

Evidence for Higgs decays to a pair of muons

Exploring the Higgs Yukawa sector

Seminarium środowiskowe „Białasówka”
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Paweł Brückman de Renstrom
(Institute of Nuclear Physics P.A.N., Cracow PL)





Iga Świątek in the Final!

2012

CERN, 4 July 2012

Ladies and gentlemen,
I think we've got it!

Discovery of a Higgs-like particle decaying
to gauge bosons



CERN, 4 July 2012

2012

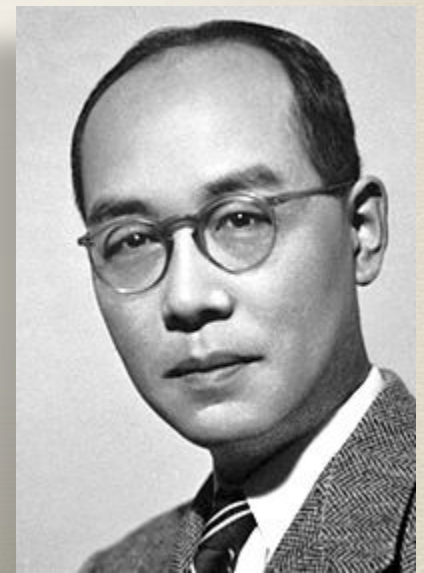


Why Yukawa interactions?

- ❑ The Yukawa interactions are not strictly needed for the Electroweak symmetry breaking via the BEH mechanism.
- ❑ However, they give us a very appealing opportunity to dynamically introduce masses of otherwise massless fermion fields: $-L_{Yukawa} = Y_{ij} (\bar{\psi}_{Li} \phi) \psi_{Rj} + h.c.$ (Weinberg '67)

↑ ↑
SU2 doublets singlet

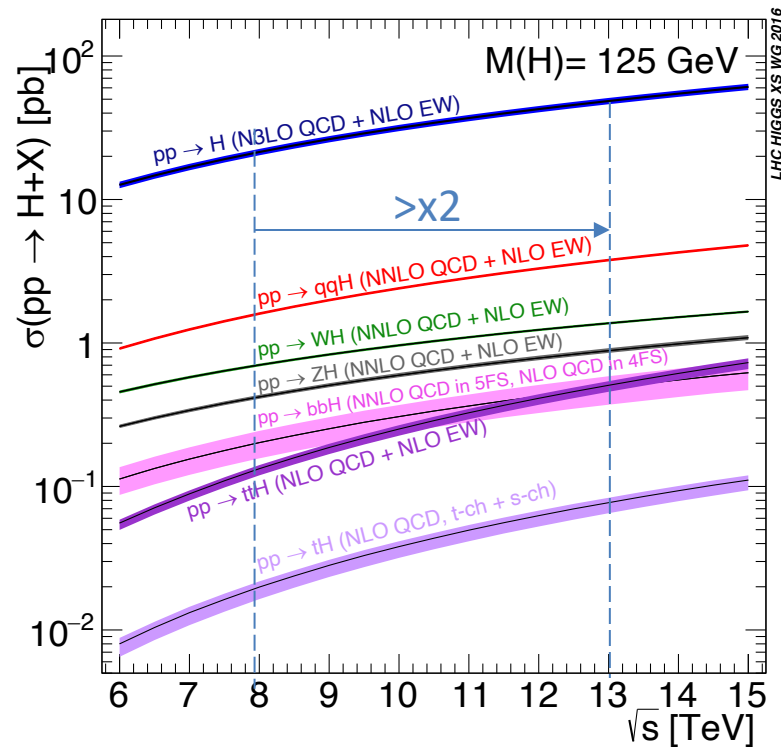
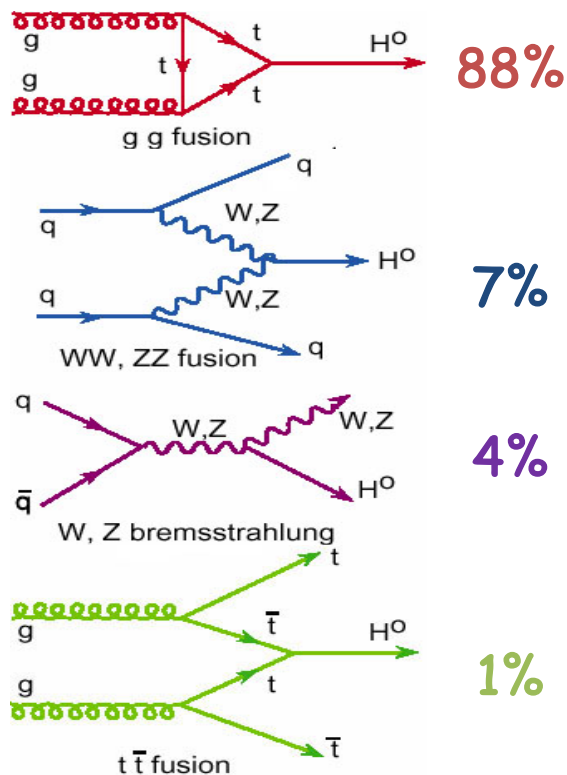
- ❑ If realized, couplings to all fermions in the SM are proportional to their masses.
- ❑ Since 2012 we have been gathering direct evidence for Yukawa couplings (indirect via ggF) - work in progress!
- ❑ Leptonic sector accessible only via direct decays.
- ❑ Is the Higgs sector minimal?



