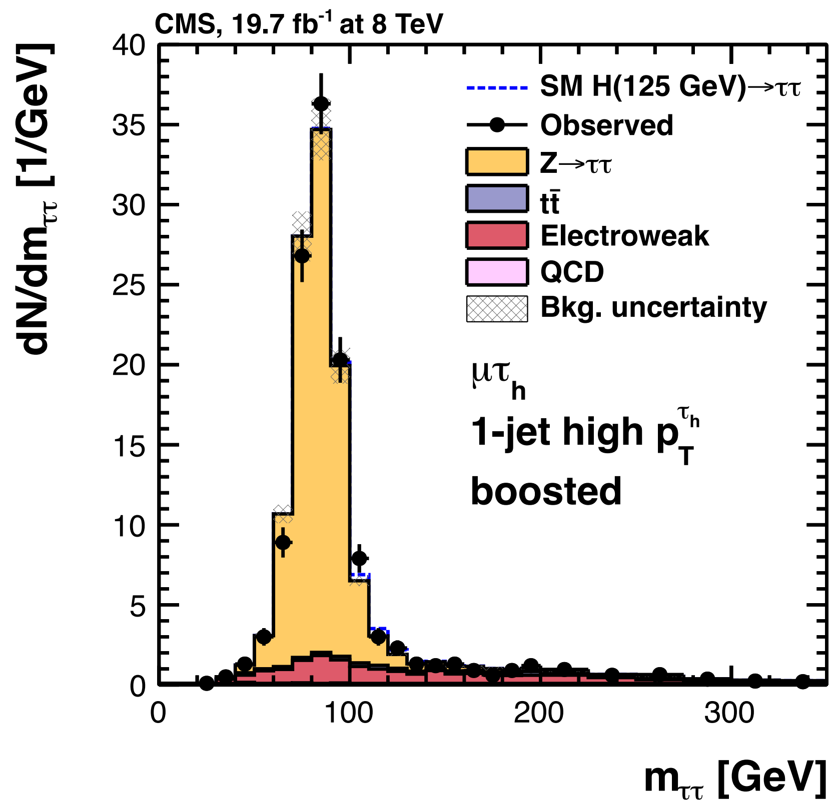
ATLAS Simulation
Pythia VH, H → bb̄ MC
2 lep., 2 jets, 2 b-tags
p_T^V inclusive
Resolutions (σ_GSC-σ)/σ_GSC
16.4 GeV --
14.4 GeV 12%
14.1 GeV 14%
Global Sequential Calib. (GSC)
+ Muon-in-Jet Correction
+ Resolution Correction
Events / 4.0 GeV
×10⁻³
m_bb [GeV]

