Higgs Boson Physics at the LHC

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Lecture 1:
Production and decay rates of the Higgs boson

Lecture 2:
Properties of the Higgs boson

Lecture 3:
Searches for BSM Higgs phenomena

Apology and Disclaimer:

- Most of the results are from ATLAS. CMS results are similar in most cases.
- I cannot possibly cover all results.
- Mistakes are mine.

Lecture 1

Production and Decay Rates of the Higgs Boson

Historical Development

In 1964, three teams published proposals on how mass could arise in local gauge theories. They are now credited for the BEH mechanism and the Higgs boson.

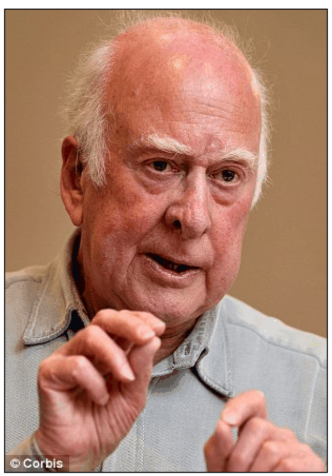
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

L to R: Kibble, Guralnik, Hagen, Englert, and Brout



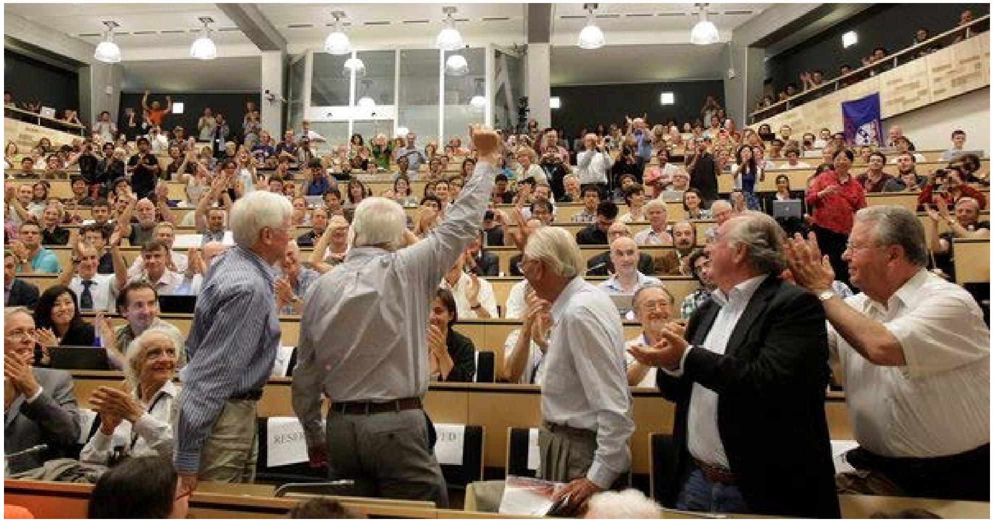
Higgs

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

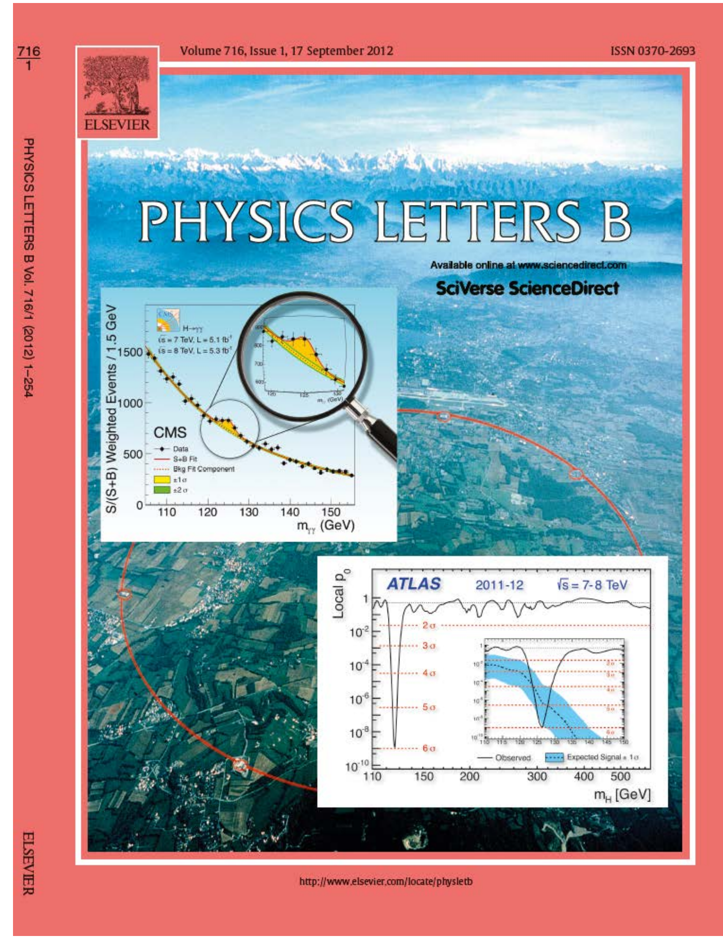
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

2013 Nobel Prize!

The 2012 Discovery



Seminar of July 4, 2012



Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

Phys. Lett. B716 (2012) 1

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

Phys. Lett. B716 (2012) 30

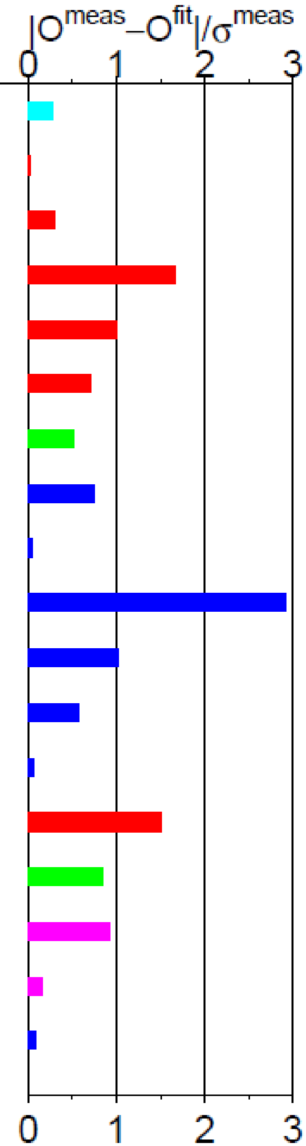
Standard Model

Standard model does not answer all the questions, but it does describe existing data remarkable well

There are very few confirmed anomalies

The EW symmetry breaking mechanism in the SM is not confirmed
$\Rightarrow$ Hunting for Higgs boson

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



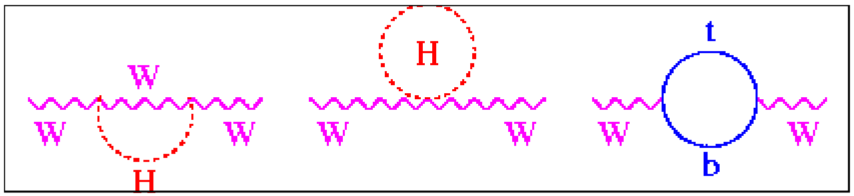
July 2011

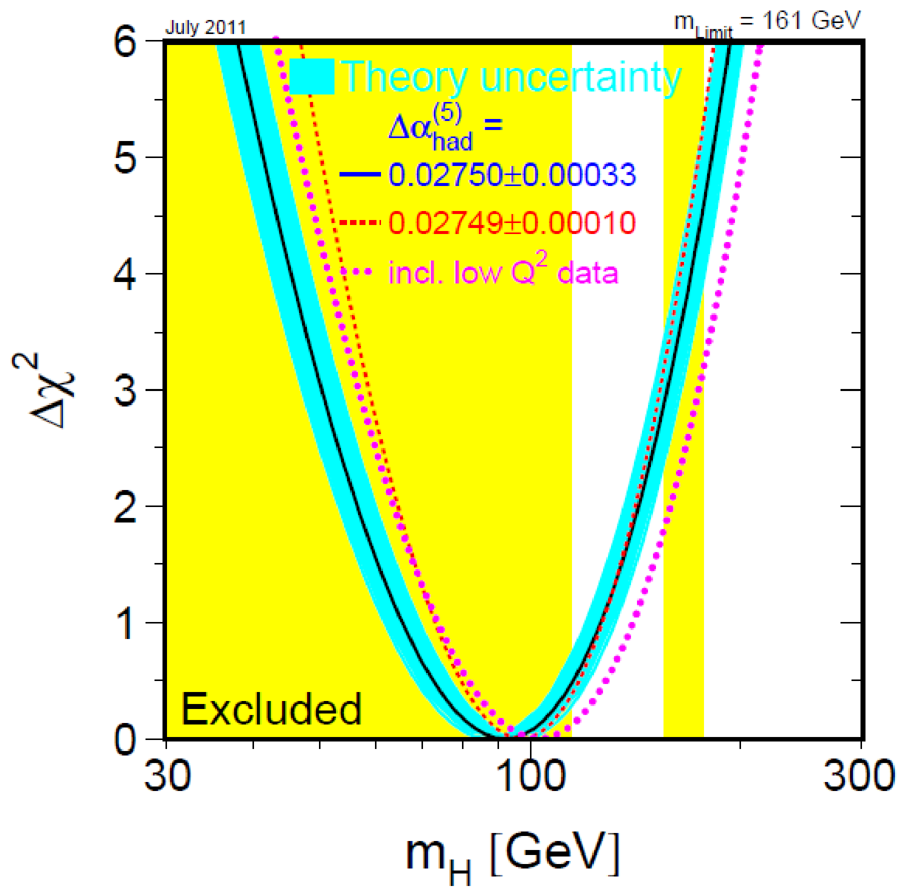
Higgs Boson Mass Constraint

Direct searches at LEP:

$$m_H > 114.4 \text{ GeV @ } 95\% \text{ CL}$$

Precision electroweak data are sensitive to Higgs mass





Preferred value from global fit:

$$m_H = 92^{+32}_{-26} \text{ GeV}$$

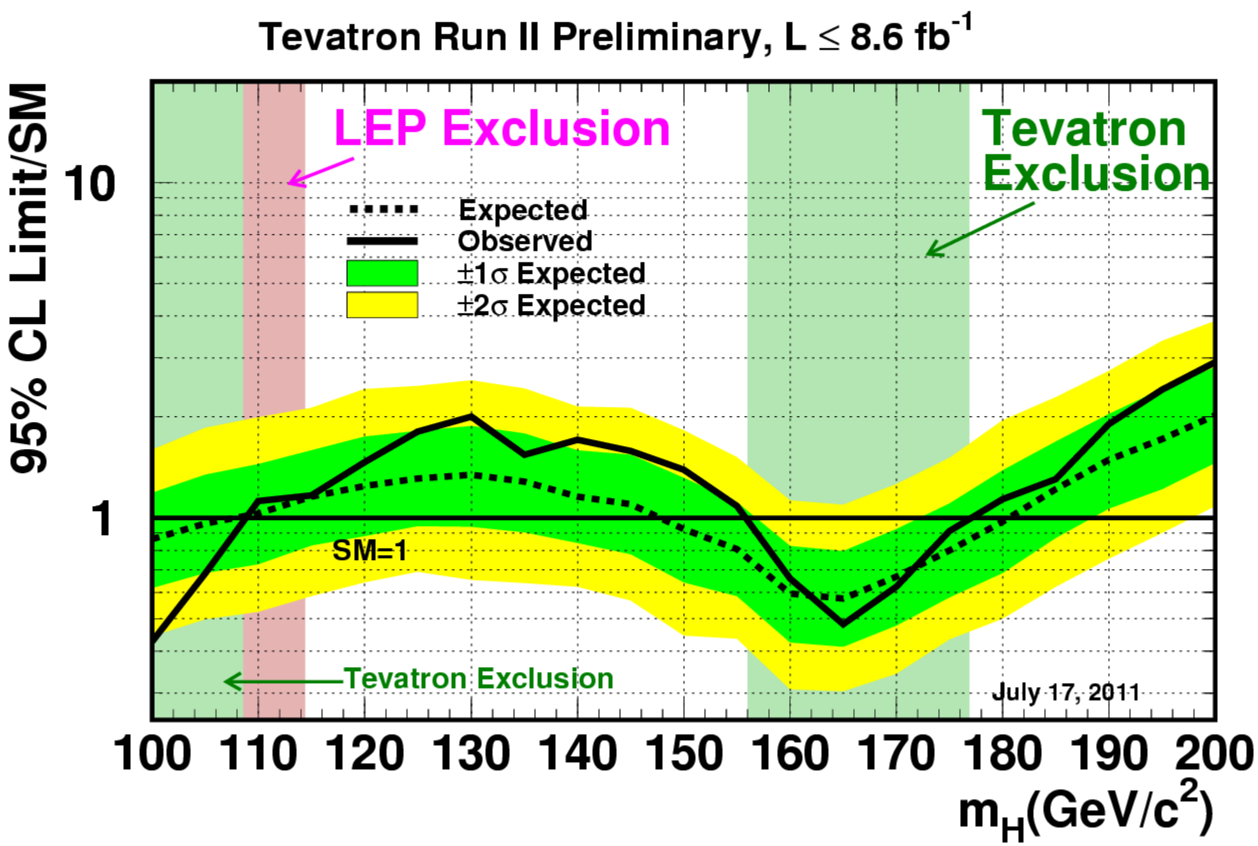
and 95% CL upper bound

$$m_H < 161 \text{ GeV}$$

Existing data suggests a low mass standard model Higgs

Higgs Searches at Tevatron

The ggF cross section is x10 smaller than that at the LHC. Main search channels are: $WH \to \ell \nu b\bar{b},\ ZH \to \nu\nu b\bar{b},\ H \to WW \to \ell\nu\ell\nu, \ldots$



The combined CDF and DØ searches resulted in a mass exclusion range of 156-177 GeV at 95% CL

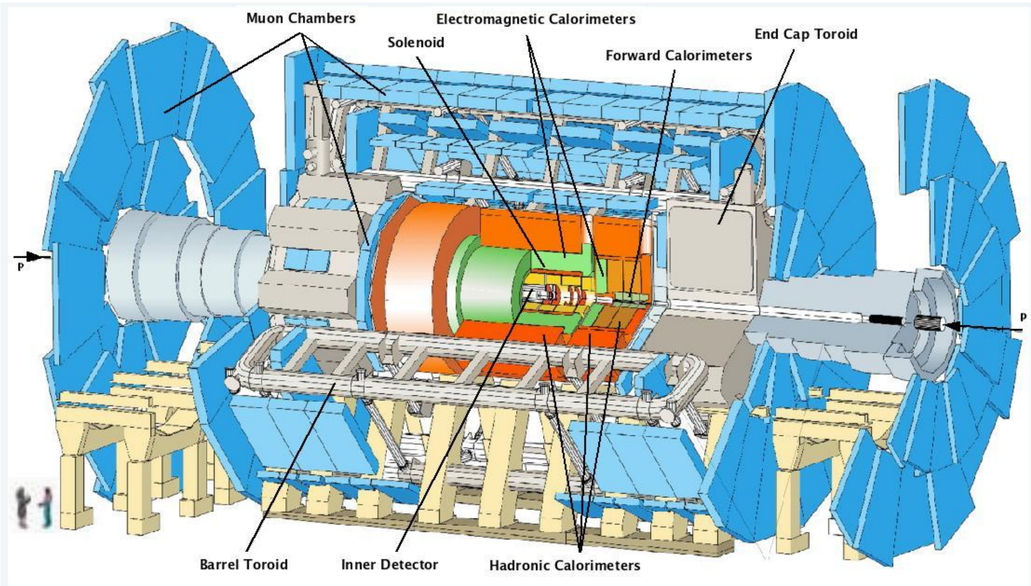
Large Hadron Collider

A Superconducting Proton-Proton Collider

Design: 14 TeV with the peak luminosity of 10^{34} cm^{-2} s^{-1}
Run 1: 7 and 8 TeV with a peak lumi ~6×10^{33} cm^{-2} s^{-1}

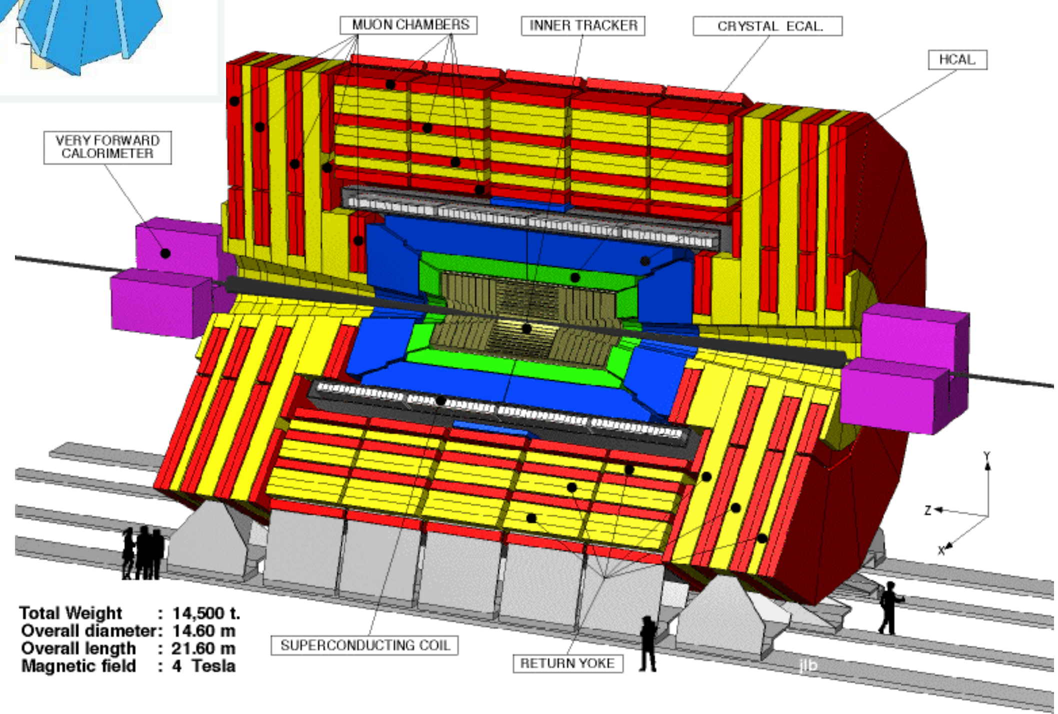
Two general purpose detectors: ATLAS and CMS

ATLAS and CMS Detectors



ATLAS

Length: 46 m
Diameter: 25 m
Weight: 7,000 t
Solenoid Field: 2 T

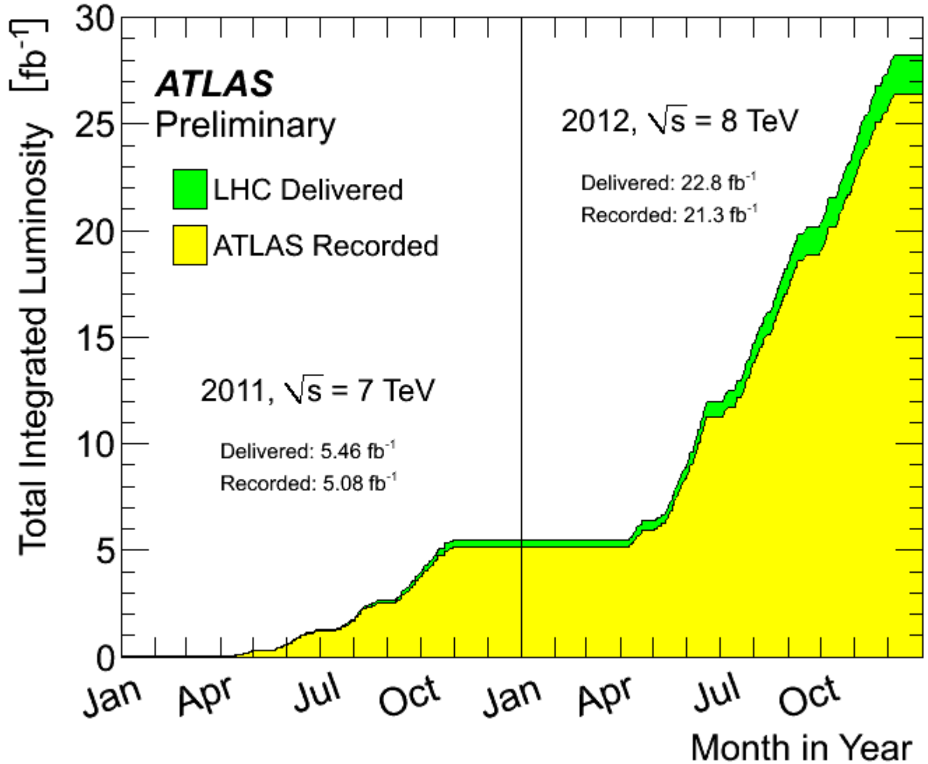


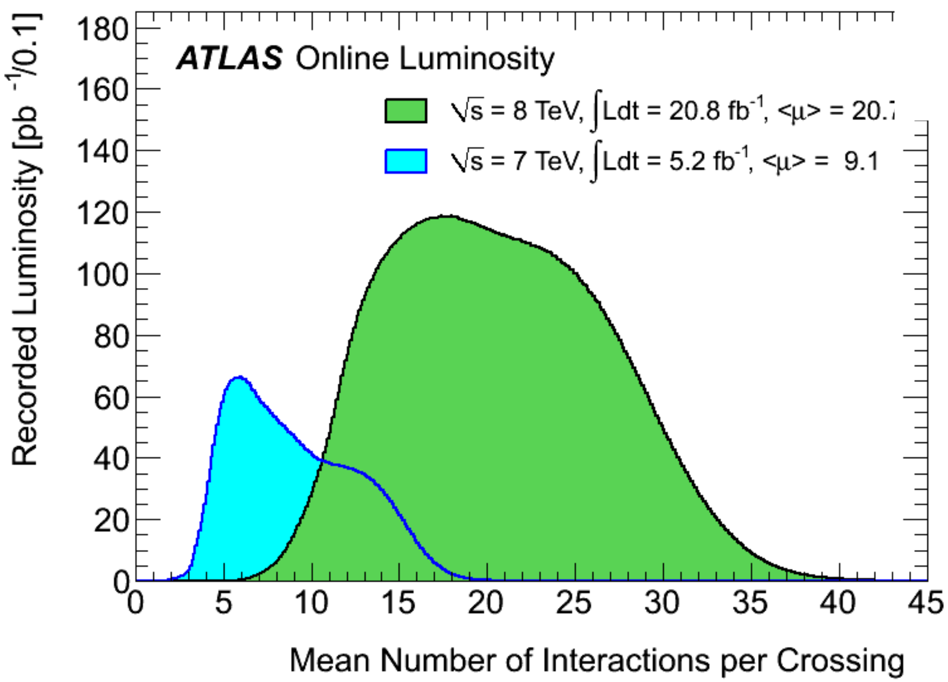
CMS

Length: 21.6 m
Diameter: 14.6 m
Weight: 14,500 t
Solenoid Field: 4 T

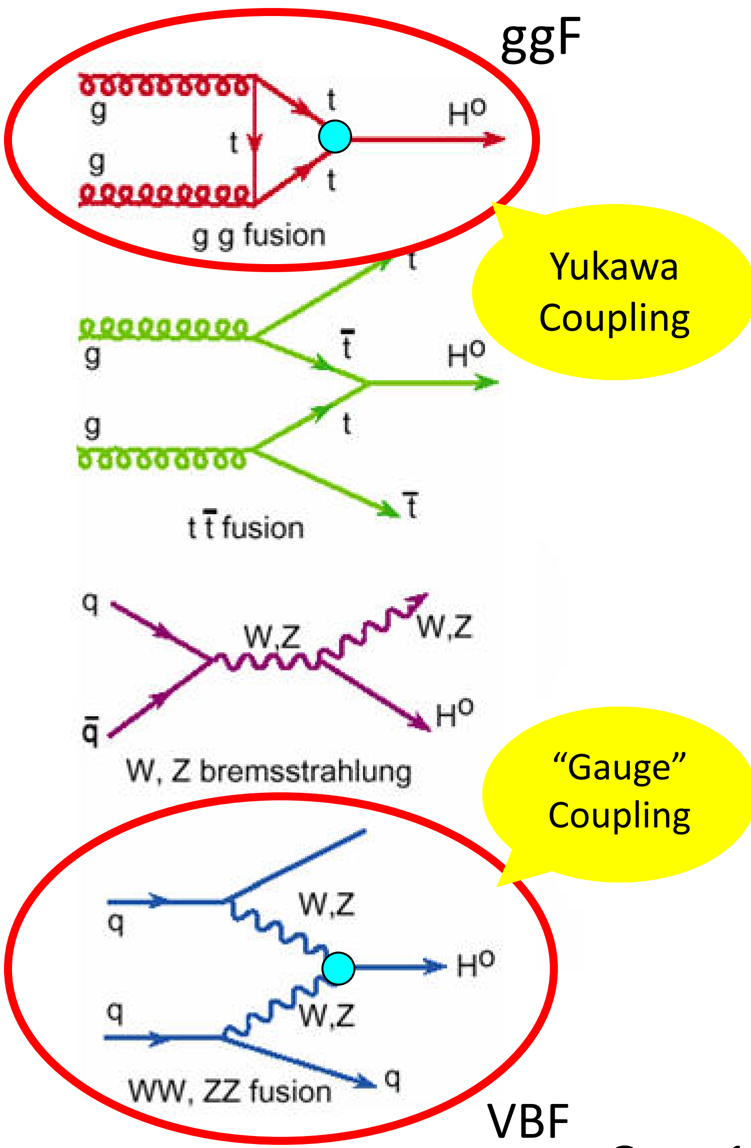
LHC Run 1

$$2011: \quad \sqrt{s} = 7 \text{ TeV}, \quad \sim 5 \text{ fb}^{-1}$$
$$2012: \quad \sqrt{s} = 8 \text{ TeV}, \quad \sim 20 \text{ fb}^{-1}$$

