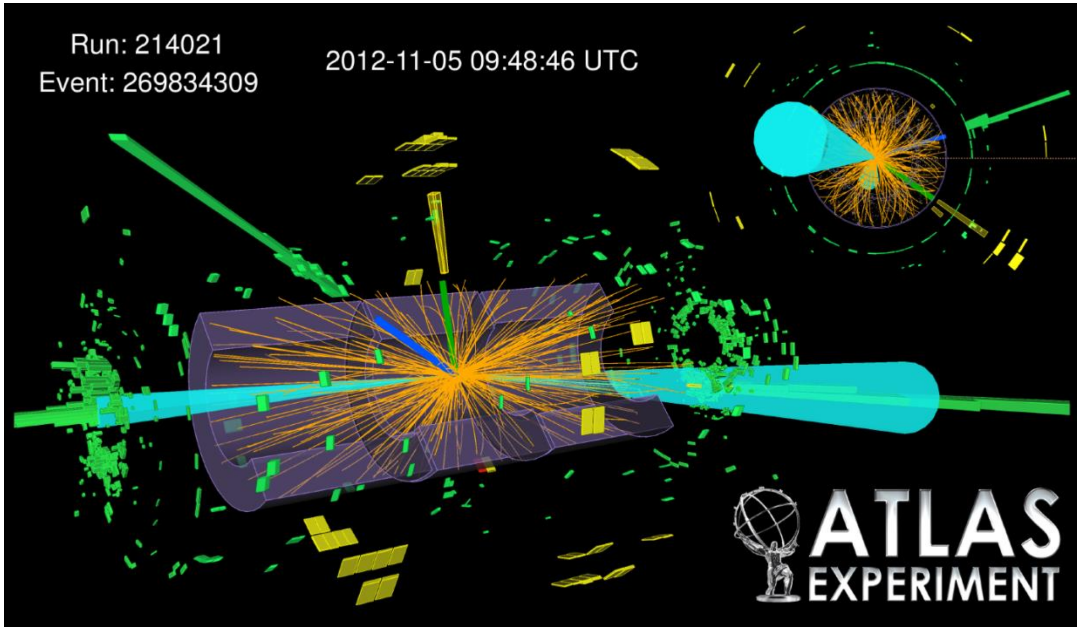


Evidence for Higgs Boson Decays to the $\tau^+\tau^-$ final state at the LHC.

Koji Nakamura (KEK)
on behalf of ATLAS&CMS collaboratio

NEWS

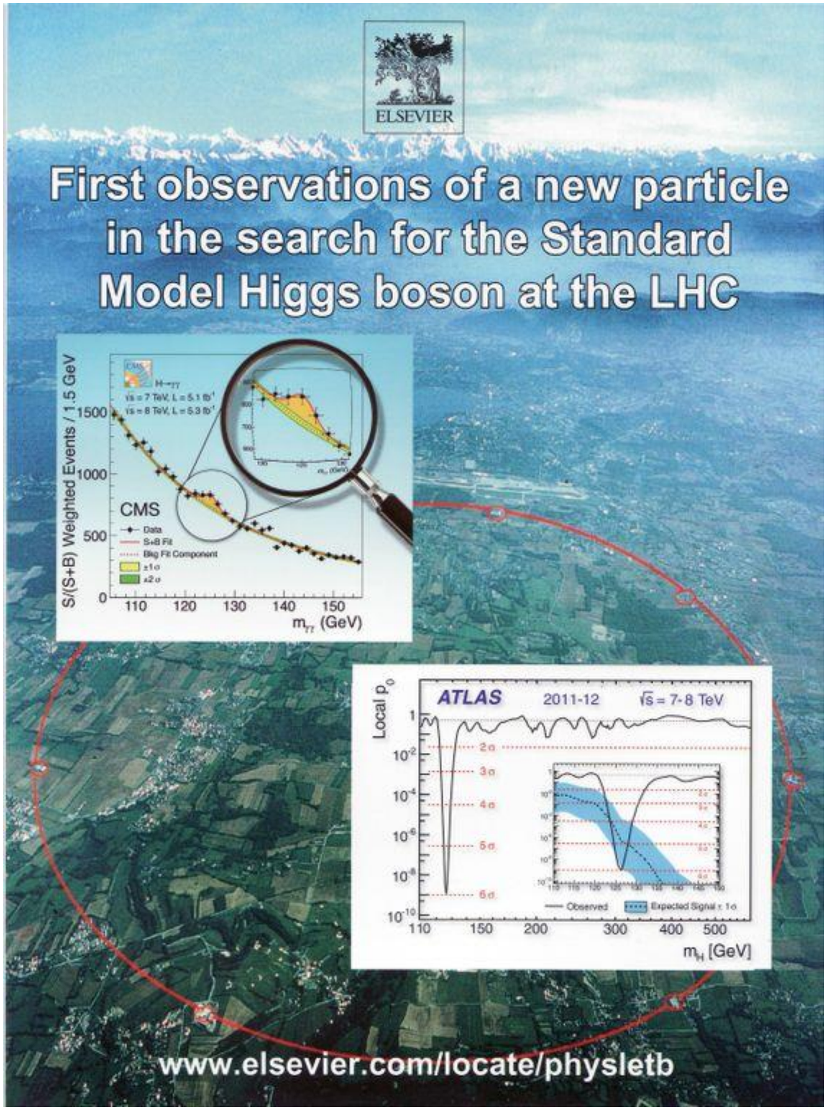
- CERN-EP seminar : 26th Nov, 2013
  - **ATLAS results on Higgs boson searches in fermion final states**
  - Twiki : https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-108/
  - CONF NOTE: http://cds.cern.ch/record/1632191

- CERN-EP seminar : 3rd Dec, 2013
  - **Direct Measurement of the Higgs Boson Fermionic Couplings at CMS**
  - Twiki : https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13004TWikiUpdate
  - NOTE : not yet available

- $H \rightarrow \tau\tau$ Collider Cross Talk seminar : 12th Dec, 2013
  - Agenda : http://indico.cern.ch/conferenceDisplay.py?confId=287044
  - No materials are in the Agenda (Black board discussion)

Introduction

Observation of a new Boson



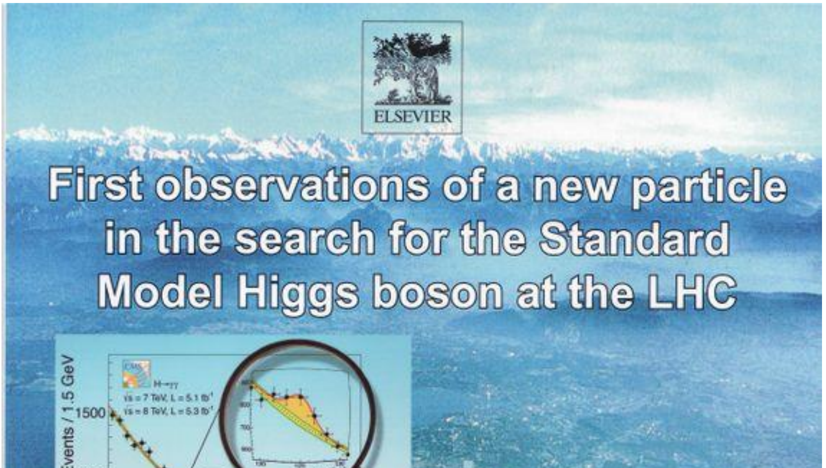
Phys.Lett. B716 (2012) 1-29

"These results provide conclusive evidence for the discovery of a new particle with mass 126.0±0.4 *(stat)*±0.4 *(sys)* GeV. "

What is "new particle"?

July 4th 2012 : ATLAS Higgs WG

Observation of a new Boson



Phys.Lett. B716 (2012) 1-29

“These results provide conclusive evidence for the discovery of a new particle with mass 126.0±0.4 *(stat)*±0.4 *(sys)* GeV. ”

What is “new particle”?

The Nobel Prize in Physics 2013

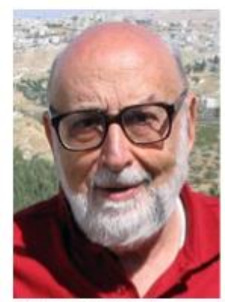


Photo: Pnicolet via Wikimedia Commons

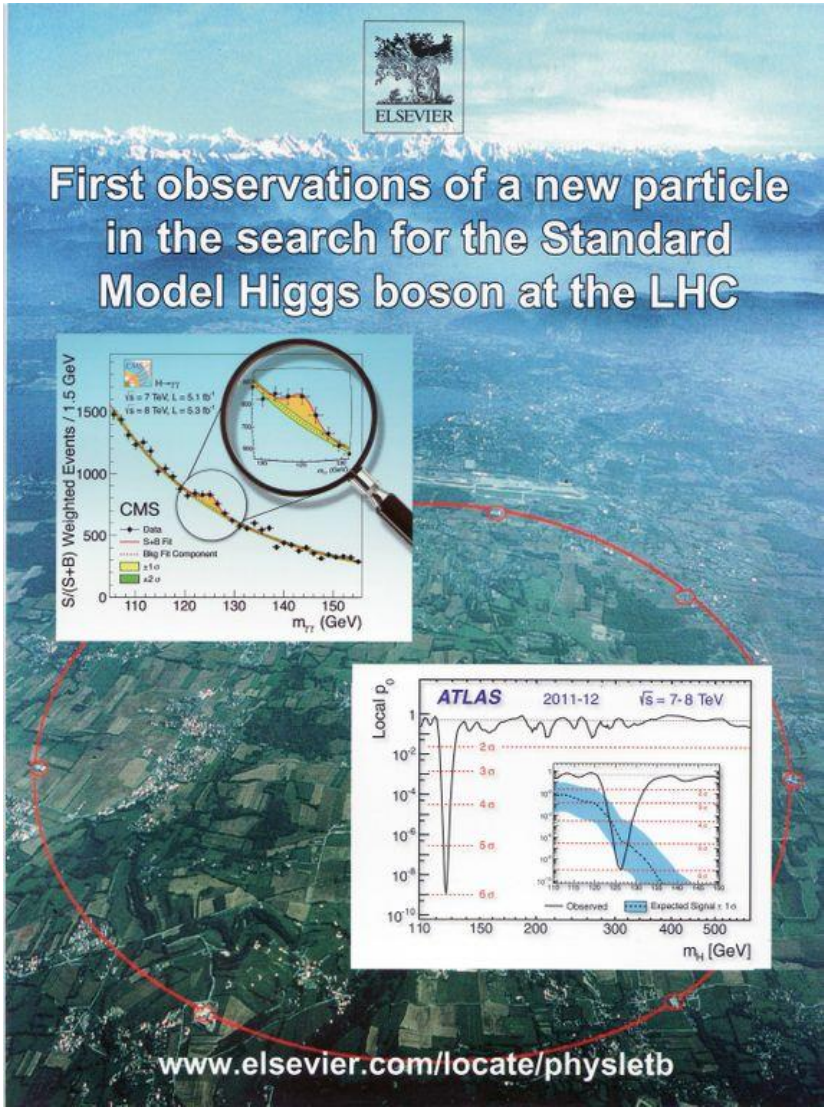
François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

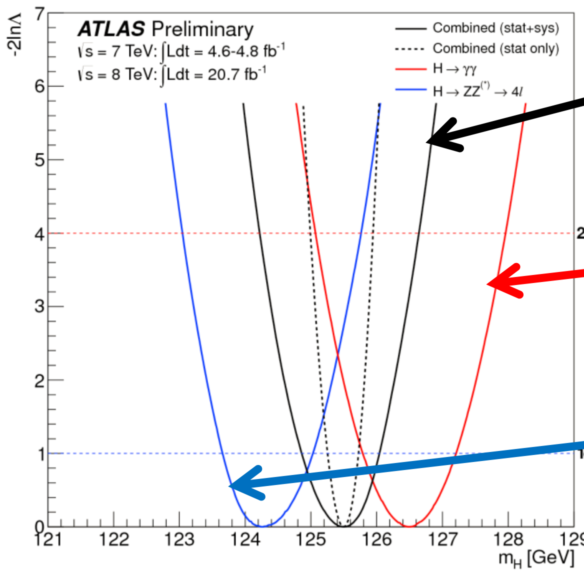
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Observation of a new Boson



What is "new particle"?

- **Mass of the particle?**
  - **125.5±0.2(stat)±0.6(sys)**

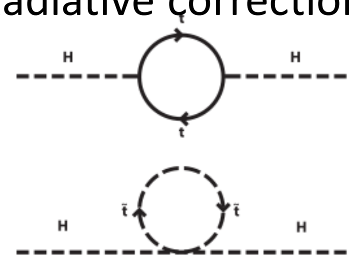


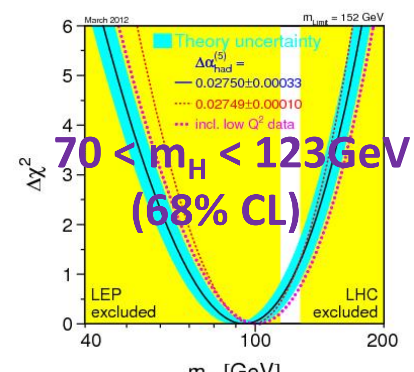
Combined
125.5±0.2(stat)±0.6(sys)

H→γγ
126.8±0.2(stat)±0.7(sys)

H→ZZ→4l
124.3±0.6(stat)±0.5(sys)

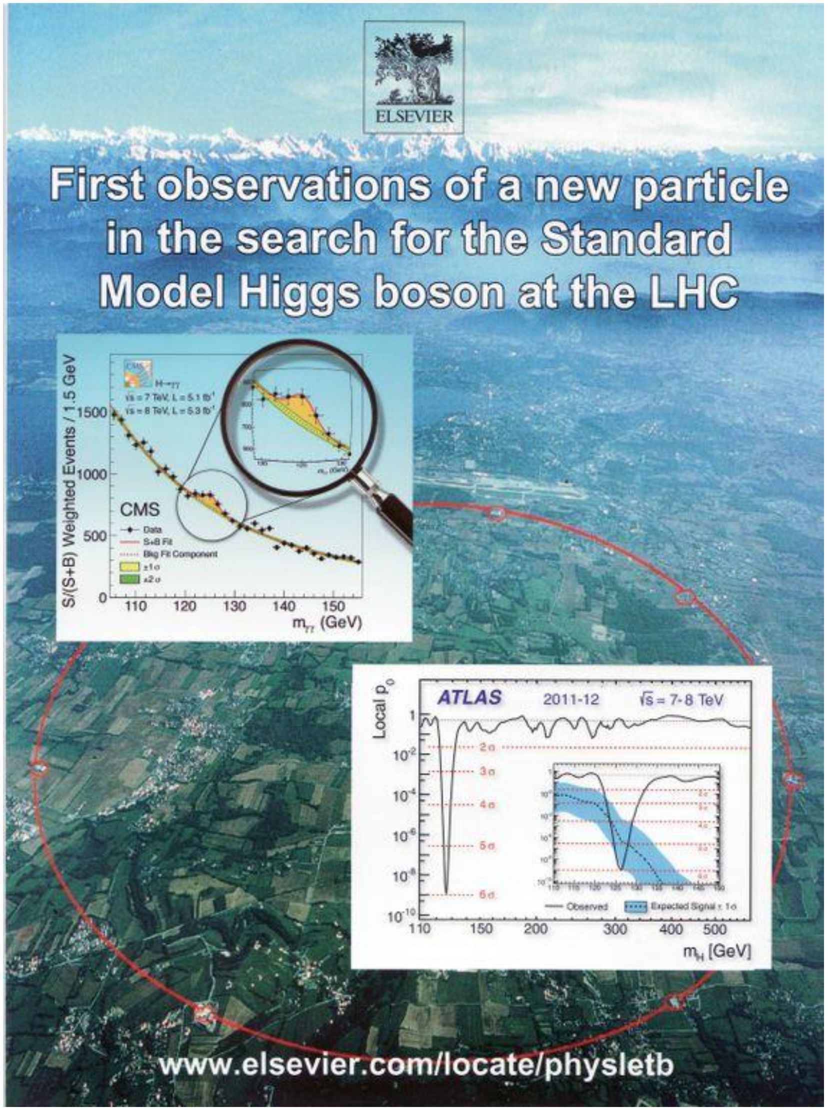
Radiative corrections





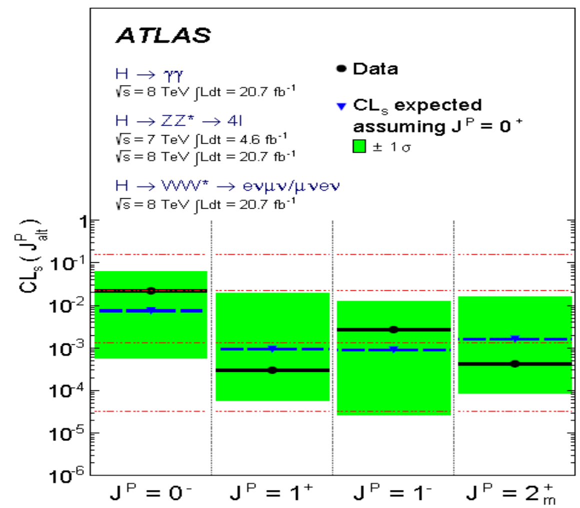
$70 < m_H < 123$GeV (68% CL)

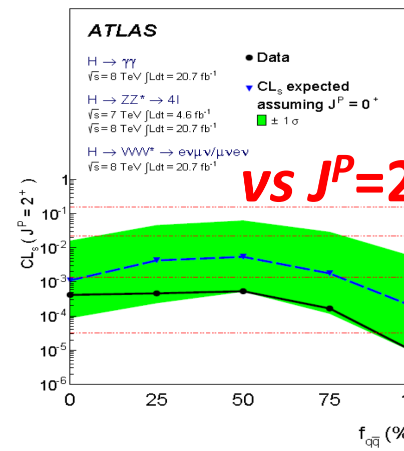
Observation of a new Boson



What is "new particle"?

- Mass of the particle?
  - 125.5±0.2(stat)±0.6(sys)
- **Spin and Parity ?**
  - Consistent with scalar ($J^P=0^+$)
  - Excluded $J^P=0^-$, 1^+, 1^-, 2^+ possibility.



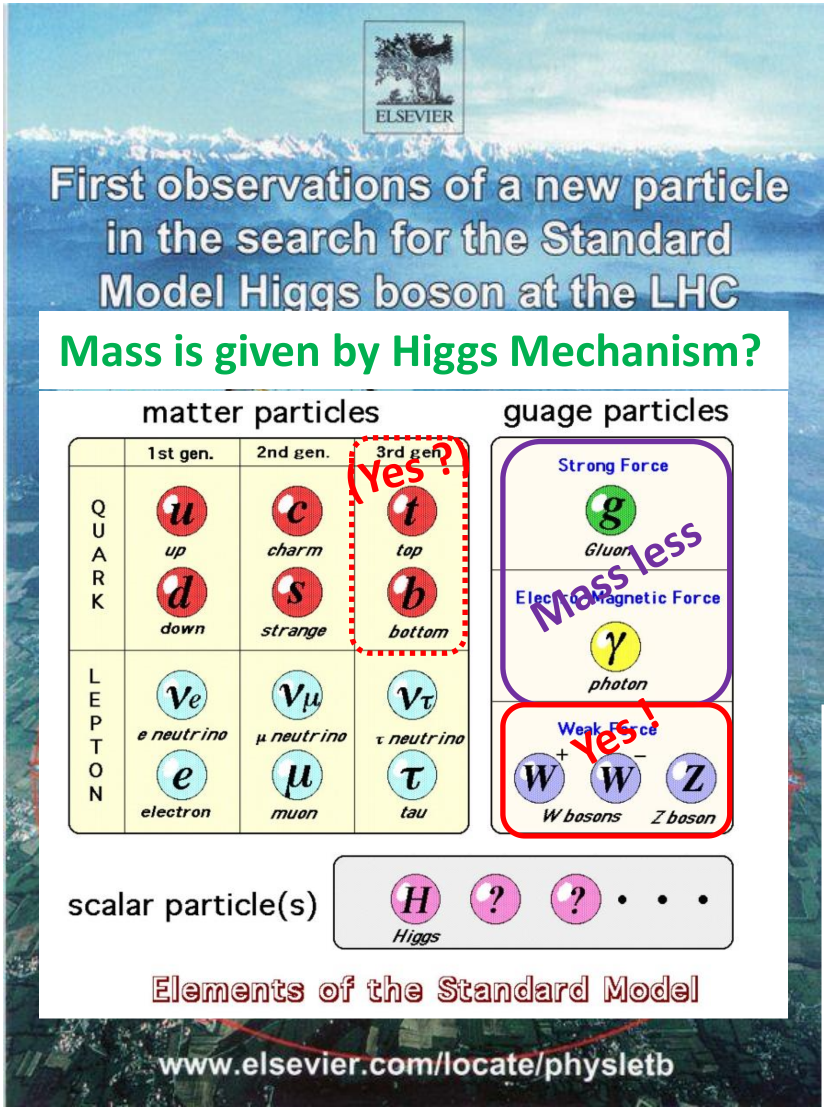


vs $J^P=2^+$

All excluded by 95%CL

First Scalar particle!