Hideki Yukawa

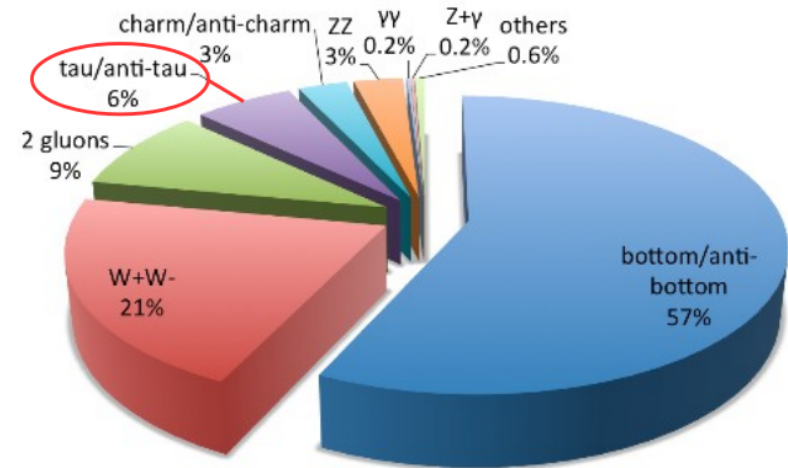
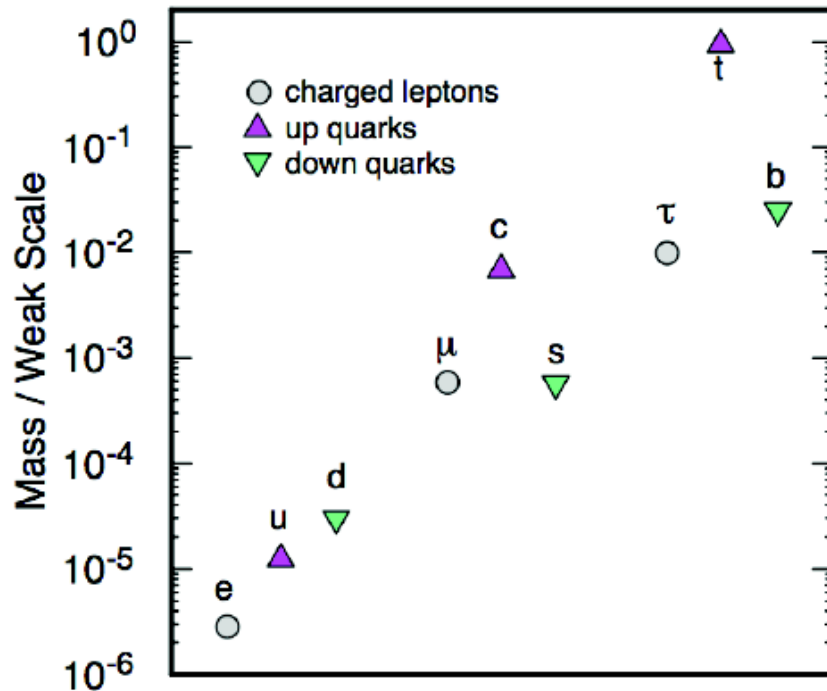
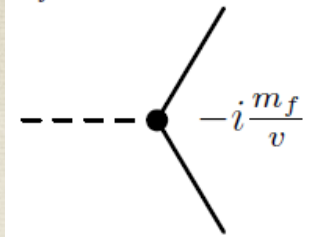
SM Higgs production @ LHC

(for 125 GeV Higgs boson)



- ❖ ttH and bbH provide direct measurement of Yukawa coupling, but challenging.
- ❖ ggH provides indirect measurement of couplings to quarks via virtual loops (top).

SM Higgs fermionic decays (for 125 GeV Higgs boson)



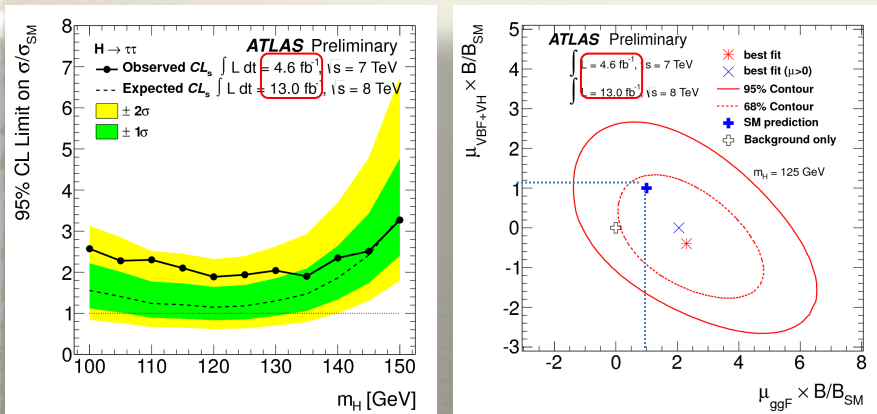
❖ $H \rightarrow b\bar{b}$	(5.7×10^{-1})
❖ $H \rightarrow \tau\bar{\tau}$	(6.2×10^{-2})
❖ $H \rightarrow \mu\bar{\mu}$	(2.2×10^{-4})
❖ $H \rightarrow e\bar{e}$	(5×10^{-9})

- ❖ Fermionic decay modes provide direct measurement of the Yukawa coupling.
- ❖ Bosonic modes encode indirect information on couplings via virtual loops.