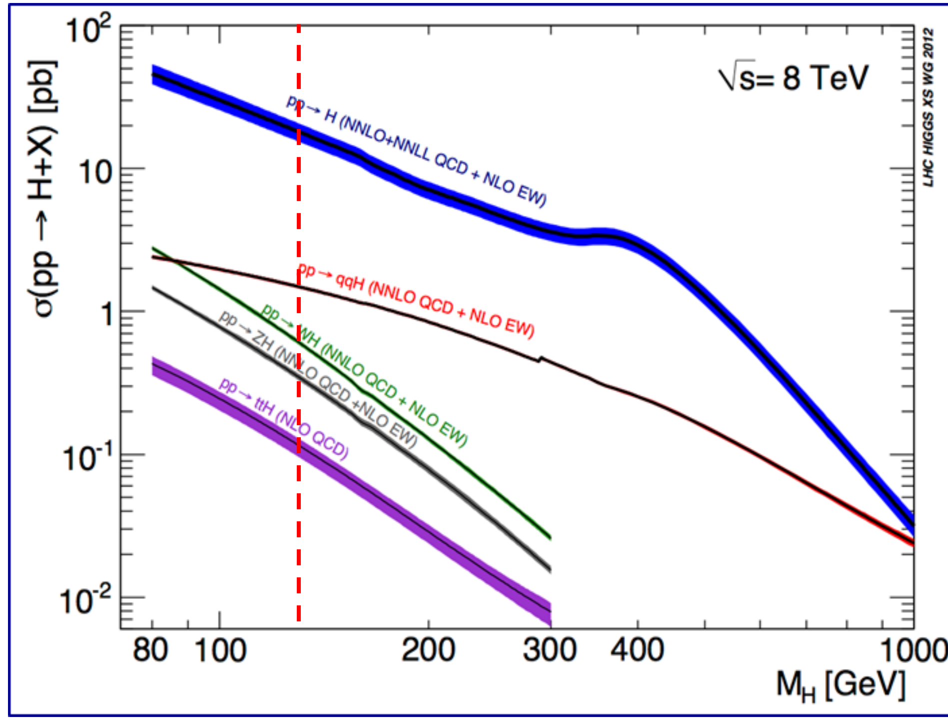




Higgs Boson Production at LHC



gluon-gluon fusion gg→H and vector-boson fusion qq→qqH diagrams dominate



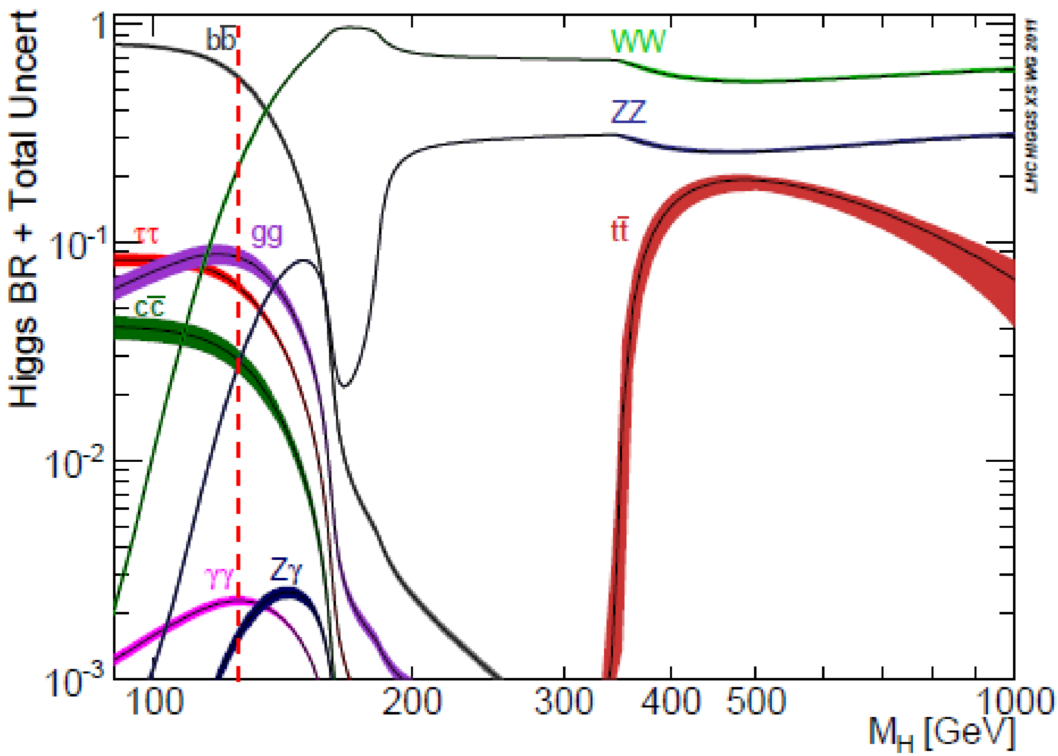
Production cross section for $m_H = 125$ GeV

Process	Tot	ggF	VBF	WH	ZH	$t\bar{t}H$
σ (pb)	22.3	19.5	1.6	0.70	0.39	0.13
σ/σ_{tot} (%)		87.4	7.2	3.1	1.7	0.6

Over 1,000,000 Higgs bosons produced at LHC in Run 1!

Higgs Boson Decays

Around 125 GeV, many accessible decay modes, rapid changes in $H \to WW^*$ and $H \to ZZ^*$ decay BR.



Branching ratio @ 125 GeV	
$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.32%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	0.23%
$H \to Z\gamma$	0.15%
$H \to \mu\mu$	0.02%

Dominant decays:

$H \to b\bar{b}$ for $m_H < 130$ GeV,

$H \to WW^*$ for $m_H < 130$ GeV

for SM-like Higgs bosons.

Theoretical Uncertainties

$\Delta\sigma/\sigma$ for pp at 8 TeV

Process	QCD scale	PDF+α_s	Total (linear sum)
ggF	±8%	±8%	±15%
$t\bar{t}$H	±7%	±8%	±15%
VBF	±1%	±4%	±5%
VH	±1%	±4%	±5%

LHC cross section working group

The uncertainties in the ggF process are starting to limit the precision of the coupling measurements.

ΔBR/BR at $M_H = 125$ GeV

decay	theory	parameters	total (linear sum)
$H \to bb$	±1.3%	±1.5%	±2.8%
$H \to \tau\tau$	±3.6%	±2.5%	±6.1%
$H \to \mu\mu$	±3.9%	±2.5%	±6.4%
$H \to WW^*$	±2.2%	±2.5%	±4.8%
$H \to ZZ^*$	±2.2%	±2.5%	±4.8%
$H \to \gamma\gamma$	±2.9%	±2.5%	±5.4%

A. Denner et al., arXiv:1107.5909

$\Gamma_{b\bar{b}} \approx 0.57\Gamma_H \Rightarrow \Delta m_b$ has a large impact on parametric uncertainties

$$\frac{\Delta\Gamma_{bb}}{\Gamma_{bb}} \sim 2\frac{\Delta m_b}{m_b} \sim 2.6\%$$

Parameter	Central Value	Uncertainty	$\overline{\text{MS}}$ masses $m_q(m_q)$
$\alpha_s(M_Z)$	0.119	±0.002	
m_c	1.42 GeV	±0.03 GeV	1.28 GeV
m_b	4.49 GeV	±0.06 GeV	4.16 GeV
m_t	172.5 GeV	±2.5 GeV	165.4 GeV

Conservative assumptions by the LHC Higgs cross section, usually 2-3x larger than PDG values.

Statistical Procedure

Construct likelihood from Poisson probabilities with parameter of interest (signal strength μ in this case):

$$L(\text{data} \mid \mu, \theta) = \text{Poisson}\left(\text{data} \mid \mu \cdot s(\theta) + b(\theta)\right) \times p\left(\tilde{\theta} \mid \theta\right)$$

μ: signal strength; θ: 'nuisance' parameters (efficiencies...)

Hypothesized value of μ is tested with a test statistic:

$$q_\mu = -2\ln\Lambda(\mu) = -2\ln\left[\frac{L\left(\mu, \hat{\hat{\theta}}(\mu)\right)}{L\left(\hat{\mu}, \hat{\theta}\right)}\right]$$

Systematic uncertainties are included as nuisance parameters constrained by chosen pdfs (Gaussian, log-normal, ...)

Combination amounts to taking product of likelihoods from different channels: $L(\text{data} \mid \mu, \theta) = \Pi_i\, L_i\left(\text{data}_i \mid \mu, \theta_i\right)$

Theory and MC Tool Box

Tremendous effort from the theory community, …

Cross section tools:

ggF:
- HIGLU (NNLO QCD+NLO EW)
- FeHiPro (NNLO QCD+NLO EW)
- HNNLO, HRes (NNLO+NNLL QCD)
- ggh@NNLO (NNLO QCD), …

VBF:
- VV2H (NLO QCD)
- VBFNLO (NLO QCD)
- HAWK (NLO QCD+EW)
- VBF@NNLO (NNLO QCD), …

VH:
- V2HV (NLO QCD)
- VH@NNLO (NNLO), …

ttH:
- HQQ (LO QCD), …

MC tools:
- aMC@NLO
- POWHEG,
- SHERPA,
- HERWIG++,
- MadGraph5, ….

Higgs decays:
- HDECAY (NLO)
- Prophecy4f (NLO), …

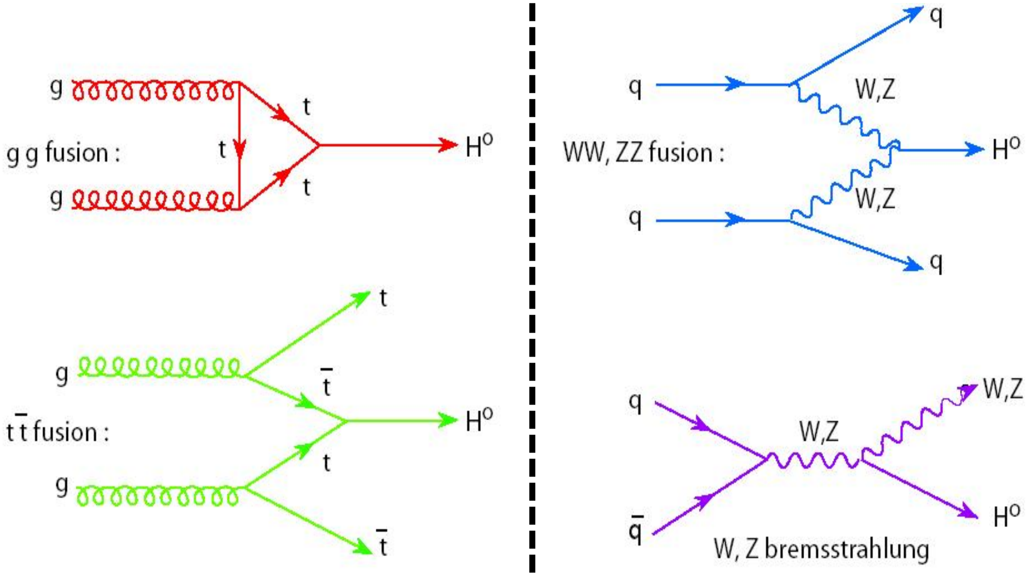
Others
- HqT (NLO+NNLL)
- ResBos (NLO+NNLL)
- MINLO
- JetVHeto
- MELA/JHU,
- MEKD, …

LHC Higgs Cross Section Working Group

+ general programs such as MCFM and many private codes…

Disentangle Production Processes – Why?

Production processes naturally fall into two groups



Strong Production
Fermion Coupling

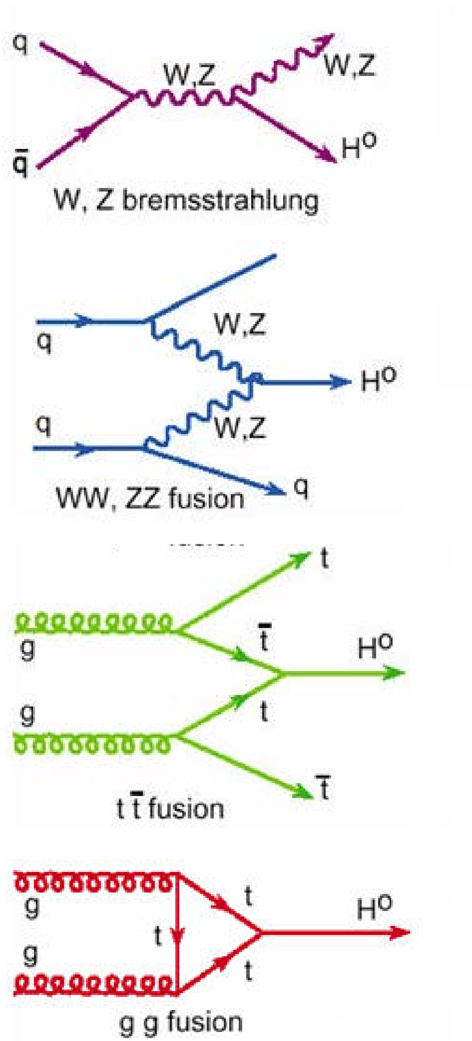
Electroweak Production,
Vector Boson Coupling

Higgs candidate events are selected from their decay signatures, independent of production.

But need to disentangle the production processes using the production signatures for property measurements.

Disentangle Production Processes – How?

From other activities in candidate events…



VH

Tagged by W/Z decay signatures:
leptons, missing ET or low-mass dijets from W or Z decays

VBF

Two high pT jets with high-mass and large pseudorapidity separation

ttH

Tagged by top decay signatures:
leptons, missing ET, multijets or b-tagged jets

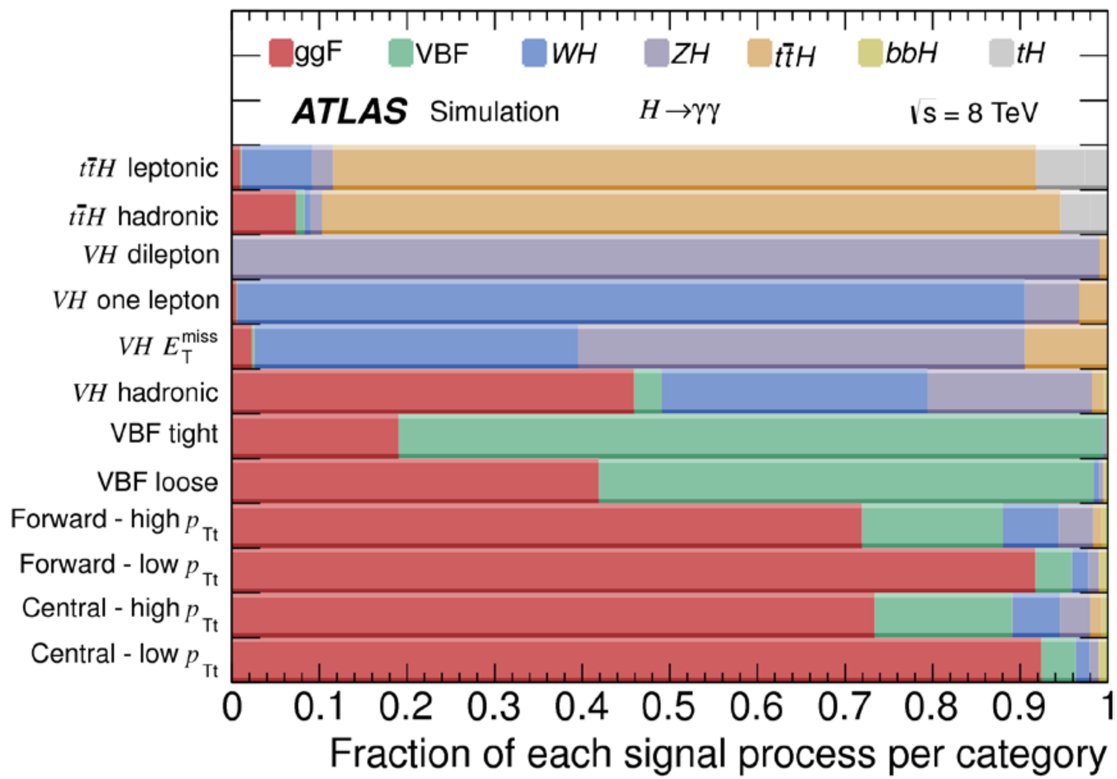
ggF

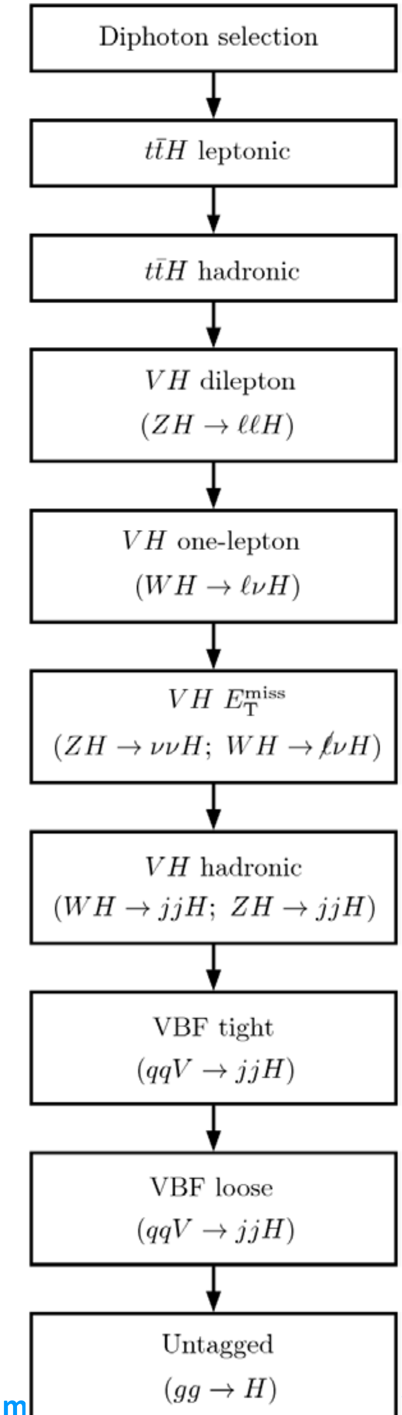
Untagged: the rest
separate into 0, 1 or 2 jets

Analysis Categorization

Categorized candidate events
- to improve S/B and
- to separate different production processes…

ATLAS $H \rightarrow \gamma\gamma$ 12 categories





Signal Strength

The measured rate relative to the SM prediction

$$\text{Signal strength: } \mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

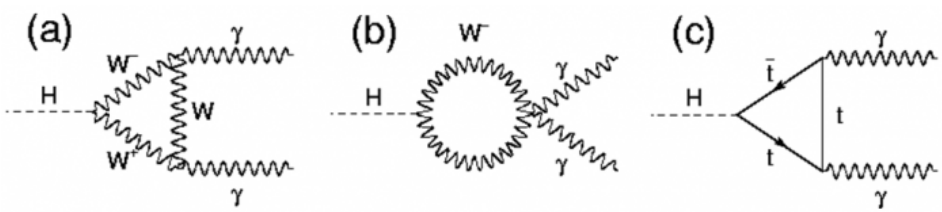
The quantify has a strong Higgs mass dependence due to the normalization to the SM prediction.

It’s meaning depends on the context. It is quoted

- inclusively, or for
- specific decay final state;
- specific production process

H → γγ Analysis

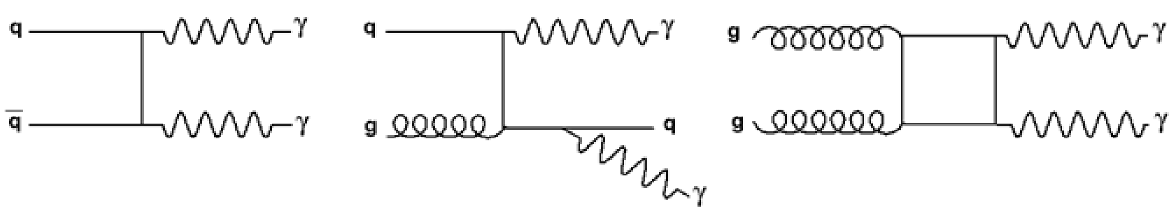
- Very simple signature, but small rate Br(H→γγ) ~ 2×10^{-3};
- Important decay mode for the low mass region (100-140 GeV)



$$\sigma_H \times Br\left(H \to \gamma\gamma\right) \sim 50 \text{ fb}$$
$$@\ m_H = 125 \text{ GeV, 8 TeV}$$

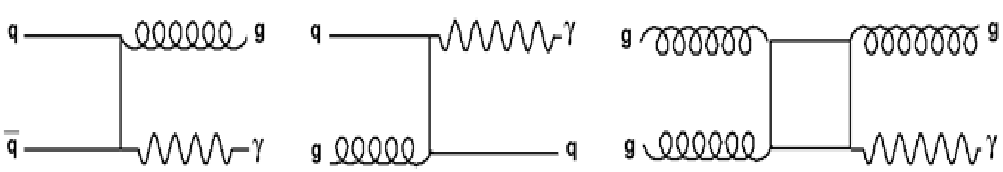
~500 events in 2011+2012 sample!

- Irreducible background from γγ production



$$\sigma\left(\gamma\gamma\right) \sim 40 \text{ pb}$$

- Reducible background from γj and jj productions



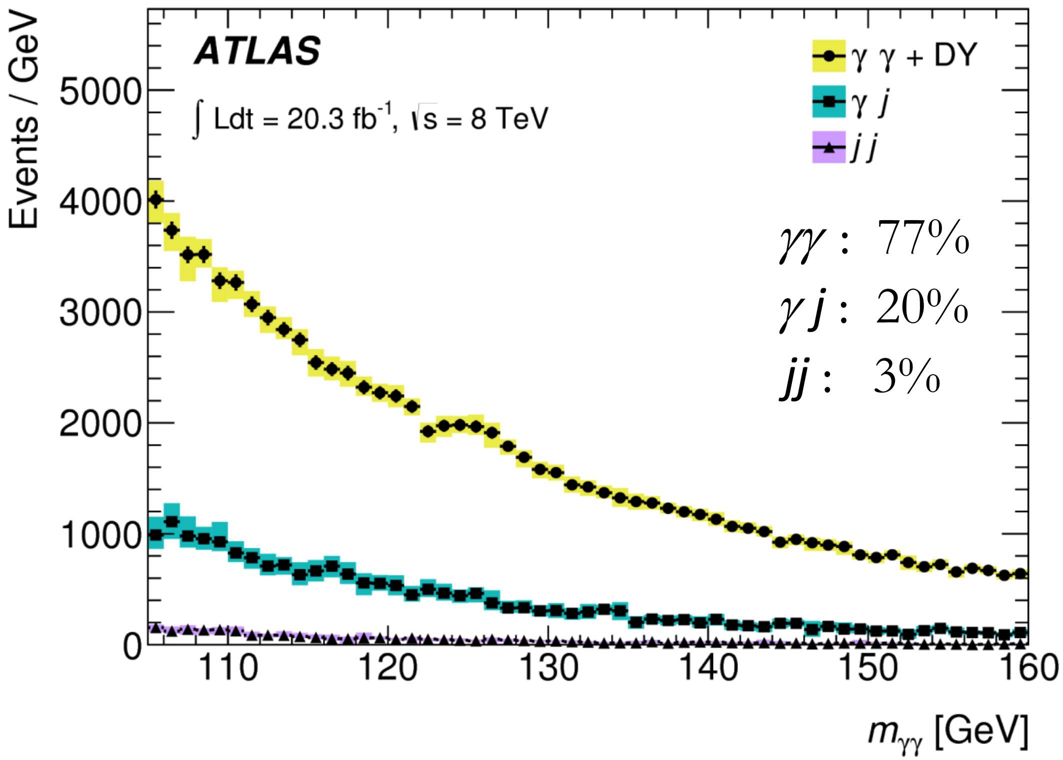
$$\sigma\left(\gamma j\right) \sim 3\times10^{5} \text{ pb}$$
$$\sigma\left(jj\right) \sim 6\times10^{8} \text{ pb}$$

Theoretical uncertainty $\Delta\sigma/\sigma \sim 30\%$, not reliable !