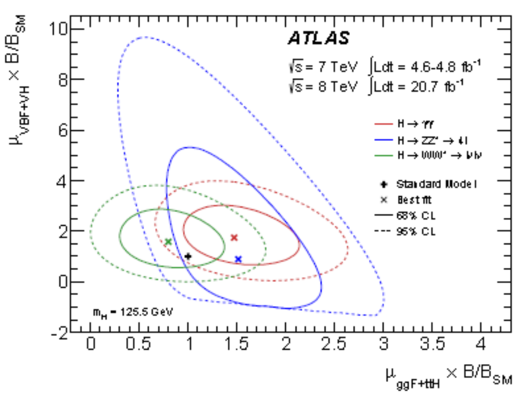
Observation of a new Boson

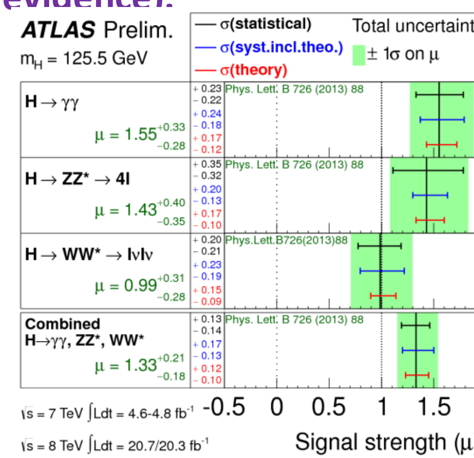


What is “new particle”?

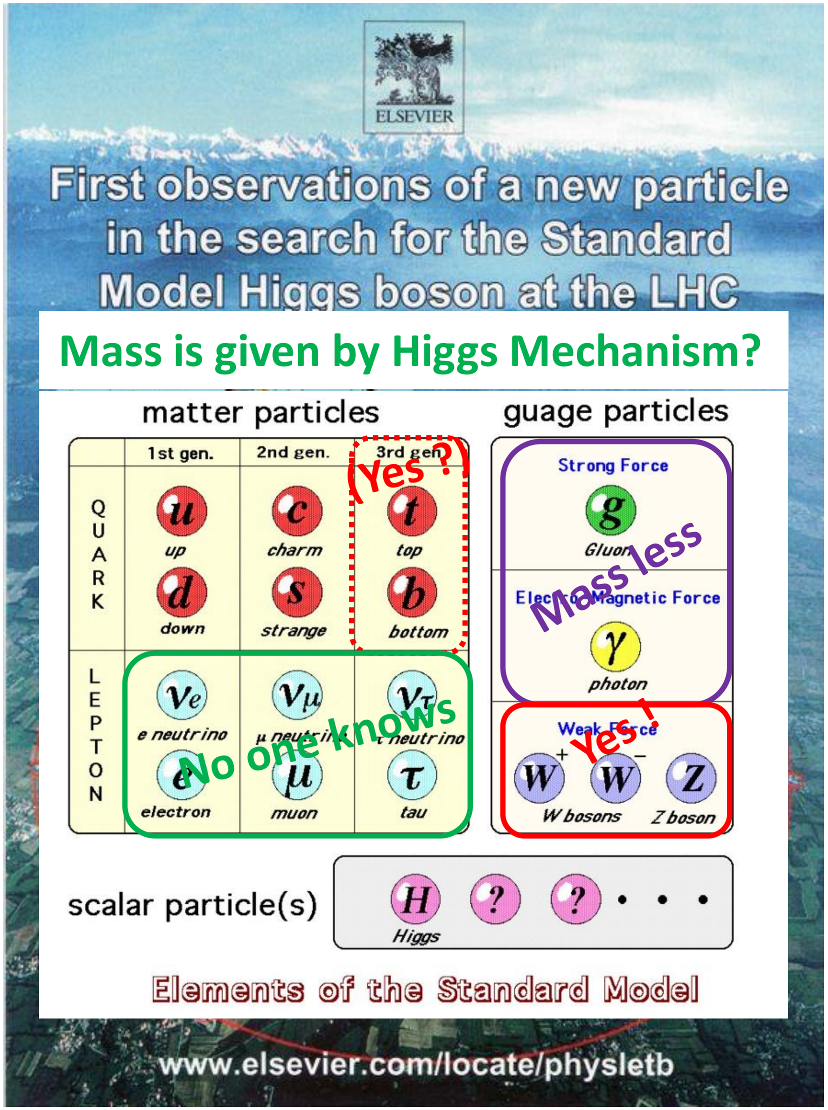
- Mass of the particle?
  - **125.5±0.2(stat)±0.6(sys)**
- Spin and Parity ?
  - **Consistent with scalar ($J^P=0^+$)**
  - **Excluded $J^P=0^-$, 1^+, 1^-, 2^+ possibility.**
- **Coupling**
  - **HWW, HZZ, H◯γγ decays exist (>3σ)**
  - **Observed ggF (gg◯H), VBF(WWH,ZZH) production process (>3σ)**

→New particle must couple with Vector Bosons and probably Quarks(no direct evidence).





Observation of a new Boson



What is "new particle"?

- Mass of the particle?
  - 125.5±0.2(stat)±0.6(sys)
- Spin and Parity ?
  - Consistent with scalar (J^P=0^+)
  - Excluded J^P=0^-, 1^+, 1^-, 2^+ possibility.
- Coupling
  - HWW, HZZ, H◯γγ decaies exist (>3σ)
  - Observed ggF (gg◯H), VBF(WWH,ZZH) production process (>3σ)

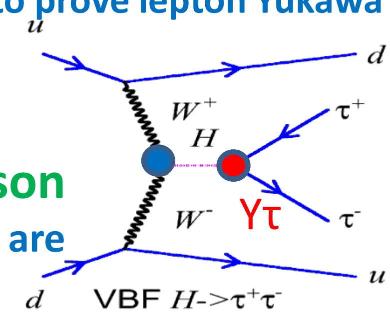
  →New particle must couple with Vector Bosons and probably Quarks(no direct evidence).

How about leptons?

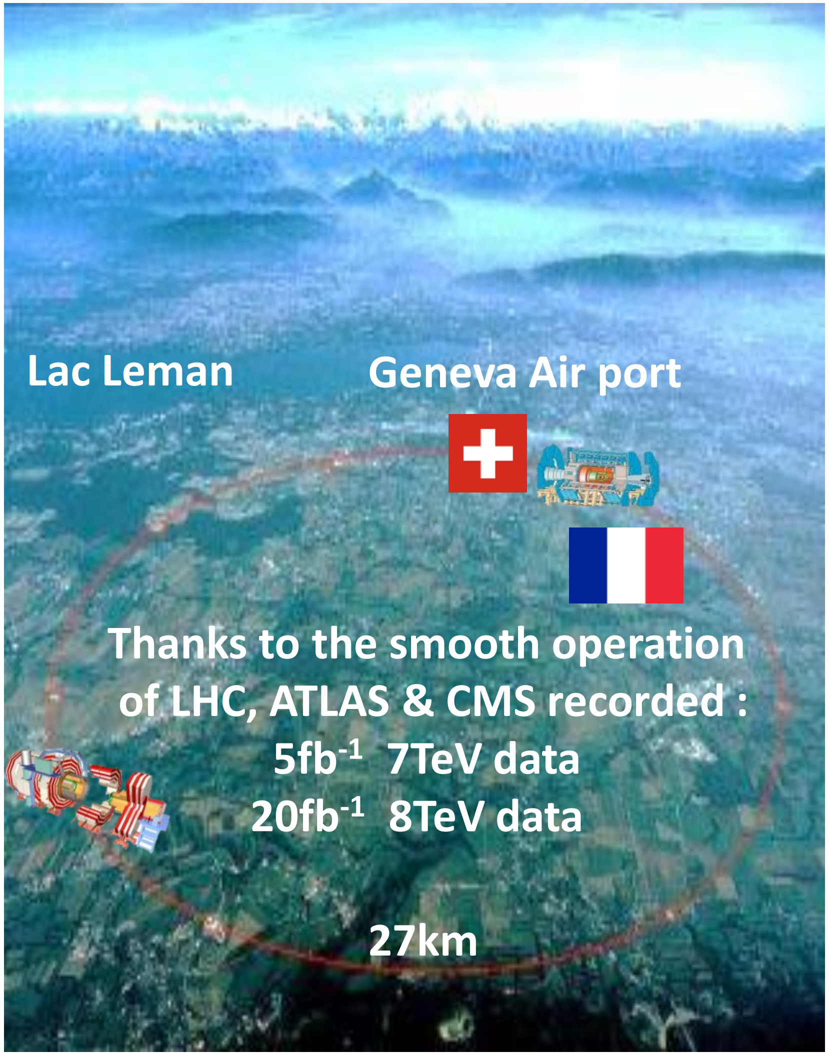
- No one knows…
- Need direct lepton(τ) decay to prove lepton Yukawa coupling!!

Final important piece to call the particle as SM Higgs Boson

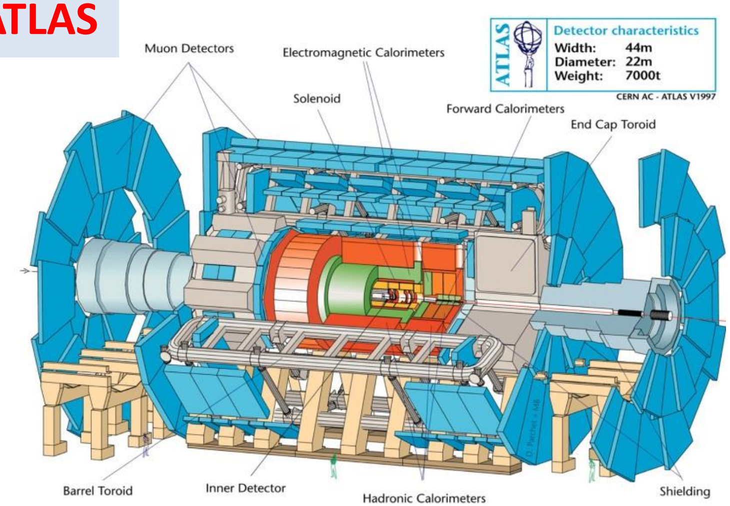
All the fundamental particle masses are given by Higgs mechanism?



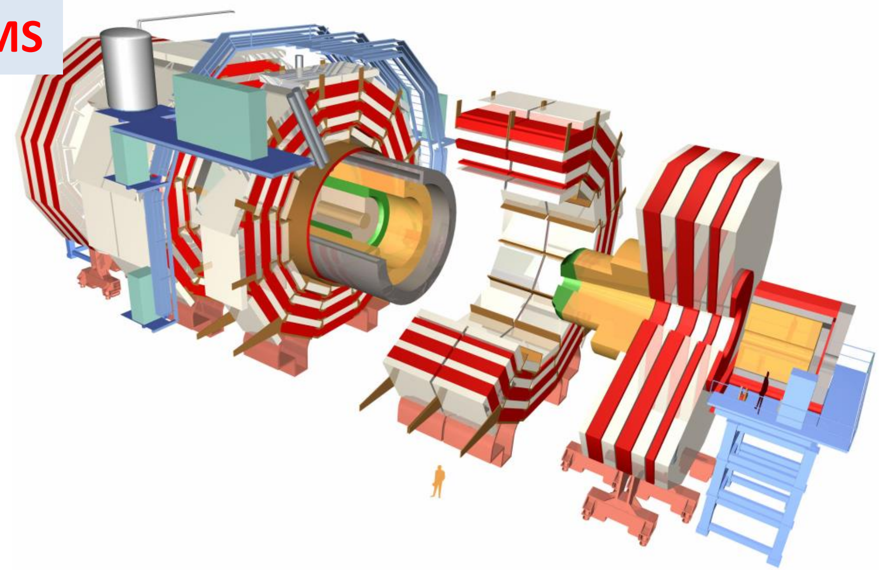
LHC and ATLAS experiment



ATLAS

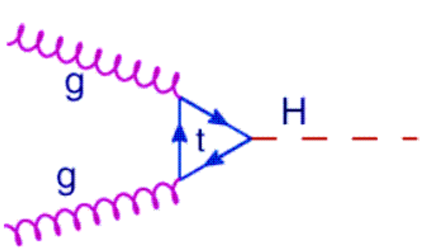


CMS

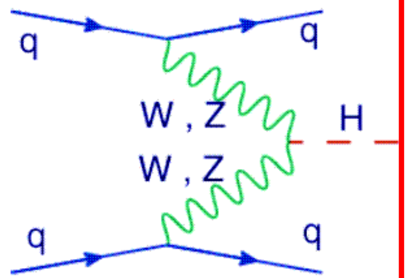


Higgs production and decay @ LHC

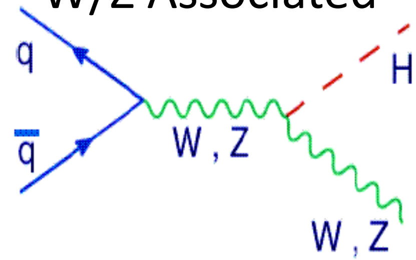
Gluon Fusion(ggF)



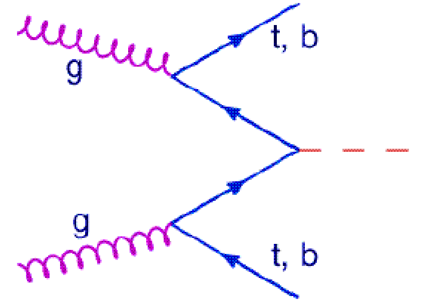
Vector Boson Fusion



W/Z Associated



tt/bb Associated

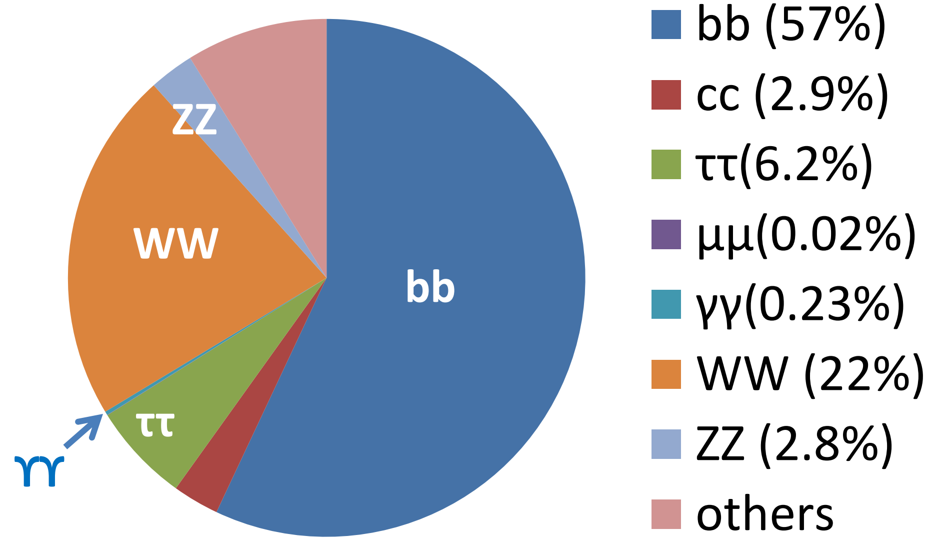


Now we know the cross section and Branching ratio!

Process	8TeV σ [pb]	14TeV σ [pb]
Gluon Fusion	**19.1**	**49.9**
Vector Boson Fusion	**1.57**	**4.18**
W/Z Associated	1.11	2.39
tt/bb Associated	0.128	0.611

8TeV @125.5GeV
14TeV @125GeV

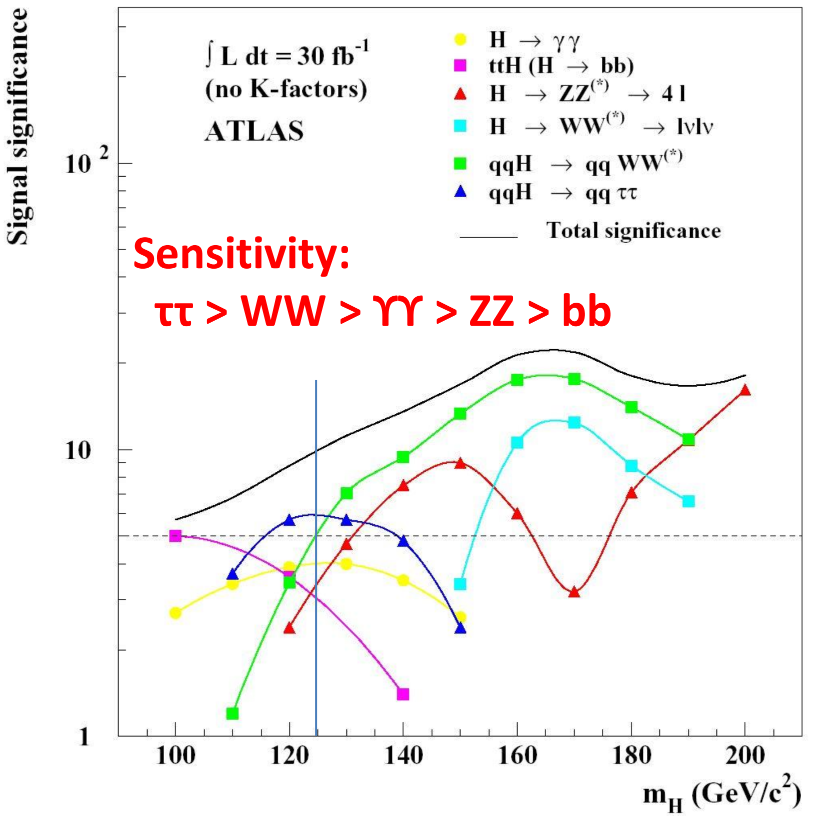
@125.5GeV



Sensitivity for each channel

Before experiment…

arXiv:hep-ph/0402254



ATLAS 2011+2012 Full data

$5fb^{-1}$(7TeV)+$20fb^{-1}$(8TeV)

Decay channel	Expected sensitivity	Observed Sensitivity
H(124.3)→ZZ	4.4σ	6.6σ
H(126.8)→ϒϒ	4.1σ	7.4σ
H(125)→WW	3.7σ	3.8σ
H(125)→ττ		NEW
H(125)→bb	1.6σ	0.4σ

H→ττ (Nov 2012)

$5fb^{-1}$(7TeV)+$13fb^{-1}$(8TeV)

H(125)→ττ	1.7σ	1.1σ

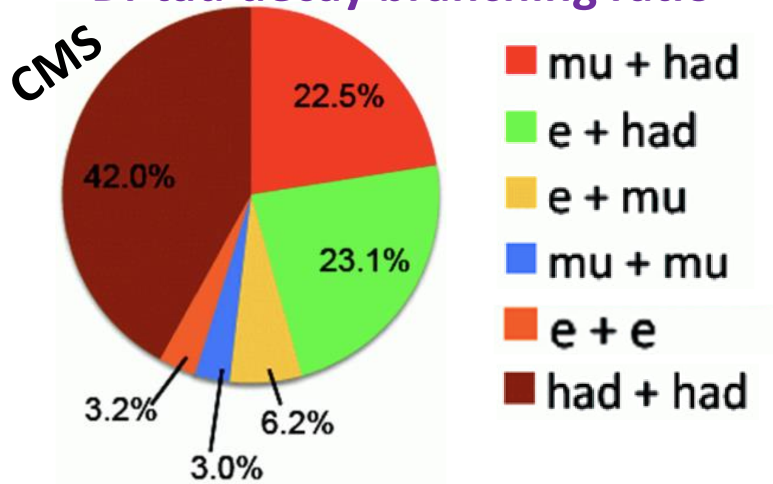
- Repeated analyses by using full data (13→$20fb^{-1}$) didn't expect reaching evidence.