2013 Exactly seven years ago, a year after the Higgs discovery and just after the announcement of Nobel prize to F. Englert and P. Higgs, I had the privilege to give a talk at this seminar entitled "What do we know about leptonic decays of the Higgs boson? Is the Higgs sector minimal?"

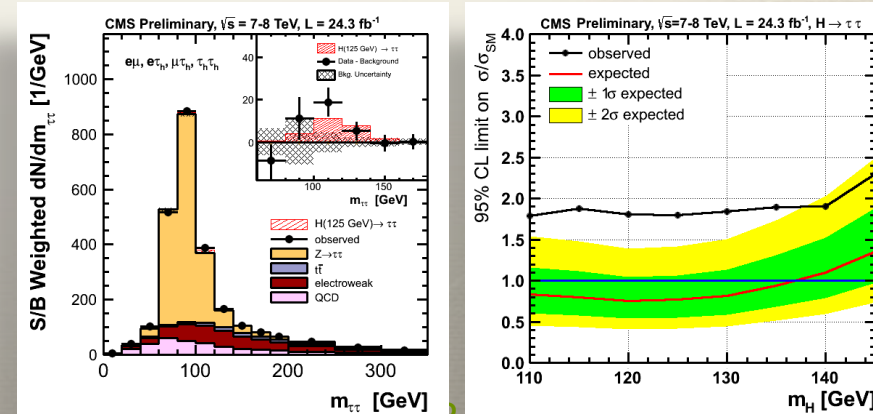
ATLAS results (CONF-2012-160)

- 4.6 fb⁻¹ @ 7 TeV and 13.0 fb⁻¹ @ 8 TeV analysed.
- Update to full statistics imminent!
- $\mu = 0.7 \pm 0.7$; significance 1.1 σ (1.7 expected) @ 125 GeV



CMS results (HIG-13-004)

- All 24.3 fb⁻¹ @ 7 & 8 TeV analyzed.
- $\mu = 1.1 \pm 0.4$; significance 2.9 σ (2.6 expected) @ 125 GeV
- Higgs mass has been estimated at $m_H = 120^{+9}_{-7}$ GeV