H → γγ Analysis

About 40% of the photons convert into e^+e^- pair, reconstruct both converted and unconverted photons. Simple kinematic selection:

$$E_T^{\gamma} > 25\ \mathrm{GeV};\ E_T^{\gamma_1} > 0.35\ m_{\gamma\gamma},\ E_T^{\gamma_2} > 0.25\ m_{\gamma\gamma}$$



Background is dominated by genuine diphoton production.
Model it using sidebands with functional forms.

H → γγ Analysis

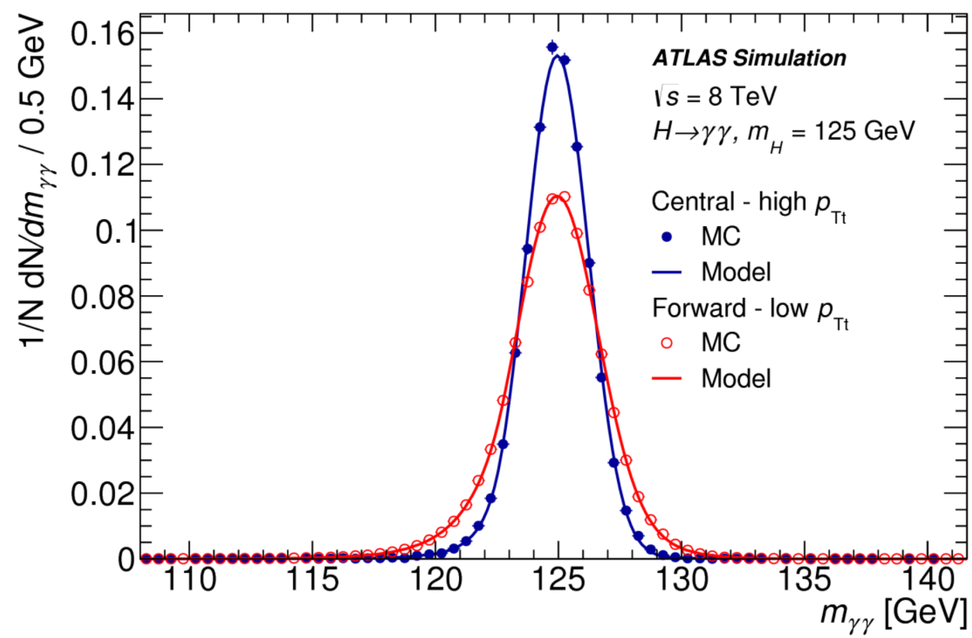
Full reconstruction of the Higgs decay final state, very little else to distinguish signal from backgrounds other than mass:

$$m_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}\left(1-\cos\Delta\phi_{\gamma\gamma}\right)$$

Mass resolution is the key, dominated by the energy resolution.

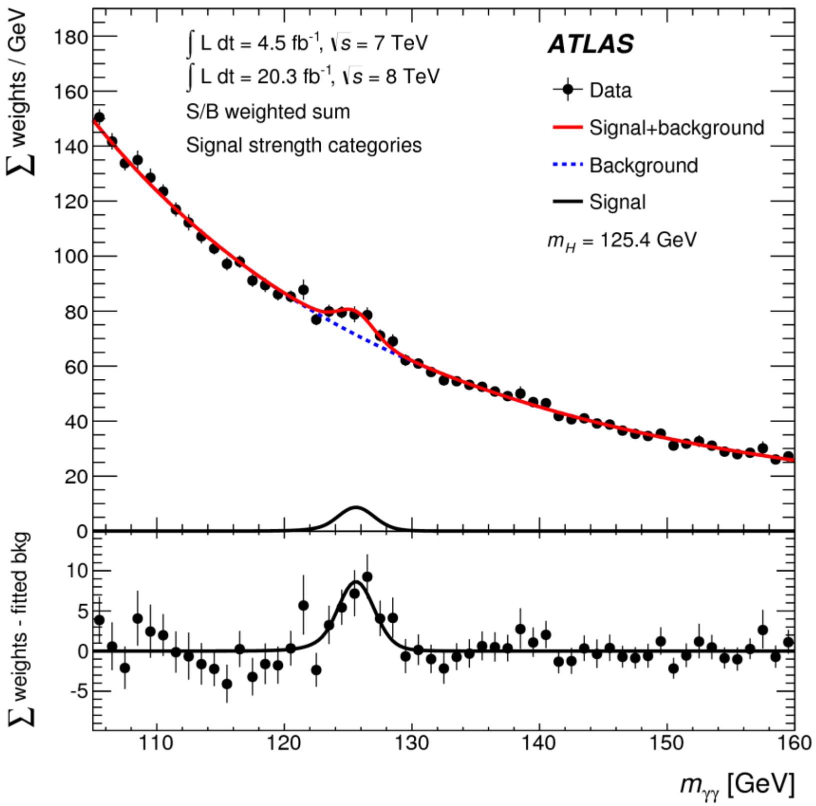
	Category	$\sqrt{s}$=7 TeV σ_{68} [GeV]	σ_{90} [GeV]
	Central - low p_{Tt}	1.36	2.32
Best	Central - high p_{Tt}	1.21	2.04
Worst	Forward - low p_{Tt}	1.69	3.03
	Forward - high p_{Tt}	1.48	2.59
	VBF loose	1.43	2.53
	VBF tight	1.37	2.39
	VH hadronic	1.35	2.32
	VH $E_{\mathrm{T}}^{\mathrm{miss}}$	1.41	2.44
	VH one-lepton	1.48	2.55
	VH dilepton	1.45	2.59
	$t\bar{t}H$ hadronic	1.39	2.37
	$t\bar{t}H$ leptonic	1.42	2.45

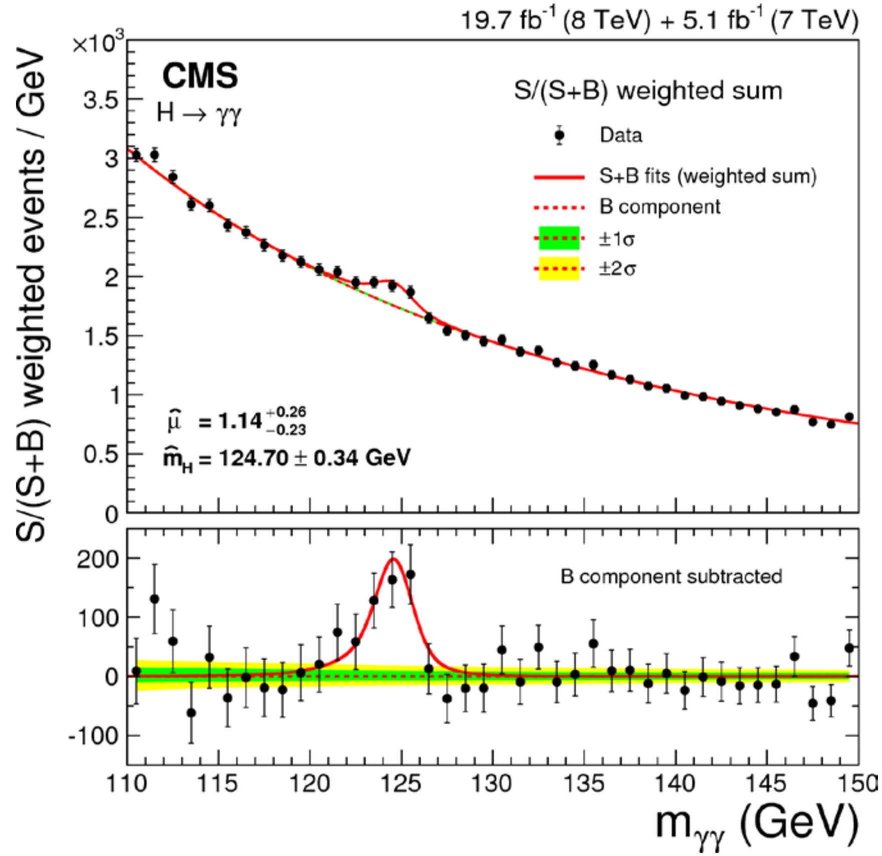
Typical resolution ~1.5 GeV



H→γγ Analysis

arXiv:1408.7084 (ATLAS)



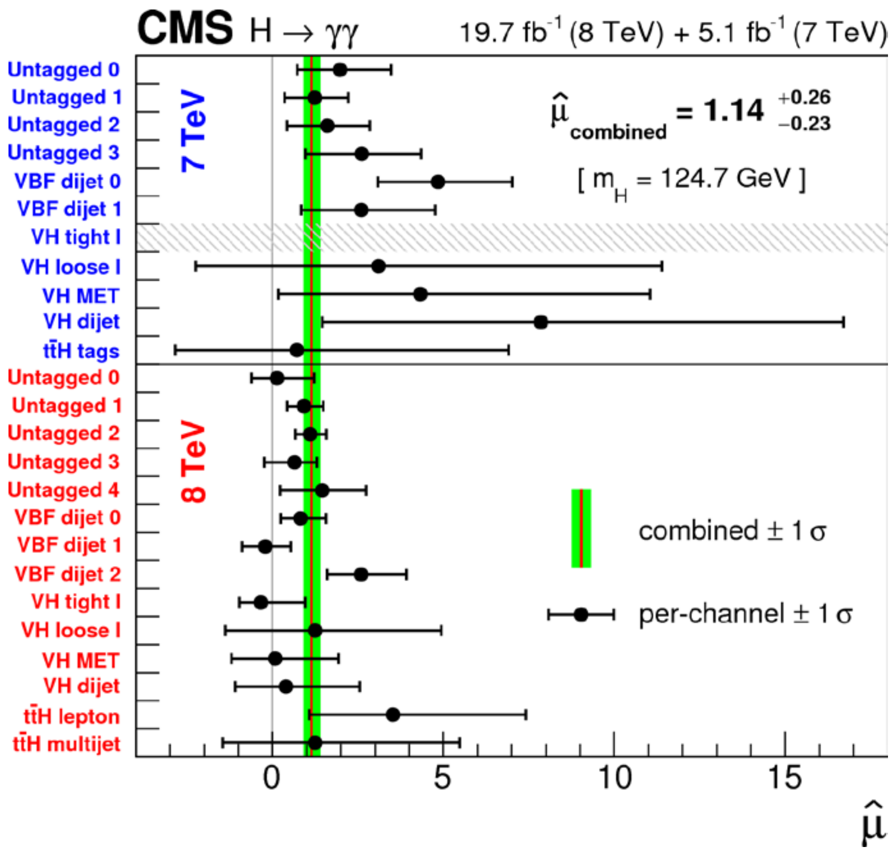


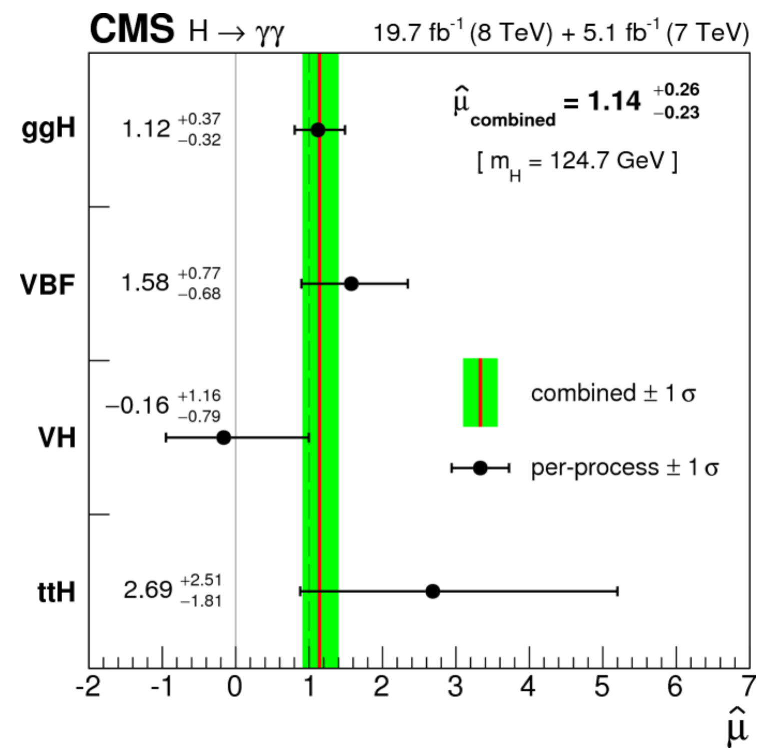
arXiv:14070558 (CMS)

	ATLAS	CMS
Peak mass	125.4 GeV	124.7 GeV
Significance (expected)	5.2σ (4.6σ)	5.7σ (5.2σ)
Signal strength	1.17 ± 0.27	$1.14^{+0.26}_{-0.23}$

H→γγ: Categories

arXiv:1407.0558 (CMS)

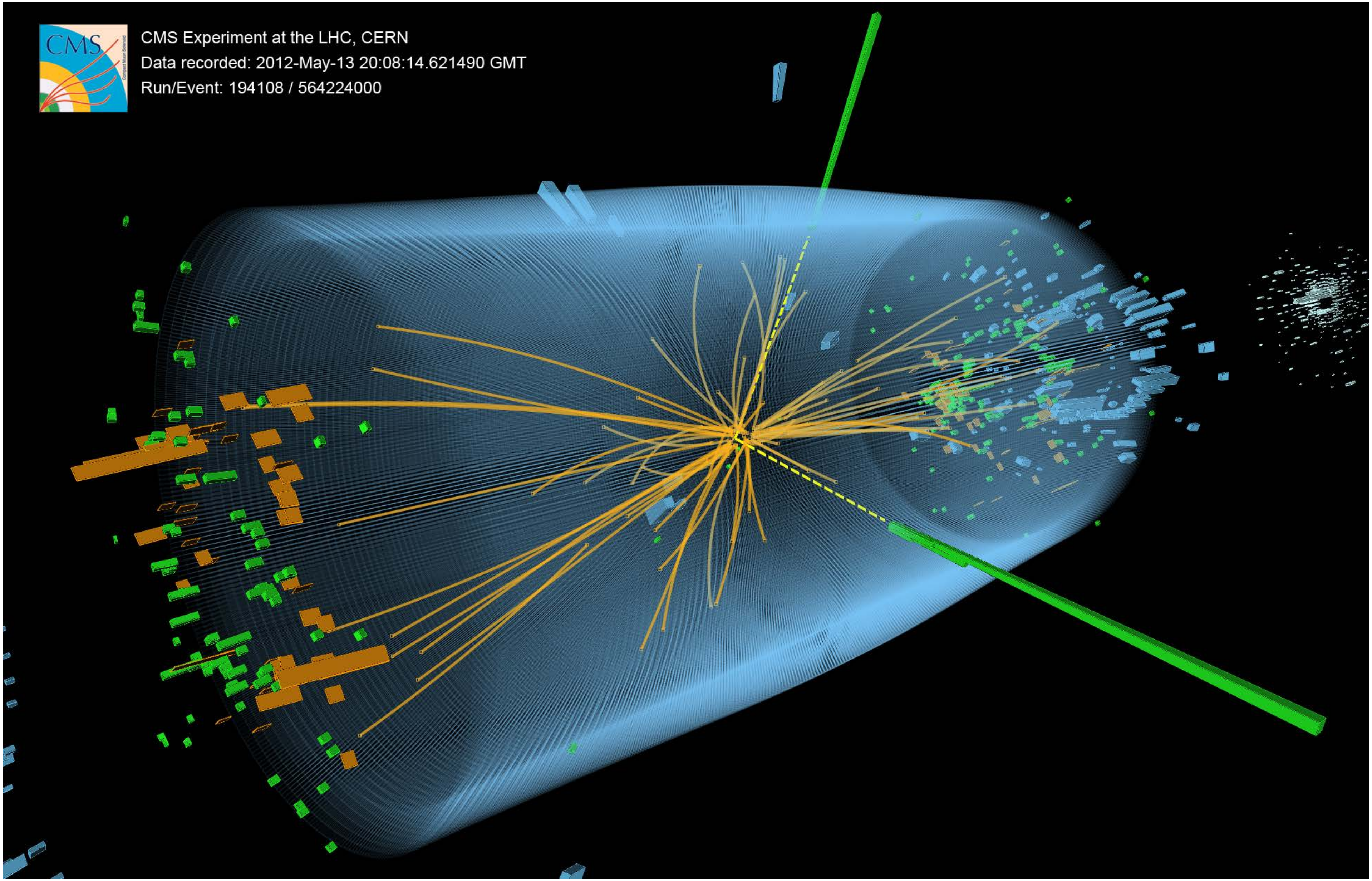




Enabling the signal strength measurements for different processes:

Electroweak (Yukawa coupling)

vs strong (“Gauge” coupling) productions


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

H→ZZ*→4ℓ Analysis

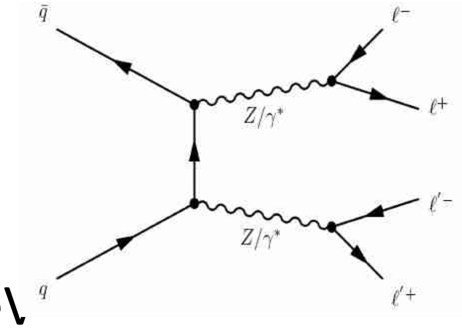
The gold-plated channel over a wide range of potential Higgs mass.

Clean signature:

- 4 isolated leptons, full reconstruction;
- Mass peak over backgrounds, good mass resolution.

Small backgrounds:

Irreducible SM ZZ* production
and reducible Z+jets, top, …



$\ell = e, \mu$

But even smaller signal rate @125 GeV

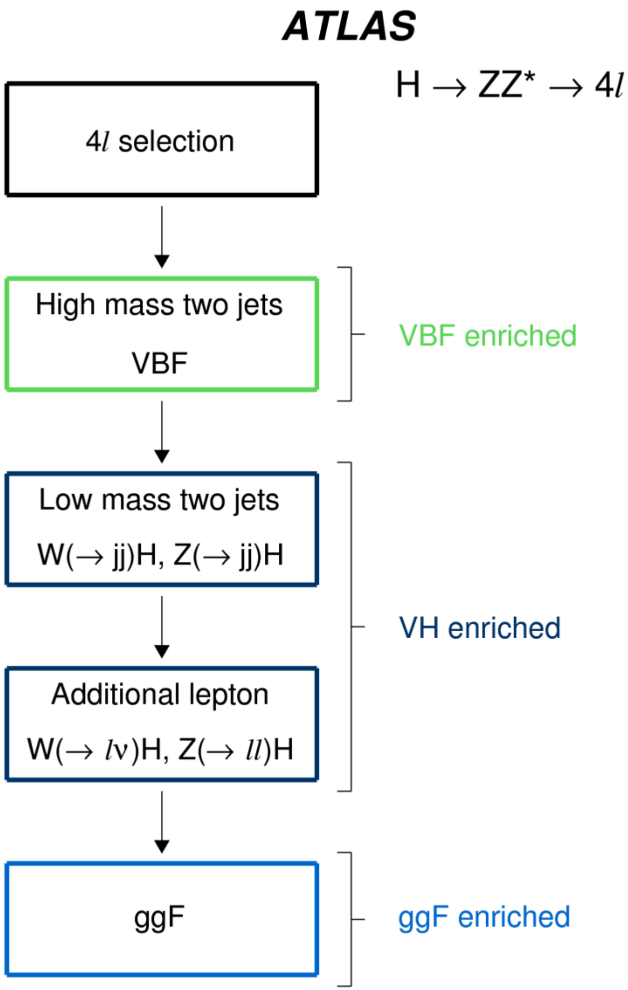
$$\sigma(H)\times BR\left(H \rightarrow ZZ^* \rightarrow 4\ell\right) \sim 2.7 \text{ fb @ 125 GeV}$$

⇒ ~25 events in 2011+2012 samples

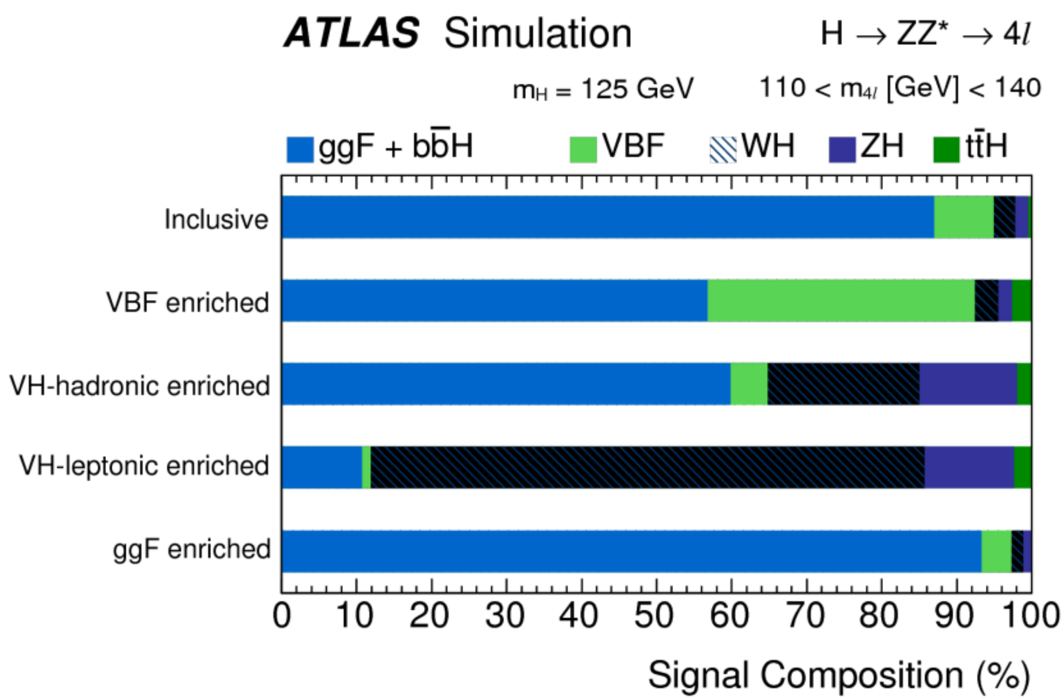
Selection efficiency to the 4th power of lepton efficiency:

$0.7^4 \sim 0.25$, $0.8^4 \sim 0.41$ ⇒ critical to improve lepton selection!