MUTAU MASS DISTRIBUTIONS

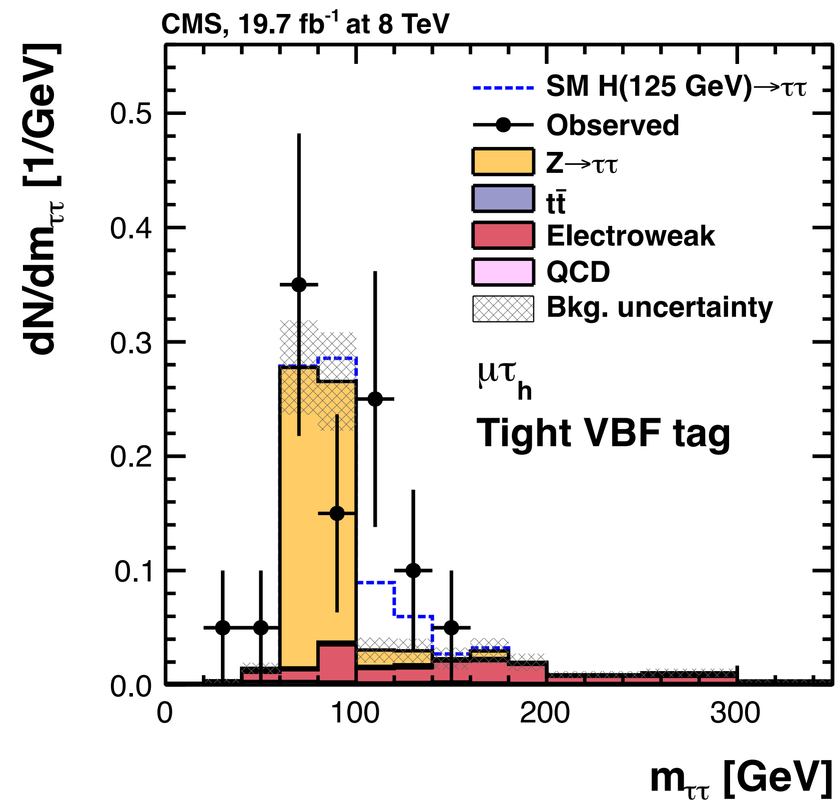
0 jet



1 jet



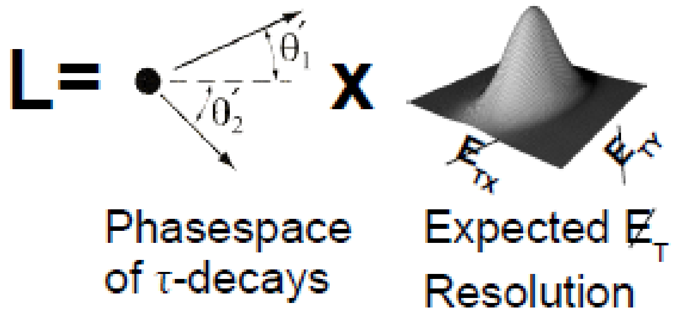
2 jet (VBF)