2014

ATLAS

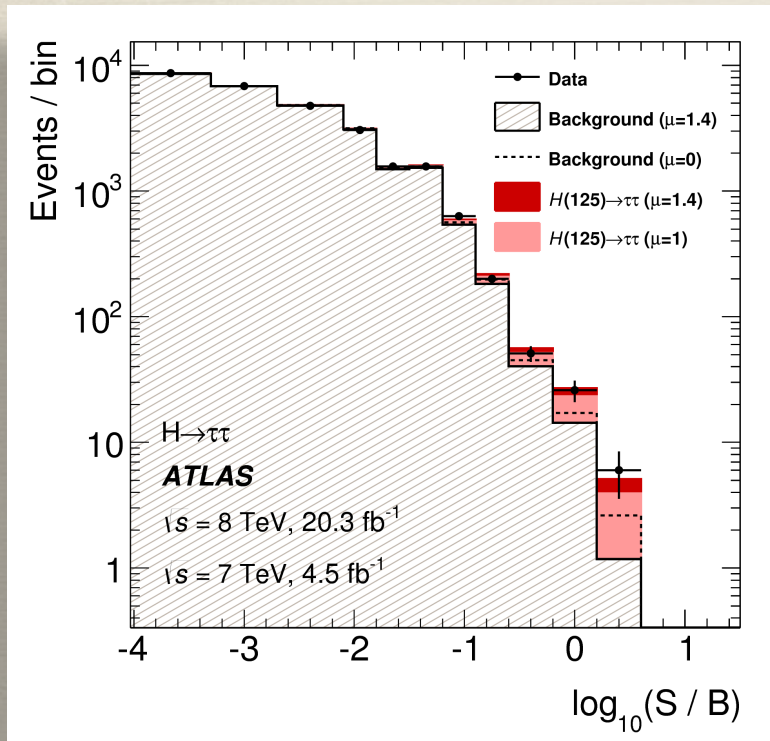
Run 1

JHEP 04 (2015) 117

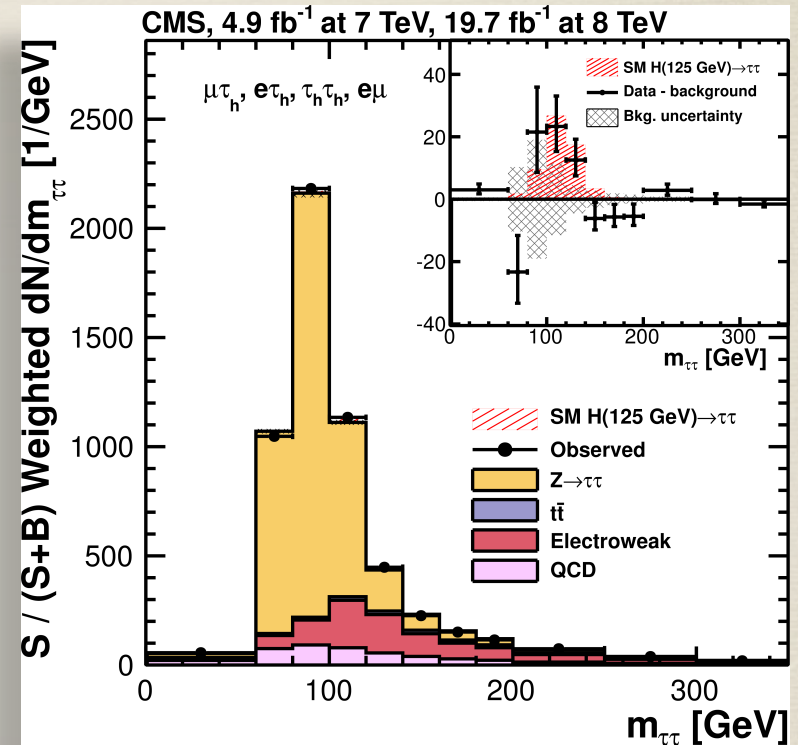
 $H \rightarrow \tau\tau$

CMS

JHEP 05 (2014) 104



Signal strength: $\mu = 1.43^{+0.43}_{-0.37}$
 Significance: $S = 4.5(3.4 \text{ exp.})\sigma$



Signal strength: $\mu = 0.78 \pm 0.27$
 Significance: $S = 3.2(3.7 \text{ exp.})\sigma$

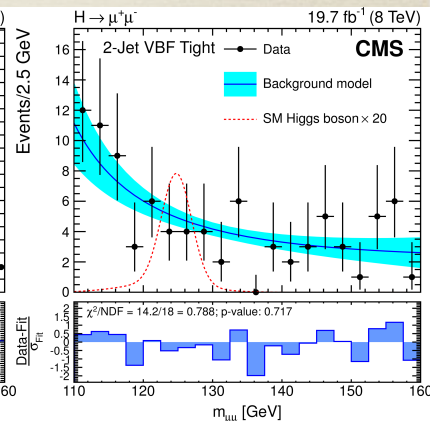
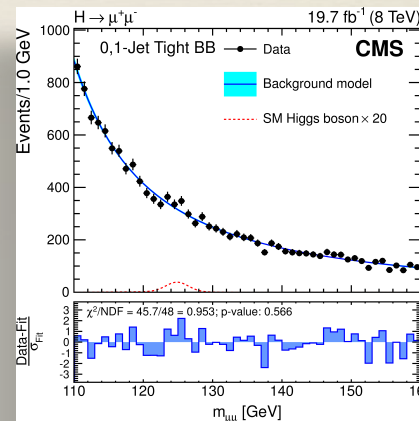
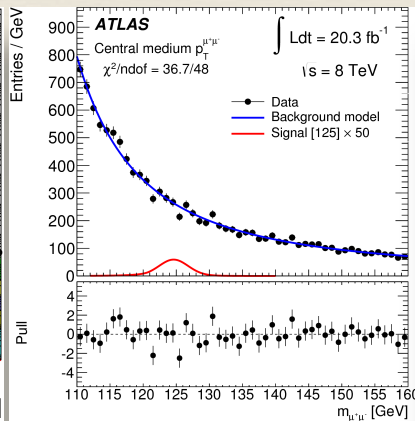
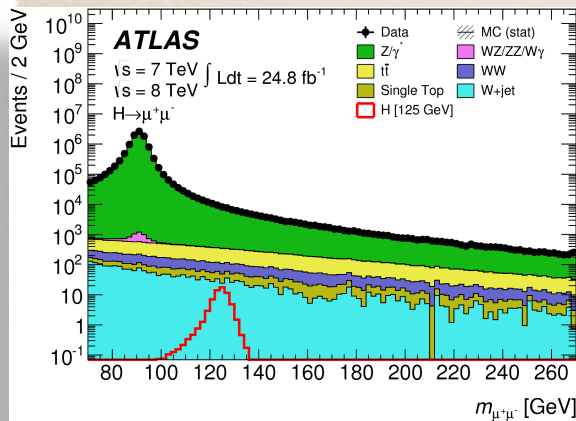
First direct evidence for Higgs fermionic decays (couplings)

2014

Run 1 Search for $H \rightarrow \mu\mu$

ATLAS Physics Letters B 738 (2014) 68-86

CMS Phys. Lett. B 744 (2015) 184



- ❖ 4.5+20.3 fb⁻¹ @ 7/8 TeV analysed.
- ❖ 7 categories in η , p_T , ggF/VBF
- ❖ Simultaneous ML fit to S+B model
- ❖ No evidence for signal found.
- ❖ 5.0+19.7 fb⁻¹ @ 7/8 TeV analysed.
- ❖ 15 categories in η , p_T , ggF/VBF
- ❖ Simultaneous ML fit to S+B model
- ❖ No evidence for signal found.