H→ZZ*→4ℓ Analysis



Signal compositions
in each category

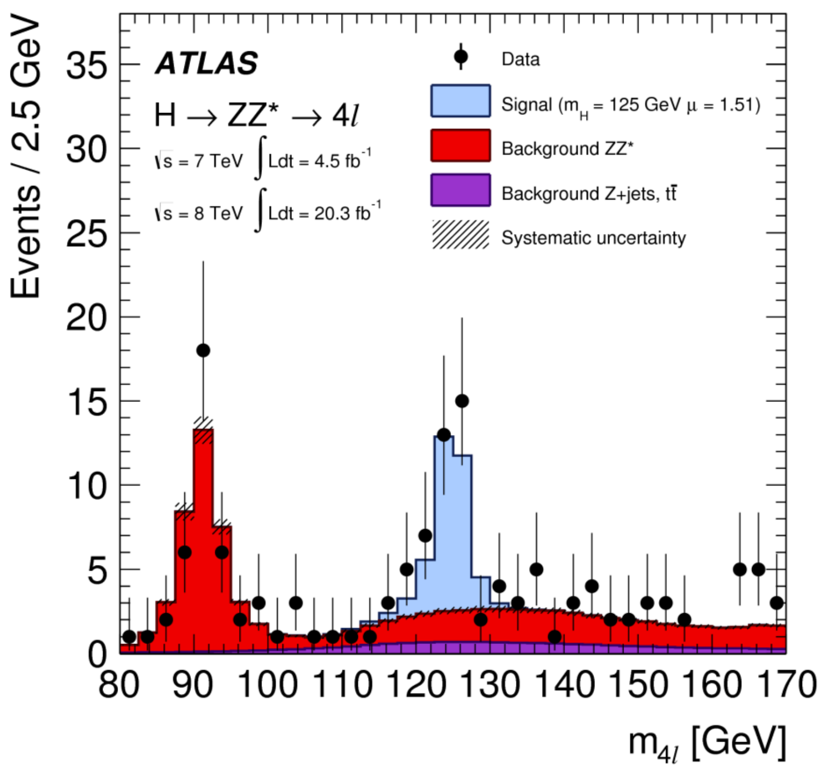


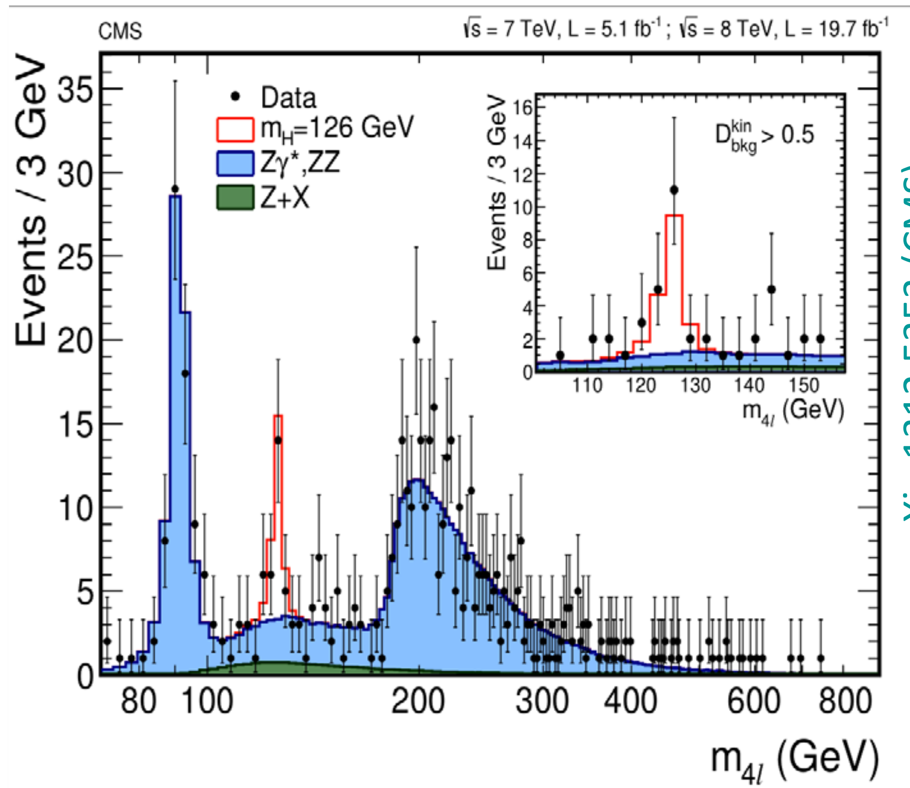
H→ZZ*→4ℓ Analysis

A narrow resonance over small background from mainly irreducible SM ZZ contribution:

	ATLAS	CMS
Peak mass	124.4 GeV	125.6 GeV
Excess significance	8.1σ (6.2σ)	6.8σ (6.7σ)
Signal strength	$1.44^{+0.40}_{-0.33}$	0.93 ± 0.27

arXiv:1408.5191 (ATLAS)





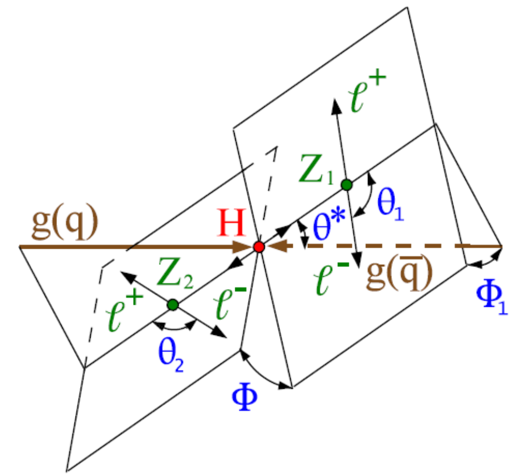
arXiv:1312.5353 (CMS)

H→ZZ*→4ℓ: Kinematics Exploration

Compared with $H \to \gamma\gamma$, more complicated kinematics for 4ℓ final states $\Rightarrow$ advanced techniques can improve sensitivity significantly:

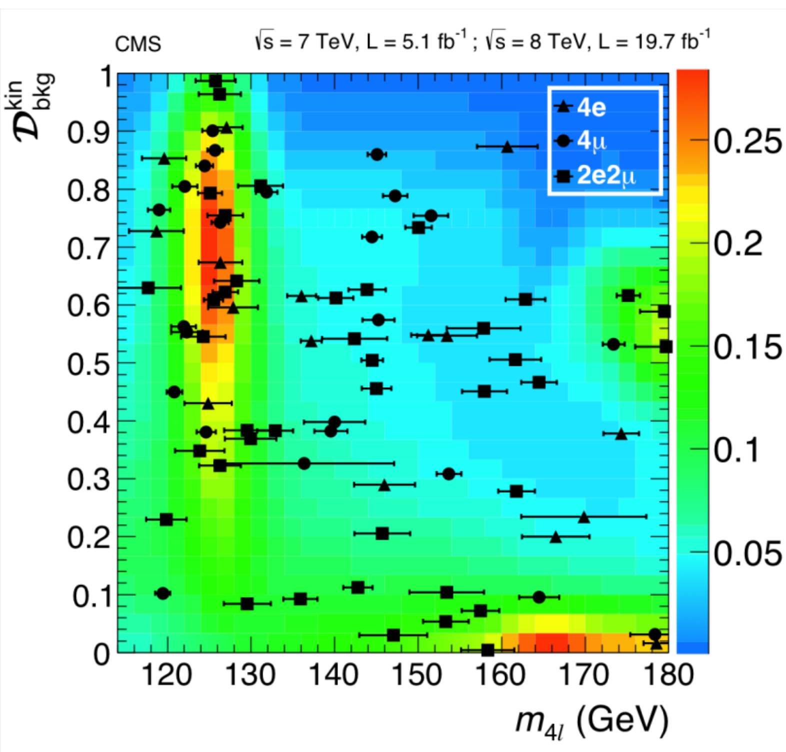
ATLAS: Boosted Decision Tree

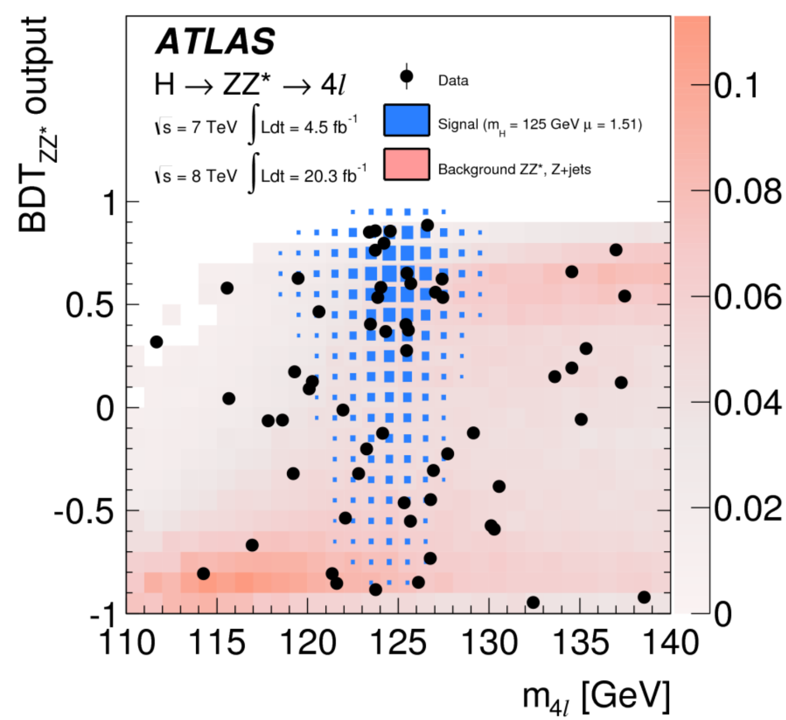
CMS: Matrix-Element based discriminant



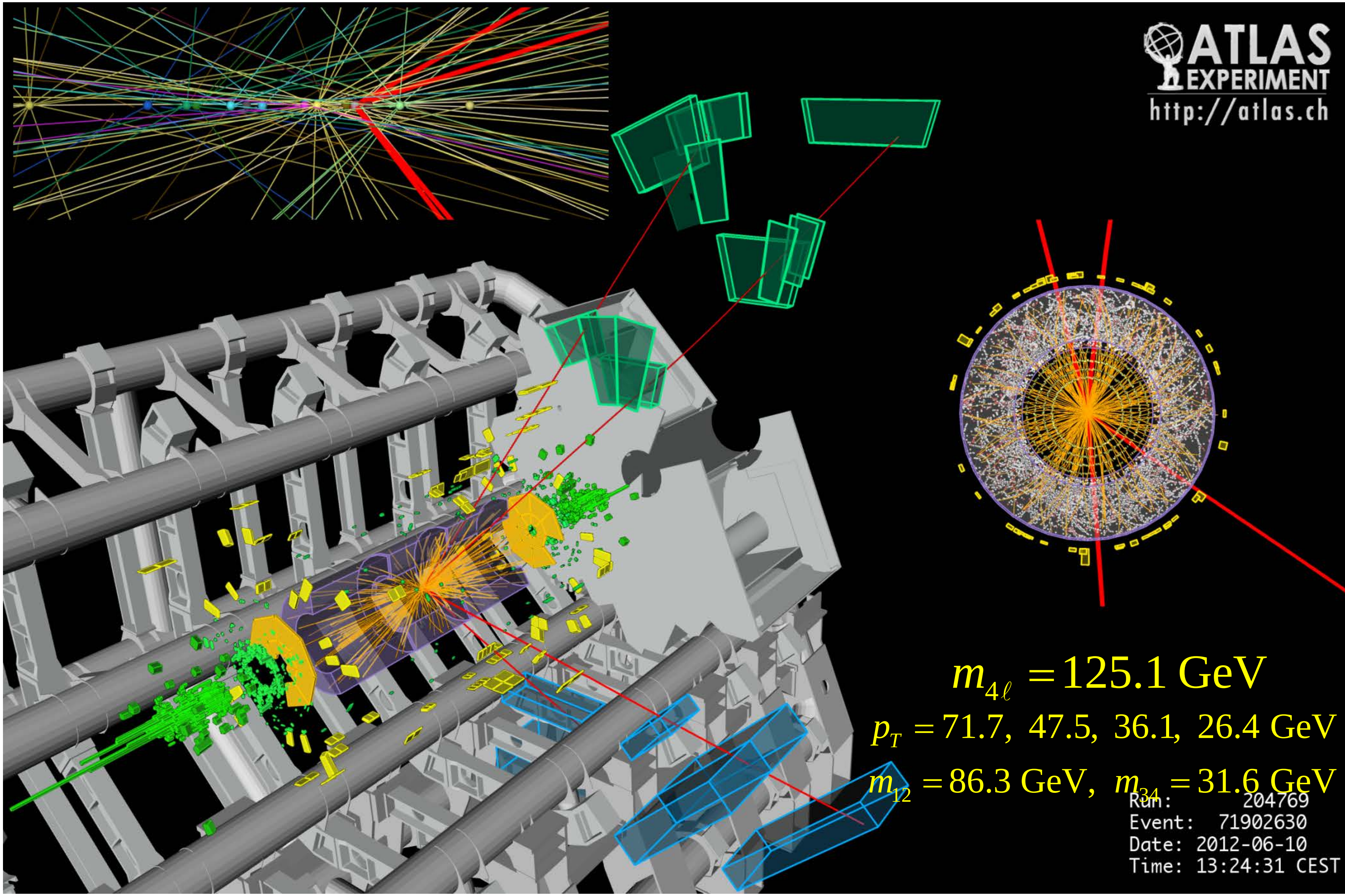
$$\mathcal{D}_{\rm bkg}^{\rm kin} = \frac{\mathcal{P}_{0^+}^{\rm kin}}{\mathcal{P}_{0^+}^{\rm kin} + \mathcal{P}_{\rm bkg}^{\rm kin}} = \left[1 + \frac{\mathcal{P}_{\rm bkg}^{\rm kin}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{0^+}^{\rm kin}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

arXiv:1312.5353 (CMS)





arXiv:1408.5191 (ATLAS)

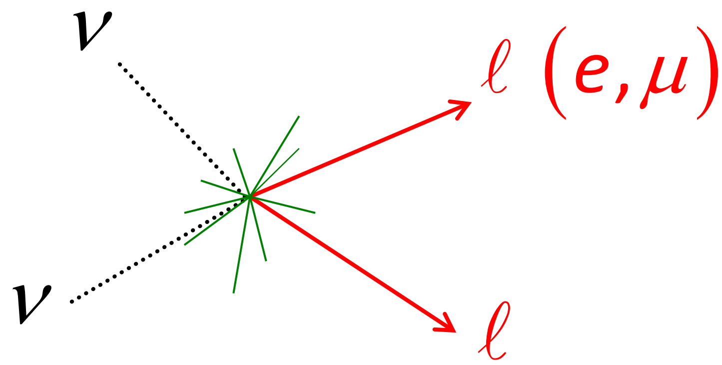


$m_{4\ell} = 125.1$ GeV

$p_T = 71.7,\ 47.5,\ 36.1,\ 26.4$ GeV

$m_{12} = 86.3$ GeV, $m_{34} = 31.6$ GeV

$H \to WW^* \to \ell\nu\ell\nu$ Analysis



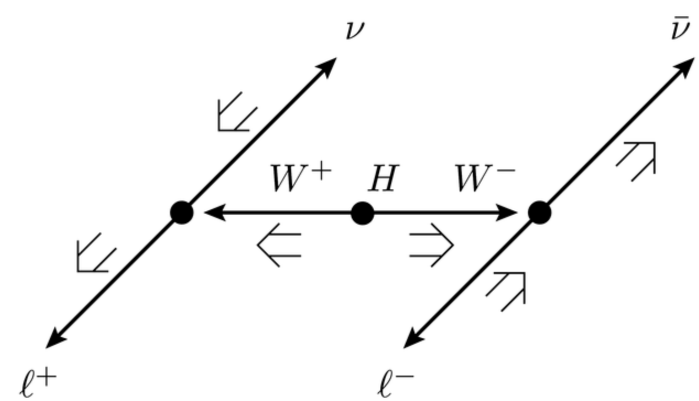
$\sigma(H) \times BR(H \to WW^* \to \ell\nu\ell'\nu) \sim 224$ fb
@ 125 GeV, 8 TeV

$\Rightarrow$ ~2300 events in 2011+2012 samples

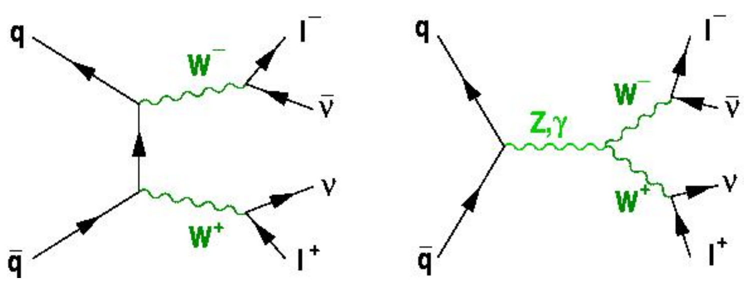
Main background:

WW, $t\bar{t}$, W/Z+jets, WZ/ZZ/Wγ,...

WW from the scalar Higgs is expected to have different kinematics

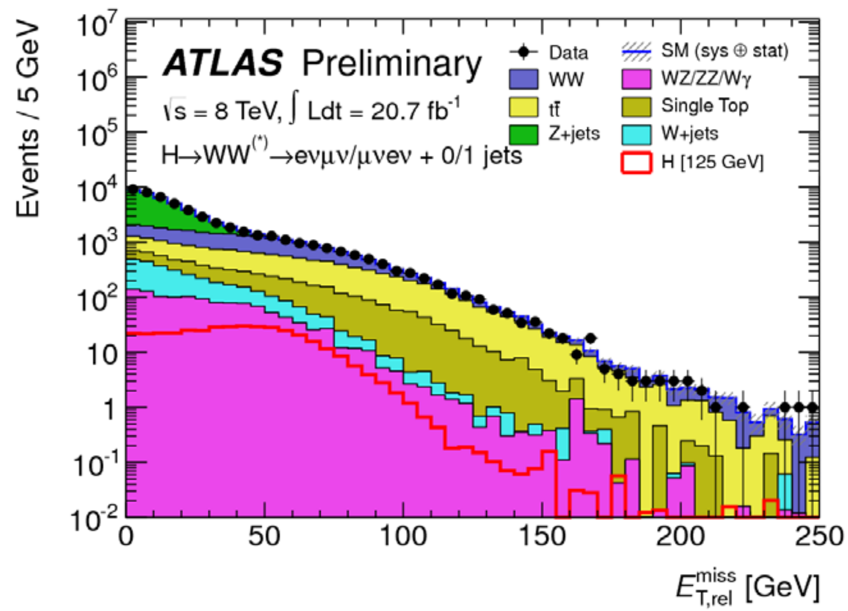


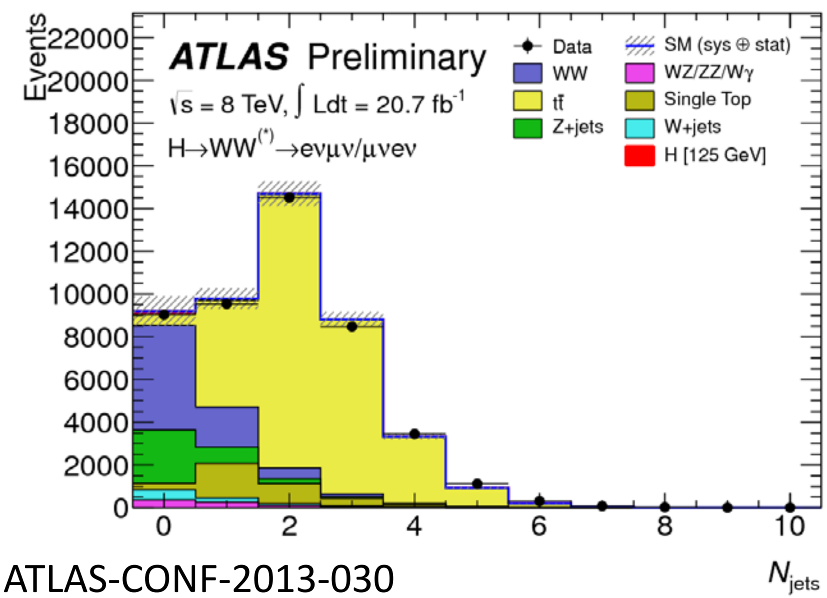
The SM WW is “irreducible”



The spin correlation leads to a smaller average opening angle between the two leptons

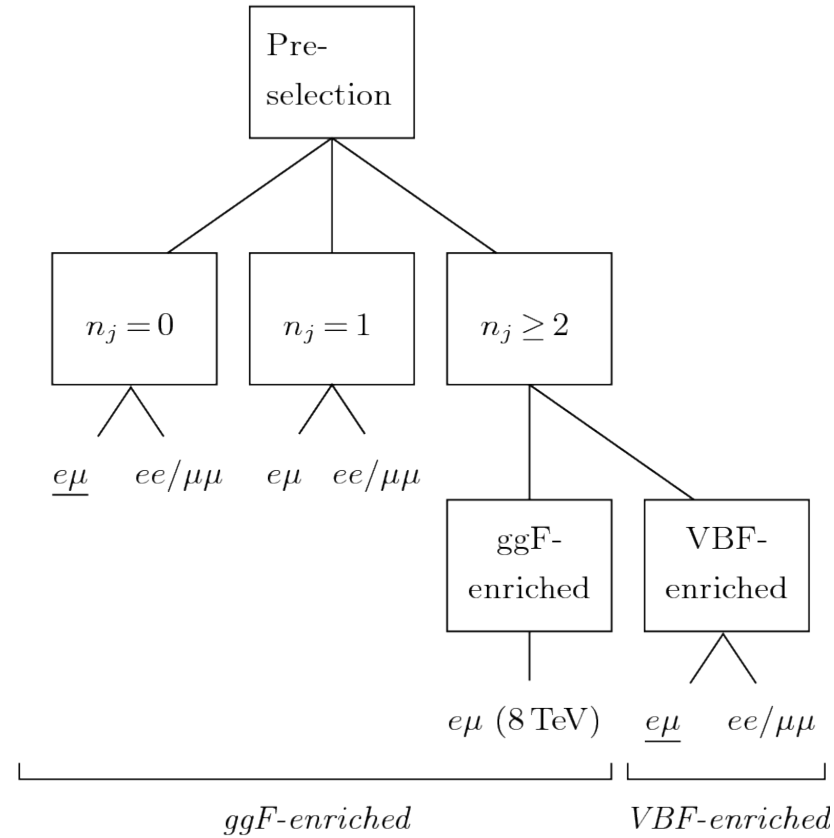
H→WW*→ℓνℓν Analysis





ATLAS-CONF-2013-030

The background is strongly dependent on the jet activity and lepton flavors
⇒ dividing analyses into jet bins and lepton flavors

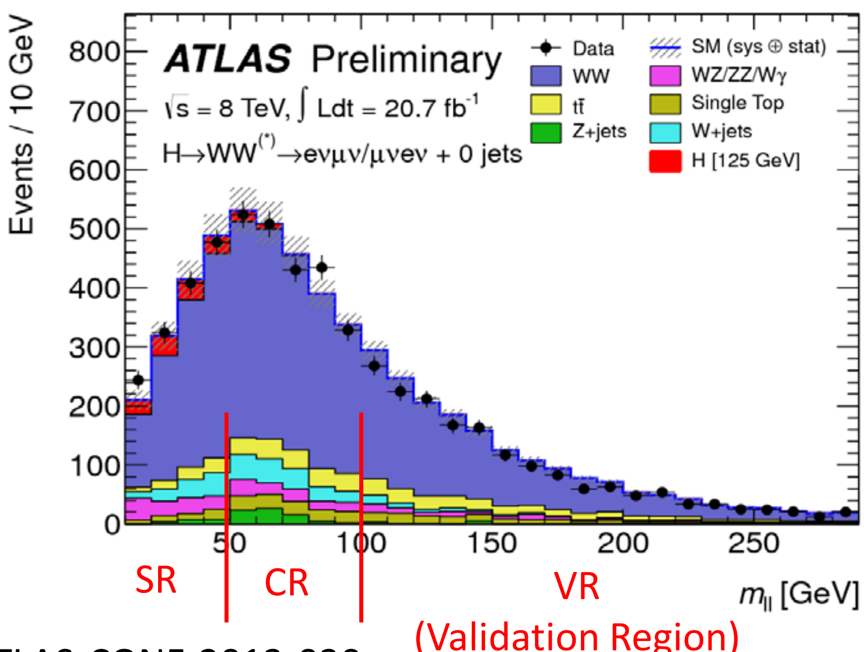


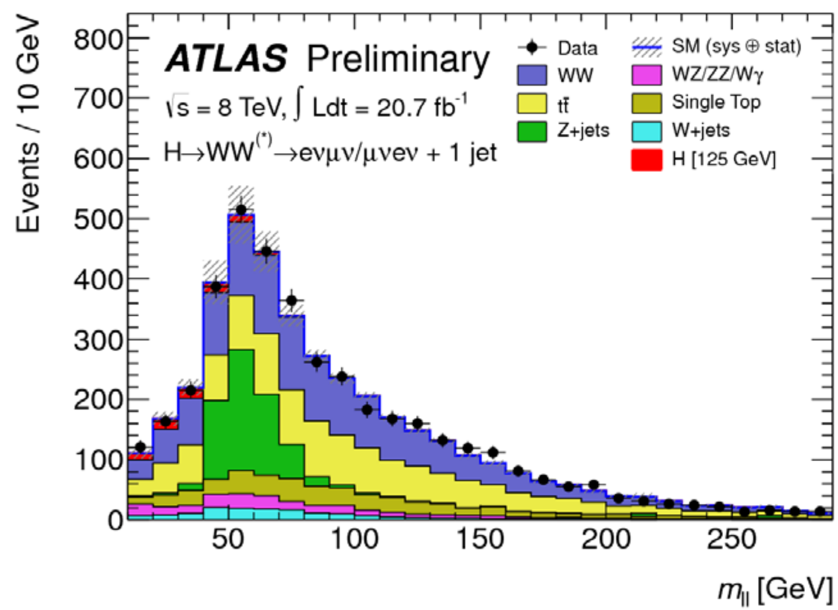
arXiv: 1412.2641

H→WW*→ℓνℓν Analysis

Most of the signal is in the 0-jet bin where the SM WW is the largest background. Control region (CR) is used to normalize the WW background in the signal region (SR):

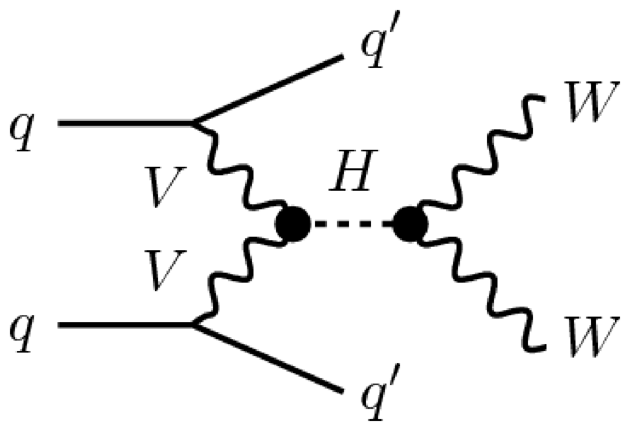
$$N_{Data}^{SR} = \left(\frac{N^{SR}}{N^{CR}}\right)_{MC} \times N_{Data}^{CR} = \left(\frac{N_{Data}}{N_{MC}}\right)_{CR} \times N_{MC}^{SR} = \boxed{R_{NF}} \times N_{MC}^{SR}$$