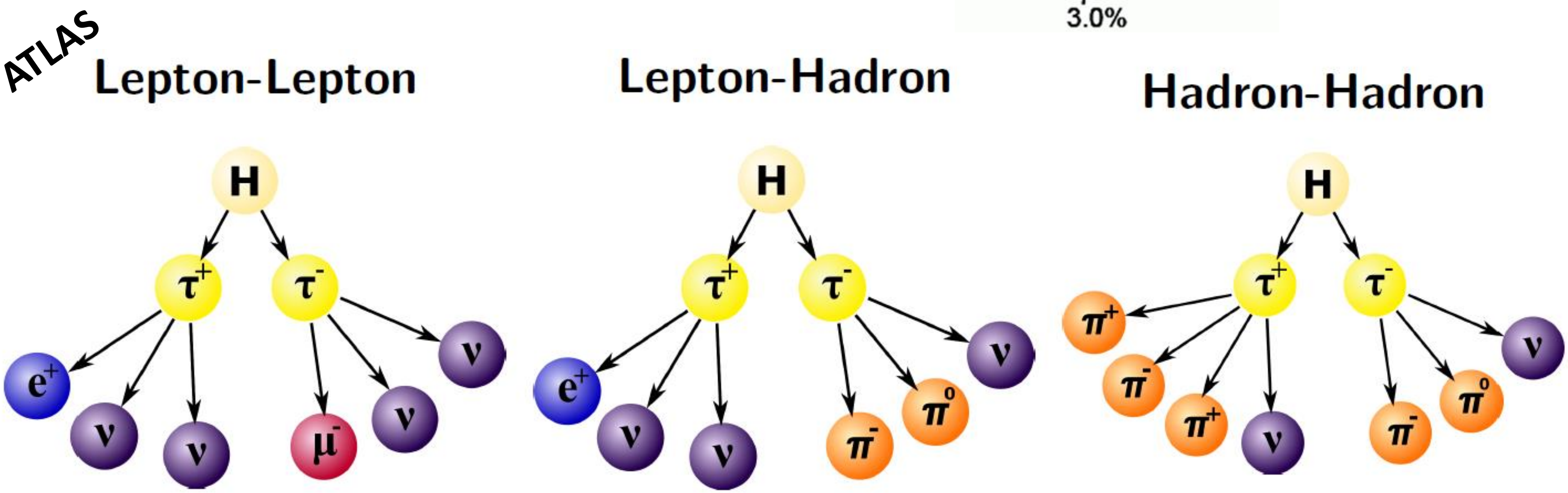
Analysis Strategy

Analysis channels

- Analysis was optimized for each di-tau decay mode.
  - Different trigger, object selection and backgrounds.
- ATLAS uses 3 channels and CMS uses 6 channels.

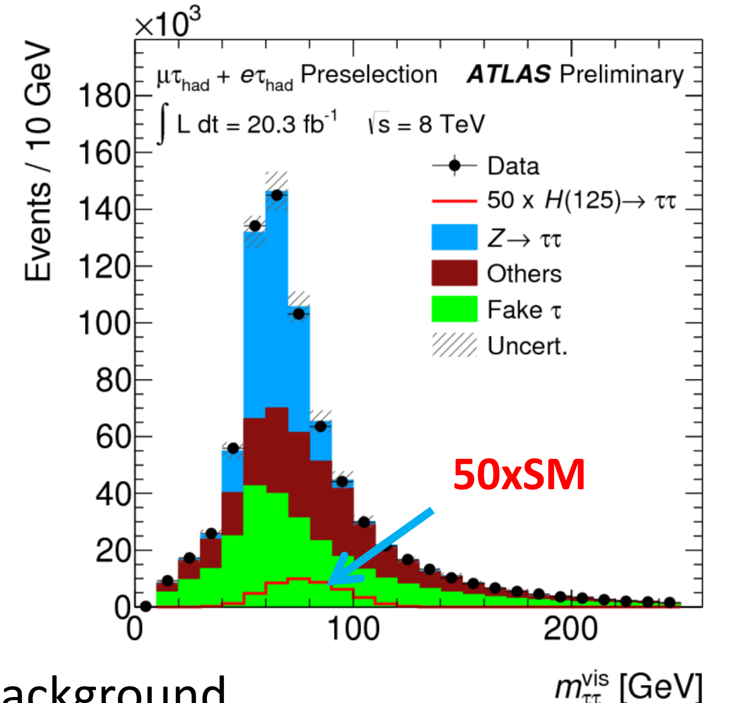
Di-tau decay branching ratio





Why is H→ττ difficult? How to improve?

After di-tau candidate , S/B ratio is <0.001, while typical systeamtics of backgrounds are ~20%.



Quite different approaches were taken by ATLAS and CMS

- ATLAS (8TeV)
  - Used very simple categorization (**6 categories**)
  - Used MVA technique to separate signal from background. (Used **MVA score as discriminant**.)
- CMS (7+8TeV)
  - Split data to many categories(**>50 categories**) based on S/B ratio.
  - Used Cut based analysis. (Used **Mass as discriminant**.) except ee and μμ channel (MVA analysis).

Di-tau Mass reconstruction

Di-tau invariant mass should be an important discriminating variable from backgrounds. But having 2-4ν in a event.

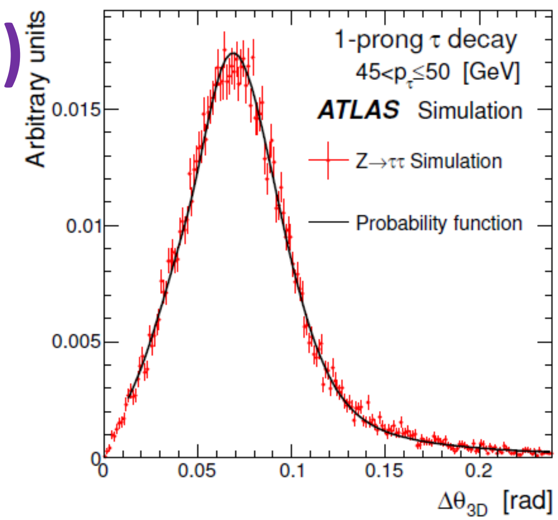
Need…

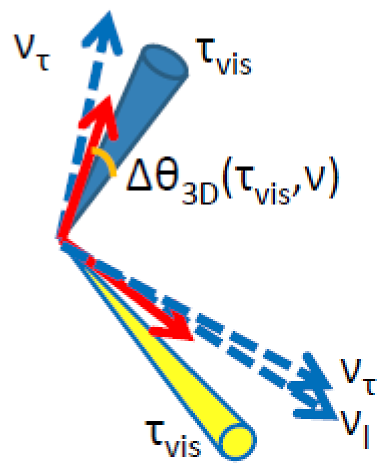
Event by Event estimator of true di-τ mass likelihood.

Full reconstruction of event kinematics.

Missing Mass Calculator(MMC)

- Solve τ, E_T^{miss} in $\Delta\phi(\tau_{vis},\nu)$ parameter space using $\Delta\theta_{3D}(\tau_{vis},\nu)$ template from simulation as PDF.



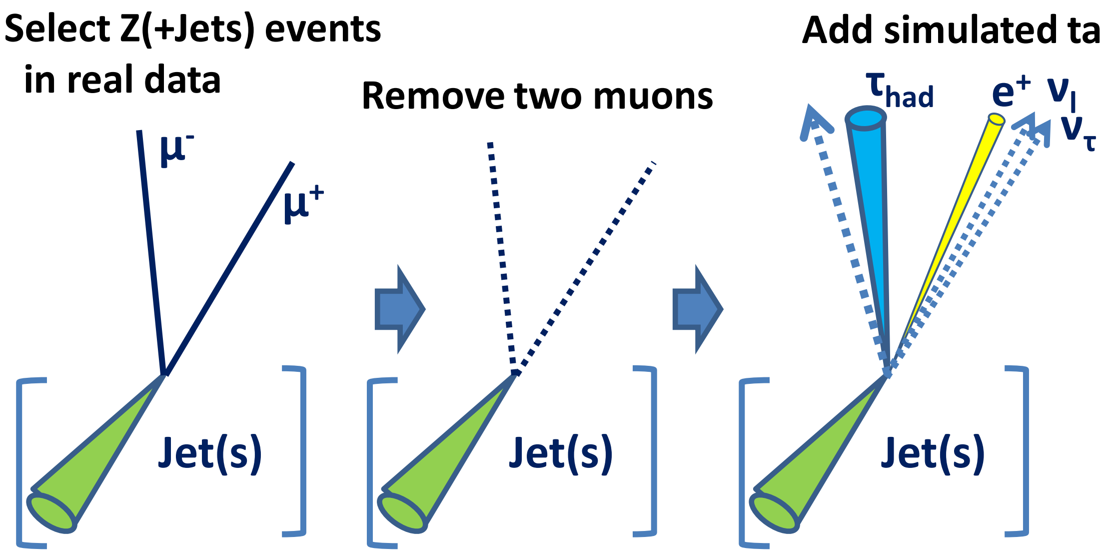


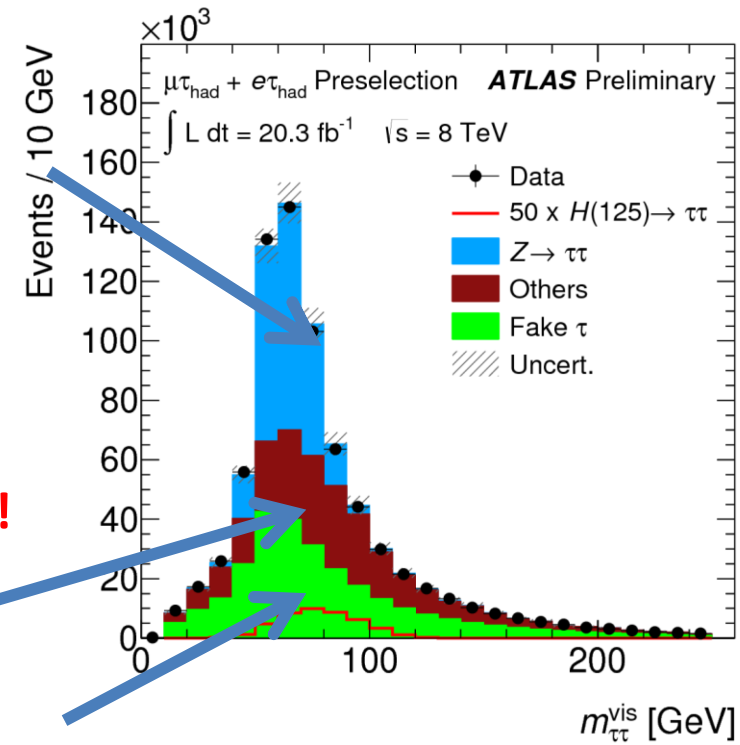
CMS uses the similar method with Matrix element

Background estimation overview

- Most important background is Z→ττ (irreducible).

Z→ττ estimated by embedding method





→ All jet kinematics and p_T^Z are from real data!

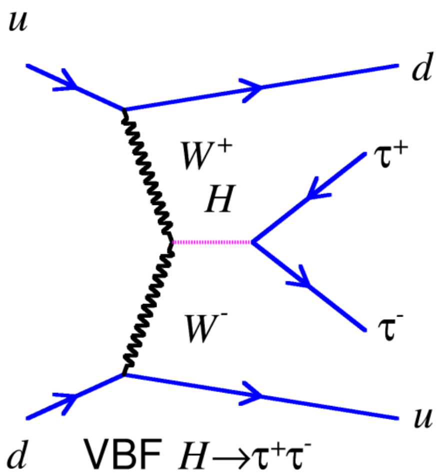
Z→ee/μμ + jets, Top, di-boson Estimated by MC with correction.

QCD and W+Jets – Data driven estimation for both shape and Normalization.

ATLAS analysis

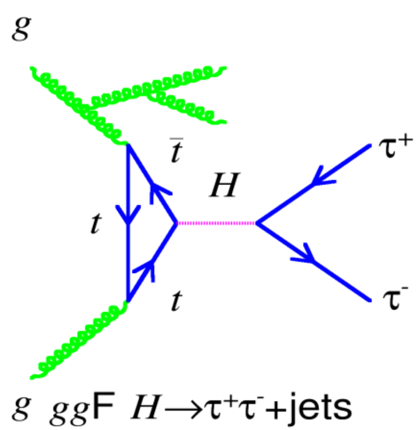
Categorization

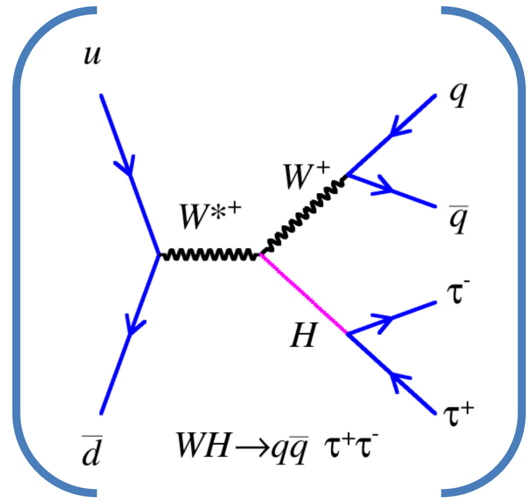
VBF category



- Find VBF jets with loose selection.
- Train BDT for VBF signal.

Boosted category





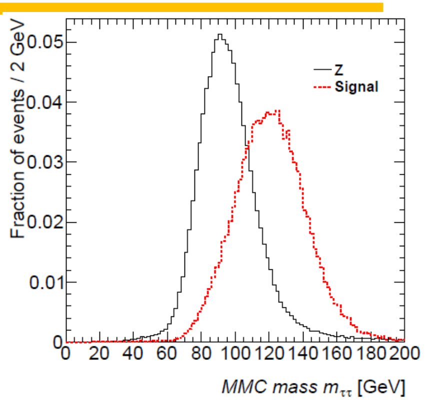
- Select events with high vector sum pT of tautau decay products.
- Not included non-boosted events.

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

Boosted	$p_{\rm T}(j_1) >$ (GeV)	40	-	-
	$p_{\rm T}^{H} >$ (GeV)	100	100	100
	b-jet veto for jet $p_{\rm T} >$ (GeV)	25	30	-

BDT input variables

- Trained BDT for each 3 channels and for VBF/Boosted separately. (total 6 categories)
  - **125GeV signal MC for the signal template.**
- MMC($m_{\tau\tau}$) is also included as one of the most powerful variable for the training.



VBF category

Variable	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$M_{\tau\tau}^{MMC}$	•	•	•
$\Delta R_{\tau\tau}$	•	•	•
$\|\eta_{j2} - \eta_{j1}\|$	•	•	•
$m_{j1,j2}$	•	•	•
$\eta_{j1} \times \eta_{j2}$		•	•
p_T^{Total}		•	•
$E_T^{miss}\phi$ centrality		•	•
$min(\Delta\eta_{\ell1\ell2,jets})$	•		
$\ell1 \times \ell2$ η centrality	•		
$\Delta\eta_{j3,j1j2}$	•		
m_T		•	
ℓ η centrality		•	
τ_1 η centrality			•
τ_2 η centrality			•

Boosted category

Variable	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$M_{\tau\tau}^{MMC}$	•	•	•
$E_T^{miss}\phi$ centrality	•	•	•
$\Delta R_{\tau\tau}$		•	•
sum P_T		•	•
$P_T(\tau_1)/p_T(\tau_2)$		•	•
$m_{\tau\tau,j1}$	•		
$m_{\ell1,\ell2}$	•		
$\Delta\phi_{\ell1,\ell2}$	•		
sphericity	•		
$p_T^{\ell1}$	•		
p_T^{j1}	•		
$E_T^{miss}/p_T^{\ell2}$	•		
m_T		•	
τ_{1x}			•
τ_{2x}			•

Background estimation and validation

	Lep-had	Leplep	hadhad
Z→ττ	Shape : Embedding Norm : **Fit in SR** (+ Δη CR for hadhad)		
Fake (QCD)	Fake factor Estimation (used Anti-tau CR) Shape&Norm : data	Template fit method (used non-isol CR) Shape&Norm : data	Shape : not OS data Norm : **Fit in Δη CR**
Fake (W+jets)			MC
Z→ll (l→τ)	Shape & Norm : MC (with SF)	Shape : MC Norm : **Fit in ZCR** (80<mll<100)	MC(very small)
Z→ll(Jet→τ)	Shape : MC Norm : **Fit in Zll CR**		
Top	Shape : MC Norm : **Fit in b-tag CR**		MC(very small)
Diboson	Shape & Norm : MC (very small)		

: Background estimated by (at least partially) data-driven way.

Fit in XX : The CRs are included in the Profile Likelihood Fit (Fit model.)

Background estimation and validation

NOTE: MVA(BDT) analysis has to be carefully validated :

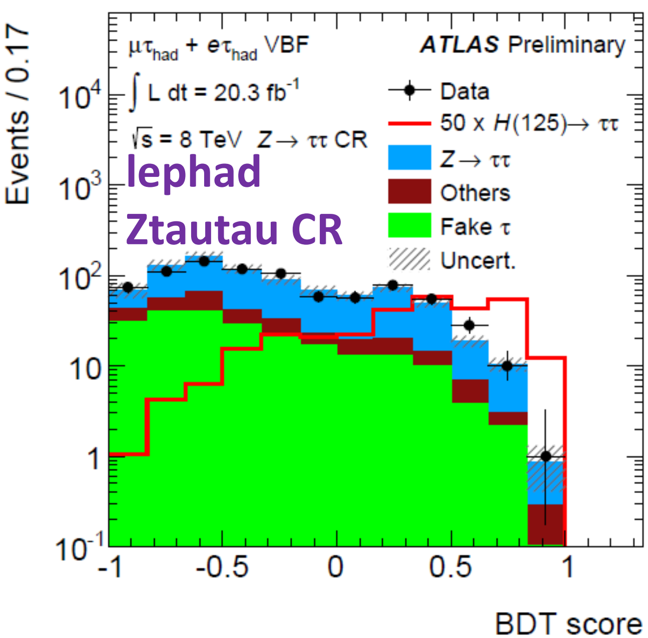
if all training variables are modeled well. → **OK.** (See conf note)

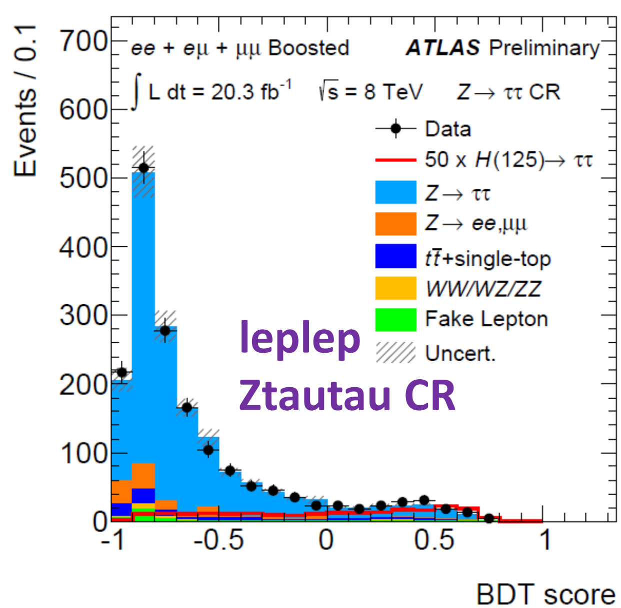
if all variable correlations are also modeled.