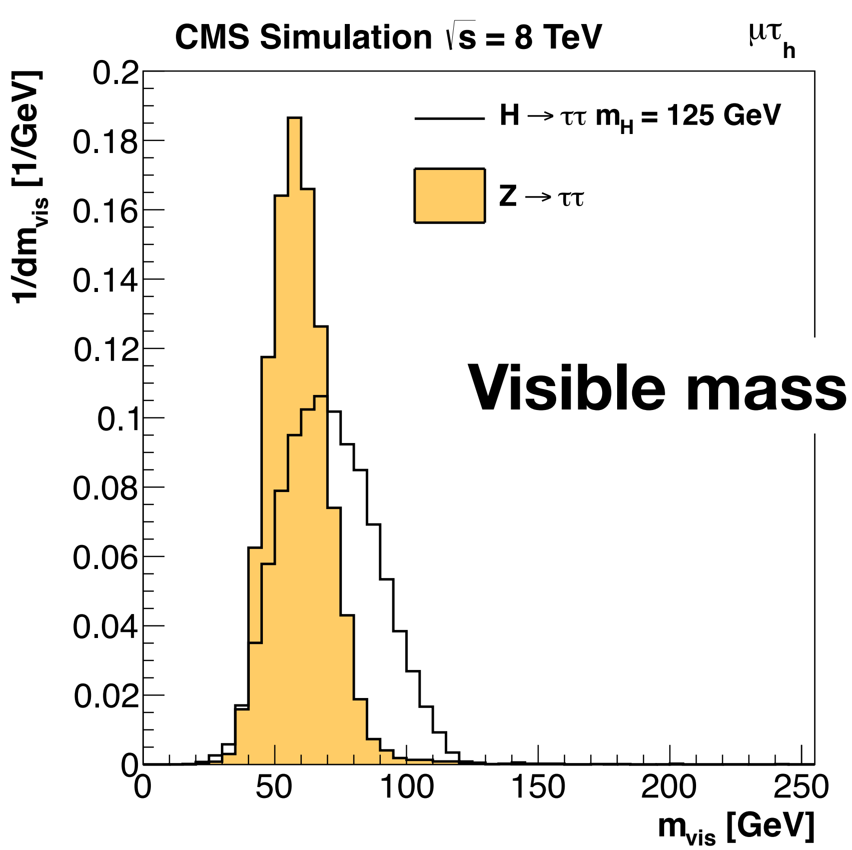


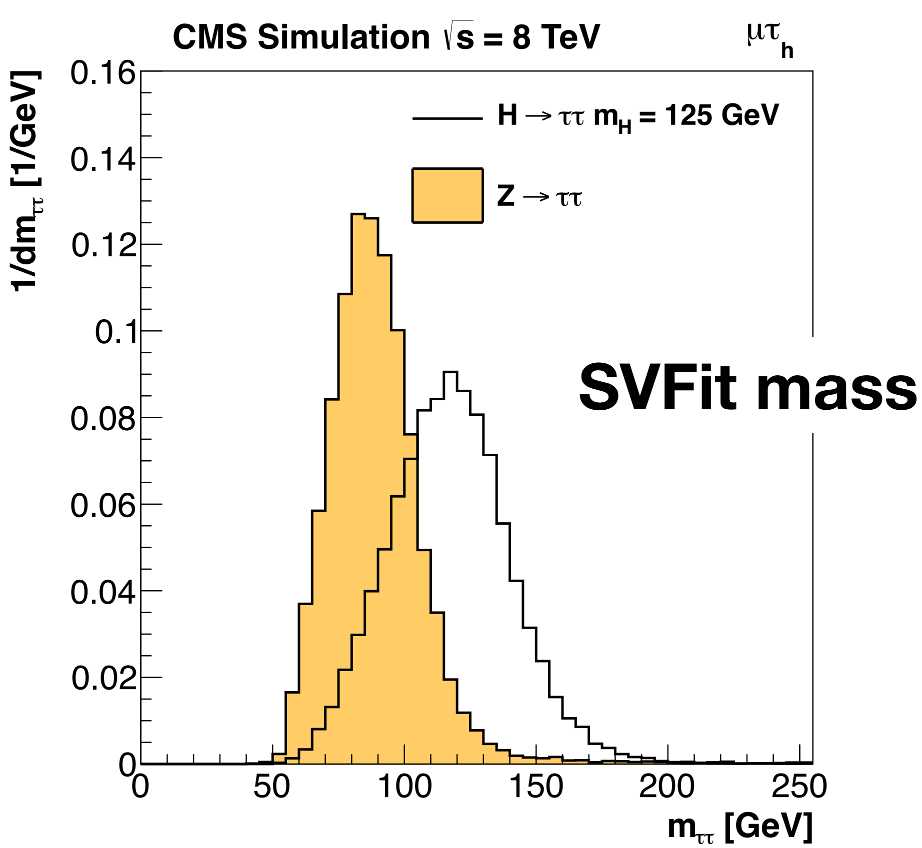
- **0-jet** categories have large statistics but low S/B and thus provide good constraints for the main uncertainties
  - Tau ID efficiency
  - Tau Energy Scale
- **1-jet** (boosted) categories show better $m_{\tau\tau}$ resolution
- **2-jets** (VBF) categories show low bkg contamination and good S/B

SVFIT ALGORITHM

- Kinematic **maximum likelihood fit to estimate mass of ττ system**
- Estimated on event-by-event basis using four-momenta of visible decay products, E_x^{miss}, E_y^{miss}, and expected E_T^{miss} resolution
- **10-20% resolution** on reconstructed $m_{\tau\tau}$ depending on channel/category