ATLAS-CONF-2013-030

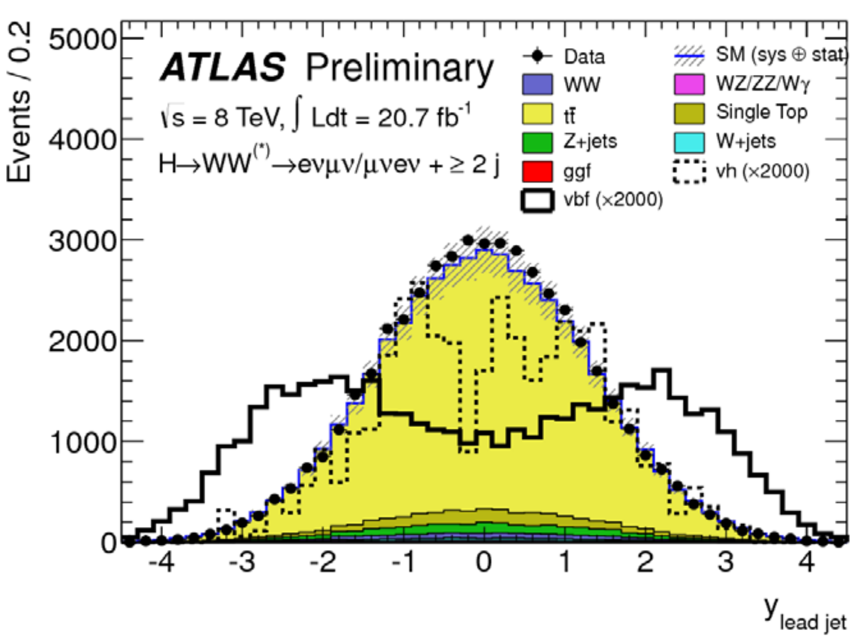
H→WW*→ℓνℓν VBF Analysis

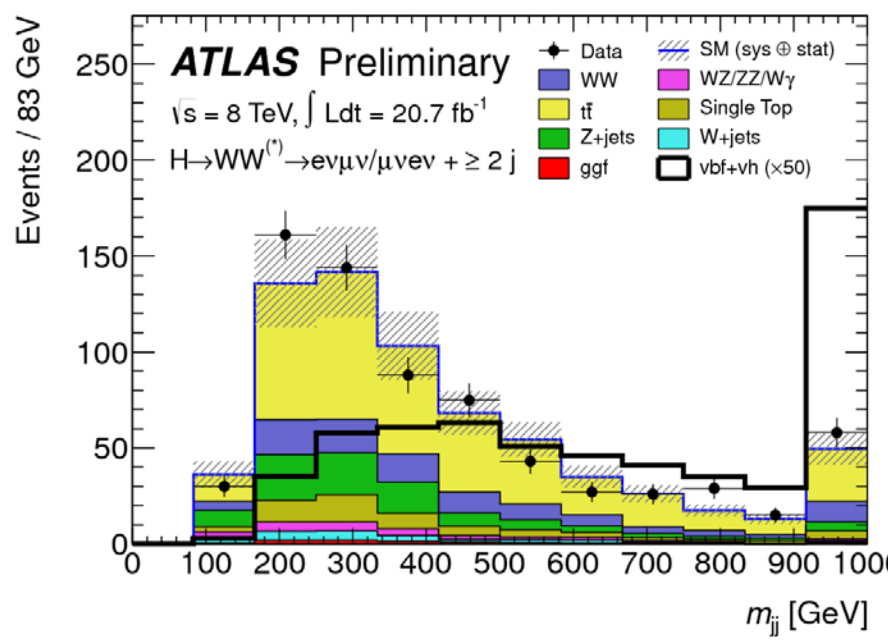


Two tagging jets in addition to the Higgs candidate:

- large dijet mass;
- wide separation in rapidity

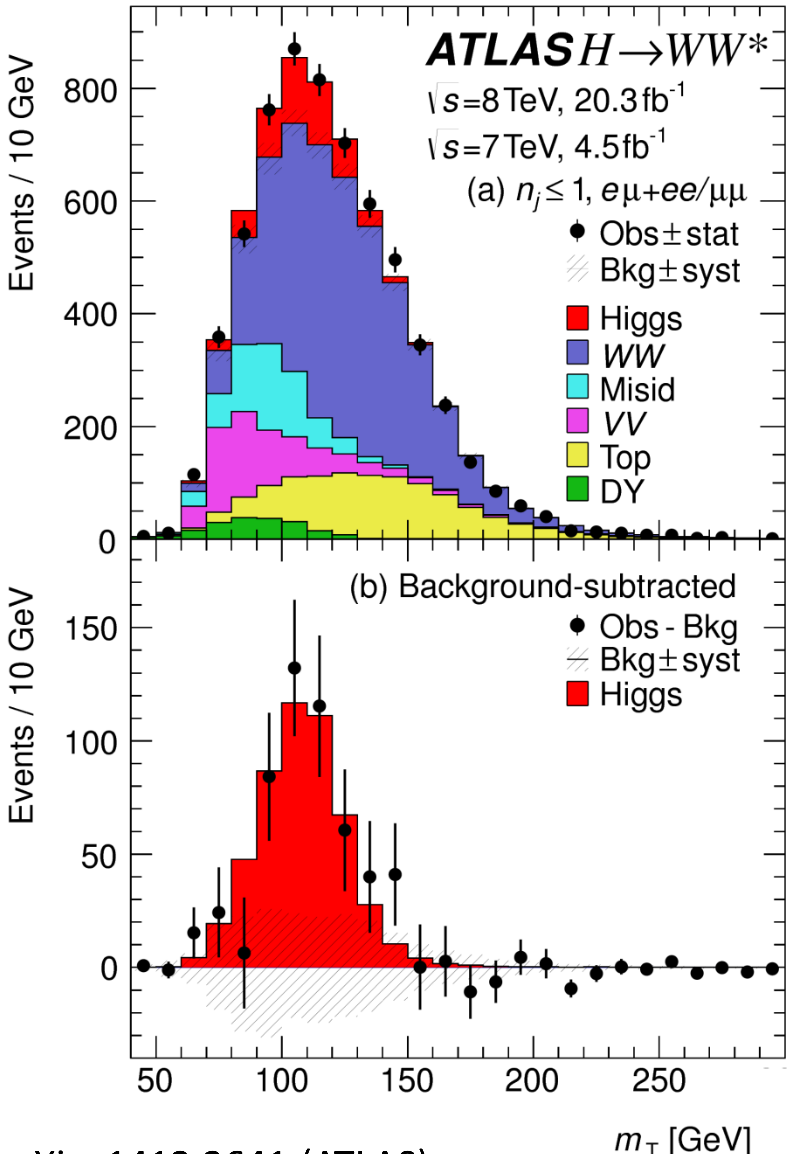
b-jet veto to reduce the dominant top background.





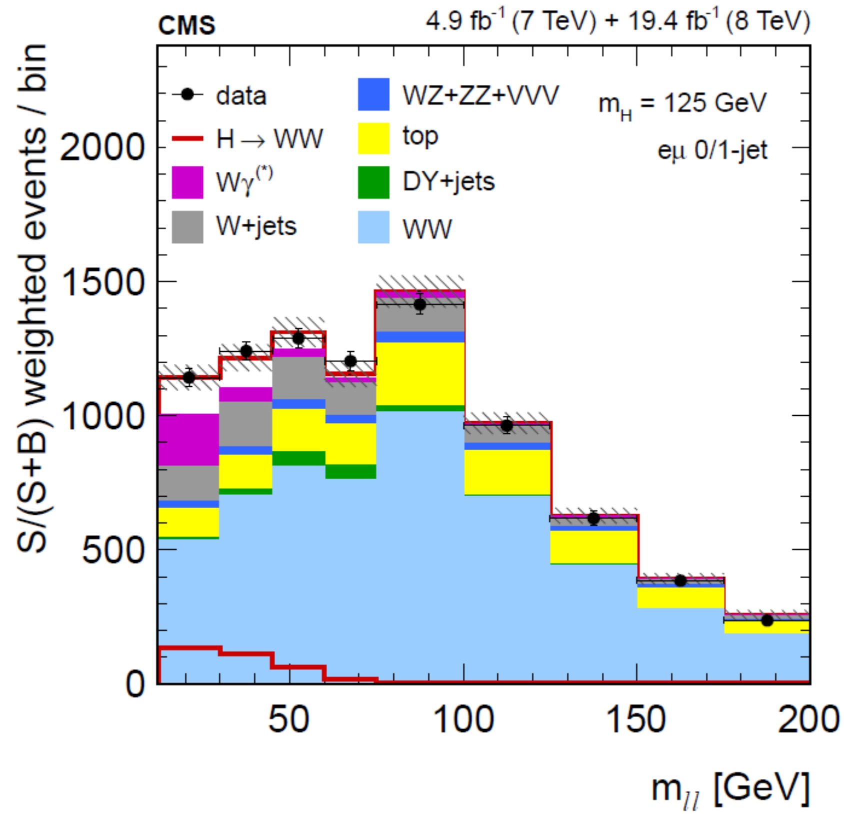
arXiv: 1412.2641

H→WW*→ℓνℓν Analysis

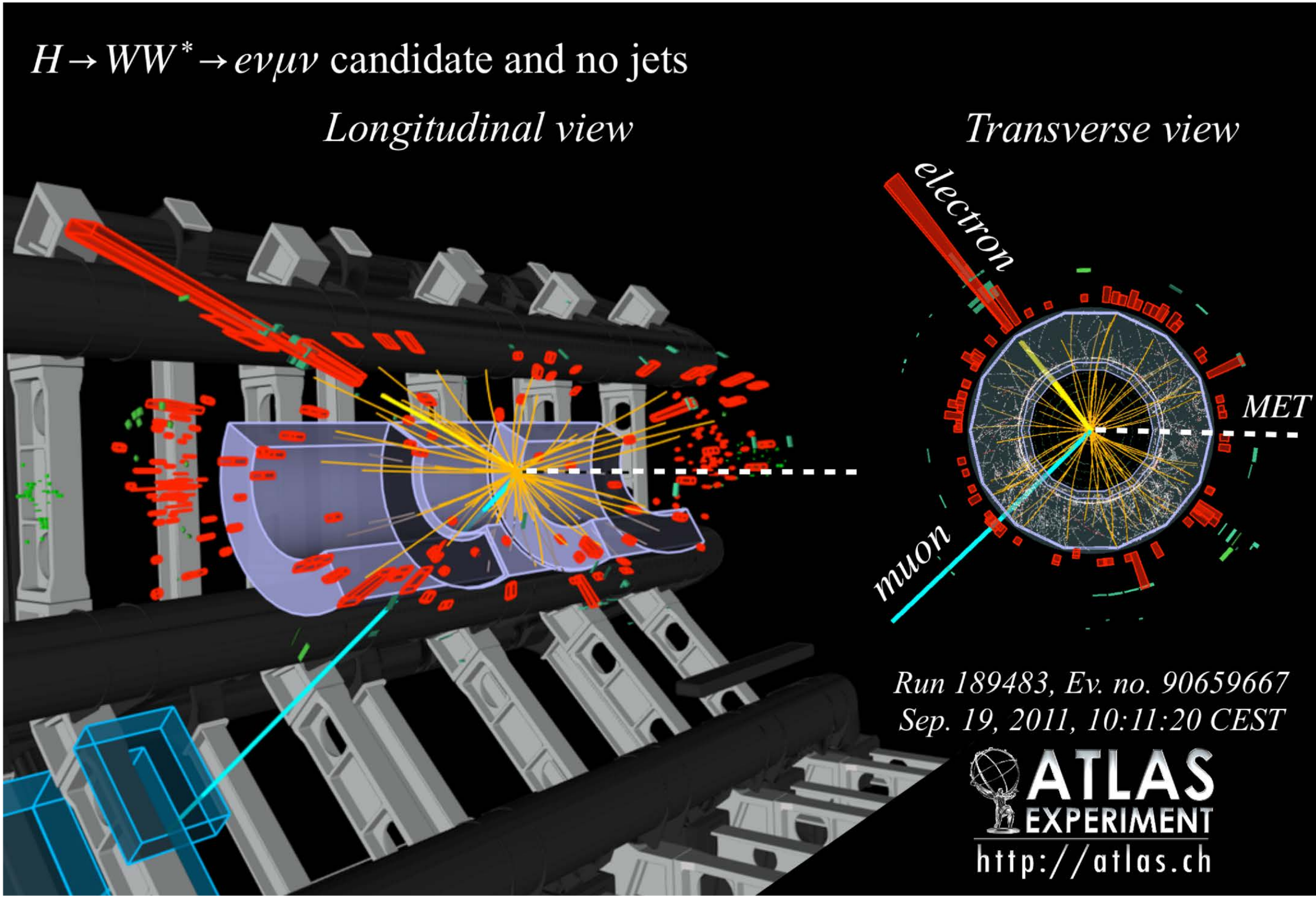


arXiv: 1412.2641 (ATLAS)

	ATLAS	CMS
@ mass	125.4 GeV	125.6 GeV
Excess significance	6.5σ (5.9σ)	4.3σ (5.8σ)
Signal strength	$1.16^{+0.24}_{-0.21}$	$0.72^{+0.20}_{-0.18}$



arXiv:1312.1129 (CMS)


$H \rightarrow WW^{*} \rightarrow e\nu\mu\nu$ candidate and no jets
Longitudinal view
Transverse view
electron
MET
muon
Run 189483, Ev. no. 90659667
Sep. 19, 2011, 10:11:20 CEST
ATLAS
EXPERIMENT
http://atlas.ch

H→ττ

$\sigma(H)\times BR(H\rightarrow\tau\tau)\sim$ 1.4 pb @ 125 GeV

An important search channel at low mass, likely the only final state for Higgs-lepton coupling measurements upon discovery.

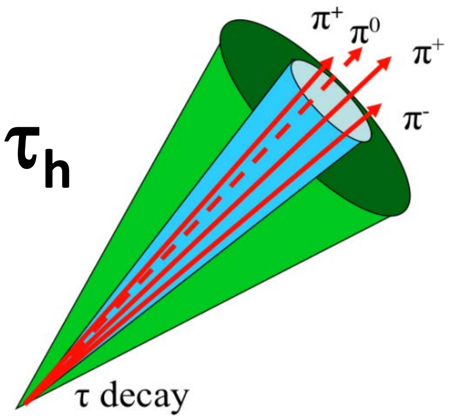
Three search final states depending on tau decays:

$$H\rightarrow\tau\tau\rightarrow\ell\ell+4\nu\ (12\%)$$
$$H\rightarrow\tau\tau\rightarrow\ell\tau_h+3\nu\ (46\%)$$
$$H\rightarrow\tau\tau\rightarrow\tau_h\tau_h+2\nu\ (42\%)$$

Hadronic tau identification:

One or three charged tracks;
Collimated calorimeter energy deposits;
Large leading track momentum

τ_h



Major backgrounds:

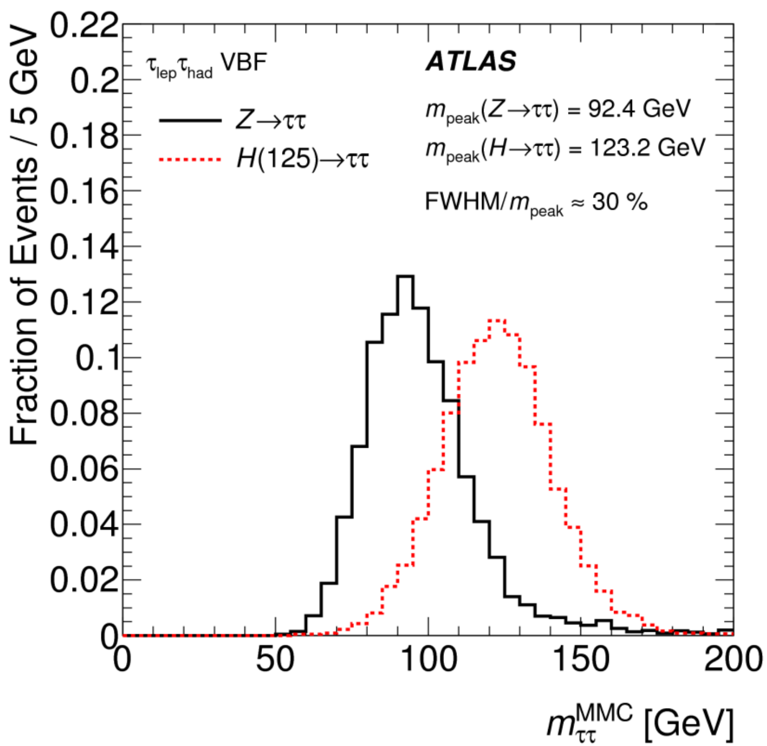
Z(→ττ)+jets, estimated using embedding method
Multijets, estimated using same-sign events.

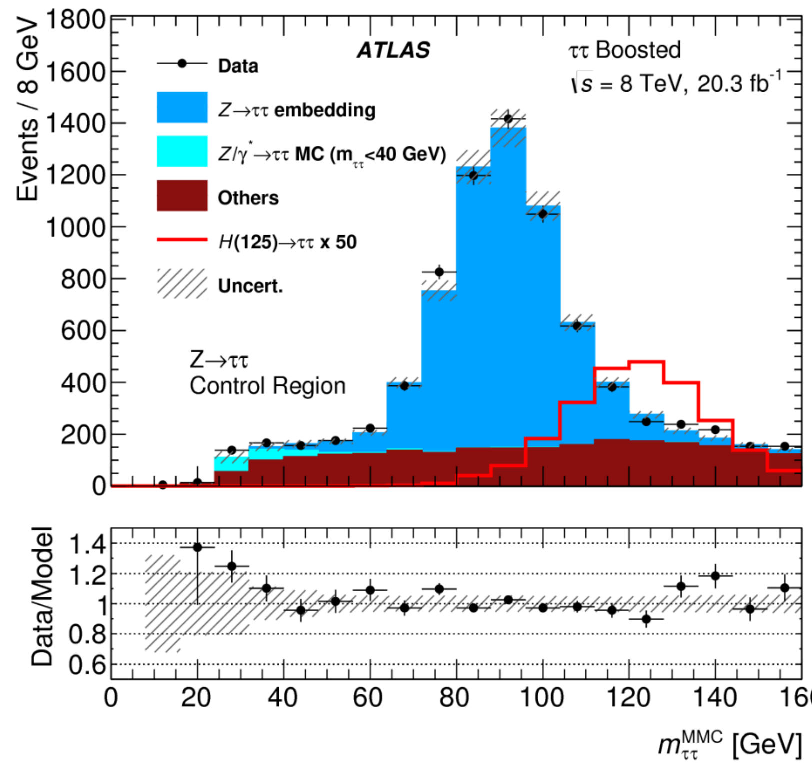
H→ττ Analysis: ditau Mass

Ditau mass reconstruction using the Missing Mass Calculator:

- Solving the unconstrained system by assuming neutrinos are in the direction of the visible tau decay products;
- Weight solutions based on Etmiss resolution and decay topologies;
- Return the most probably ditau mass value

Typical $\tau\tau$ mass resolution $\sim$15%.



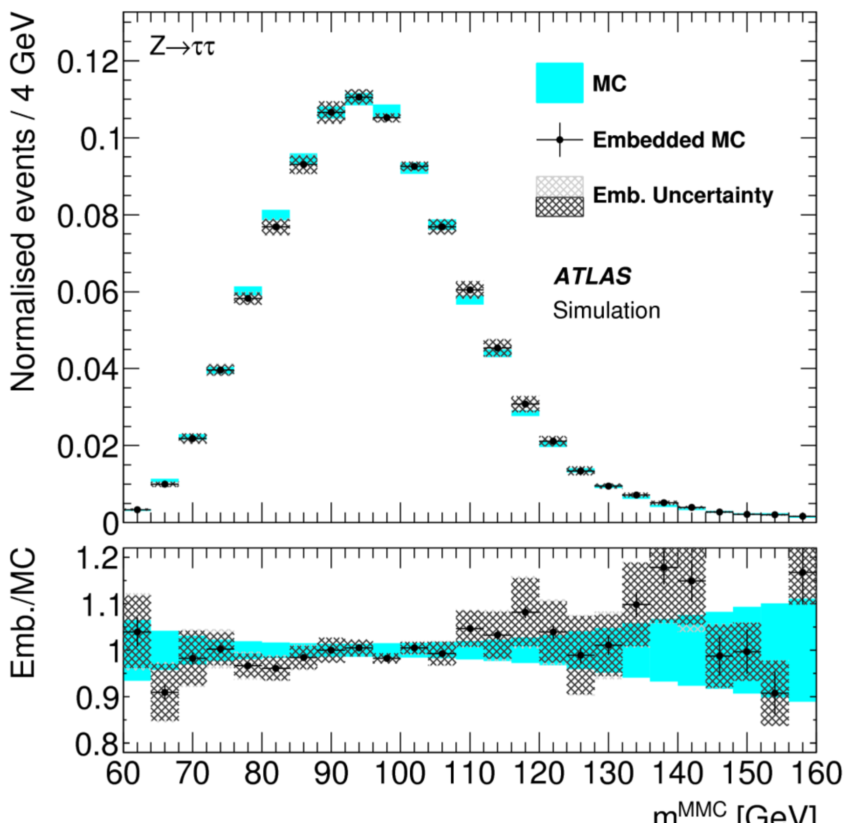


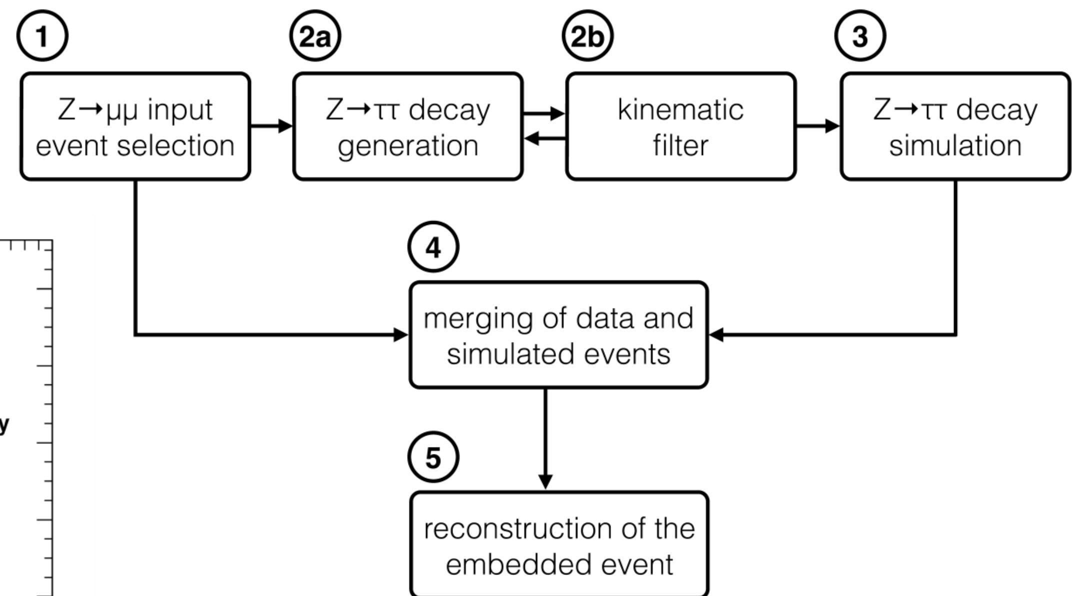
H→ττ Analysis: Embedding

Simulating Z→ττ background using data through embedding:

- Select Z→μμ events in the data
- Replace the two muons with simulated taus

arXiv: 1506.05623



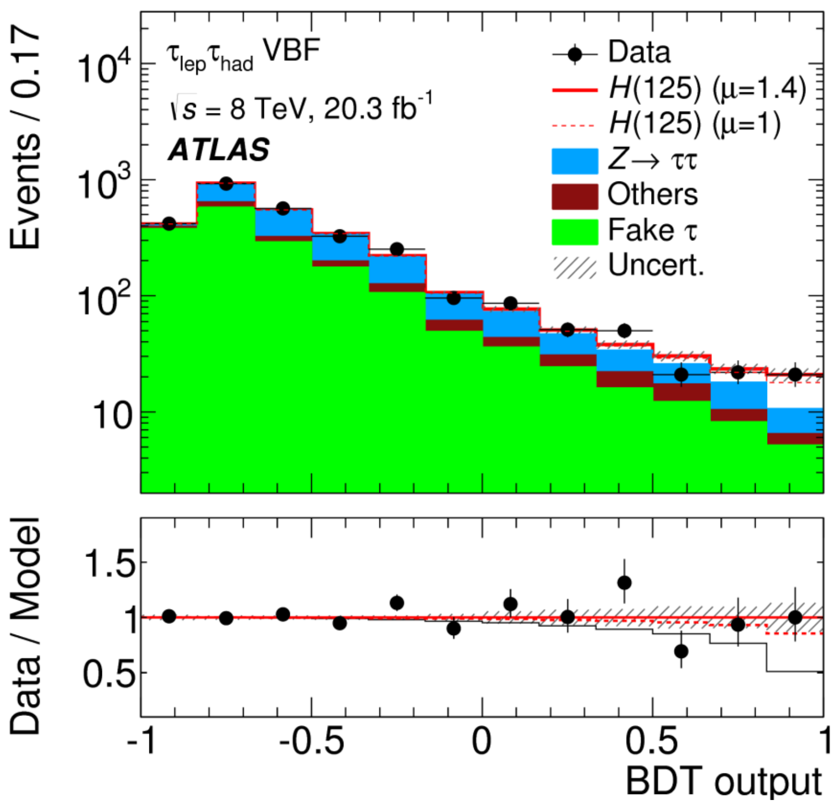


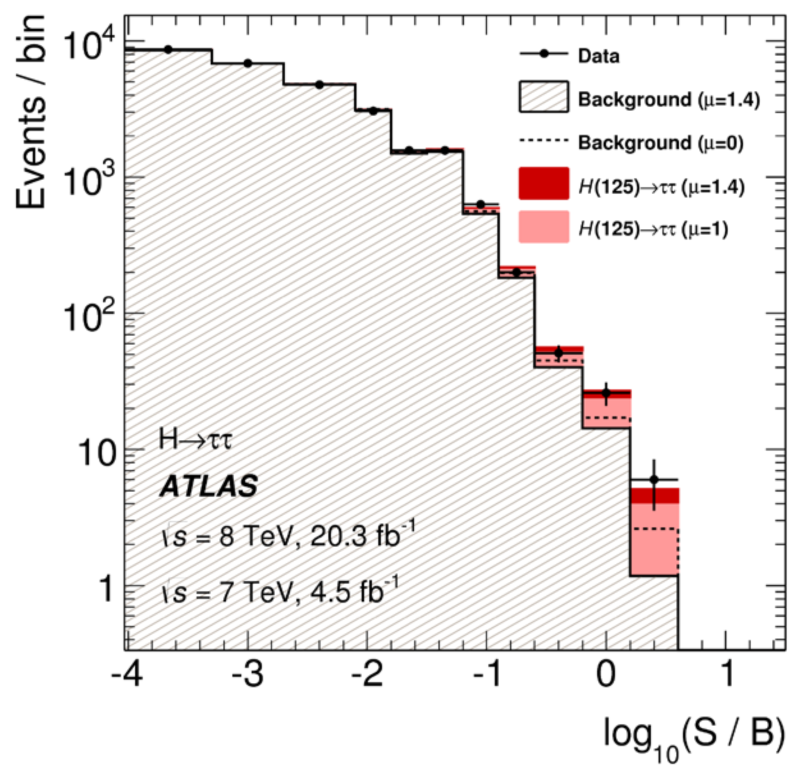
Pileup, underlying events and noise effects are from data.