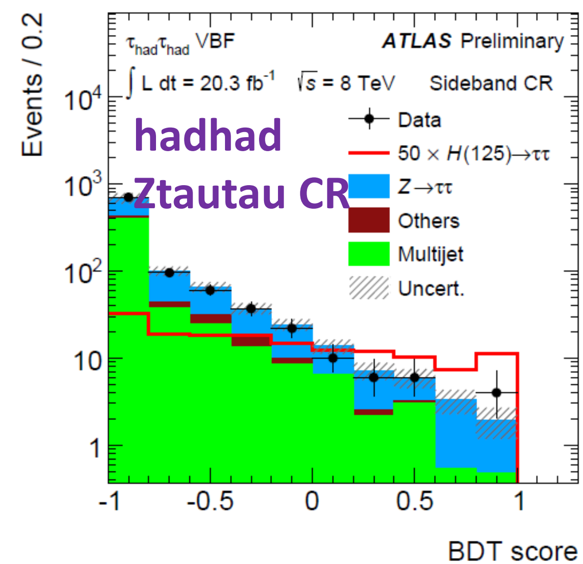
→ **checked BDT score for each CRs to check all backgrounds.**

- $m_{\tau\tau}$ sideband CR as Z→tautau validation region

$Z \rightarrow \tau\tau$



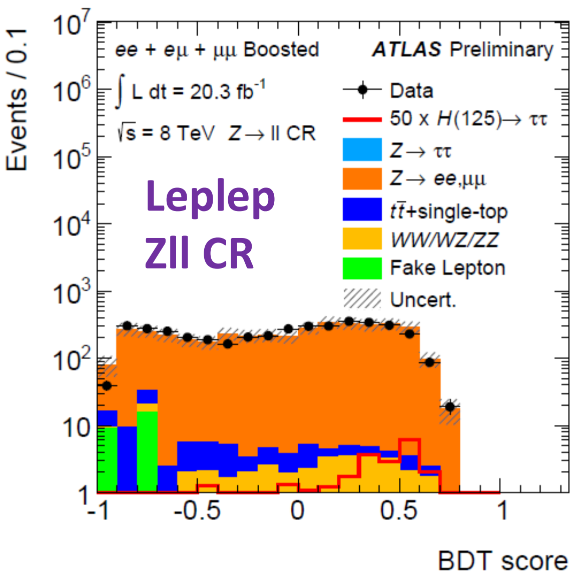




Background estimation and validation

- Z→ll CR (mll~mZ) for leplep channel

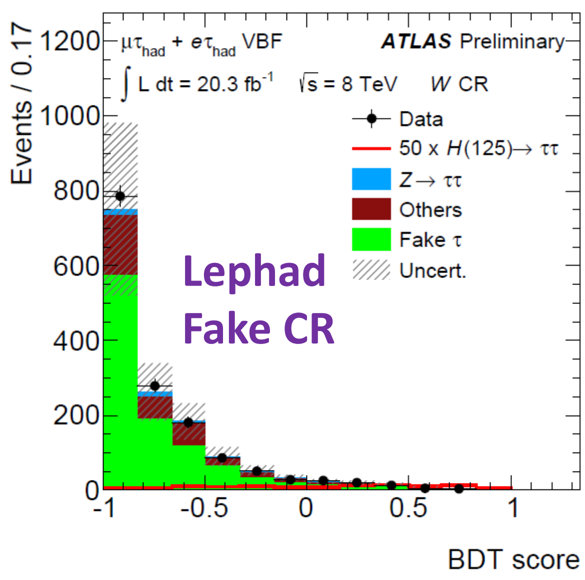
Z→ ee,μμ



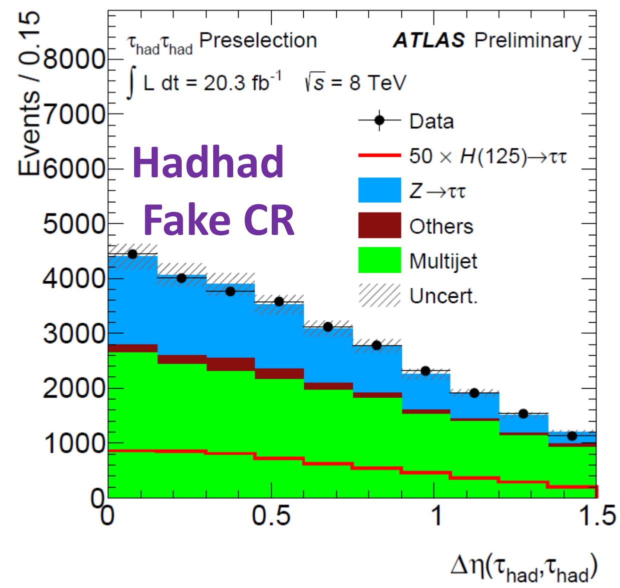
- W+jets & QCD CR

Fake τ

lephad (high mT)



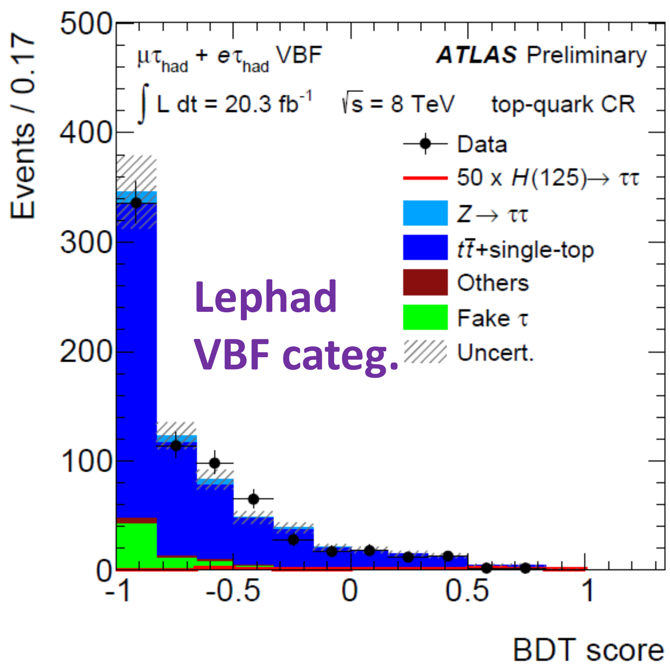
hadhad(pre-selection)

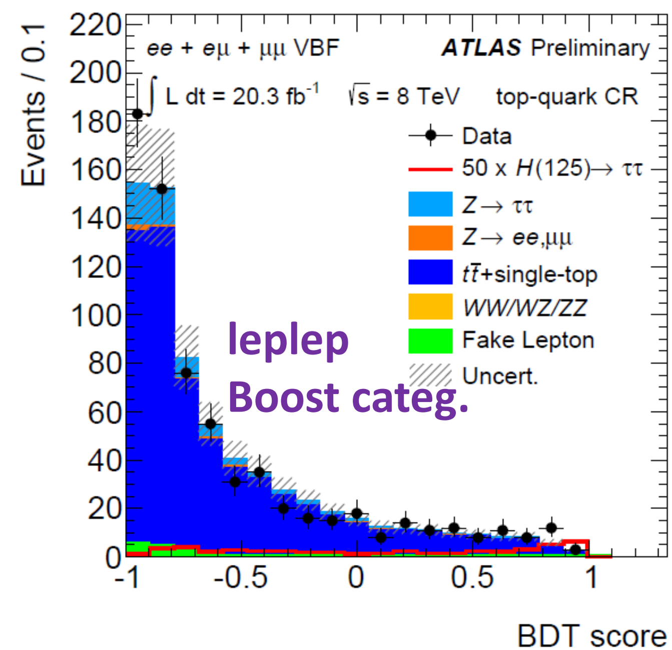


Background estimation and validation

- Top CR by requiring at least one b-tagged jets.

$t\bar{t}$+single-top

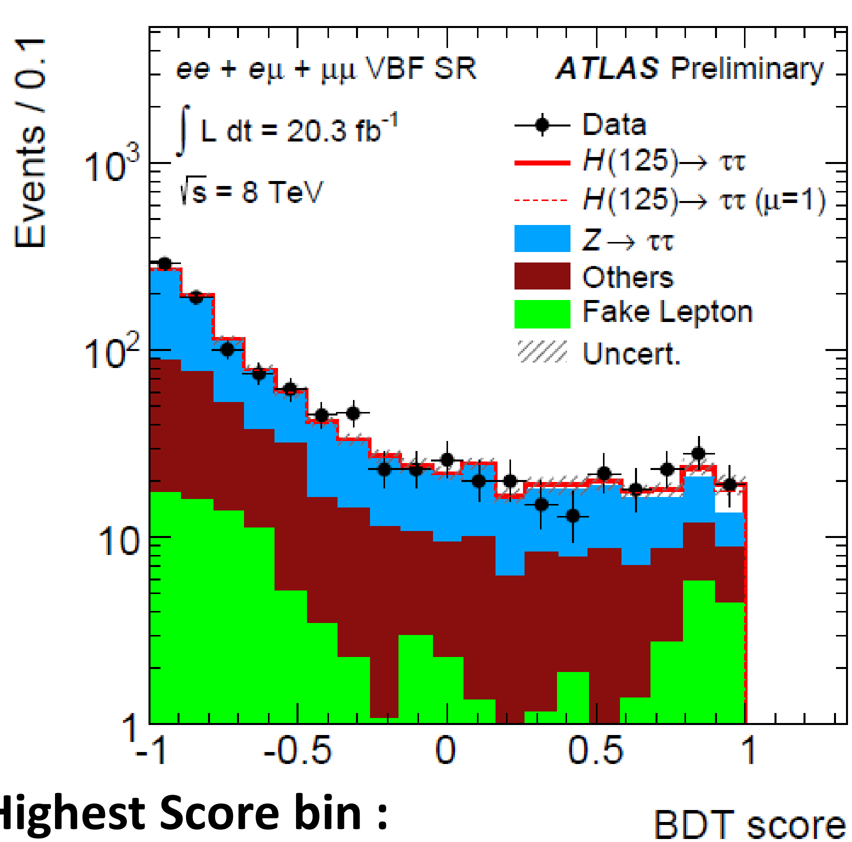


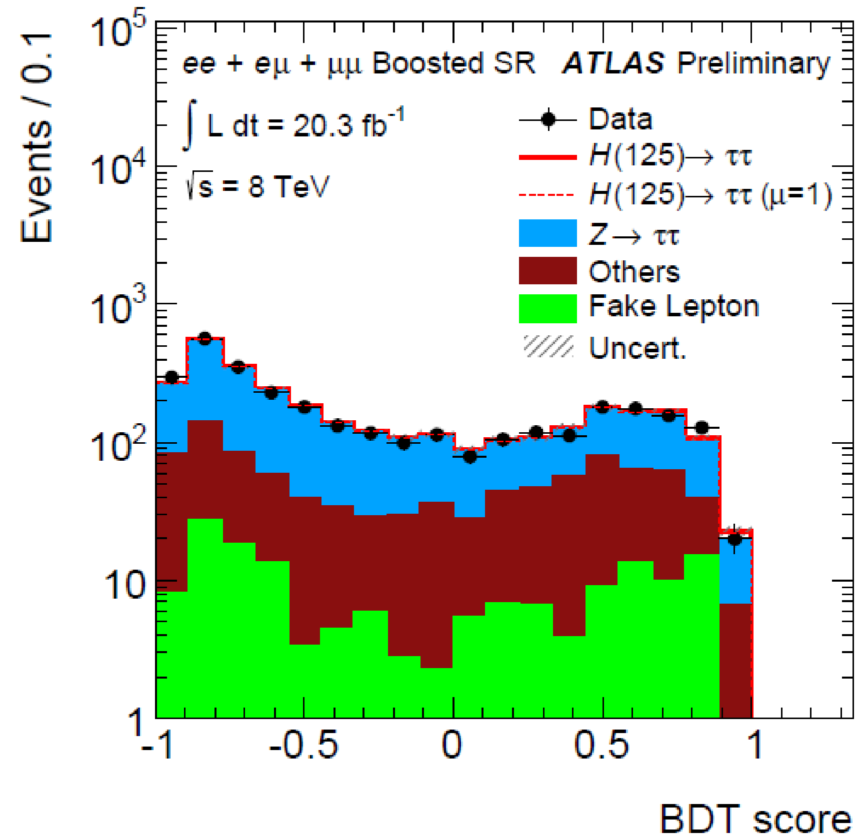


→ All training variables and BDT score distributions in each CRs are modeled by estimation.

ATLAS results

BDT distribution in leplep SR

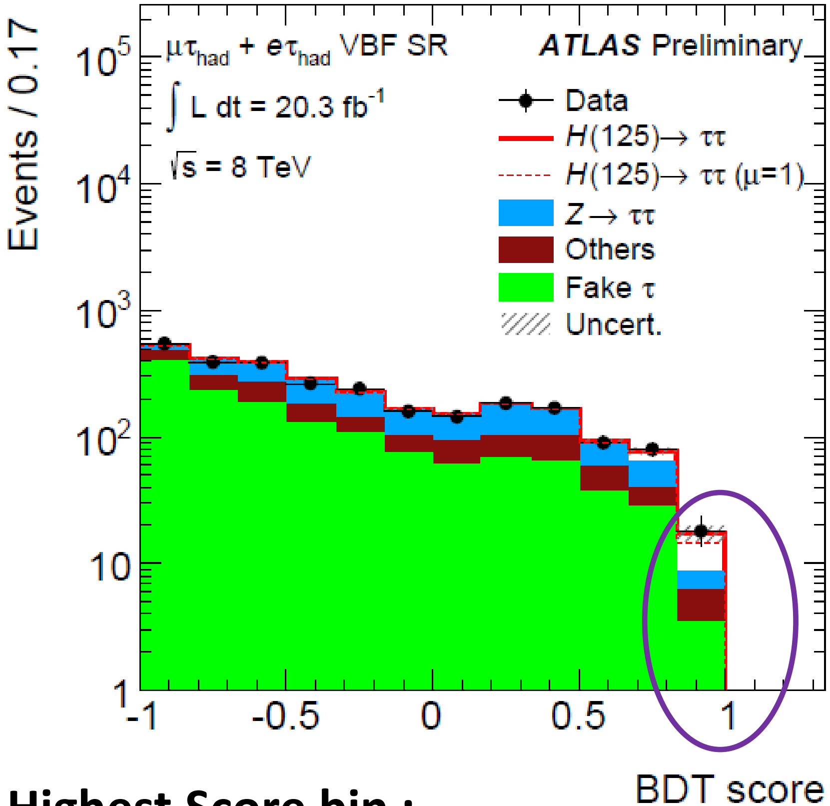




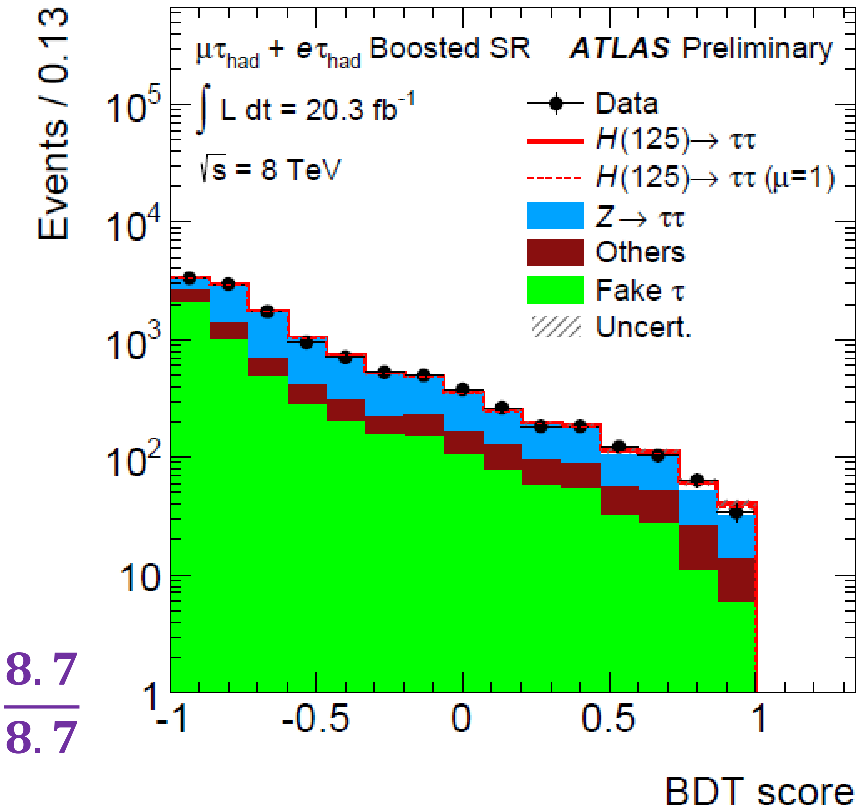
Highest Score bin :

	ggF	VBF	VH	Z→ττ	Fake	Top	Others	S/B
VBF	0.7±0.4	5.0±1.5	--	4.6±0.6	4.5±1.7	1.8±0.4	2.7±0.4	**0.42**
boosted	1.7±0.7	0.7±0.2	0.2±0.1	13±1	0.8±0.3	3.5±0.9	2.3±0.2	**0.13**

BDT distribution in lephad SR



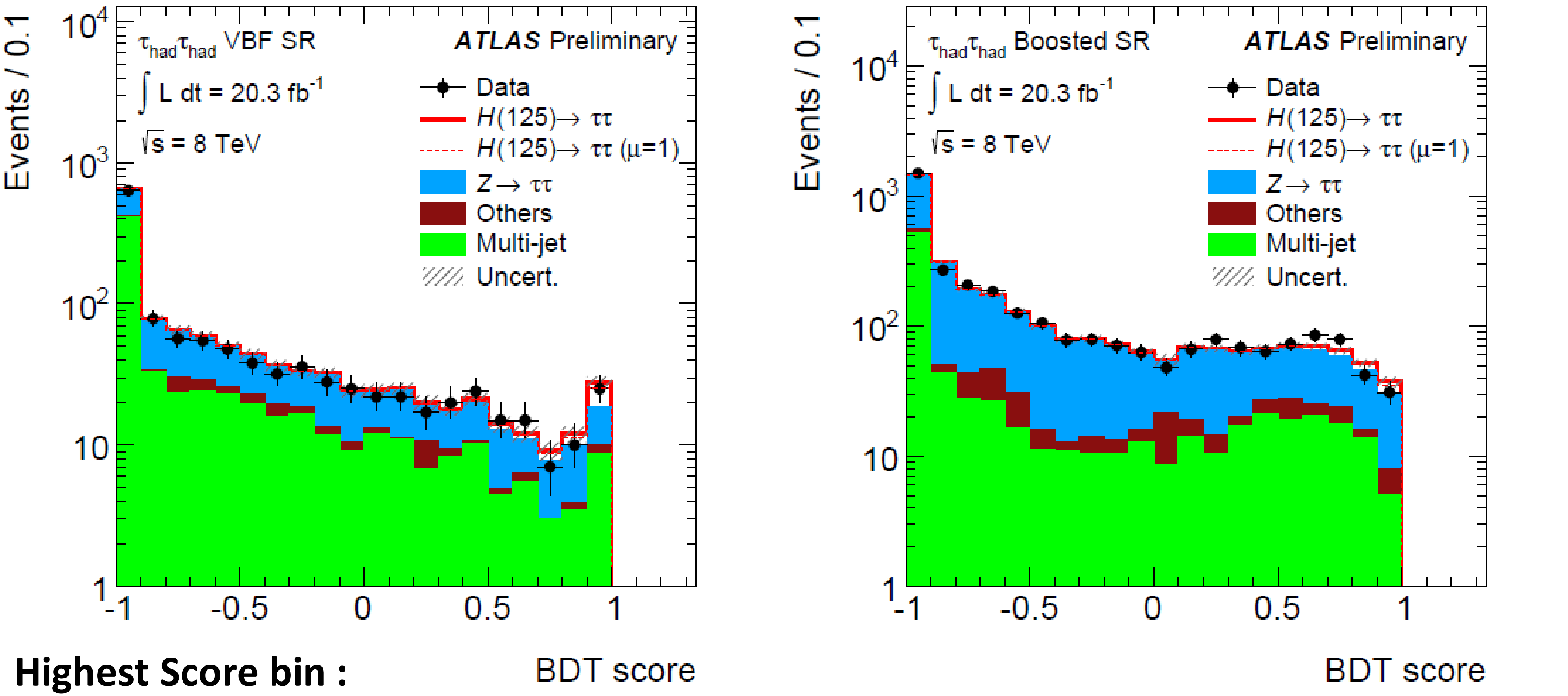
$$\frac{S}{B} = \frac{8.7}{8.7}$$



Highest Score bin :

	ggF	VBF	VH	Z→ττ	Fake	Top	Others	S/B
VBF	1.2±0.6	7.5±2.2	--	2.4±0.4	3.5±0.5	1.5±0.4	1.3±0.7	1.0
boosted	5.5±2.1	1.3±0.4	1.2±0.3	18±2	5.8±1.4	2.2±0.3	5.5±1.2	0.25