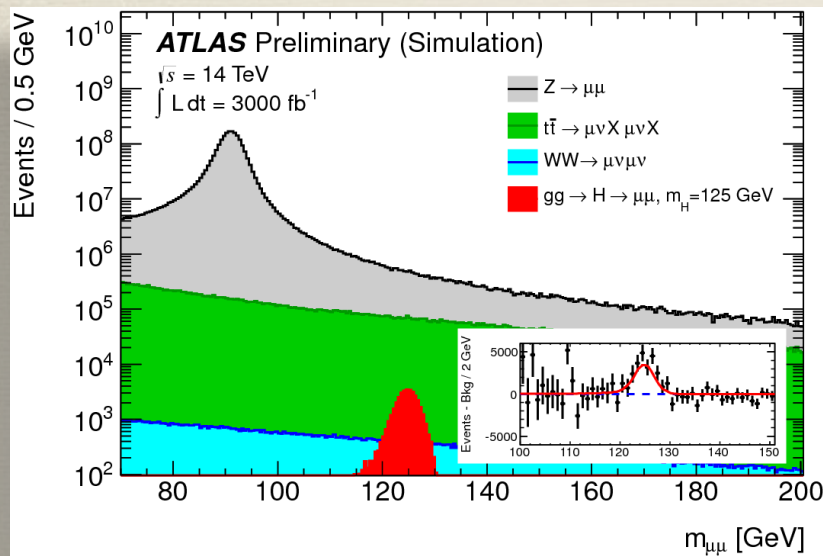
95% CL @ $m_H=125.5$ GeV:
 $7.0(7.2 \text{ exp.}) \times \sigma_{\text{SM}}$
 $\text{BR}(H \rightarrow \mu\mu) < 1.5 \times 10^{-3}$

95% CL @ $m_H=125.5$ GeV:
 $7.4(6.5 \text{ exp.}) \times \sigma_{\text{SM}}$
 $\text{BR}(H \rightarrow \mu\mu) < 1.6 \times 10^{-3}$

Yukawa couplings are not universal! Statistics limited

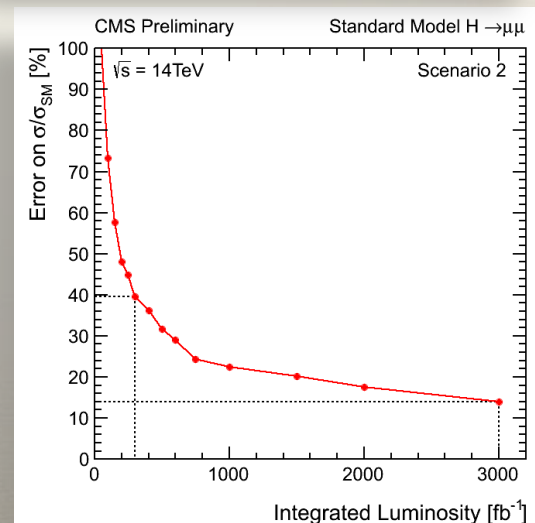
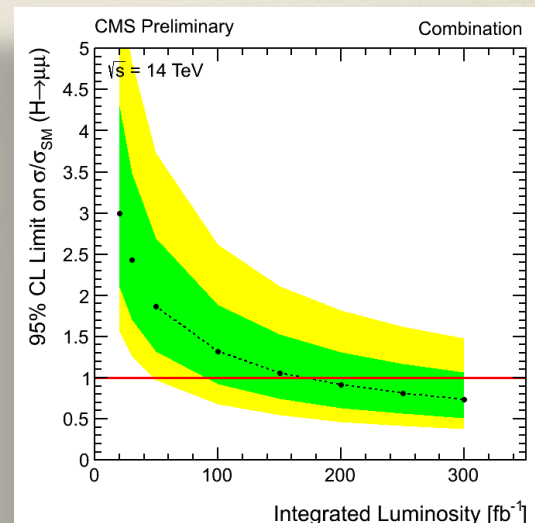
H $\rightarrow\mu\mu$ search: outlook

ATLAS (ATL-PHYS-PUB-2012-004)



- ❖ Are Higgs leptonic couplings $\sim m_F$?
- ❖ $>6\sigma$ significance exp. @3000 fb^{-1}
- ❖ Signal strength μ with $\sigma < 0.2$
- ❖ Small systematics
- ❖ Statistics limited!
- ❖ Strong case for HL LHC!

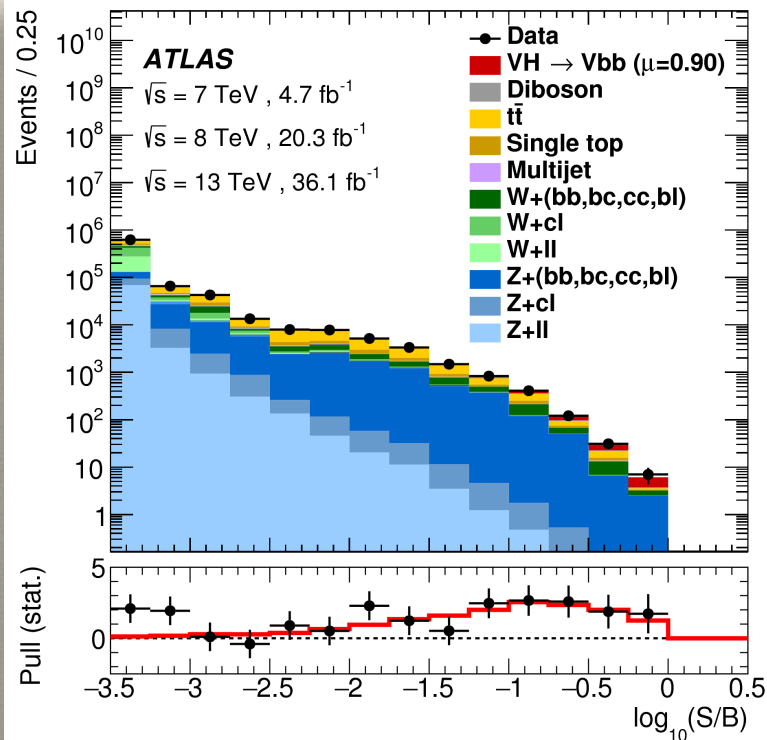
CMS (HIG-13-007)