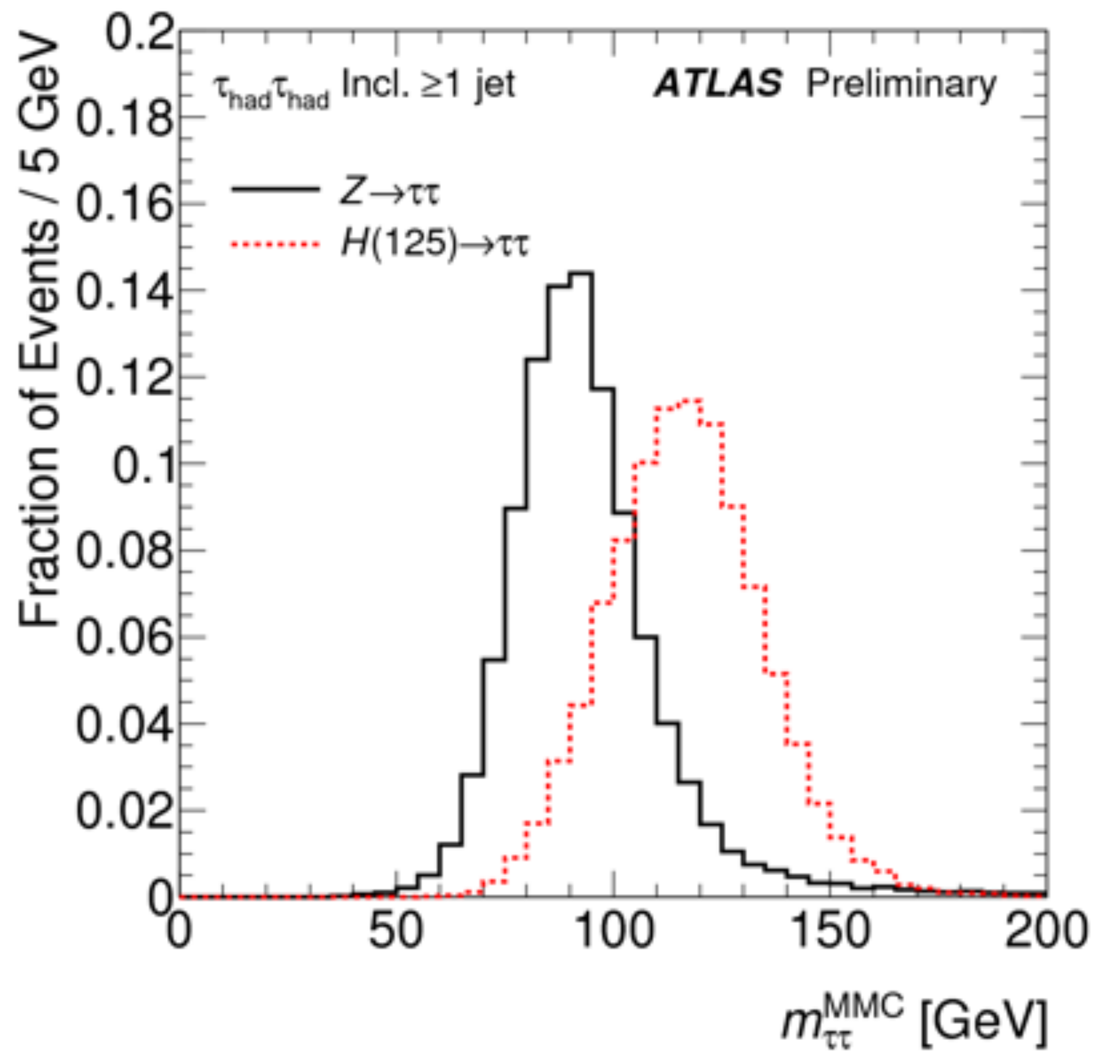




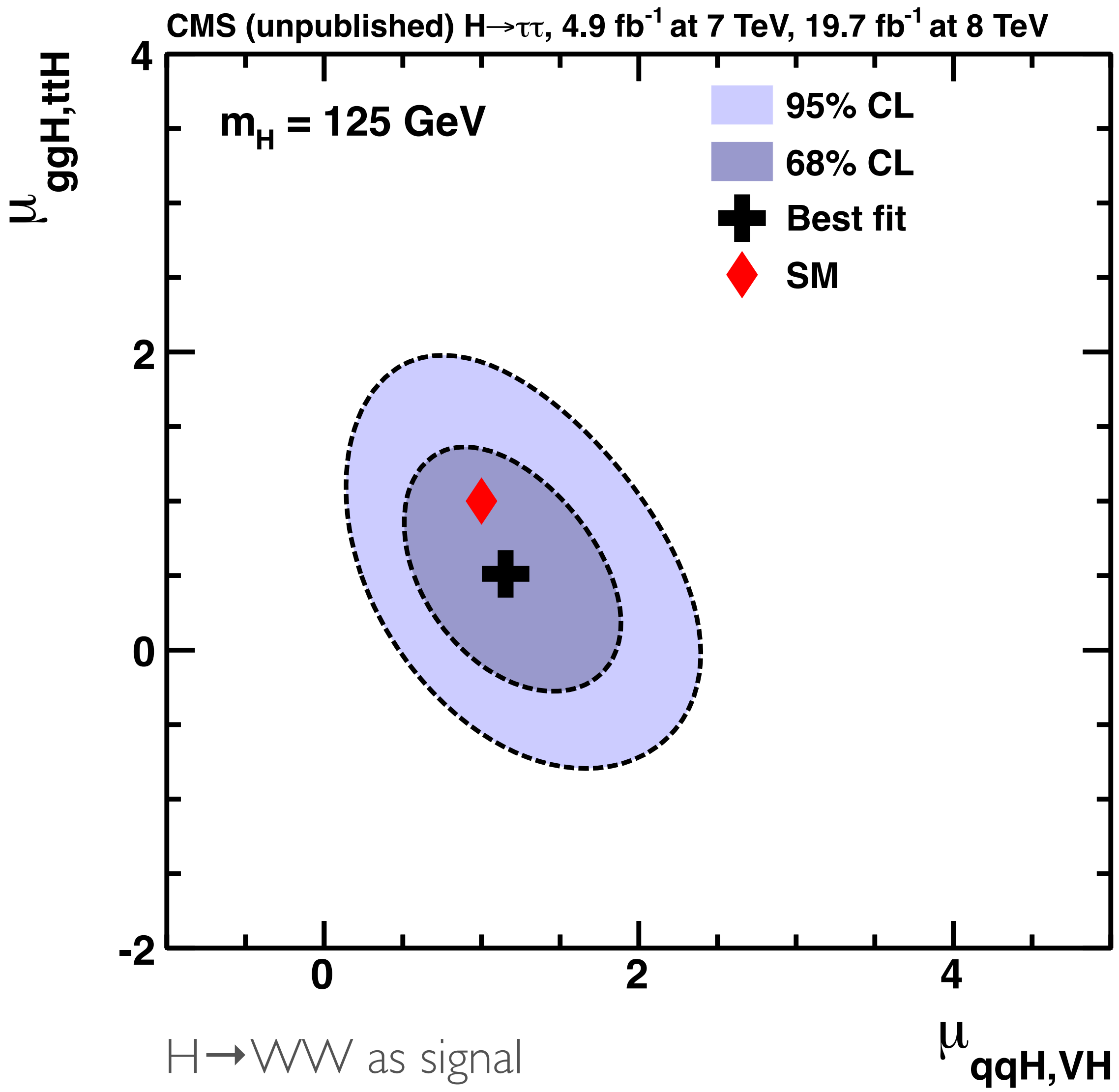
SVFit di-τ mass is used as mass discriminator for the statistical interpretation for $\mu\tau_h$, $e\tau_h$, $e\mu$, $\tau_h\tau_h$ channels