BDT distribution in hadhad SR

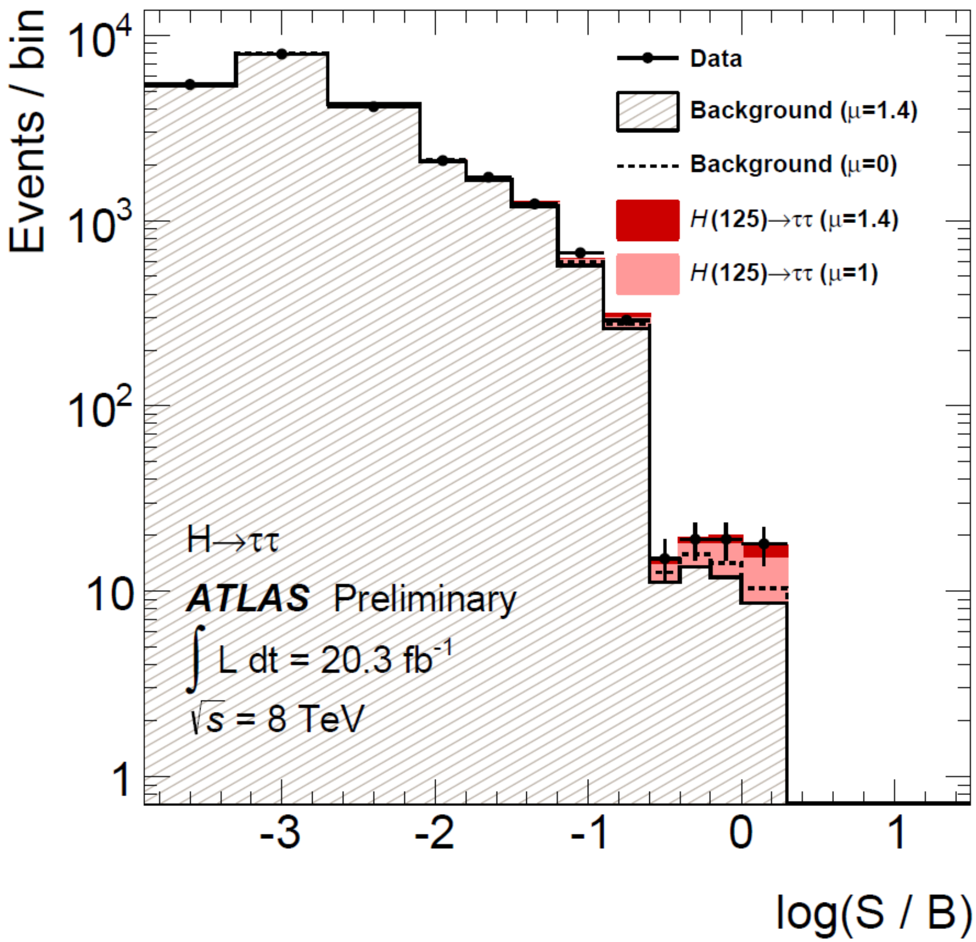


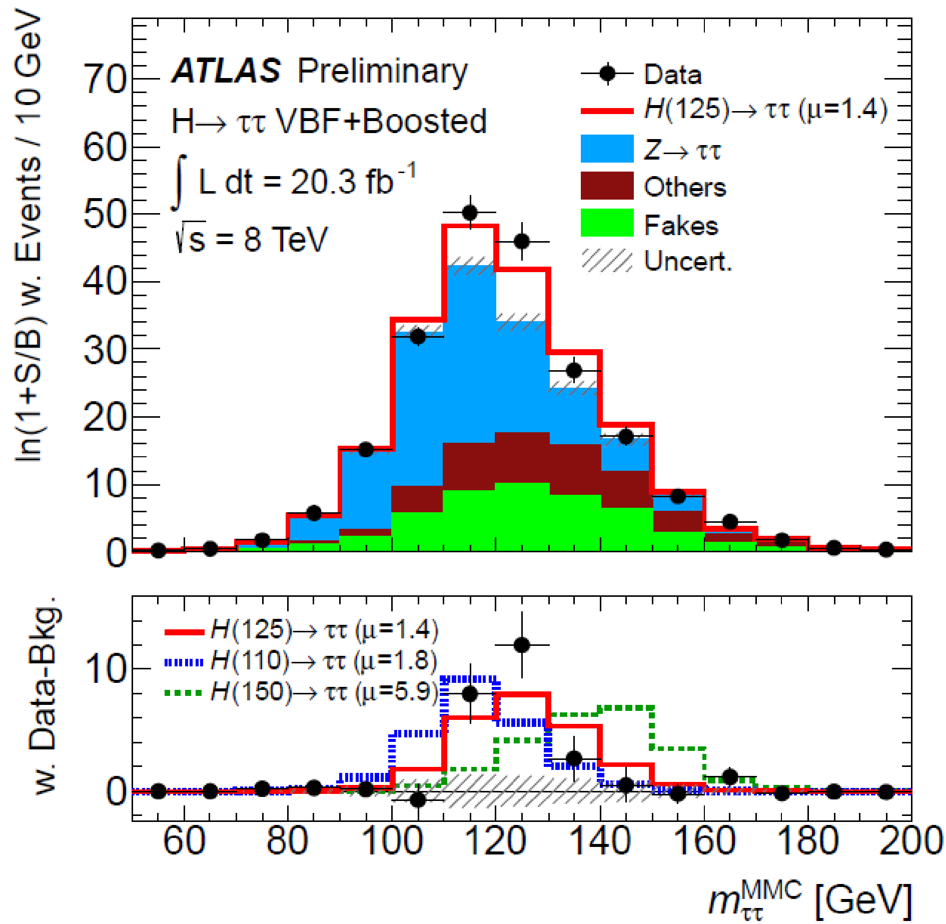
Highest Score bin :

	ggF	VBF	VH	$Z \rightarrow \tau\tau$	Fake	Others	S/B
VBF	2.0±0.9	5.9±1.8	--	5.3±1.0	5.9±0.9	0.6±0.1	**0.67**
boosted	2.3±0.9	0.6±0.2	0.7±0.2	9.7±1.6	1.4±0.2	0.07±0.02	**0.32**

Summary plots

- Event yield as a function of log(S/B) for all signal region BDTscore-bins.
- MMC distribution where events are weighted by ln(1+S/B).



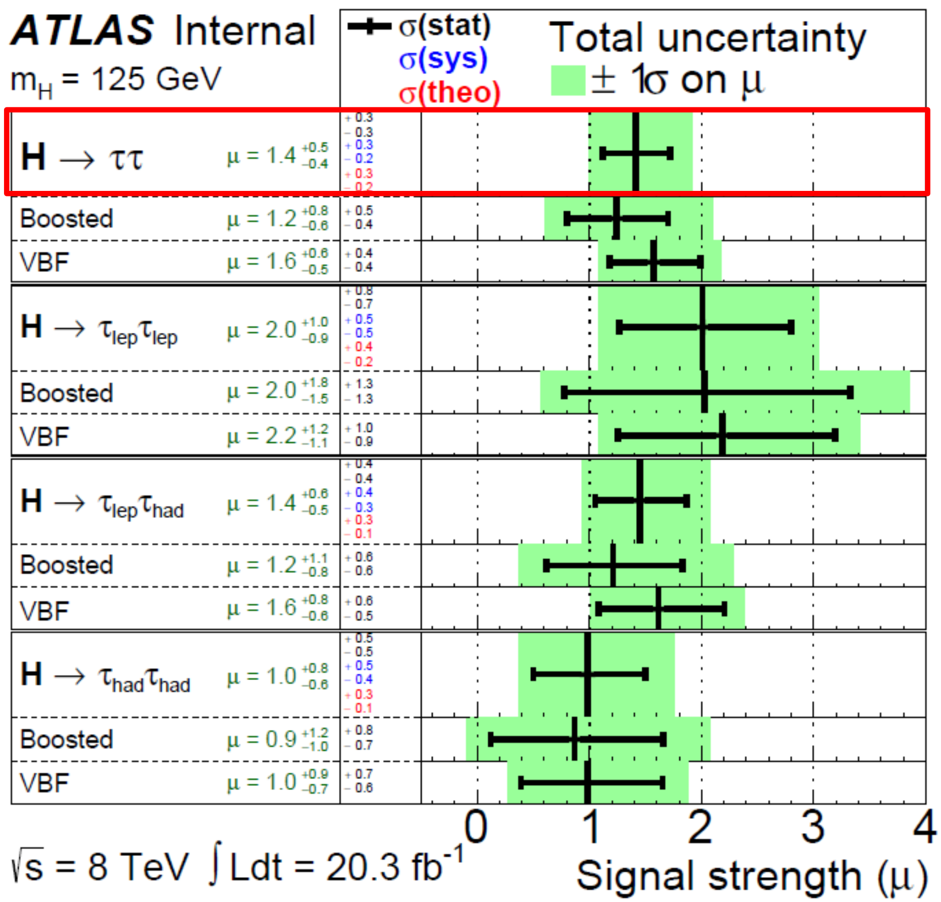


Significance and Signal strength

Evidence of H→ττ decay!

For mH=125GeV,

p_0^{exp} = 6.2 x 10^{-4} (3.2σ), **p_0^{obs} = 1.9 x 10^{-5} (4.1σ)**



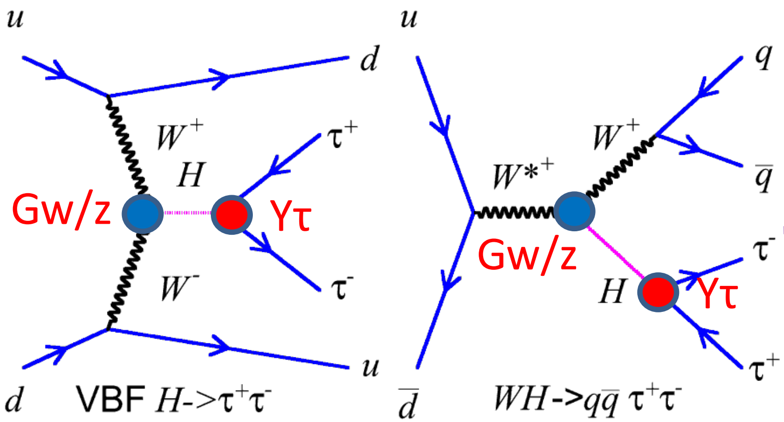
Assuming mH=125GeV :

μ_{best}=1.4+0.5-0.4

Impact of uncertainty sources

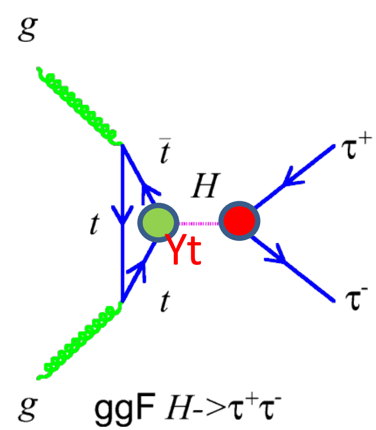
Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \to \ell\ell$ normalization ($\tau_{lep}\tau_{had}$ boosted)	0.13
ggF $d\sigma/dp_T^H$	0.12
JES η calibration	0.12
Top normalization ($\tau_{lep}\tau_{had}$ VBF)	0.12
Top normalization ($\tau_{lep}\tau_{had}$ boosted)	0.12
$Z \to \ell\ell$ 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

Production dependence

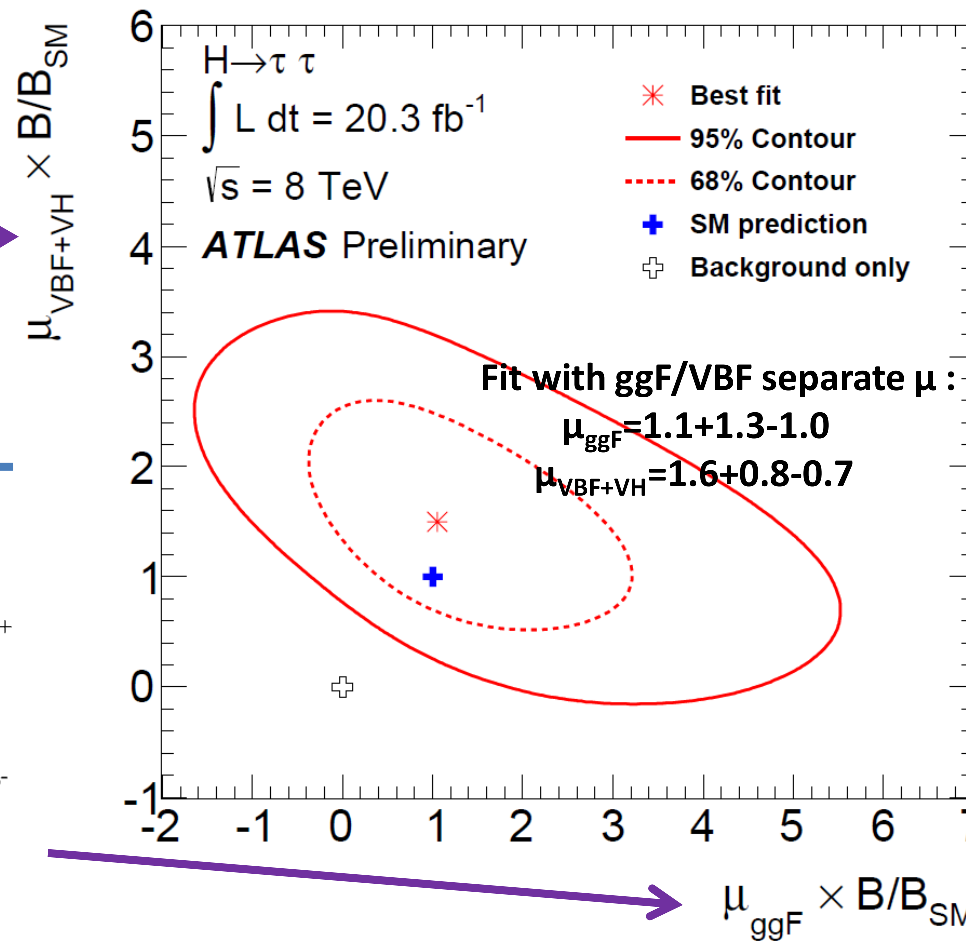


$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}}$$

$= \mu_{VBF+VH}$



$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \mu_{ggF}$$

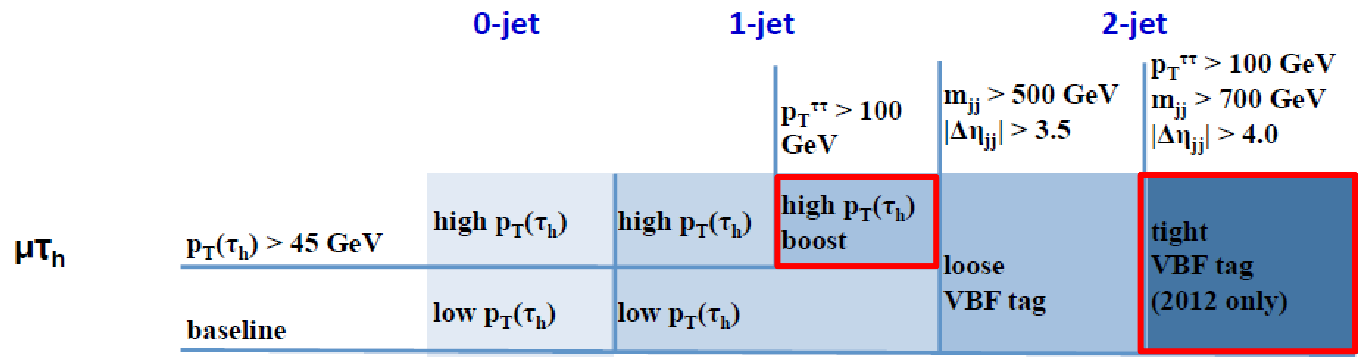


Both ggF and VBF production process are consistent to the SM!

CMS Analysis

Categorization

- Categorize events based on different S/B ratio.
  - Introduced new high sensitivity categories.



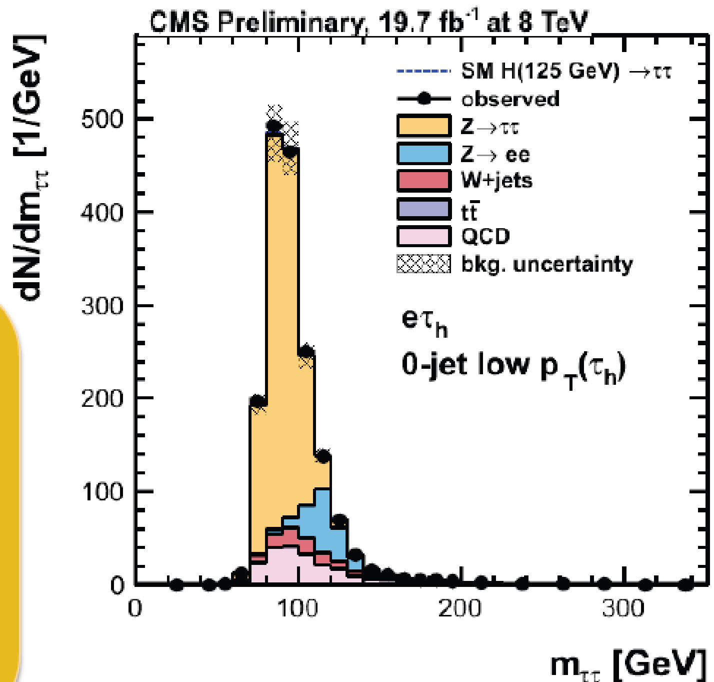
- Each di-tau decay channels have at most 7 categ.
  - 27 categories for 8TeV
  - 24 categories for 7TeV
  - Total : 51 categories

had + had	3(3) categ.	Used mass discriminant
mu + had	7(6) categ.	
e + had	6(5) categ.	
e + mu	6(5) categ.	
mu + mu	6(5) categ.	MVA score discriminant
e + e	5(5) categ.	

- Used MVA for ee/μμ channels

Background estimation

All normalizations are data-driven



Different from ATLAS

W+jets:
- Normalization from high m_T control region
- Shape from MC

$Z\rightarrow\tau\tau$:
embedded samples
No MET/JES scale uncertainties
Shape estimation and correction for selection efficiencies

ttbar:
- Normalization from eμ b-tag control region
- Shape from MC

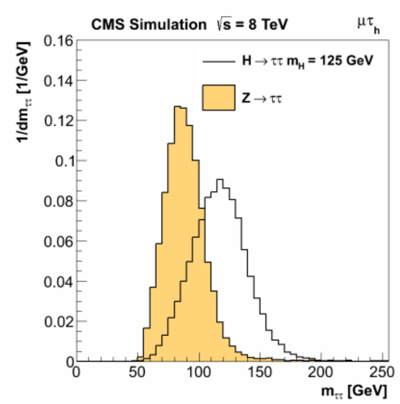
$Z\rightarrow ee/\mu\mu$
- Normalization scale factor from tag-and-probe in data
- Shape from MC

Different from ATLAS

QCD:
- Normalization from ratio of same-sign(SS) to opposite-sign (OS) data events
- Shape from SS data events

Systematic uncertainties

	Uncertainty	Affected samples	Change in acceptance
Experimental uncertainties	Tau energy scale	signal & sim. backgrounds	shape
	Tau ID & trigger	signal & sim. backgrounds	8–19%
	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 boson plus 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	shape
	Jet energy scale	signal & sim. backgrounds	0–20%
	E_T^{miss} scale	signal & sim. backgrounds	1–12%
	$\varepsilon_{b\text{-tag}}$ b jets	signal & sim. backgrounds	0–8%
	$\varepsilon_{b\text{-tag}}$ light-flavoured jets	signal & sim. backgrounds	1–3%
Background estimation	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	15–45%
	Norm. QCD multijet	QCD multijet	6–70%
	Shape QCD multijet	QCD multijet	shape
	Luminosity 7 TeV (8 TeV)	signal & sim. backgrounds	2.2% (2.6%)



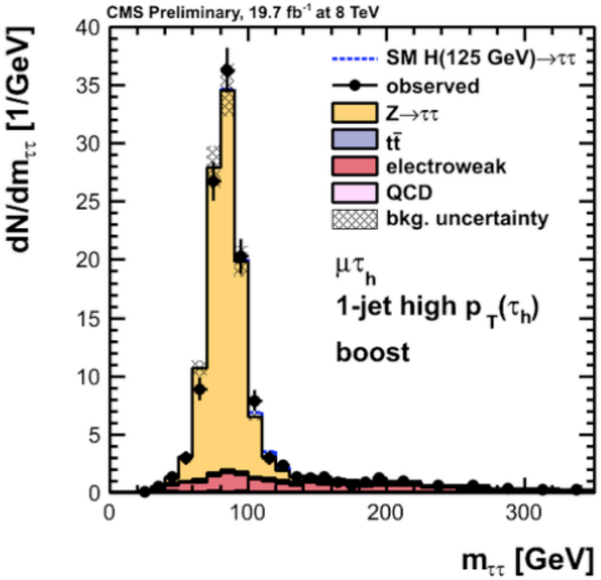
Tau Energy Scale(TES) uncertainty is one of the dominant uncertainty unlike ATLAS.
This is simply because CMS uses the mass discriminant which is quite sensitive to the TES.