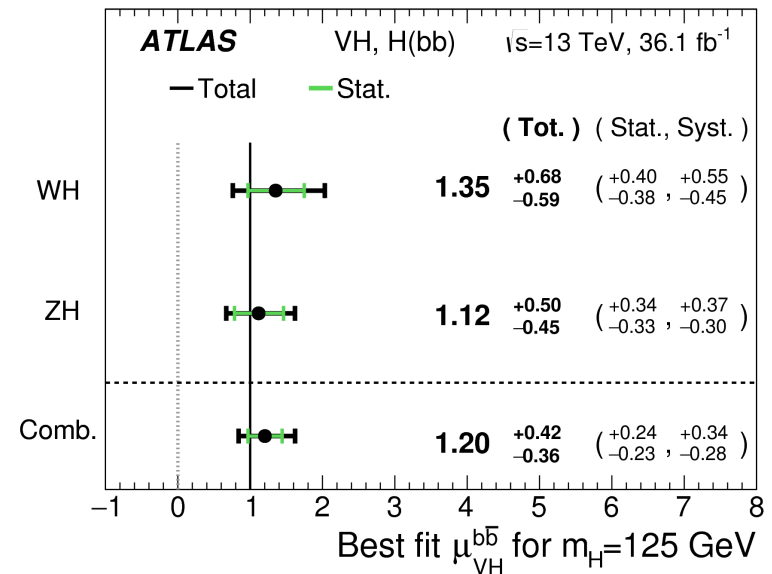
2017

Run 2 (36 fb⁻¹) VH, H→bb

ATLAS JHEP 12 (2017) 024



$ZH \rightarrow \nu b b, WH \rightarrow l \nu b b$ and $ZH \rightarrow ll b b$
 Binned ML fit to MV discriminant.

Signal strength: $\mu=1.20 \pm 0.24 \pm 0.31$ Significance: $S=3.5(3.0 \text{ exp.})\sigma$

⊕ Run 1:

Signal strength: $\mu=0.90 \pm 0.18 \pm 0.20$ Significance: $S=3.6(4.0 \text{ exp.})\sigma$

First observation!