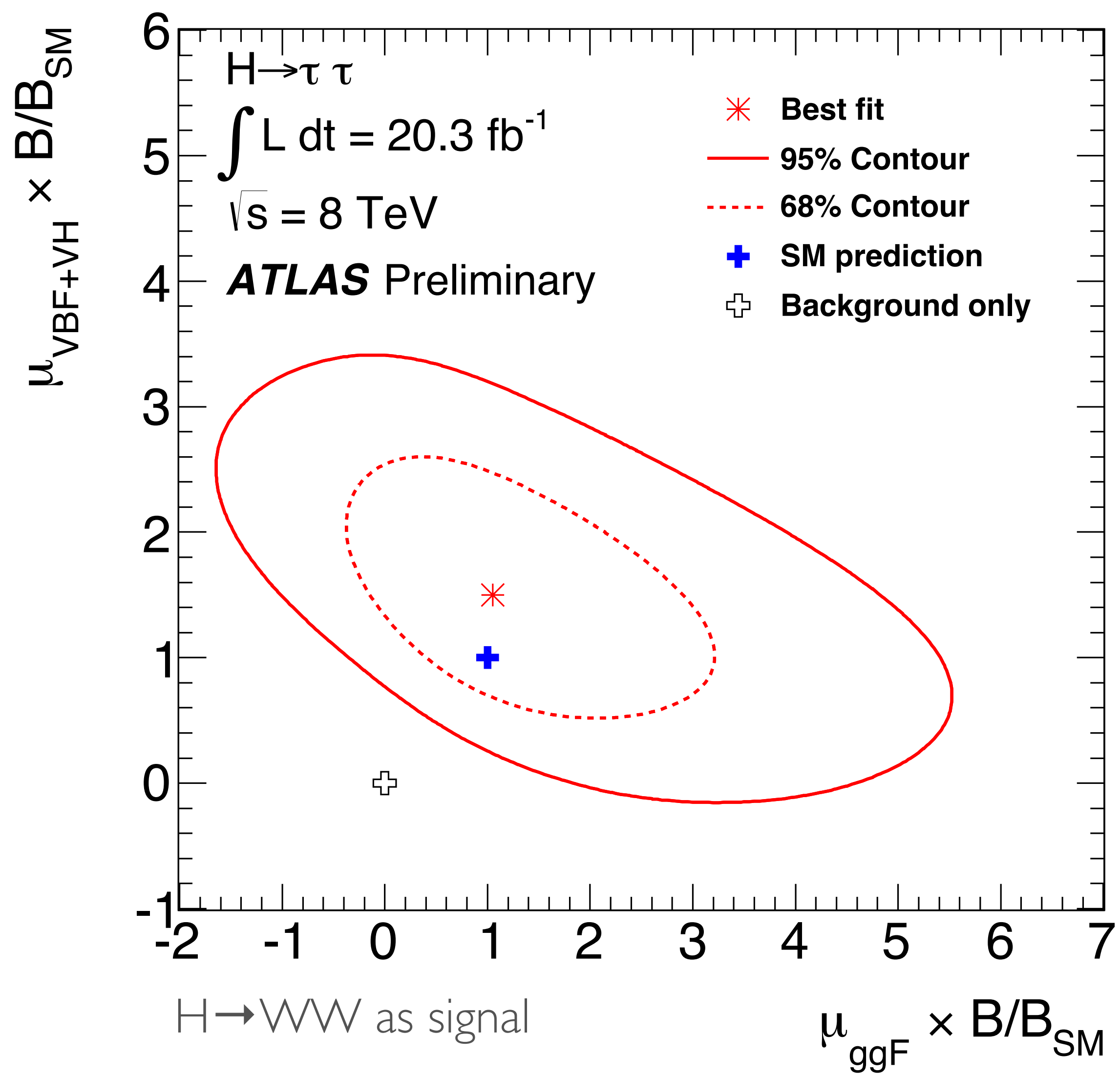
MMC ALGORITHM

- **Missing Mass Calculator MMC**
  - aims at reconstruction the invariant mass of the parent boson starting from the visible decay product and the MET
  - resolution ranges 14-21%
- **employed by the BDT**
  - one of the highest ranked and discriminating variables



HIGGS PRODUCTION MODES





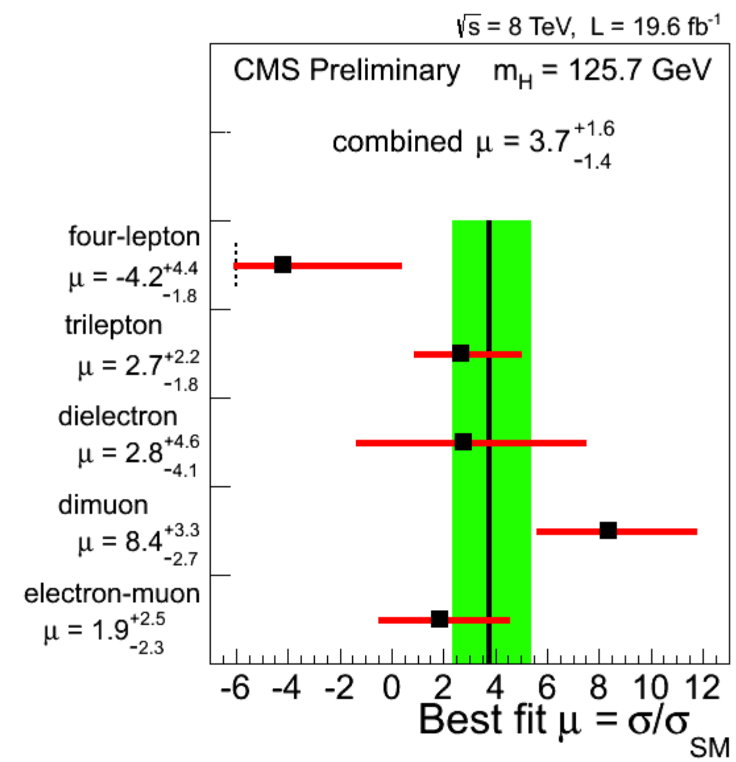
Sensitive to VBF, ggH and VH production modes