CMS Results

Mass distribution in the signal region

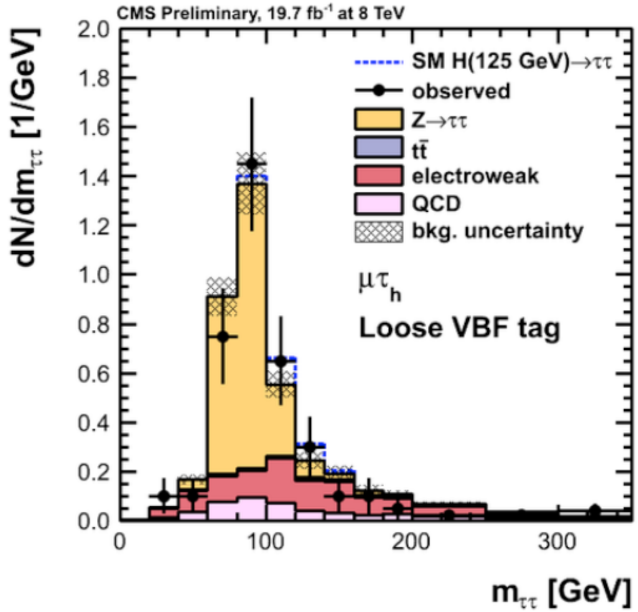
- $\mu\tau_h$ channel is the most sensitive channel

1-jet high $p_t(\tau_h)$ boost



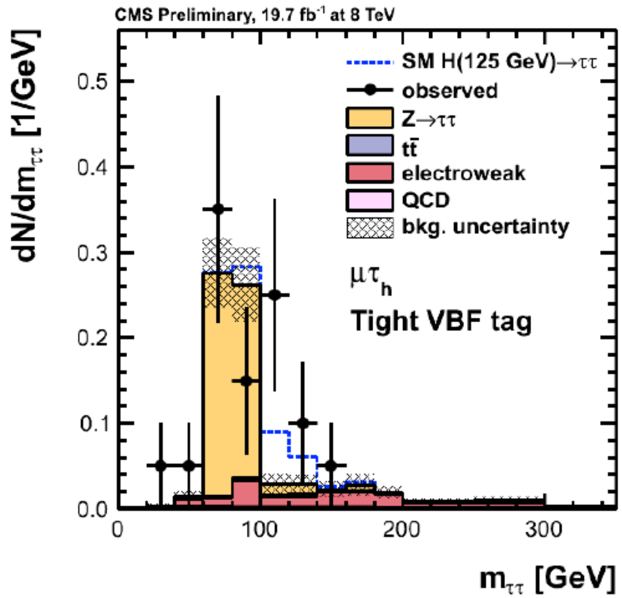
$p_t(\tau_h) > 45$ GeV
$p_t^{\tau\tau} > 100$ GeV

2-jet: loose VBF tag



$M_{jj} > 500$ GeV $|\Delta\eta_{jj}| > 3.5$

2-jet tight VBF tag

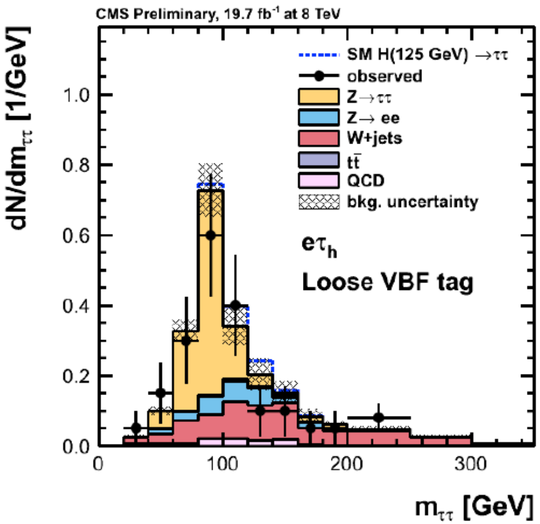


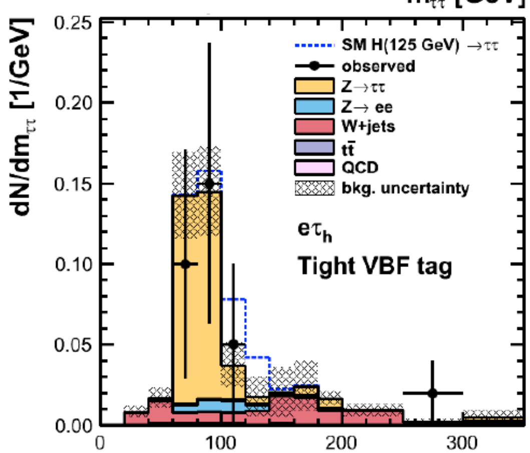
$M_{jj} > 700$ GeV, $|\Delta\eta_{jj}| > 4$
$p_t^{\tau\tau} > 100$ GeV

Mass distribution in the signal region

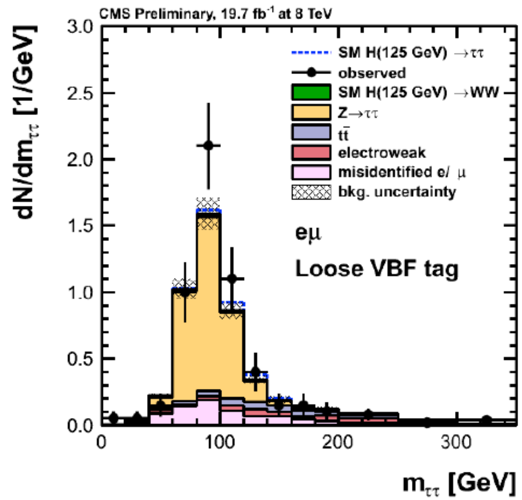
- Other VBF channels

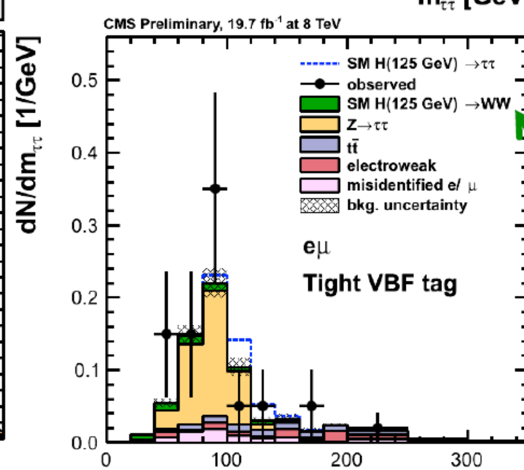
eτ



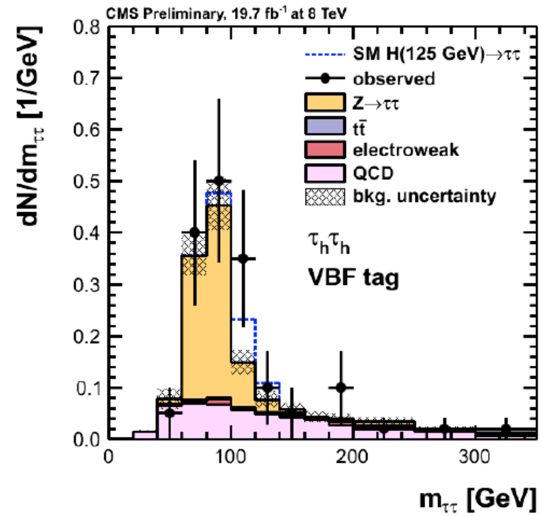


eμ





$\tau_h\tau_h$



$\tau_h\tau_h$: no tight-VBF

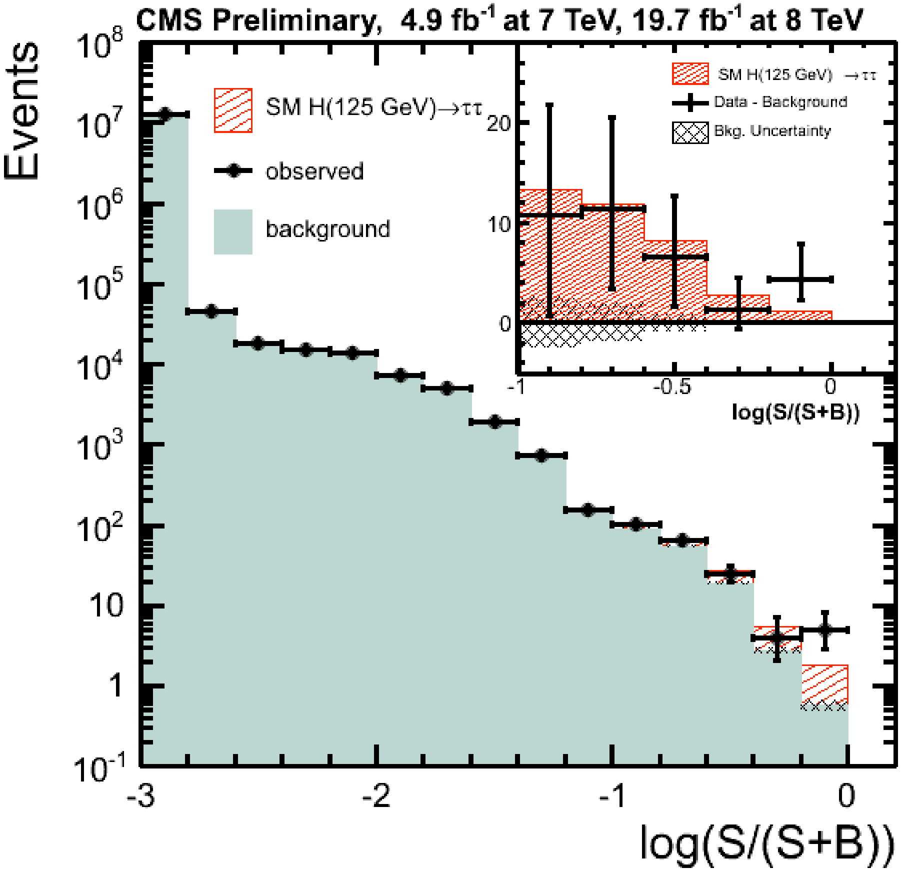
eμ:
H→WW contribution!

H→WW is treated as background to probe fermionic decay contribution

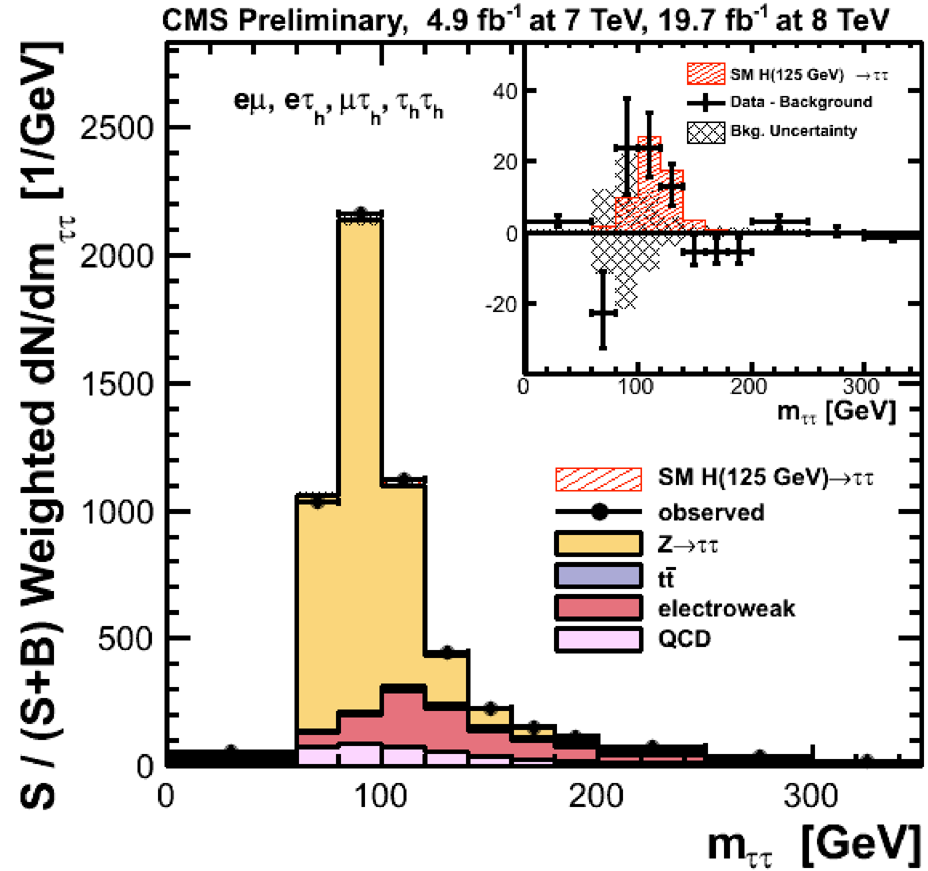
Summary plots

- Calculate S/(S+B) in every bin of the mass distributions of every event category and channels.
- Weighted by S/(S+B) using 68% region around the $m_{\tau\tau}$ peak.

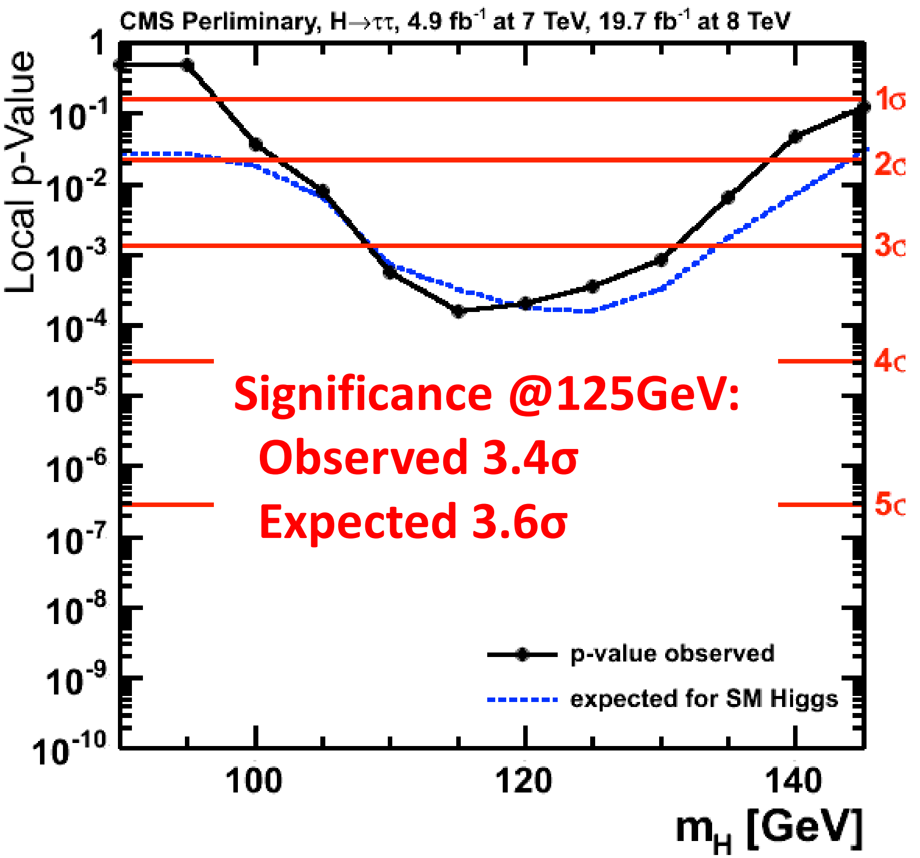
All channels : $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, ee, $\mu\mu$

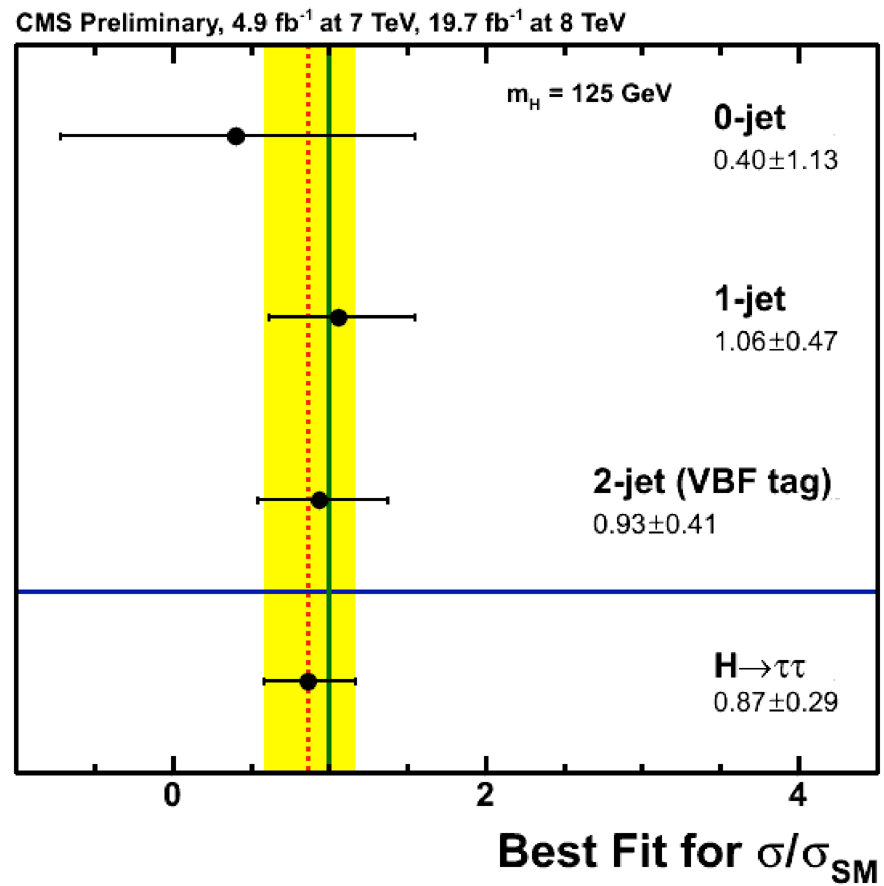


$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ Only



Significance and Signal strength





Assuming mH=125GeV :

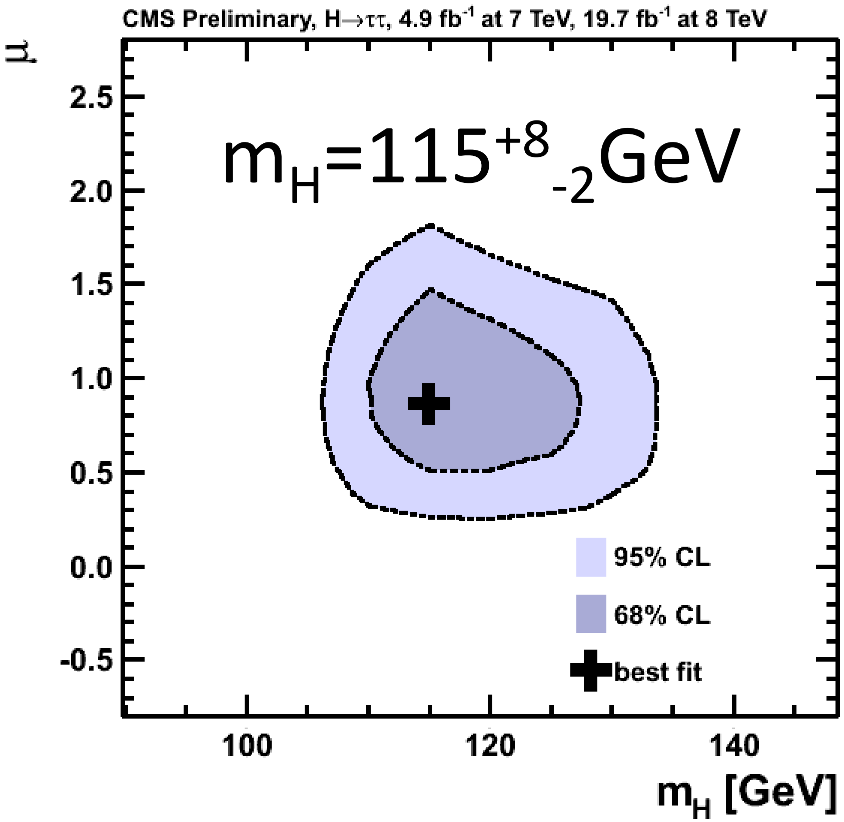
Evidence of H→ττ decay!