H→ττ Analysis

Large rate, but also large backgrounds, trigger and reconstruction are challenging.

Two major categories: VBF and boosted ggF. Using MVA after basic event selection to enhance signal-background separation.

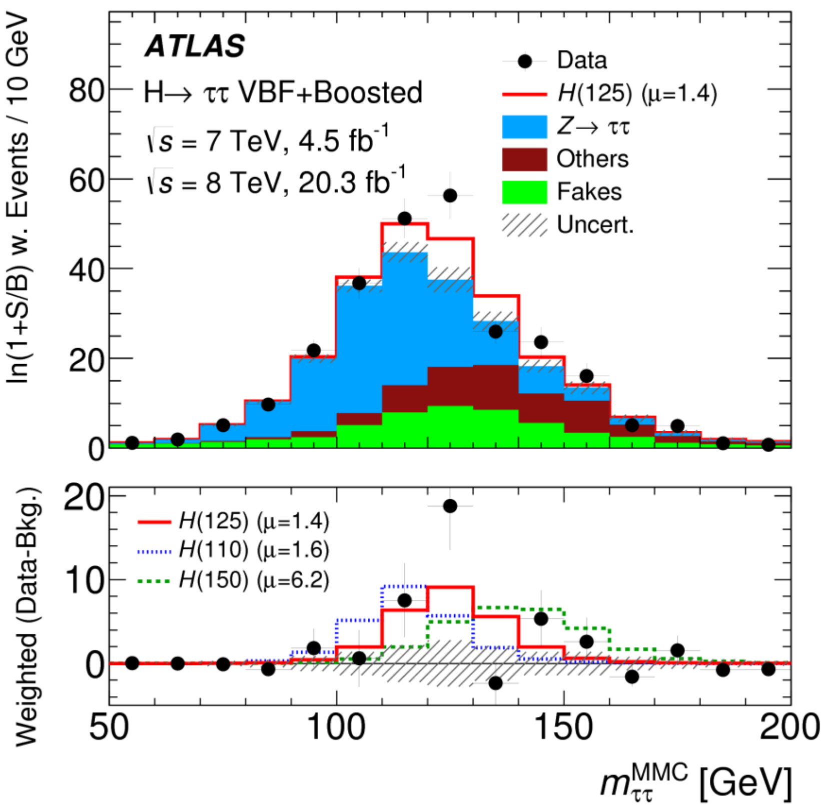




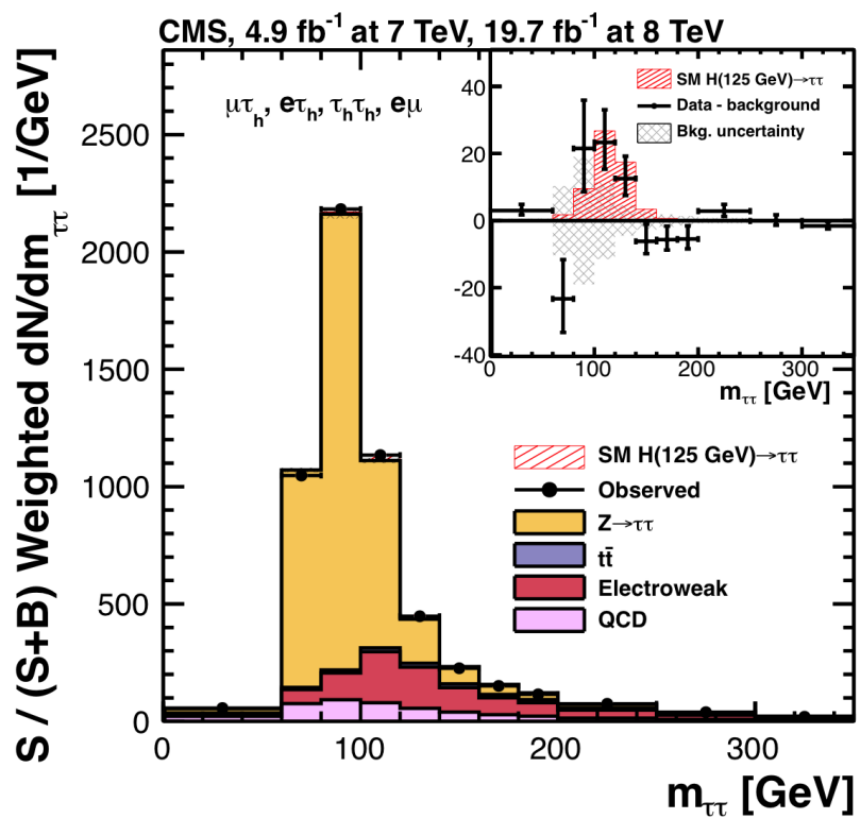
arXiv:1501.04943 (ATLAS)

H→ττ Analysis

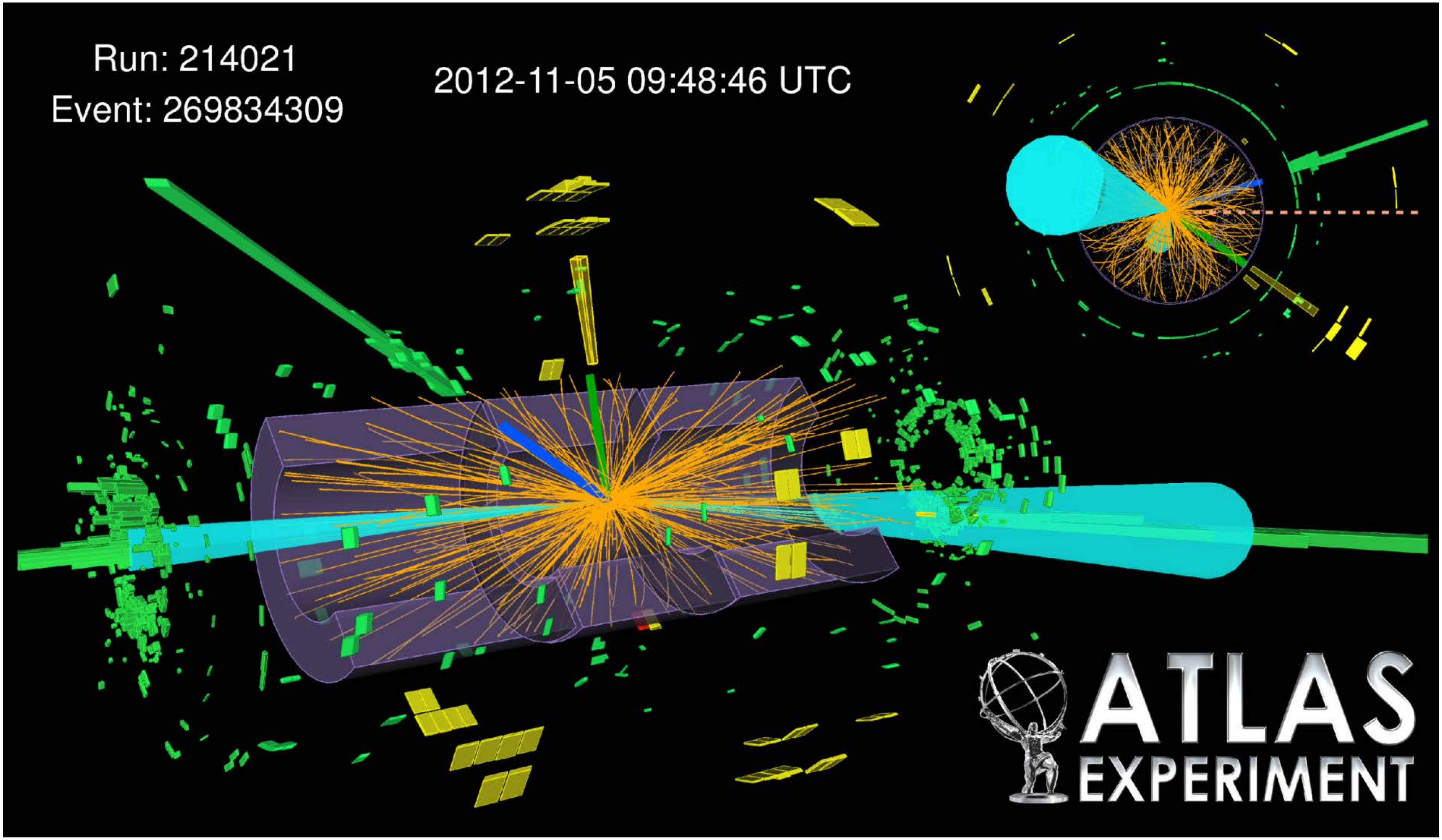
	ATLAS	CMS
@ mass	125.4 GeV	125 GeV
Significance	4.5σ (3.4σ)	3.4σ (3.6σ)
Signal strength	$1.43^{+0.43}_{-0.37}$	0.78 ± 0.27



arXiv:1501.04943 (ATLAS)



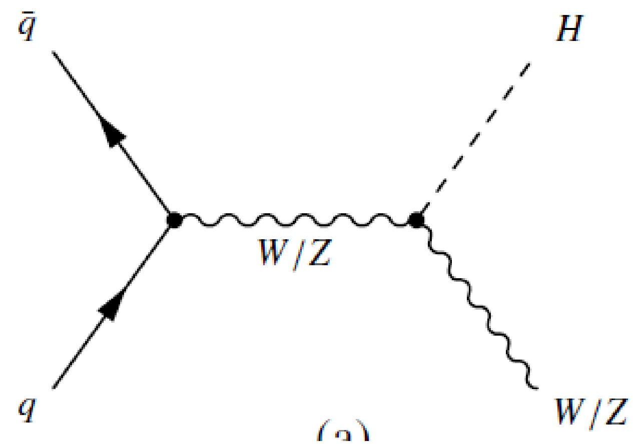
arXiv:1401.5041 (CMS)


Run: 214021
Event: 269834309
2012-11-05 09:48:46 UTC
ATLAS
EXPERIMENT

VH with H→bb

$H \to b\bar{b}$ has an even higher rate ($\times$10) than $H \to \tau\tau$, but with no leptons, photons, nor missing ET from the Higgs decays

$\Rightarrow$ has to rely on associated objects such as V $(W$ or Z$)$ in the VH production.



Three final states:

0-lepton: $\nu\nu b\bar{b}$ (ZH);

1-lepton: $\ell\nu b\bar{b}$ (WH);

2-leptons: $\ell\ell b\bar{b}$ (ZH)

$\sigma(VH) \times BR(H \to b\bar{b}) \sim 0.57$ pb @ 125 GeV, 8 TeV

Main backgrounds are V+jets and top production. Split the analyses further according to p_T^V, number of jets and b-tagging information

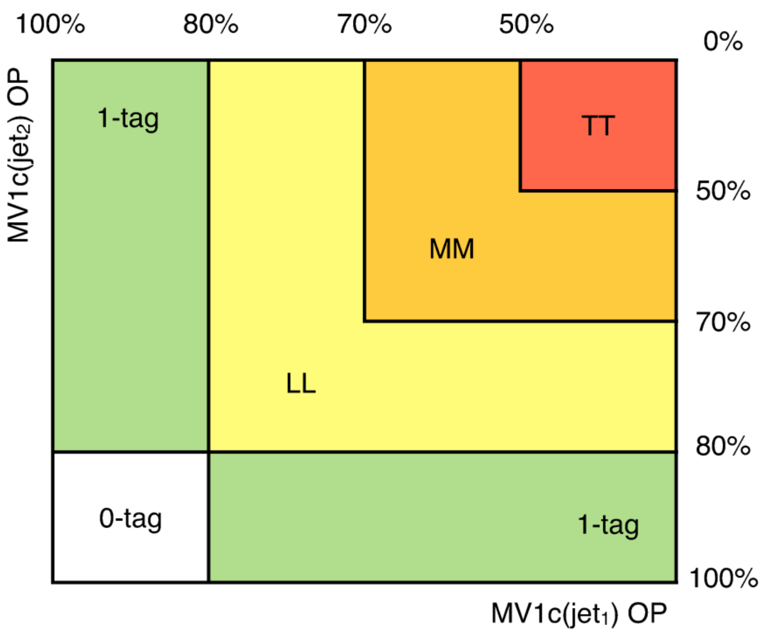
VH with H→bb

Full H→bb reconstruction, but poor mass resolution (10-15%),

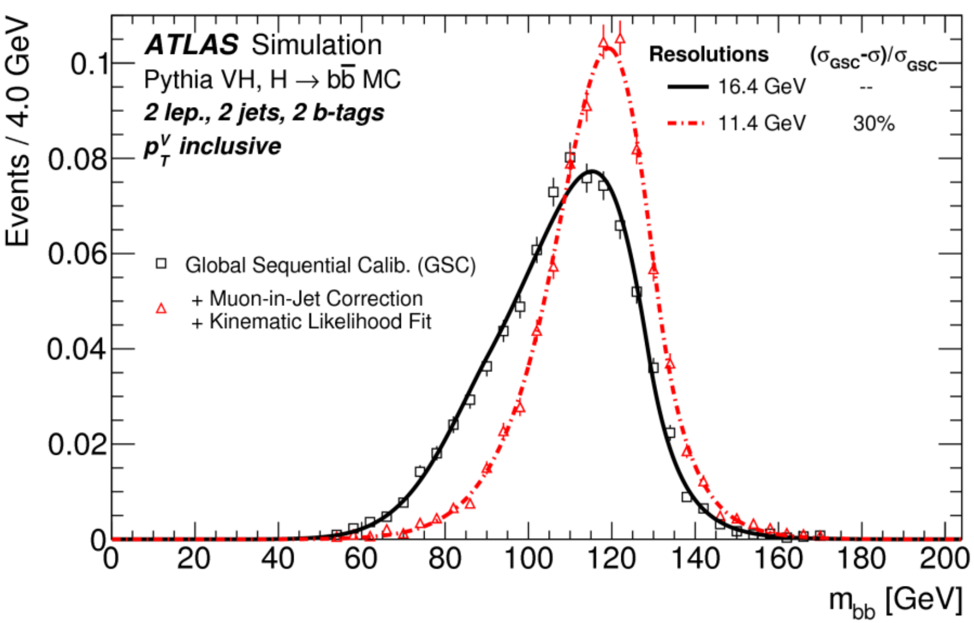
b-tagging critical to reduce V+light-jet backgrounds,

Similar sensitivities from WH and ZH

b-tagging quality



mass resolution



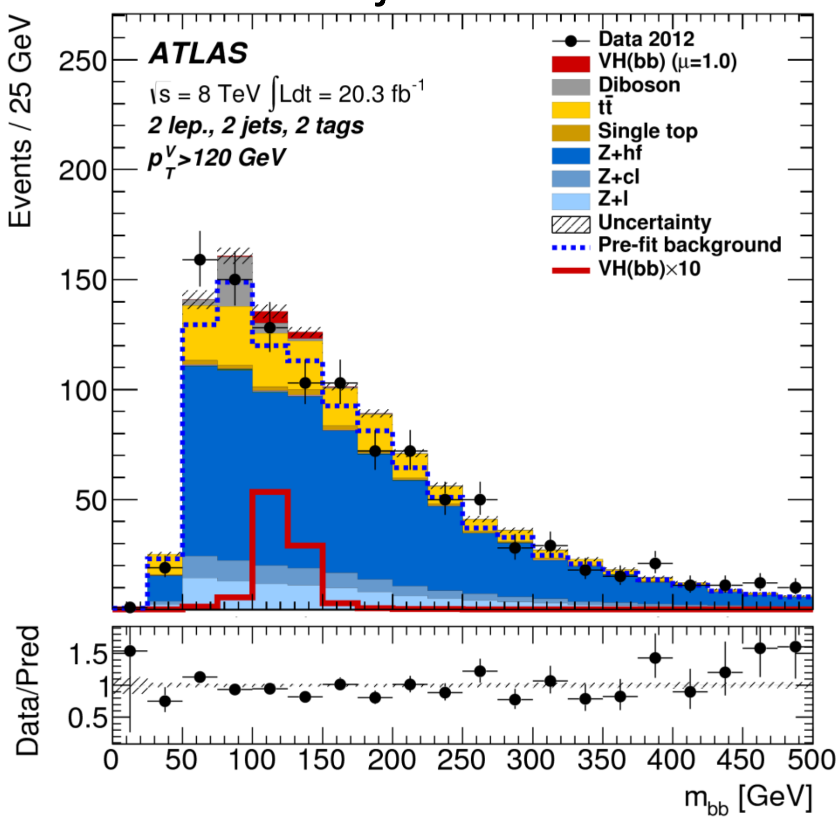
VH with H→bb

Extensive categorization:

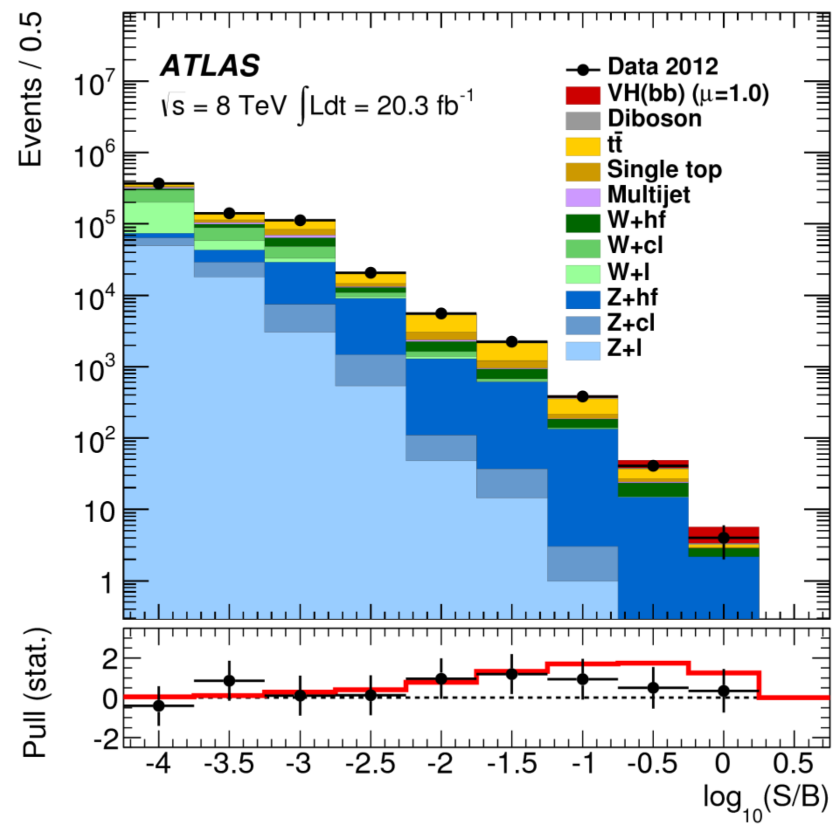
$N_{jet} = 2$ or 3; $p_T^V < 120$ or > 120 GeV; $N_{b\text{-}jet} = 1$ or 2; quality of b-tagging

Two independent analyses: dijet mass and BDT method

dijet



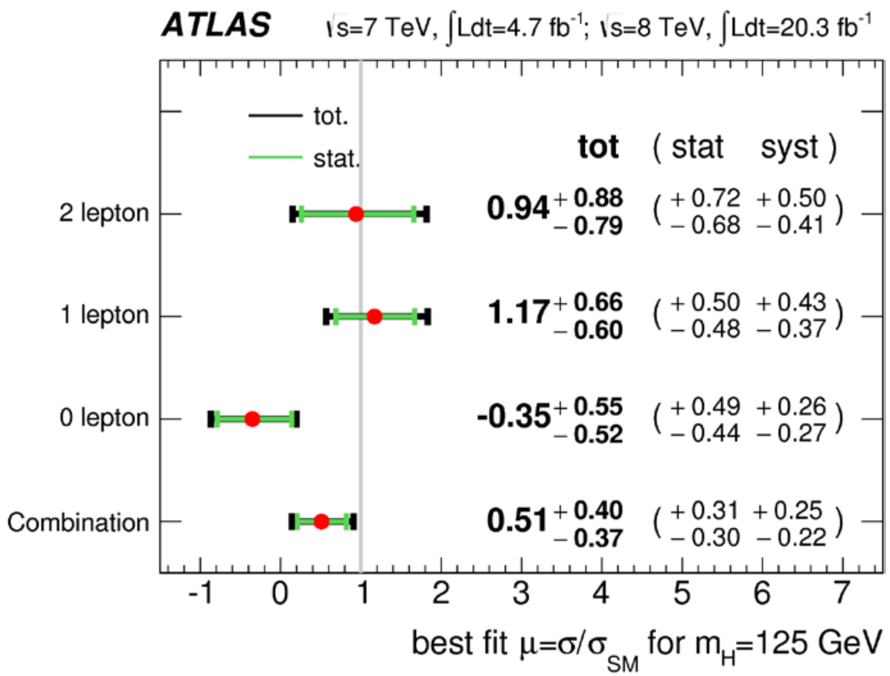
BDT

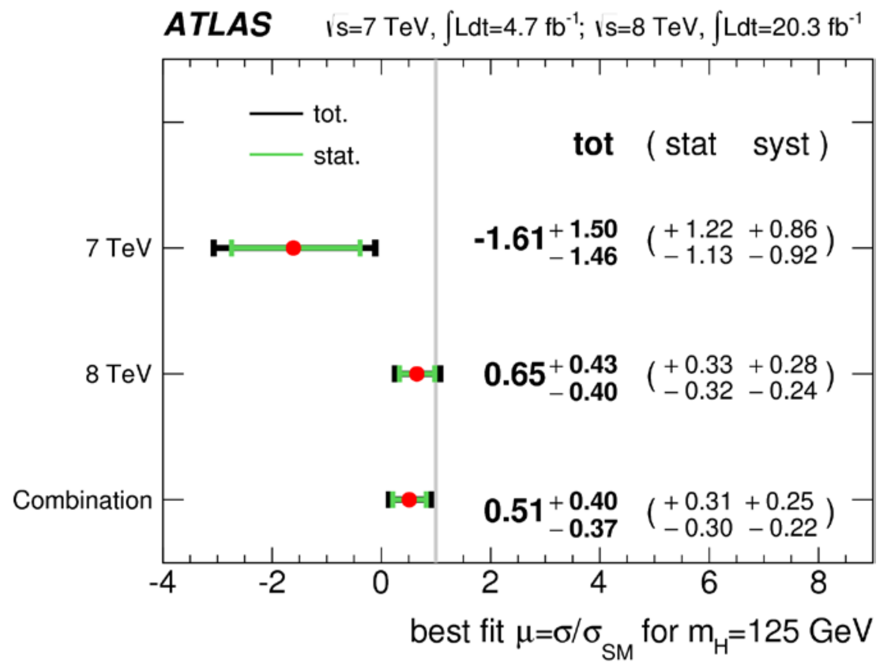


arXiv: 1409.6212 (ATLAS)