TTH 2L SS INVESTIGATION

several cross checks carried out by the ttH group in CMS, summarised in these slides

The result

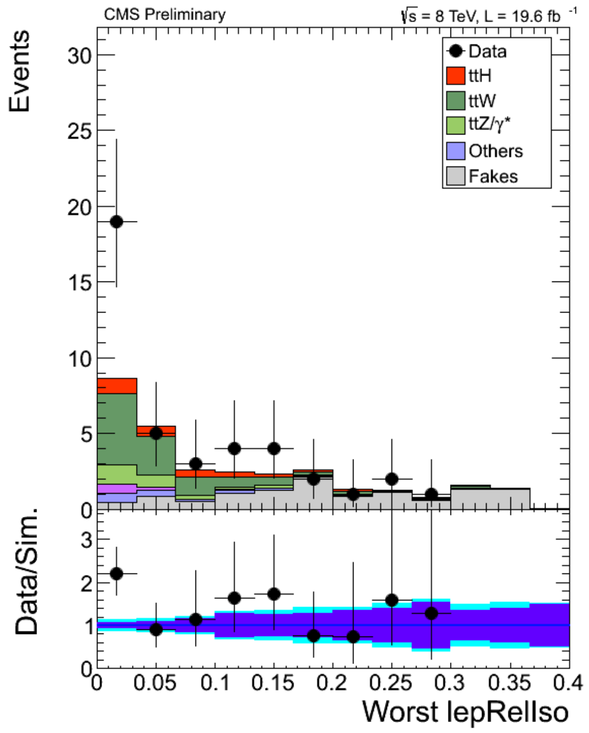
- The results in the different channels are fairly close to the SM Higgs predictions except the $\mu^{\pm}\mu^{\pm}$ final state, where an excess is observed
  - The results in the five final states are consistent with a common signal strength at the 16% level.
  - The μ from the combined fit is consistent with the SM Higgs prediction (μ = 1) at the 3% level (1.9σ)



TTH 2L SS INVESTIGATION

Leptons

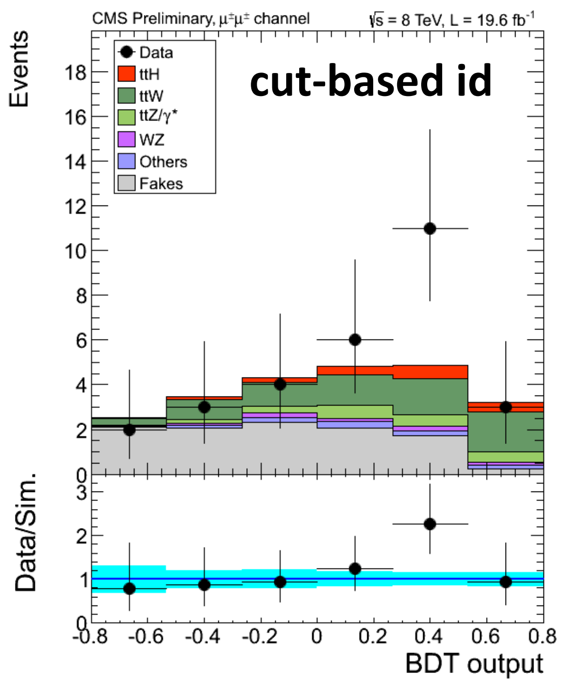
- The events in excess are characterized by having both leptons very well isolated.
- Scrutiny of the events also confirms that both leptons are well reconstructed in the tracker and muon system, and that their charge is correctly assigned.