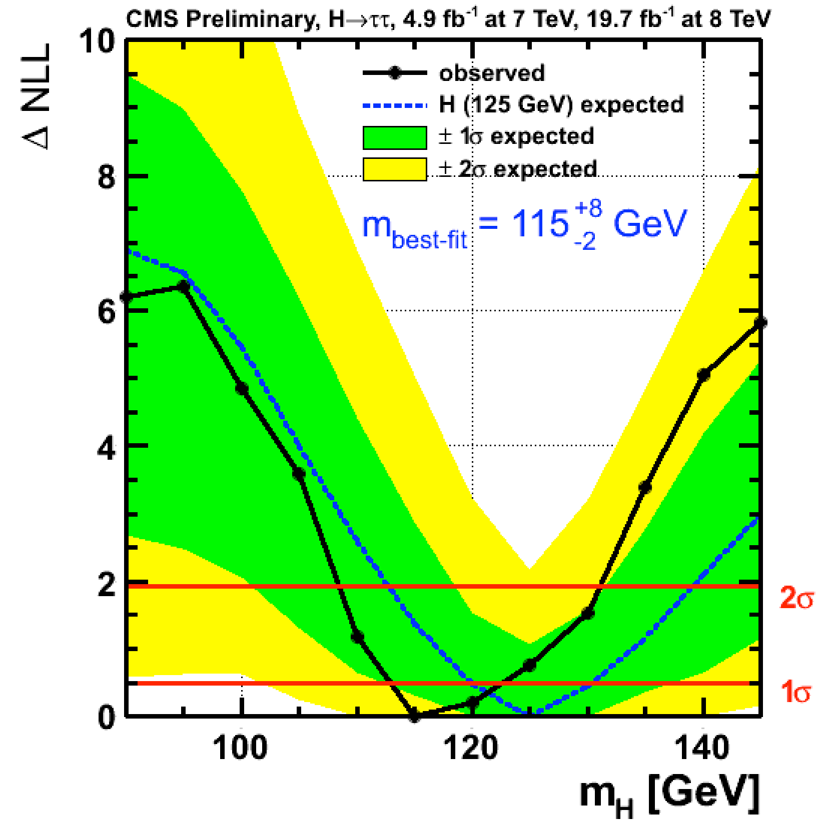
$\mu_{best} = 0.87 \pm 0.29$

Mass measurement of the resonance?

Mass sensitivity in CMS

- Since CMS uses the mass distribution as discriminant, it is possible to measure the mass.





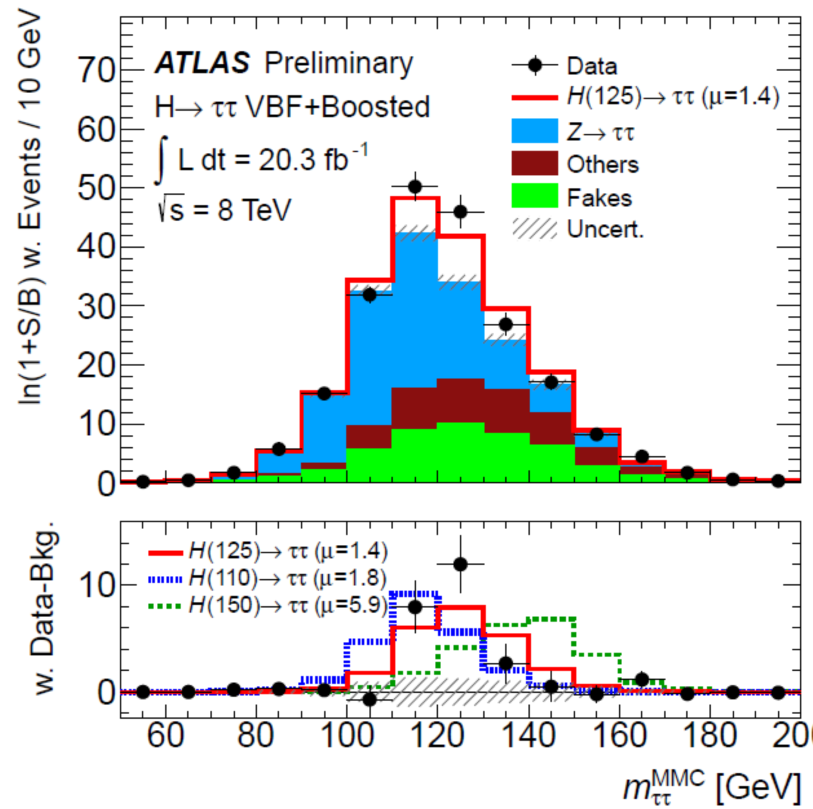
Mass sensitivity in ATLAS

- ATLAS uses BDT score as discriminant, less sensitive to the mass measurement.

But once we use the weighted mass plots, the mass sensitivity is similar to CMS results

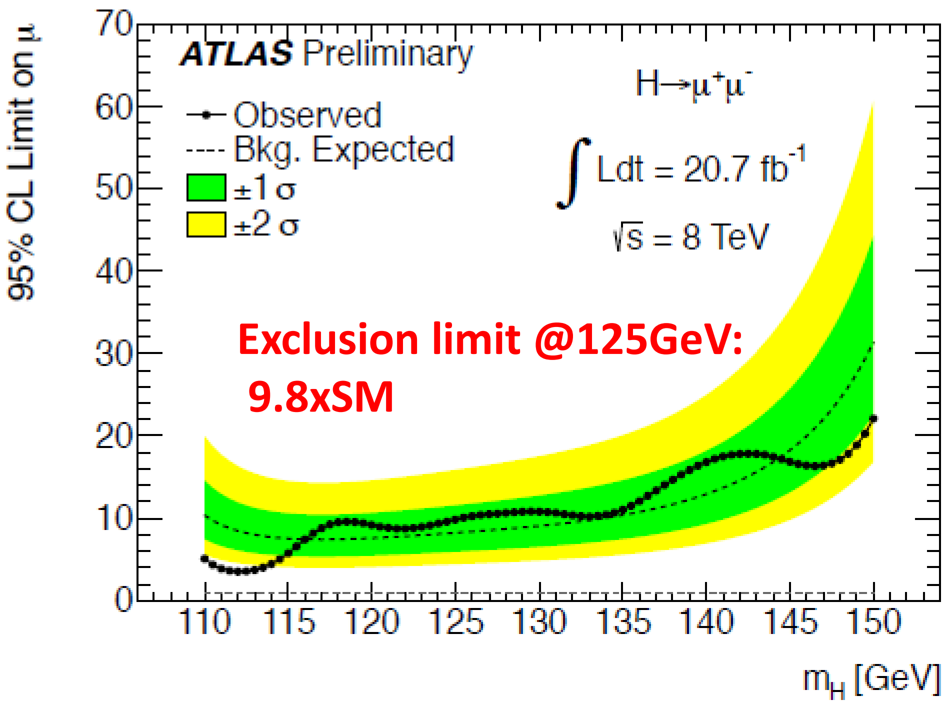
Best fit :
mH=120GeV mu=1.4

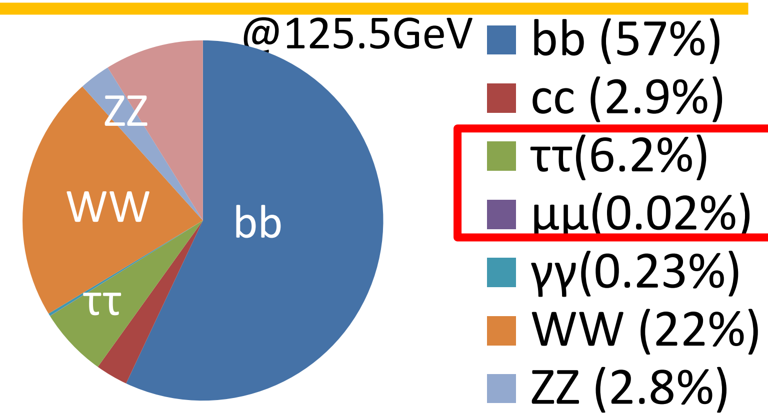
But mass sensitivity is quite low.

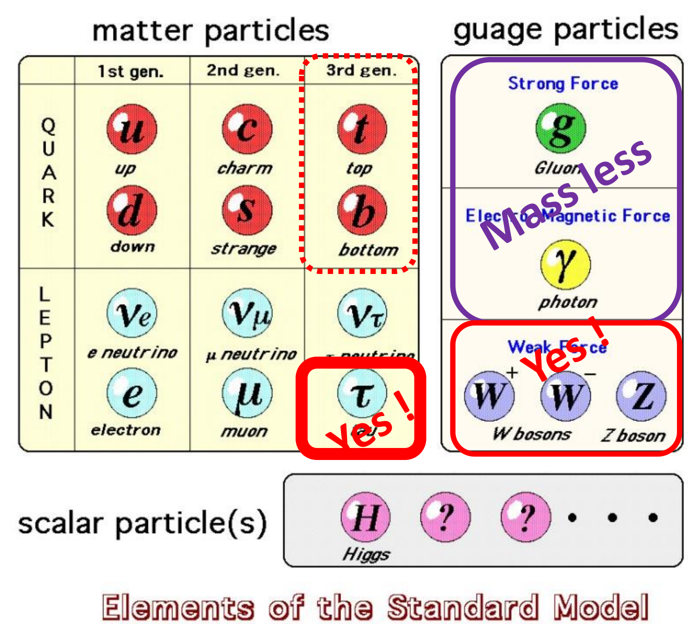


Lepton universality ?

- H→μμ decay is also searched.







This correspond to the BR(H→μμ)<0.2%

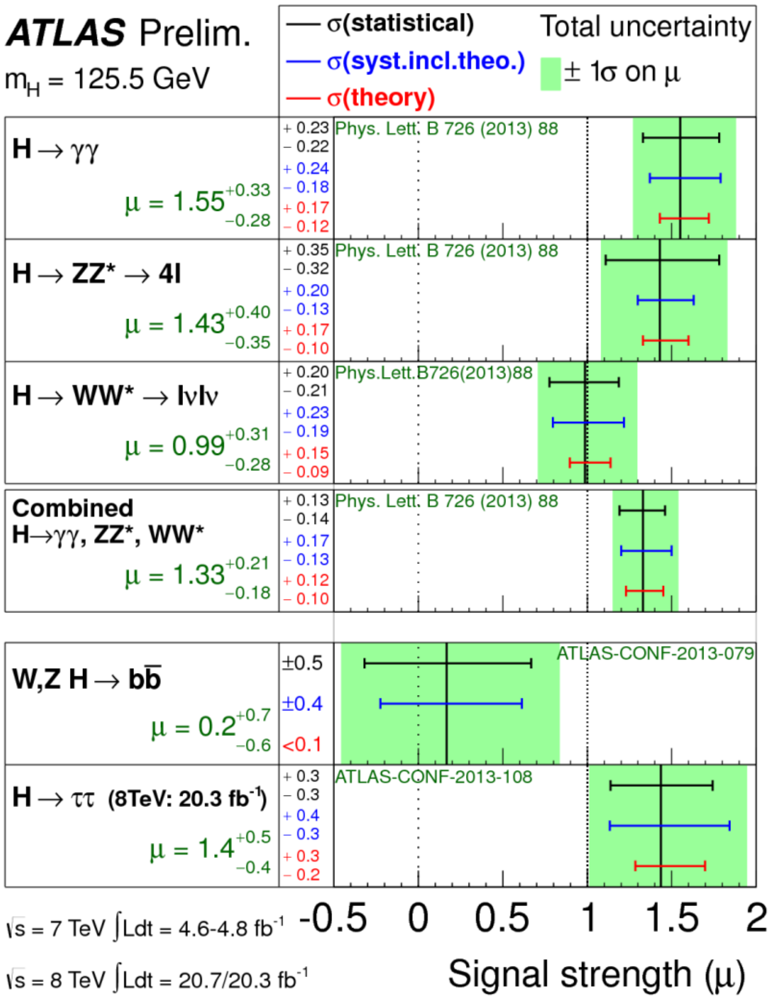
So, BR(H→ττ) >> BR(H→μμ)

Higgs boson does not universally couple to fermions (leptons)

Conclusion

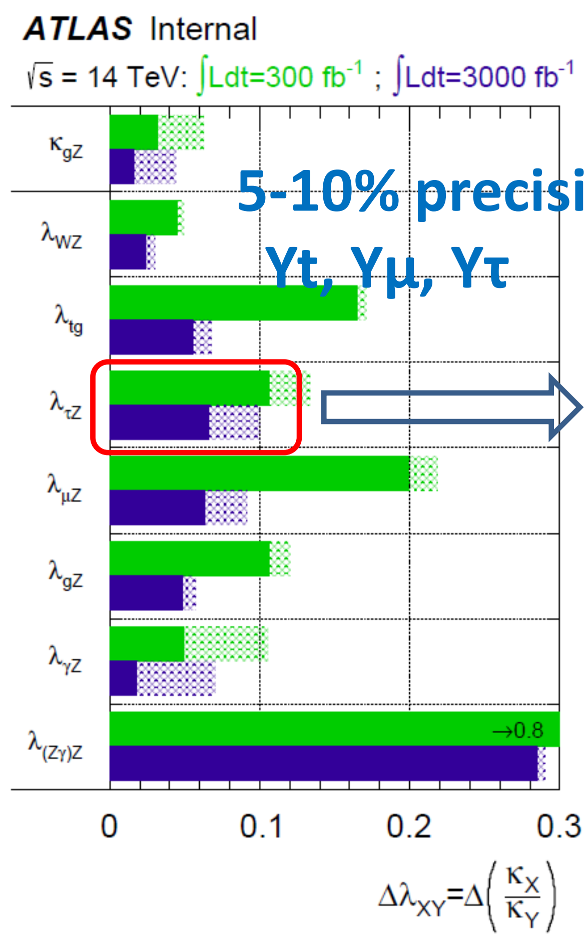
- Both ATLAS and CMS observed significant excess in tautau searches.
  - **Result @125GeV:**
    - **ATLAS: 4.1σ (expected 3.2σ)**
      - **μ_{best}=1.4+0.5-0.4**
    - **CMS: 3.4 σ (expected 3.6σ)**
      - **μ_{best}=0.87±0.29**
  - **This is 4th channel which observed significant excess.**
  - **First strong evidence of fermion decay of the Higgs Boson!**

Decay channel	Expected sensitivity	Observed Sensitivity
H(124.3)→ZZ	4.4σ	6.6σ
H(126.8)→γγ	4.1σ	7.4σ
H(125)→WW	3.7σ	3.8σ
H(125)→ττ	3.2σ	4.1σ
H(125)→bb	1.6σ	0.4σ



Future prospect

Updated coupling measurement results are presented.



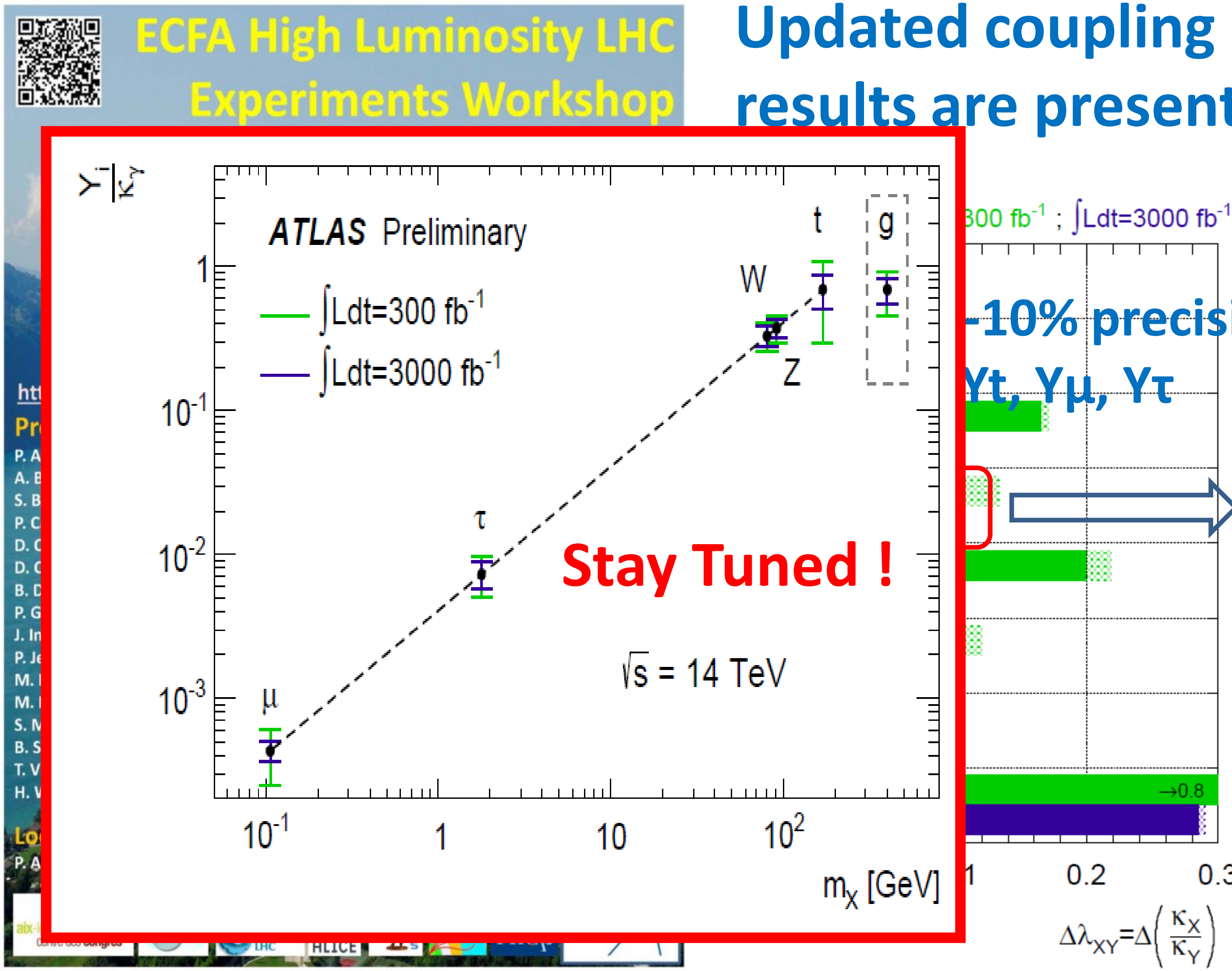
5-10% precision for Yt, Yμ, Yτ

50-100% improve !

Yτ can be measured by a few % precision!

Future prospect

Updated coupling measurement results are presented.