VH with H→bb

Low signal yield in 0 lepton (ZH) and 7 TeV data



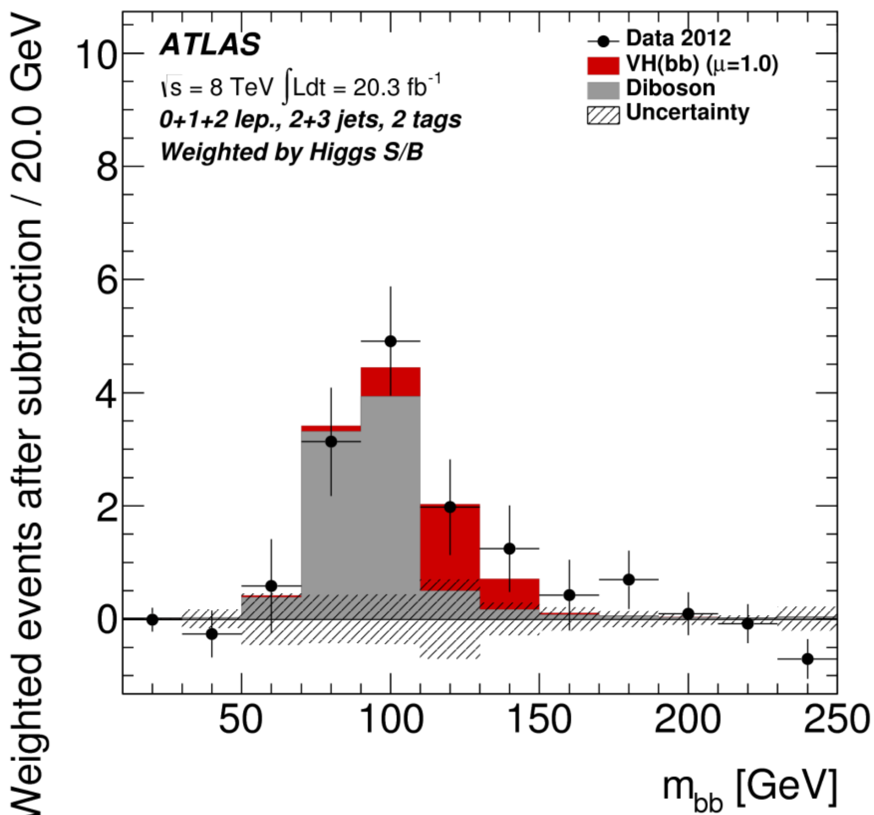


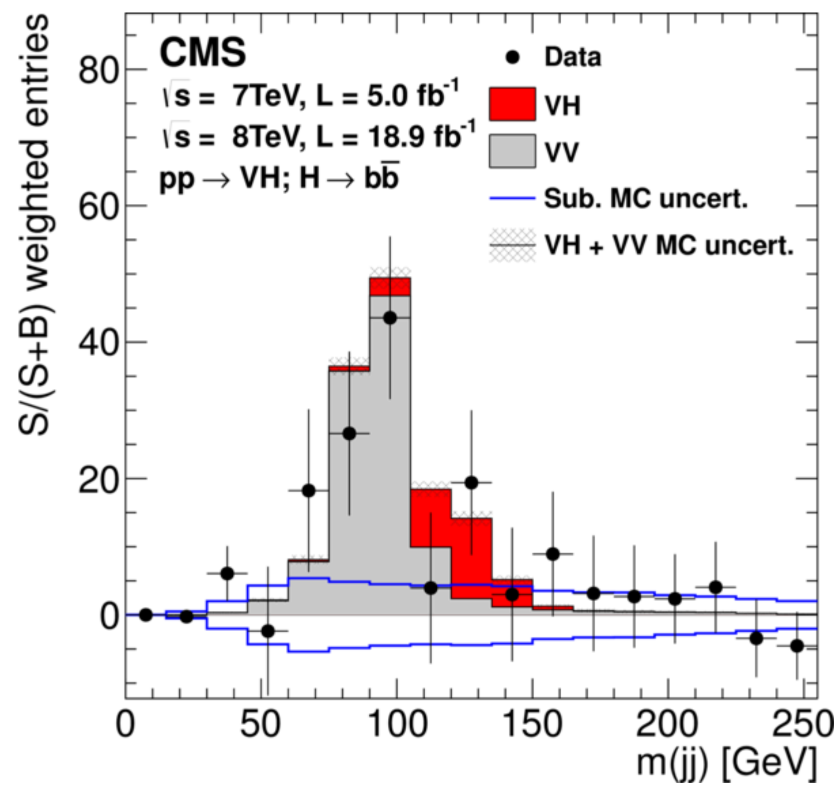
arXiv: 1409.6212 (ATLAS)

VH with H→bb

	ATLAS	CMS
@ mass	125.4 GeV	125 GeV
Significance	1.4σ (2.6σ)	2.1σ (2.1σ)
Signal strength	0.52 ± 0.40	1.0 ± 0.5

Data-Background (except VZ)





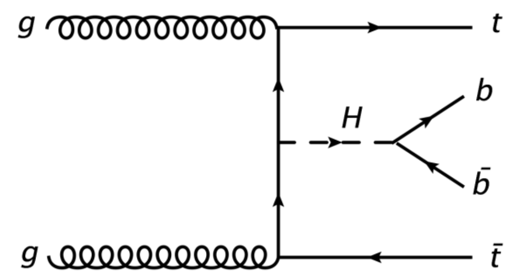
arXiv: 1409.6212 (ATLAS)

ttH Production

Searches for additional Higgs boson in $t\bar{t}$ events
$\Rightarrow$ allow direct study of the top-Higgs Yukawa coupling,

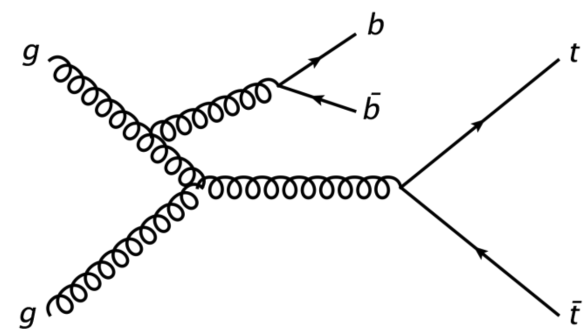
Three analyses based on Higgs decays:

$H \to \gamma\gamma$,
$H \to$ hadrons ($b\bar{b}$, WW, ...),
$H \to$ leptons (WW, $\tau\tau$, ZZ, ...)



$\sigma(t\bar{t}H) \sim 130$ fb @ 125 GeV

Multijets, b-tagging, missing ET or additional jets to select $t\bar{t}$ events. Use MVA techniques to reduce the hugh $t\bar{t}$ backgrounds.



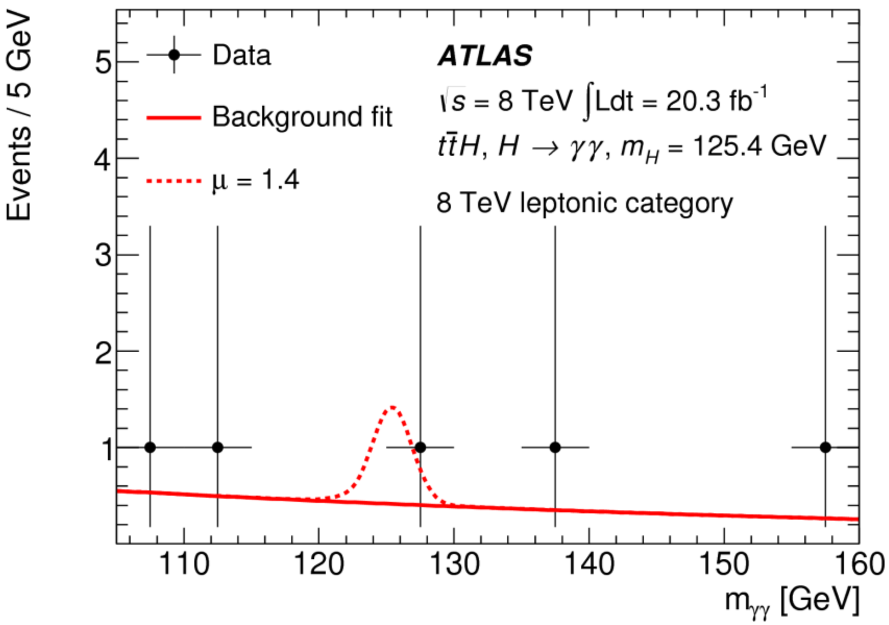
ttH with H→γγ

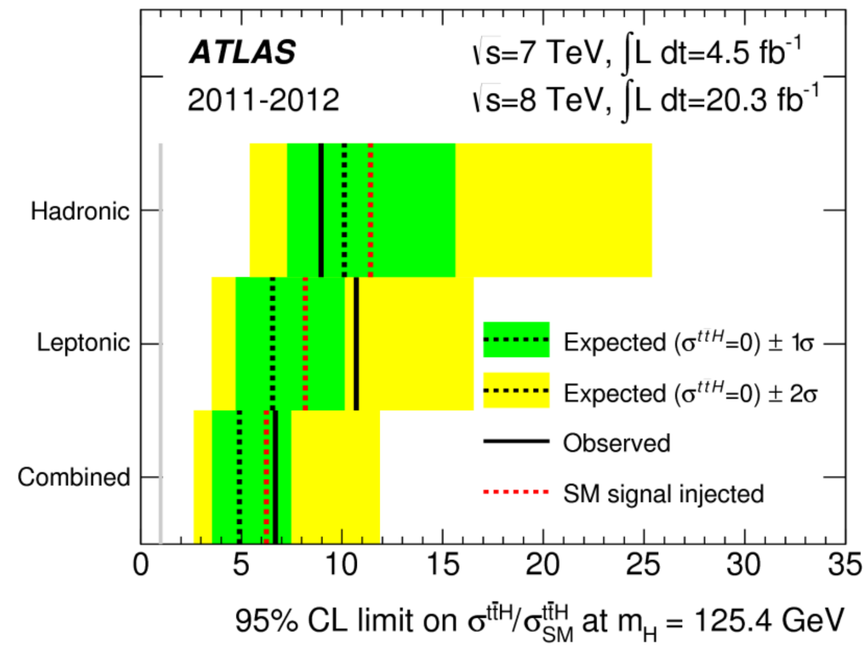
Two analysis categories:

Leptonic: $N_\ell \geq 1$, $N_{bjet} \geq 1$ and $\not{E}_T > 20$ GeV

Hadronic: $N_{jet} \geq 5$ or 6, $N_{bjet} \geq 1$ or 2, depending on jet p_T and b-tagging quality

Low statistics ⇒ no smooth sidebands in the signal region, use data control regions (loose photon identification and/or isolation) to estimate backgrounds

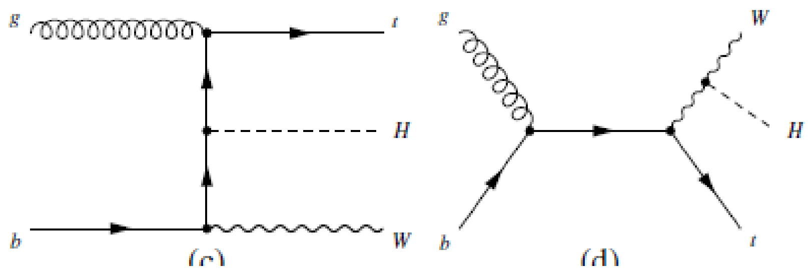




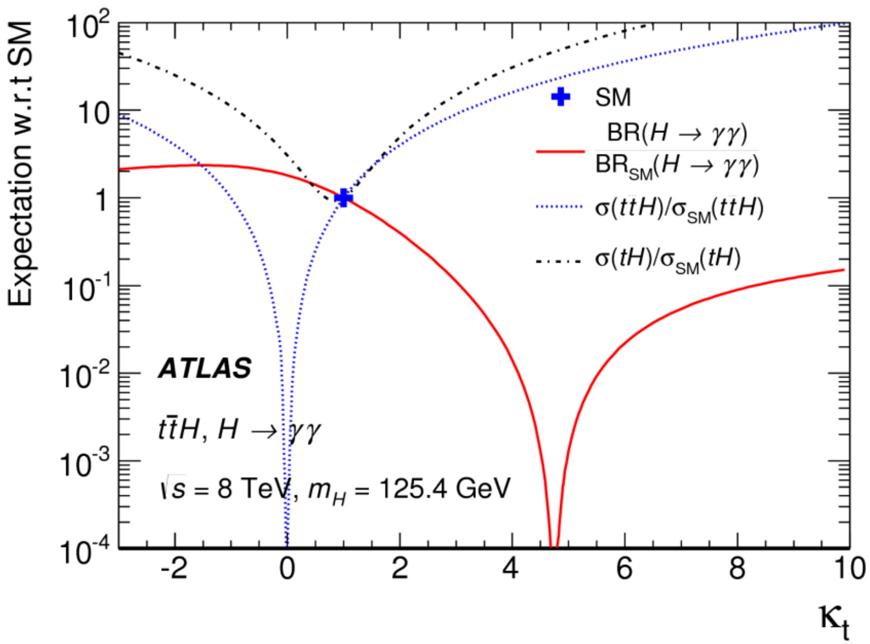
arXiv:1409.3122

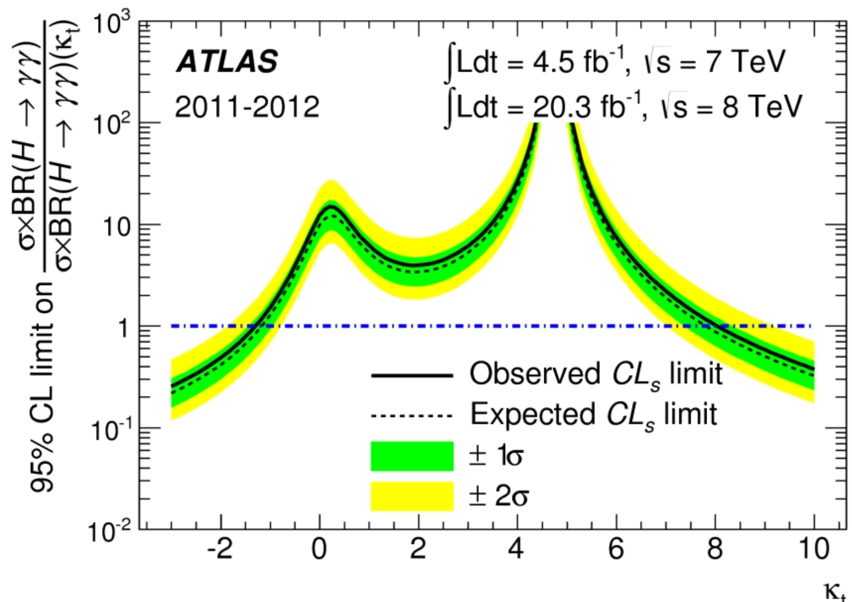
$$\mu_{ttH} = 1.4^{+2.1}_{-1.4}(\text{stat})^{+0.6}_{-0.3}(\text{syst})$$

tH with H→γγ



The analysis is also sensitive to the tH production. Because of the interference, the rate is sensitive to the relative sign of the Higgs boson couplings to W boson and to top quark





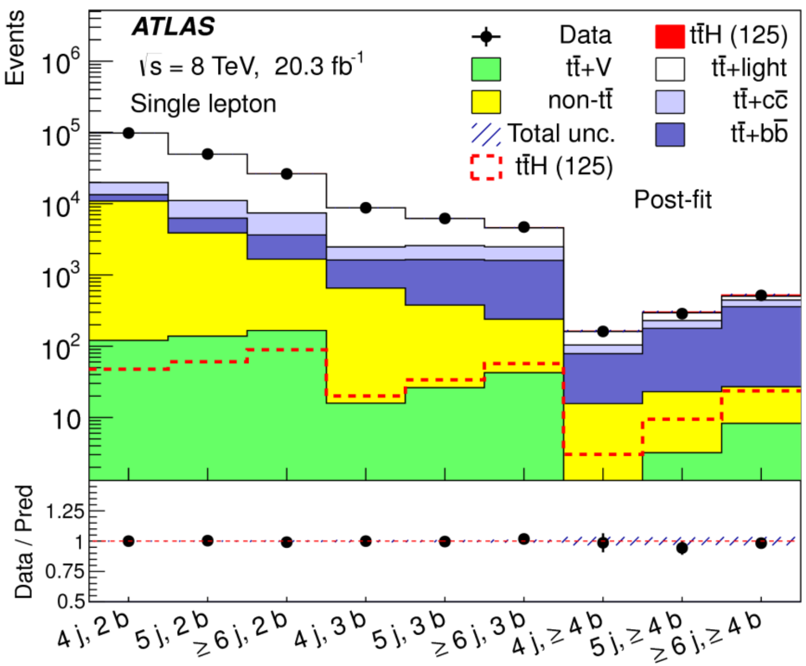
arXiv:1409.3122

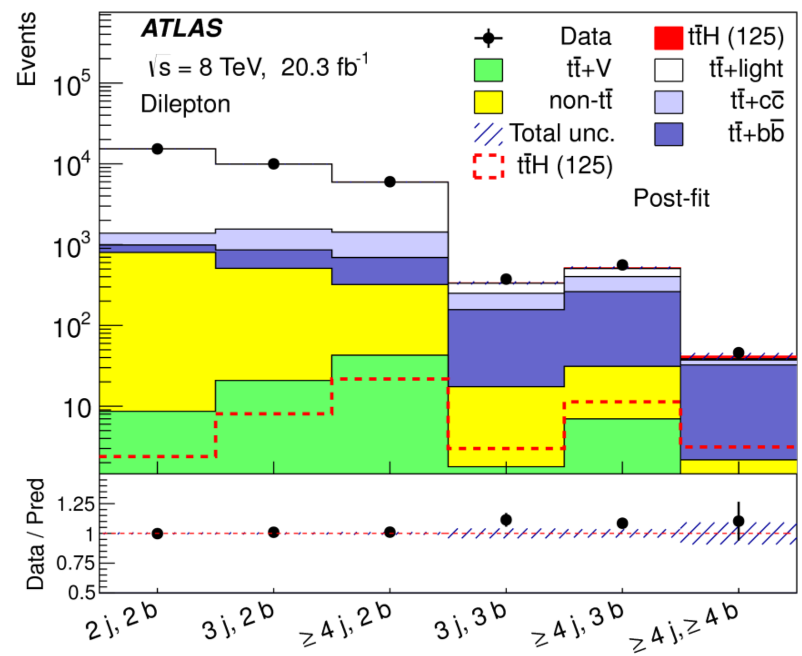
ttH with H→bb

$$pp \to ttH \to \begin{cases} \text{single lepton: } (\ell \nu b)(q\bar{q}'b)(b\bar{b}) \\ \text{dilepton: } (\ell \nu b)(\ell \nu b)(b\bar{b}) \end{cases}$$

Consider both single lepton and dilepton final states of the top quark decays. At least 4 b-jets and two additional jets for the single lepton final state

Categorization based on multiplicities of jets and b-tagged jets and employ Neural Network for signal-background separation.