TTH 2L SS INVESTIGATION

Lepton ID checks: cut-based

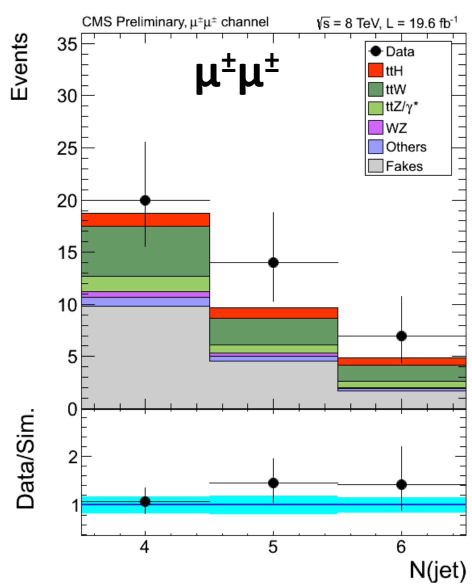
- As a cross-check, the analysis was repeated with a cut-based muon selection, instead of the lepton MVA.
- The result with the cut-based selection is compatible with the nominal one, but the sensitivity is worse.

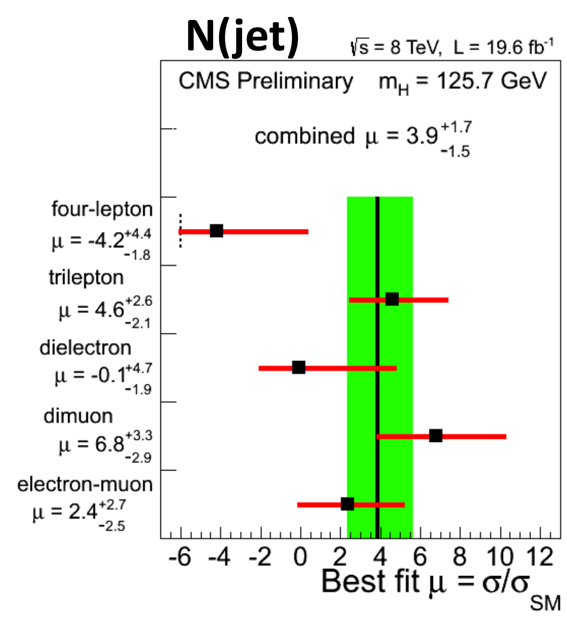


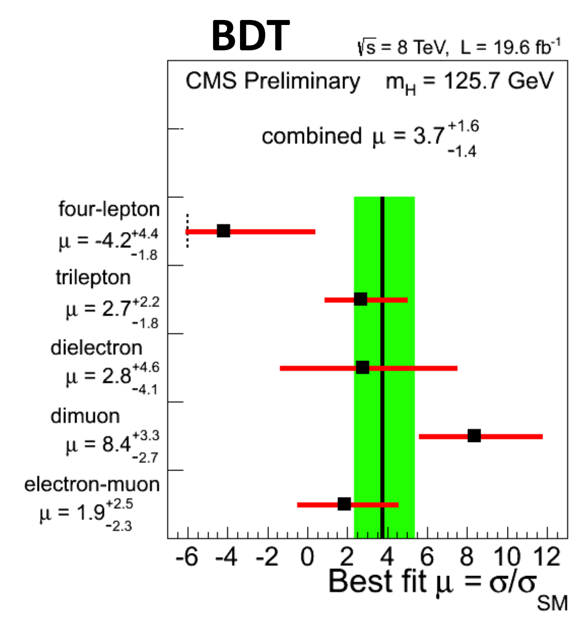
TTH 2L SS INVESTIGATION

Signal extraction check

- The signal extraction is repeated using just the multiplicity of hadronic jets as discriminating variable instead of the kinematic BDT.
- The result is compatible with the nominal one, but the sensitivity is worse (as expected)







Conclusions

- Several studies have been performed to investigate the excess in the $\mu^{\pm}\mu^{\pm}$ final state
  - no anomalies seen in the properties of the selected events
  - no indication of any issue in the lepton MVA ID and in the reducible background estimation
  - no evidence for unaccounted backgrounds
- More in general, for this analysis:
  - compatible results obtained in cross-check without using multivariate methods for lepton IDs or signal extraction
  - ttW and ttZ yields also fitted as cross-check, and found in good agreement with the theoretical predictions (i.e. no indication of problems there, nor in the signal efficiencies)