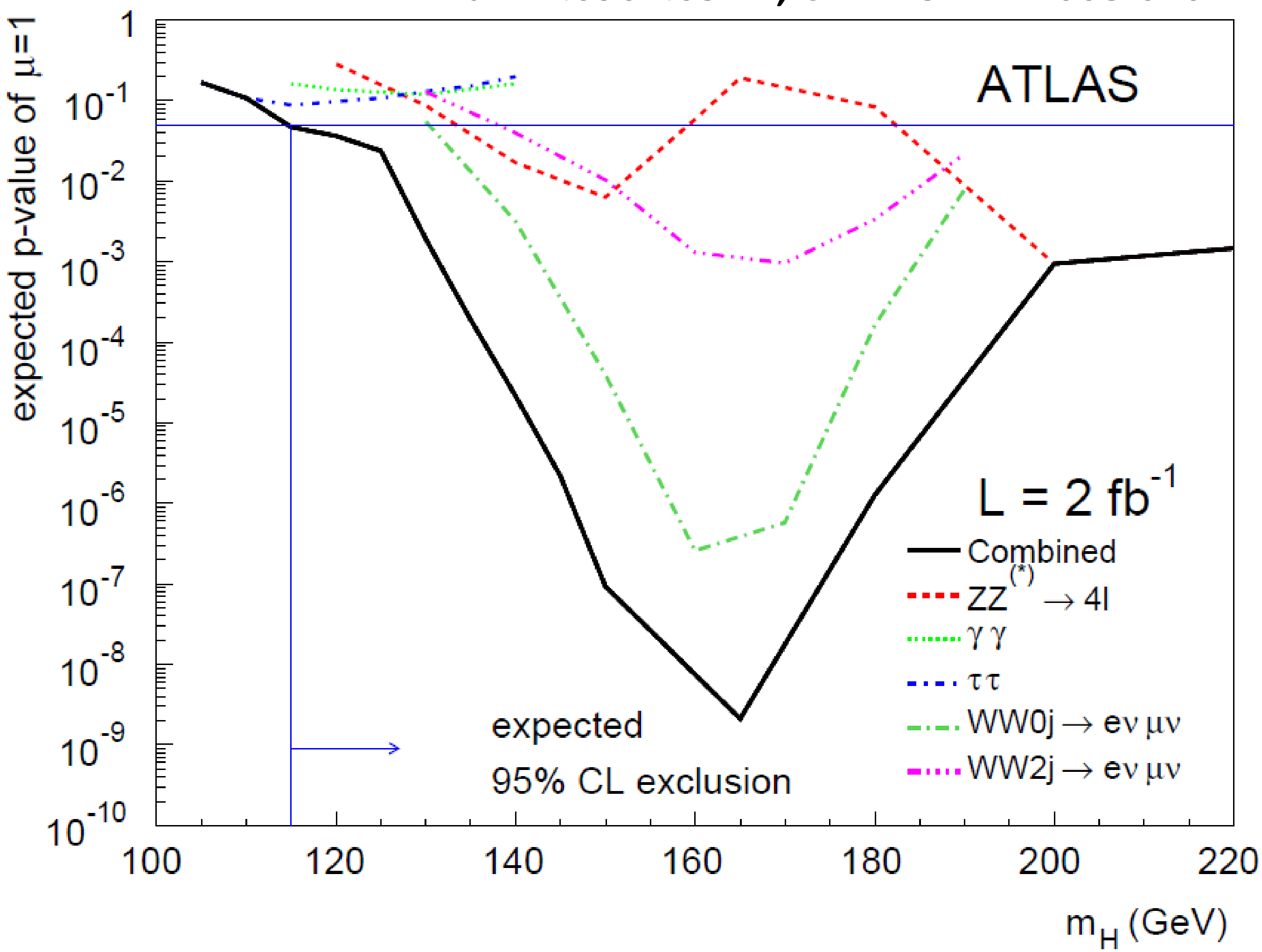
~10% precision for Yt, Yμ, Yτ

50-100% improve !

Yτ can be measured by a few % precision!

Backup

arXiv:0901.0512 ; CERN-OPEN-2008-020

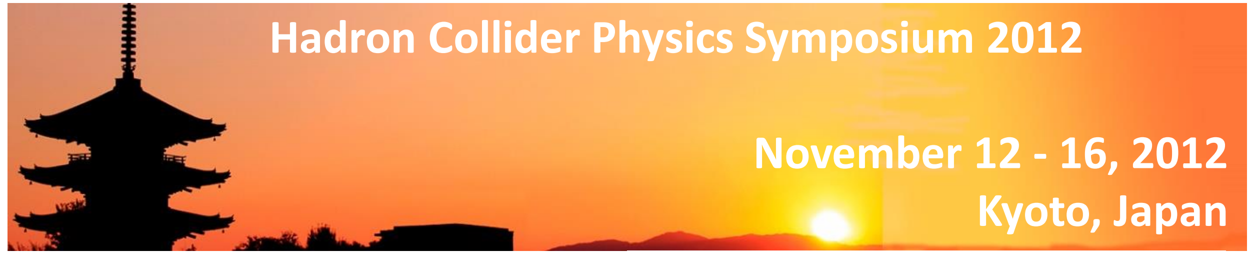


Previous result

Last tautau public results are :

ATLAS-CONF-2012-160

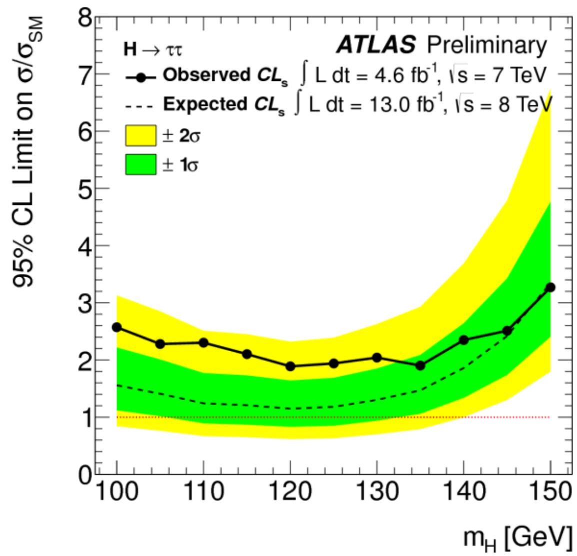
One year ago…

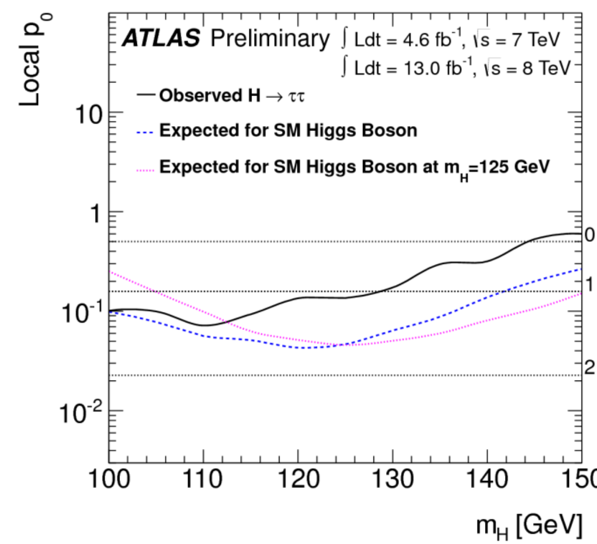


Limit (exp):1.9(1.2)xSM

p0(exp): 1.1(1.7)σ

μ= 0.7 ±0.7





- **Repeated analyses by using full data ($13\rightarrow 20 fb^{-1}$) didn’t expect reaching evidence.**

Backgrounds in highest score bins (leplep)

Process/Category	VBF			Boosted		
BDT score bin edges	0.684-0.789	0.789-0.895	0.895-1.0	0.667-0.778	0.778-0.889	0.889-1.0
ggF	0.53 ± 0.26	0.8 ± 0.4	0.7 ± 0.4	5.3 ± 2.1	5.2 ± 2.0	1.7 ± 0.7
VBF	1.15 ± 0.35	2.0 ± 0.6	5.0 ± 1.5	1.01 ± 0.33	1.5 ± 0.5	0.67 ± 0.22
WH	< 0.05	< 0.05	< 0.05	0.71 ± 0.22	0.64 ± 0.20	0.16 ± 0.05
ZH	< 0.05	< 0.05	< 0.05	0.36 ± 0.11	0.32 ± 0.10	0.06 ± 0.02
$Z \rightarrow \tau^+\tau^-$	7.6 ± 0.8	9.0 ± 0.9	4.6 ± 0.6	97 ± 7	61.5 ± 3.2	13.6 ± 1.3
Fake	2.8 ± 0.7	5.8 ± 2.0	4.5 ± 1.7	10.1 ± 3.1	15 ± 5	0.79 ± 0.29
Top	4.0 ± 0.9	2.9 ± 0.7	1.8 ± 0.4	28 ± 7	15 ± 4	3.5 ± 0.9
Others	1.97 ± 0.26	3.3 ± 0.4	2.7 ± 0.4	24.7 ± 1.9	8.8 ± 0.6	2.34 ± 0.24
Total Background	16.3 ± 1.5	20.9 ± 2.4	13.5 ± 2.4	160 ± 7	101 ± 4	20.2 ± 1.8
Total Signal	1.7 ± 0.5	2.9 ± 0.9	5.7 ± 1.7	7.4 ± 2.4	7.7 ± 2.5	2.6 ± 0.8
S/B	0.10	0.14	0.42	0.05	0.08	0.13
Data	23	28	19	156	128	20

	ggF	VBF	VH	$Z \rightarrow \tau\tau$	Fake	Top	Others	S/B
VBF	0.7 ± 0.4	5.0 ± 1.5	--	4.6 ± 0.6	4.5 ± 1.7	1.8 ± 0.4	2.7 ± 0.4	0.42
boosted	1.7 ± 0.7	0.7 ± 0.2	0.2 ± 0.1	13 ± 1	0.8 ± 0.3	3.5 ± 0.9	2.3 ± 0.2	0.13

Backgrounds in highest score bins (lephad)

Process/Category	VBF			Boosted		
BDT score bin edges	0.5-0.667	0.667-0.833	0.833-1.0	0.6-0.733	0.733-0.867	0.867-1.0
ggF	2.2 ± 0.9	3.5 ± 1.5	1.2 ± 0.6	7.7 ± 2.9	6.3 ± 2.3	5.5 ± 2.1
VBF	4.1 ± 1.2	9.2 ± 2.7	7.5 ± 2.2	1.7 ± 0.5	1.5 ± 0.5	1.3 ± 0.4
WH	< 0.05	< 0.05	< 0.05	0.95 ± 0.29	0.85 ± 0.26	0.81 ± 0.25
ZH	< 0.05	< 0.05	< 0.05	0.42 ± 0.13	0.47 ± 0.14	0.41 ± 0.12
$Z \to \tau^+\tau^-$	28.6 ± 1.4	25.0 ± 1.6	2.41 ± 0.35	48.3 ± 3.4	26.1 ± 2.7	18.4 ± 2.0
Fake	37.7 ± 1.8	27.9 ± 2.1	3.5 ± 0.5	27 ± 4	10.8 ± 1.8	5.8 ± 1.4
Top	6.5 ± 0.7	4.1 ± 0.8	1.5 ± 0.4	7.0 ± 0.9	5.7 ± 0.8	2.23 ± 0.33
Diboson	2.9 ± 0.4	3.0 ± 0.5	0.23 ± 0.04	4.8 ± 0.5	4.0 ± 0.5	1.69 ± 0.23
$Z \to \ell\ell(j \to \tau_{\mathrm{had}})$	8.7 ± 1.7	3.3 ± 0.5	0.40 ± 0.10	3.8 ± 0.5	0.71 ± 0.07	< 0.05
$Z \to \ell\ell(\ell \to \tau_{\mathrm{had}})$	2.8 ± 1.2	1.9 ± 1.2	0.7 ± 0.6	9.4 ± 1.9	4.9 ± 1.1	3.8 ± 1.2
Total Background	87.2 ± 2.7	65 ± 5	8.7 ± 2.5	101 ± 6	52 ± 4	32 ± 4
Total Signal	6.3 ± 1.8	12.7 ± 3.5	8.7 ± 2.4	10.7 ± 3.3	9.2 ± 2.8	8.0 ± 2.5
S/B	0.07	0.20	1.0	0.11	0.18	0.25
Data	90	80	18	103	64	34

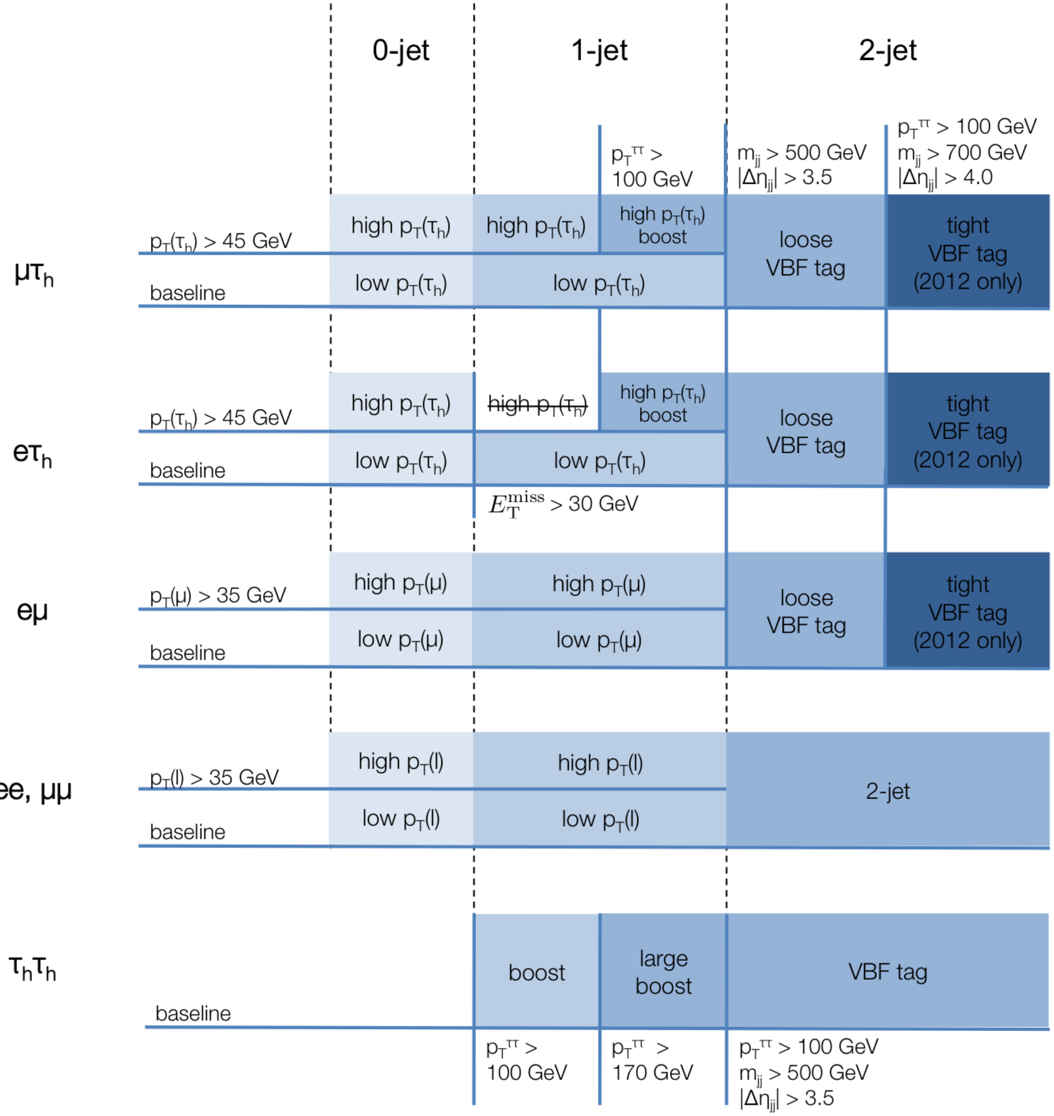
	ggF	VBF	VH	Z→ττ	Fake	Top	Others	S/B
VBF	1.2±0.6	7.5±2.2	--	2.4±0.4	3.5±0.5	1.5±0.4	1.3±0.7	1.0
boosted	5.5±2.1	1.3±0.4	1.2±0.3	18±2	5.8±1.4	2.2±0.3	5.5±1.2	0.25

Backgrounds in highest score bins (hadhad)

Process/Category	VBF			Boosted		
BDT score bin edges	0.85-0.9	0.9-0.95	0.95-1.0	0.85-0.9	0.9-0.95	0.95-1.0
ggF	0.39 ± 0.17	0.35 ± 0.16	2.0 ± 0.9	2.2 ± 0.8	2.5 ± 1.0	2.3 ± 0.9
VBF	0.57 ± 0.18	0.72 ± 0.22	5.9 ± 1.8	0.55 ± 0.17	0.61 ± 0.19	0.57 ± 0.17
WH	< 0.05	< 0.05	< 0.05	0.34 ± 0.11	0.40 ± 0.12	0.44 ± 0.14
ZH	< 0.05	< 0.05	< 0.05	0.22 ± 0.07	0.22 ± 0.07	0.22 ± 0.07
$Z \to \tau^+\tau^-$	3.2 ± 0.6	3.4 ± 0.7	5.3 ± 1.0	15.7 ± 1.7	12.3 ± 1.8	9.7 ± 1.6
Multijet	3.3 ± 0.6	2.9 ± 0.6	5.9 ± 0.9	5.2 ± 0.6	3.7 ± 0.5	1.40 ± 0.22
Others	0.38 ± 0.09	0.49 ± 0.12	0.64 ± 0.13	1.49 ± 0.27	2.8 ± 0.5	0.07 ± 0.02
Total Background	6.9 ± 1.3	6.8 ± 1.3	11.8 ± 2.6	22.4 ± 2.5	18.8 ± 2.8	11.2 ± 1.9
Total Signal	0.97 ± 0.29	1.09 ± 0.31	8.0 ± 2.2	3.3 ± 1.0	3.8 ± 1.2	3.6 ± 1.1
S/B	0.14	0.16	0.67	0.15	0.2	0.32
Data	6	6	19	20	16	15

	ggF	VBF	VH	$Z \to \tau\tau$	Fake	Others	S/B
VBF	2.0 ± 0.9	5.9 ± 1.8	--	5.3 ± 1.0	5.9 ± 0.9	0.6 ± 0.1	0.67
boosted	2.3 ± 0.9	0.6 ± 0.2	0.7 ± 0.2	9.7 ± 1.6	1.4 ± 0.2	0.07 ± 0.02	0.32

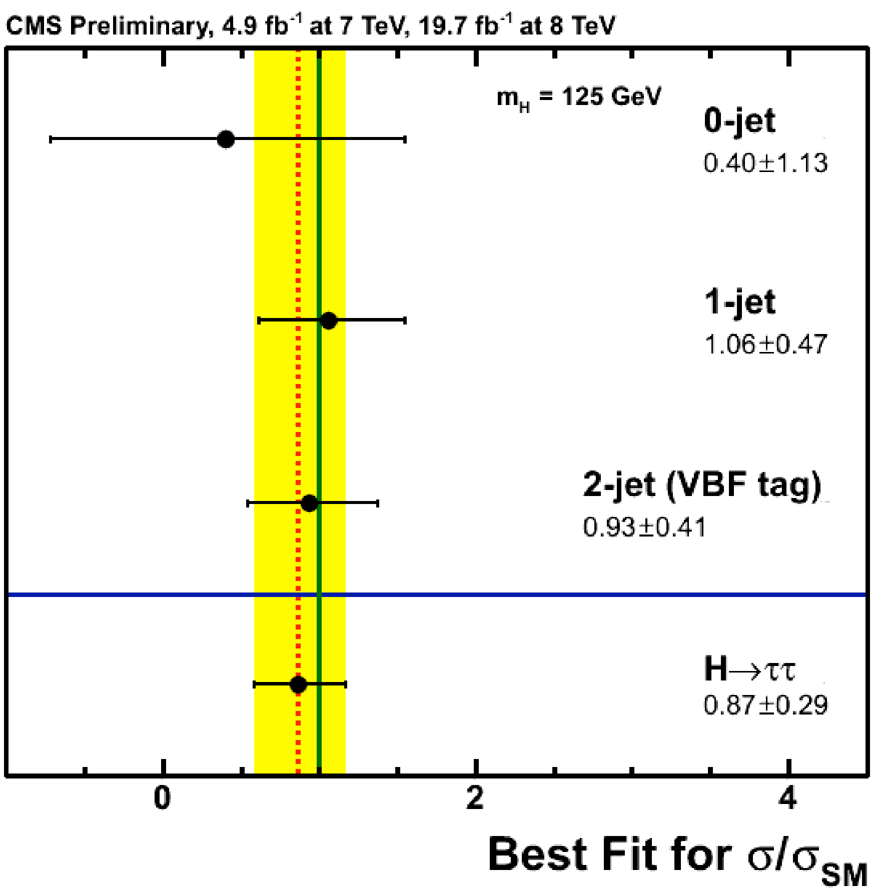
Full categorization chart



- For 7TeV analysis, loose and tight VBF categories are merged.
- 1jet e-had cahnnels used MET>30GeV cut.

Signal strength

Events split by categories



Events split by channels