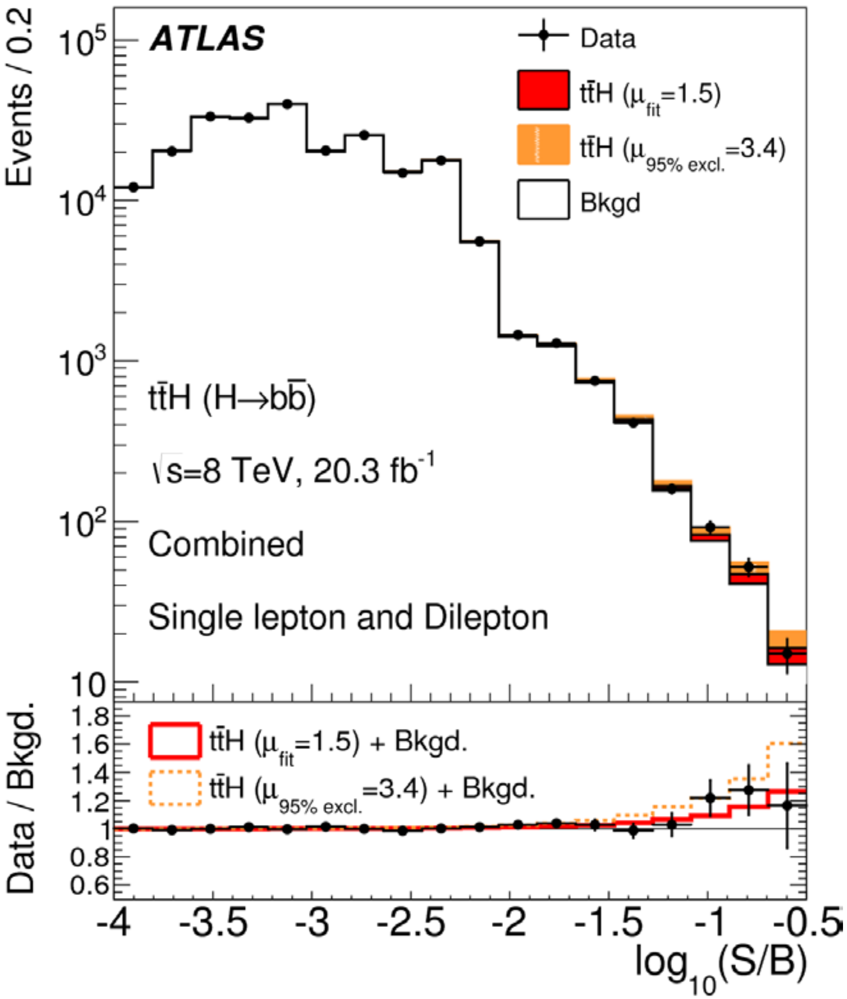




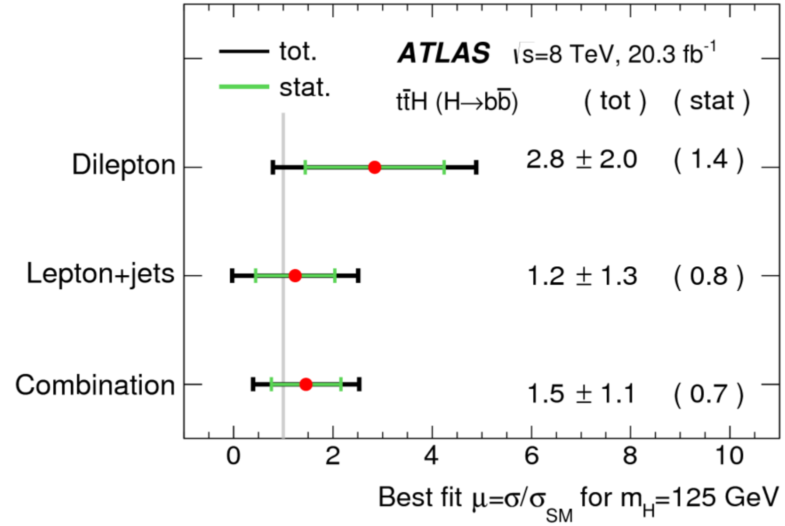
arXiv:1503.05066

ttH with H→bb

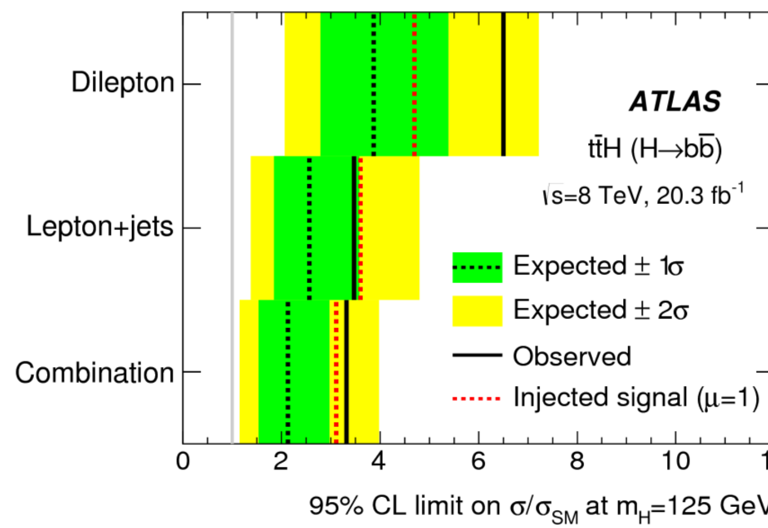
Combining bins according to S/B



Signal strength



Upper limit



$$\mu_{ttH} = 1.5 \pm 1.1$$

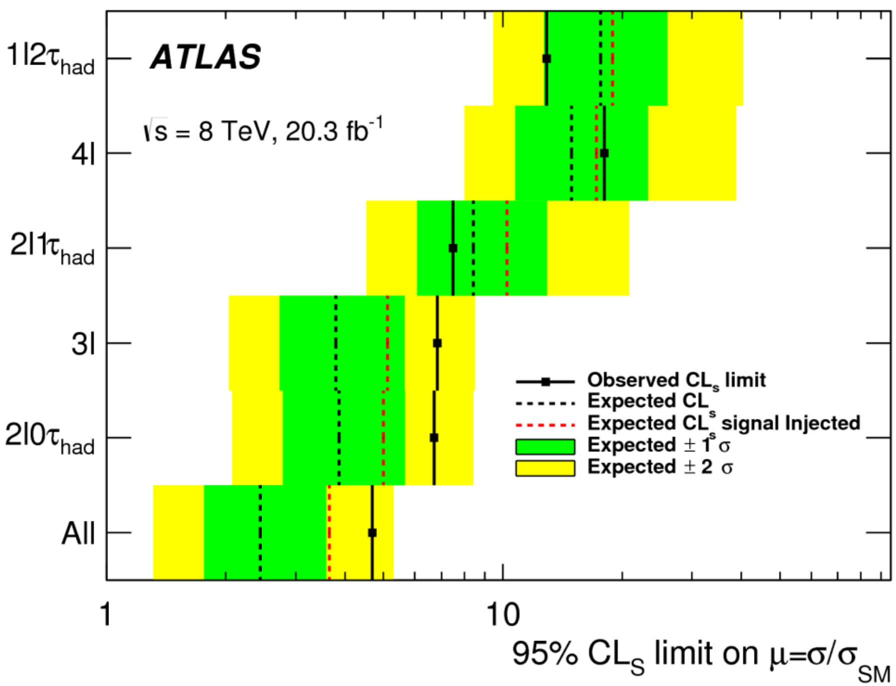
arXiv:1503.05066

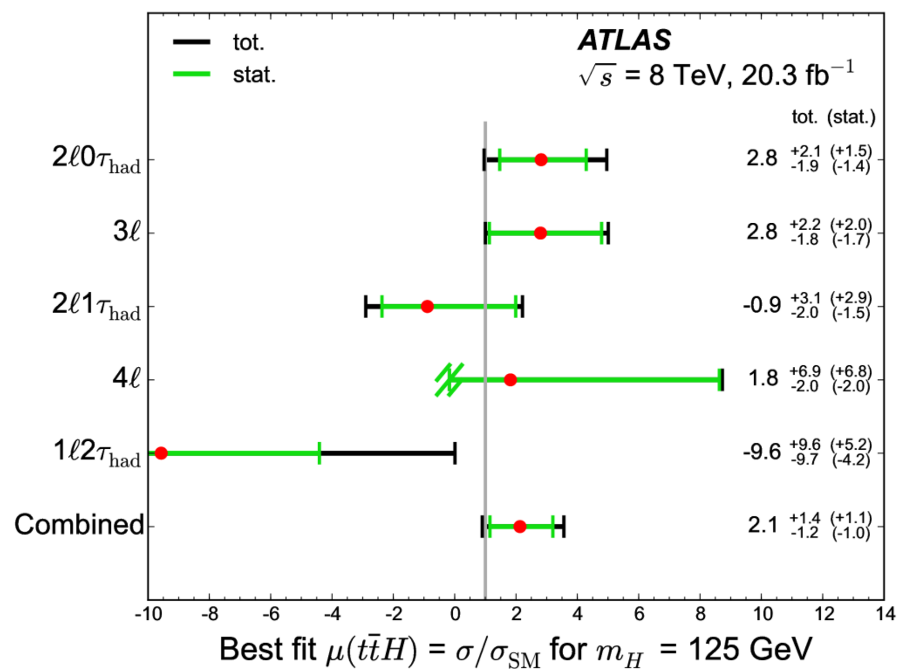
ttH with H→leptons

Multiple leptons are expected from ttH events with the decays

$t \to Wb \to \ell \nu b$ and $H \to \left(WW^*, ZZ^*, \tau\tau\right) \to \ell$'s

Five distinct analyses targeting different numbers of leptons, all candidates are required to have ≥ 1 b-tagged jets





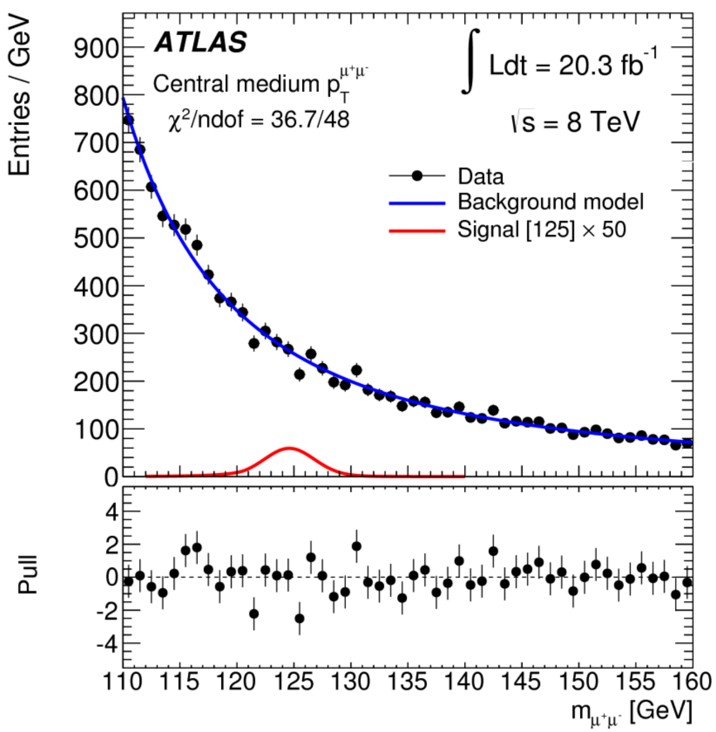
arXiv:1506.05988

$$\mu_{ttH} = 2.1^{+1.4}_{-1.2}$$

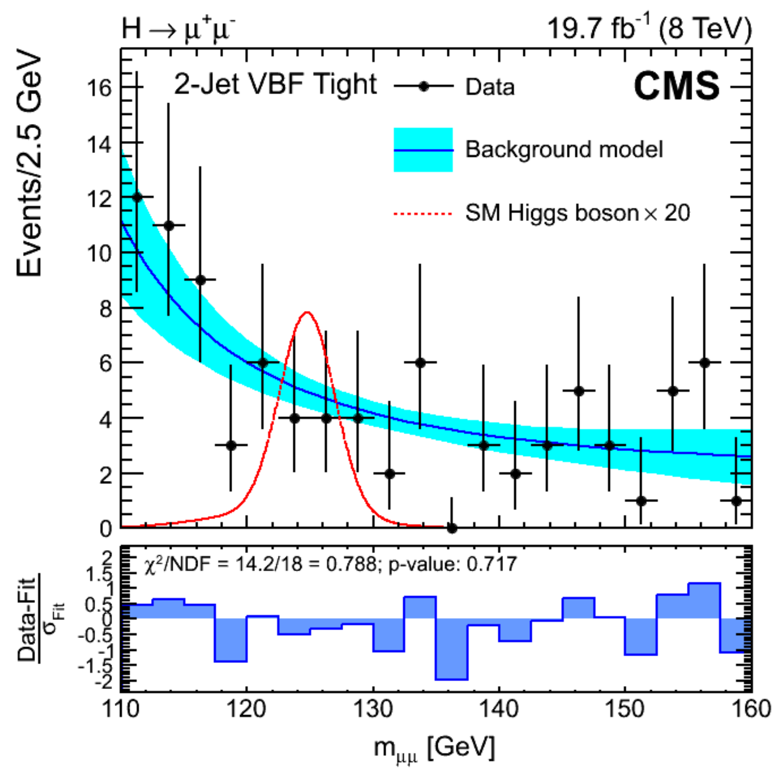
Rare Decay: $H \rightarrow \mu\mu$

Small $BR(H \rightarrow \mu\mu) = 2.2 \times 10^{-4}$ @ 125 GeV, good mass resolution ~ 2 GeV, 10 times smaller than $BR(H \rightarrow \gamma\gamma)$ with a larger background

Clean signature, but suffer from large Drell-Yan background



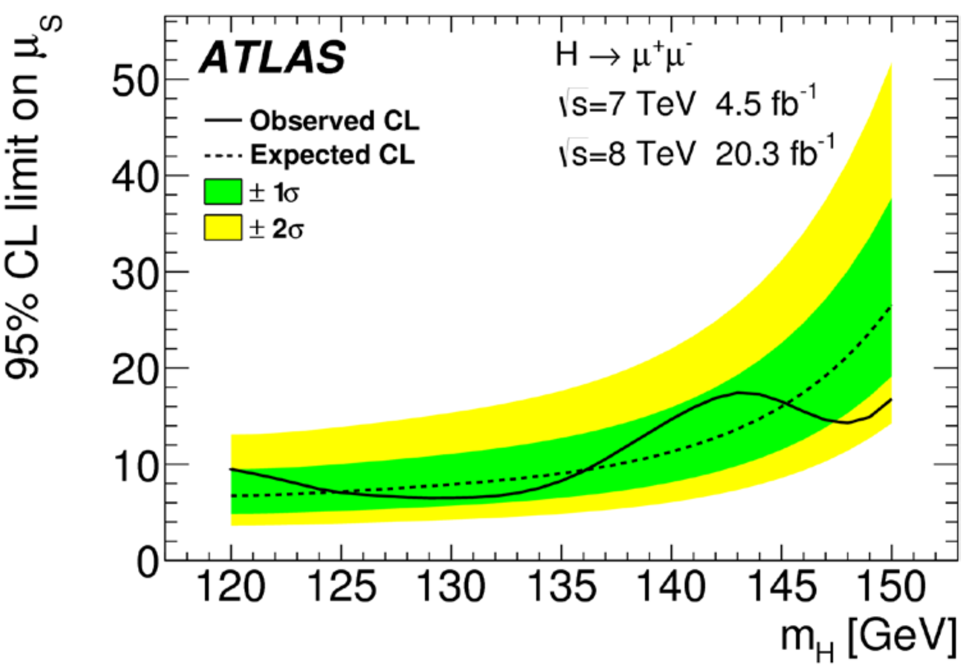
arXiv:1406.7663 (ATLAS)



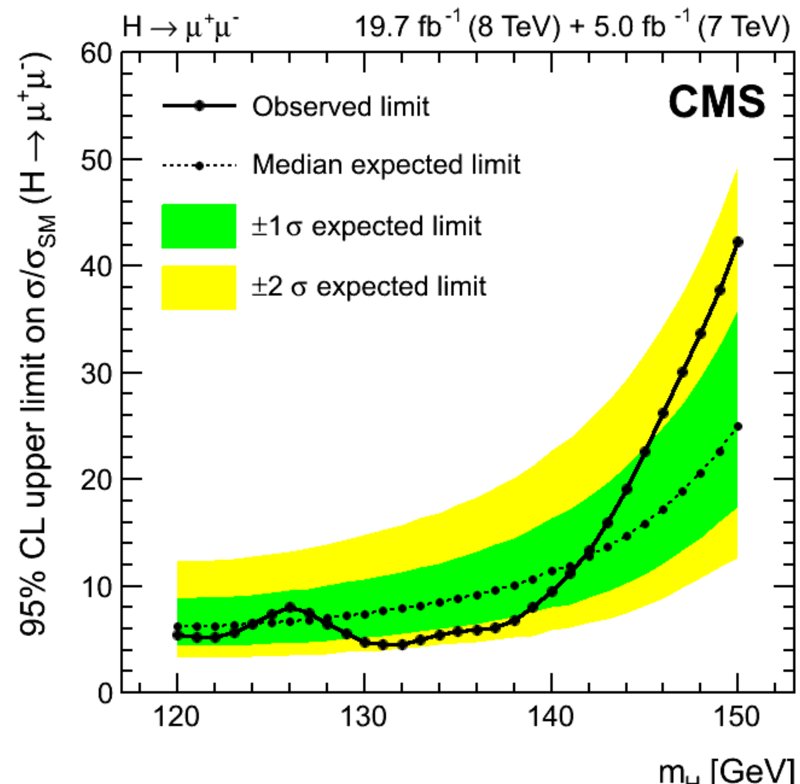
arXiv: 1410.6679 (CMS)

Rare Decay: $H \to \mu\mu$

95% CL upper limit on μ of $H \to \mu^+\mu^-$		
	ATLAS	CMS
@ Higgs mass	125.5 GeV	125 GeV
Observed	7.0	7.4
Expected	7.2	5.1



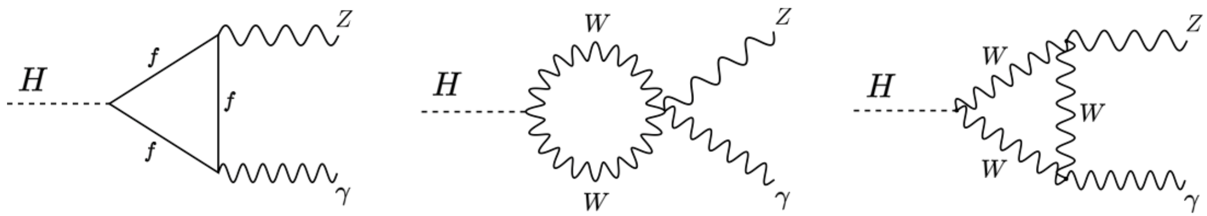
arXiv:1406.7663 (ATLAS)



arXiv: 1410.6679 (CMS)

Rare Decay: $H \to Z\gamma$

$BR(H \to Z\gamma) \approx 0.15\%$ @ 125 GeV

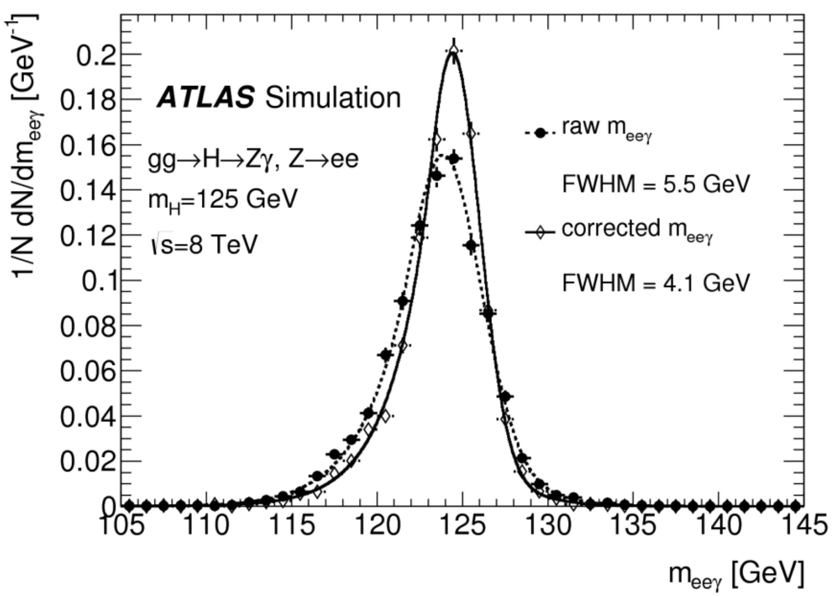


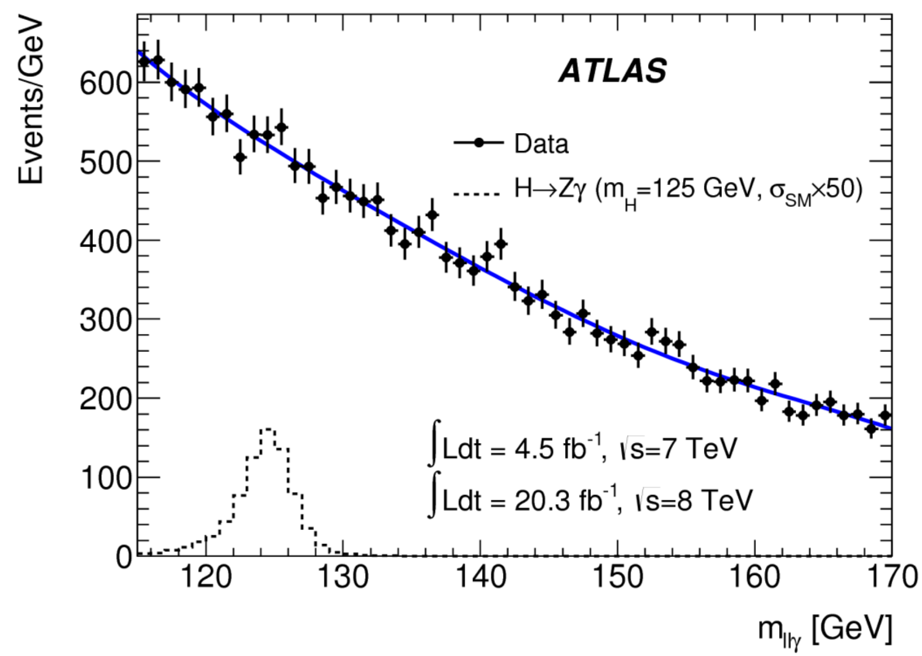
At $m_H = 125$ GeV:

$\sigma_H \times Br(H \to Z\gamma \to \ell\ell\gamma) \sim 2.3$ fb

~ 55 events in 2011+2012 dataset

Search for a narrow resonance over continuum (mostly $Z\gamma$) backgrounds

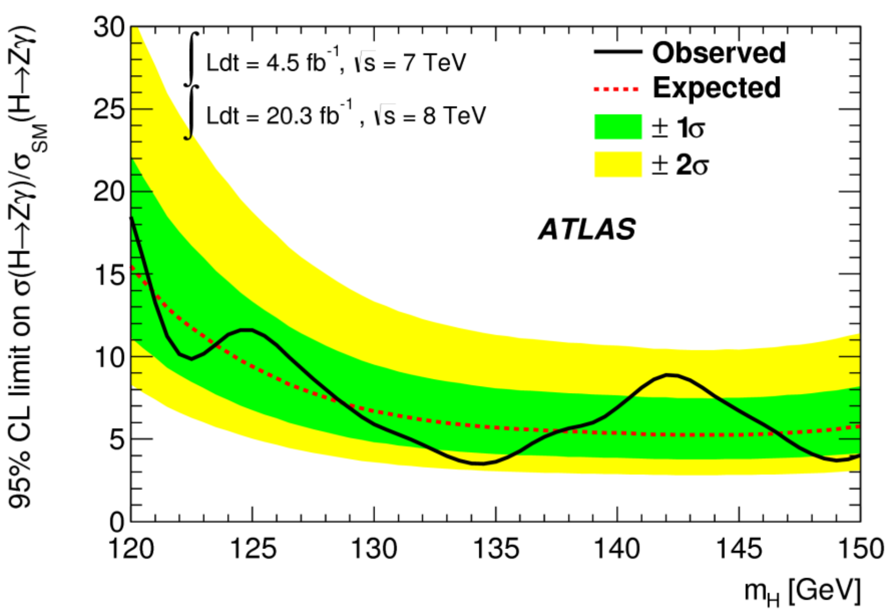




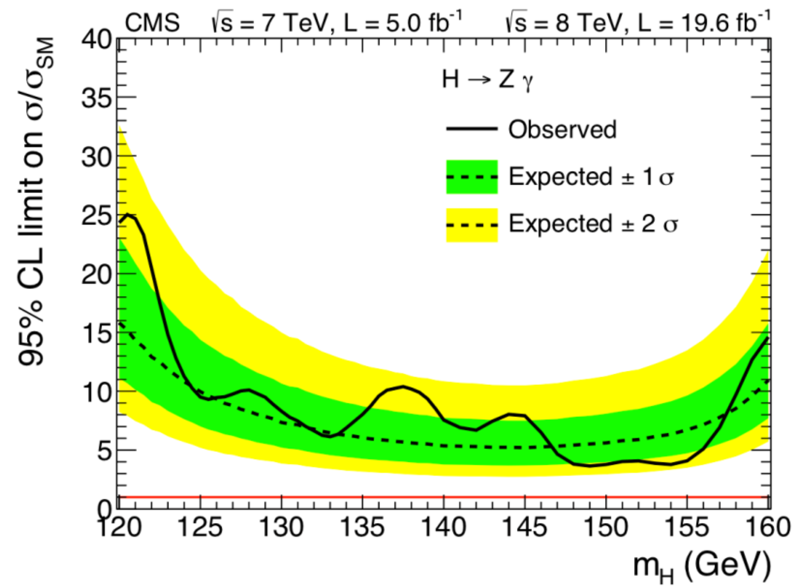
arXiv: 1402.3051 (ATLAS)

Rare Decay: $H \to Z\gamma$

95% CL upper limit on μ of $H \to Z\gamma$		
	ATLAS	CMS
@ Higgs mass	125.5 GeV	125 GeV
Observed	11	9.5
Expected	9	10



arXiv: 1402.3051 (ATLAS)

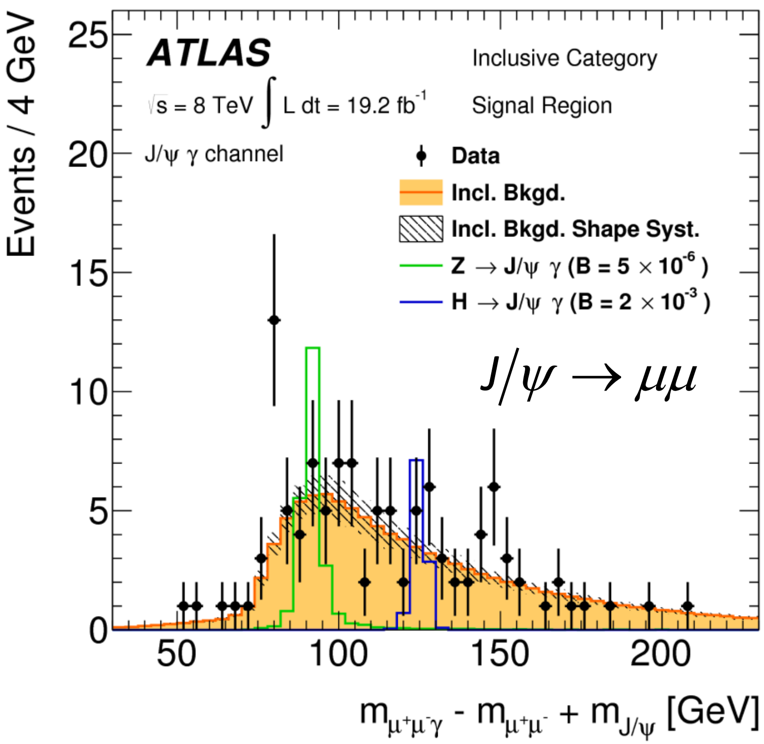


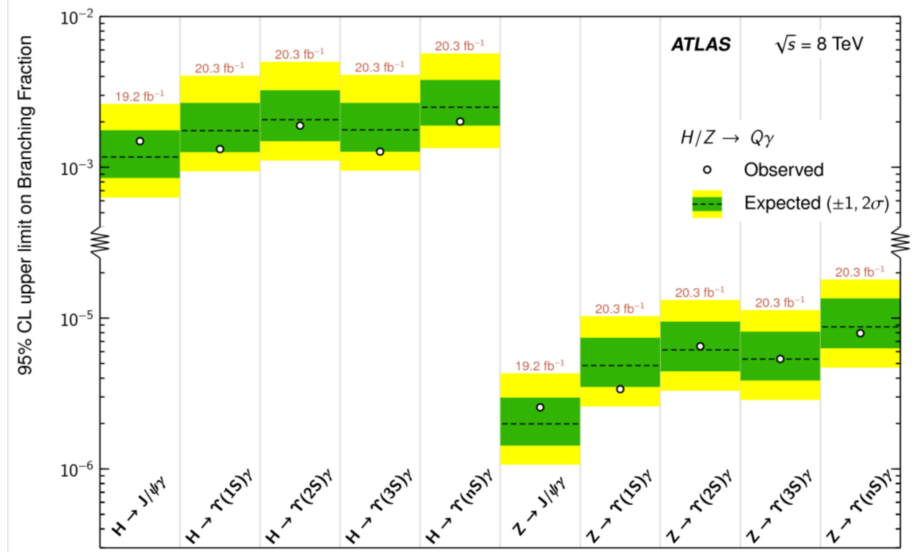
arXiv: 1307.5515 (CMS)

Search for H→J/ψ γ

$H \to J/\psi\,\gamma$ decay was proposed as a possible channel to probe the $Hc\bar{c}$ coupling at the LHC. In the SM: $\mathrm{BR}(H \to J/\psi\,\gamma) \approx (2.8 \pm 0.2) \times 10^{-6}$

Combining $J/\psi \to \mu\mu$ candidates with photons and search for a resonance at m_H





95% CL observed upper limit:

$BR(H \to J/\psi\,\gamma) < 1.5 \times 10^{-3}$

arXiv:1501.03276

ATLAS Summary