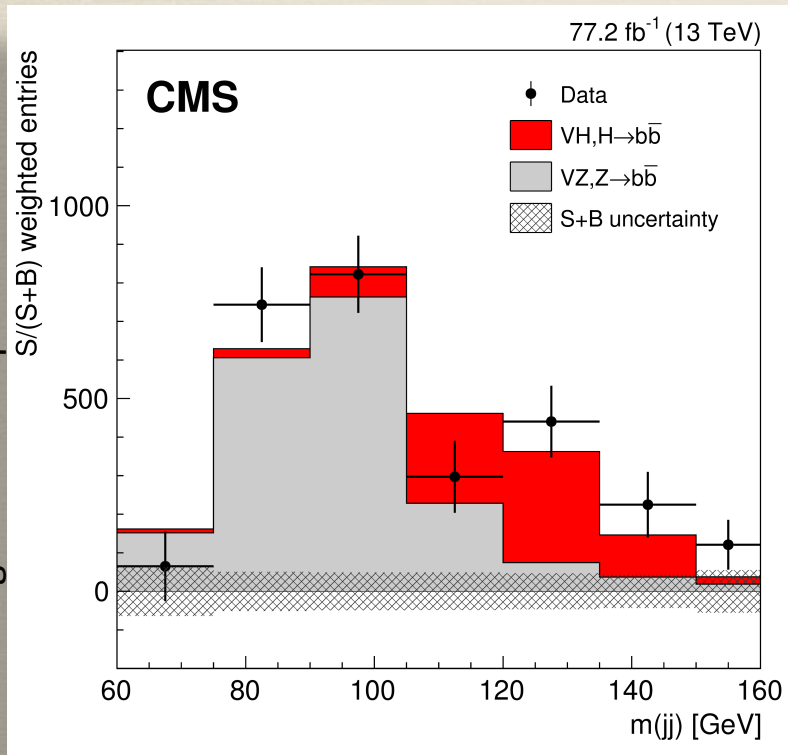
2018

Run 2 (41.3 fb⁻¹) H→bb

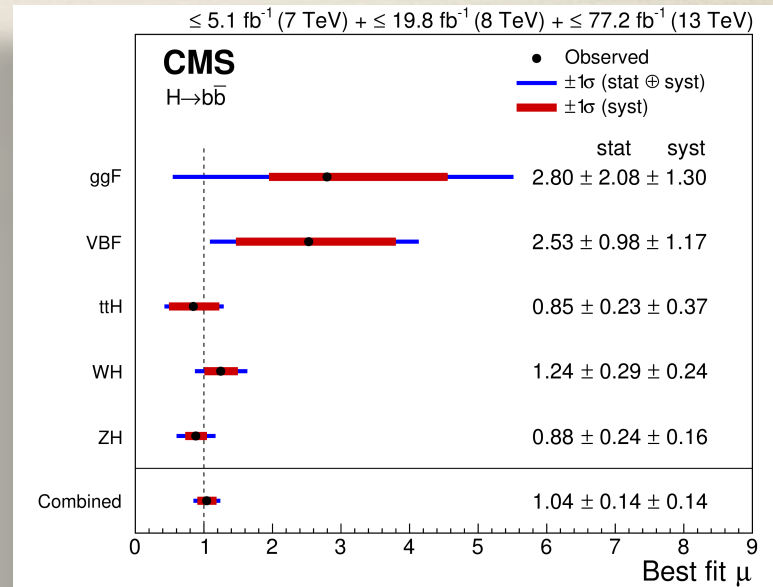
CMS

PRL 121 (2018) 121801

All backgrounds except VZ subtracted



$ZH \rightarrow \nu\nu bb$, $WH \rightarrow l\nu bb$ and $ZH \rightarrow ll bb$
Binned ML fit to MV discriminant.



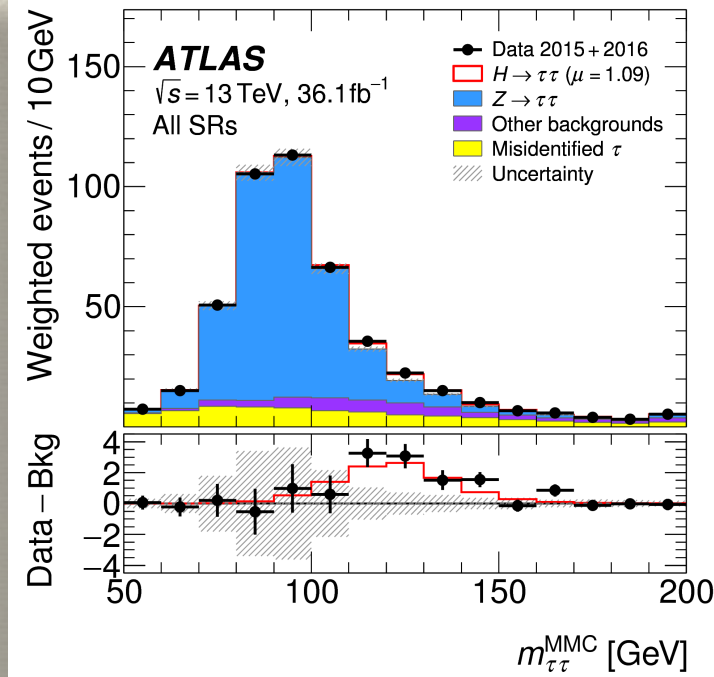
Signal strength: $\mu = 1.06 \pm 0.26$
Significance: $S = 4.4 (4.2 \text{ exp.}) \sigma$
⊕ Run 1:
Signal strength: $\mu = 1.01 \pm 0.22$
Significance: $S = 4.8 (4.9 \text{ exp.}) \sigma$

Statistics dominate

2018

Run 2 (36 fb⁻¹) $H \rightarrow \tau\tau$

ATLAS Phys. Rev. D 99 (2019) 072001



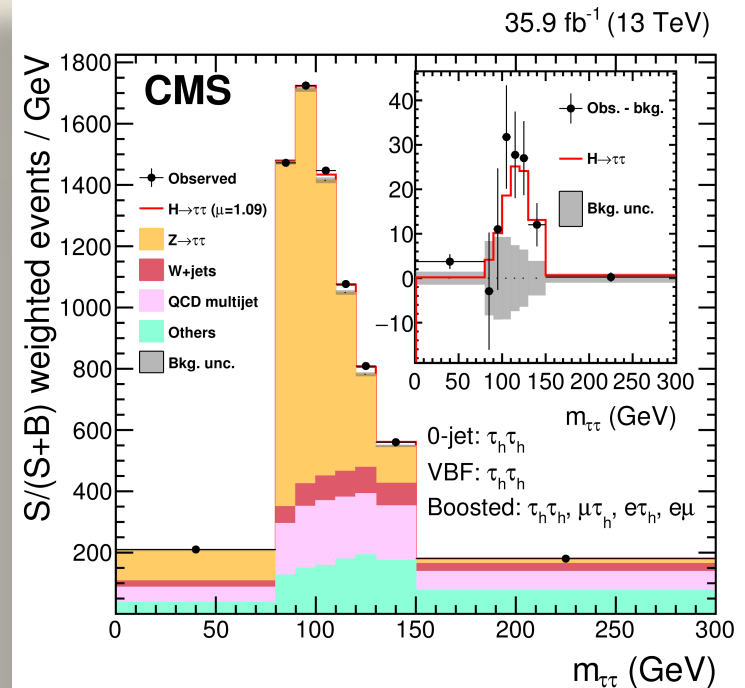
MMC: Nucl. Instrum. Meth. A 654 (2011) 481

Signal strength: $\mu = 1.09 + 0.35 - 0.30$ Significance: $S = 4.4 (4.1 \text{ exp.}) \sigma$

⊕ Run 1:

Significance: $S = 6.4 (5.4 \text{ exp.}) \sigma$

CMS Phys. Lett. B 779 (2018) 283



SVFIT: J. Phys.: Conf. Ser. 513 022035

Signal strength: $\mu = 1.09 + 0.27 - 0.26$ Significance: $S = 4.9 (4.7 \text{ exp.}) \sigma$

⊕ Run 1:

Significance: $S = 5.9 (5.9 \text{ exp.}) \sigma$

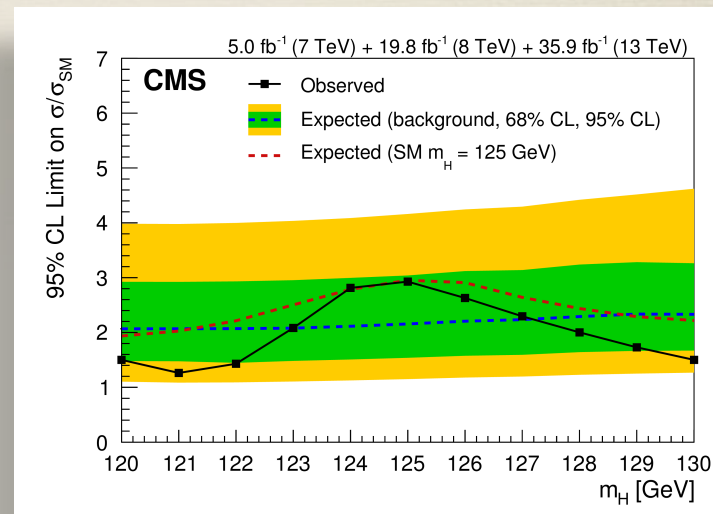
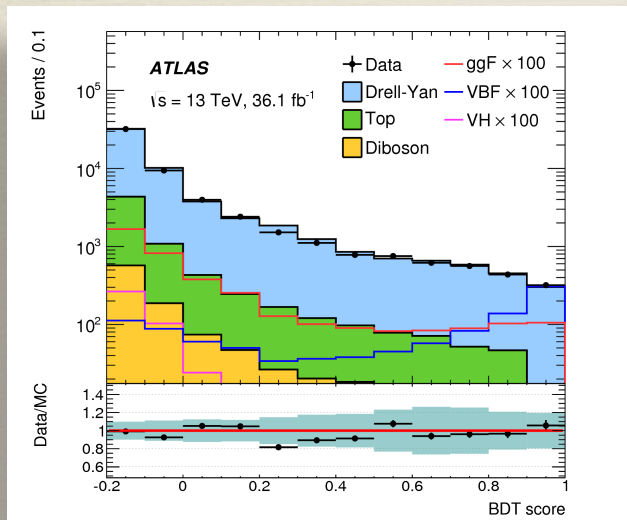
Clear observation!

2018

Run 2 (36 fb⁻¹) H → μμ

ATLAS Phys. Rev. D 99 (2019) 072001

CMS Phys. Rev. Lett. 122, 021801 (2019)



Both analyses use ML-based categories

- ❖ 36.1 fb⁻¹ @ 13 TeV analysed.
- ❖ 8 categories in η , p_T, ggF/VBF
- ❖ Simultaneous ML fit to S+B model
- ❖ No evidence for signal found.

95% CL @ m_H=125.5 GeV:3.0(3.1 exp.) × σ_{SM}⊕ Run 1: 2.8(2.9 exp.) × σ_{SM}

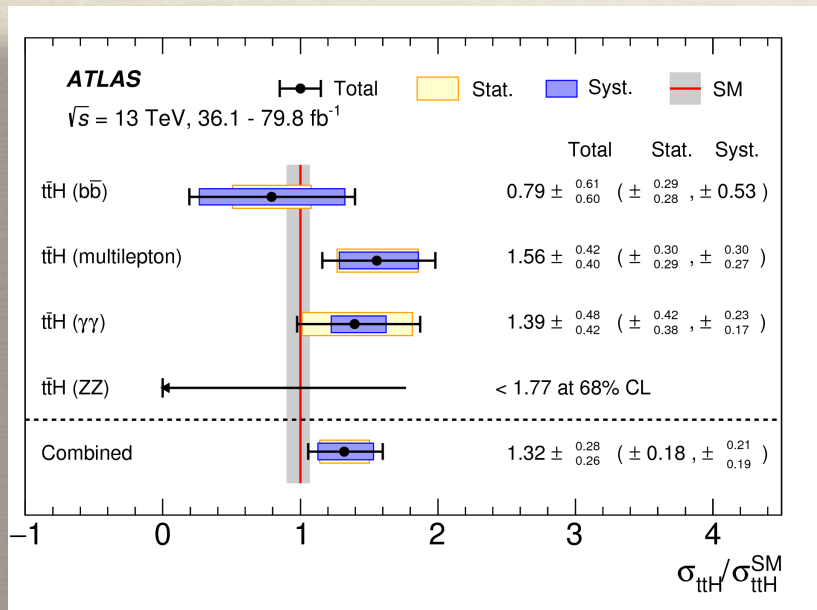
- ❖ 35.9 fb⁻¹ @ 13 TeV analysed.
- ❖ 15 categories based on BDT
- ❖ Simultaneous ML fit to S+B model
- ❖ No evidence for signal found.

95% CL @ m_H=125.5 GeV:3.0(2.5 exp.) × σ_{SM}⊕ Run 1: 2.9(2.2 exp.) × σ_{SM}

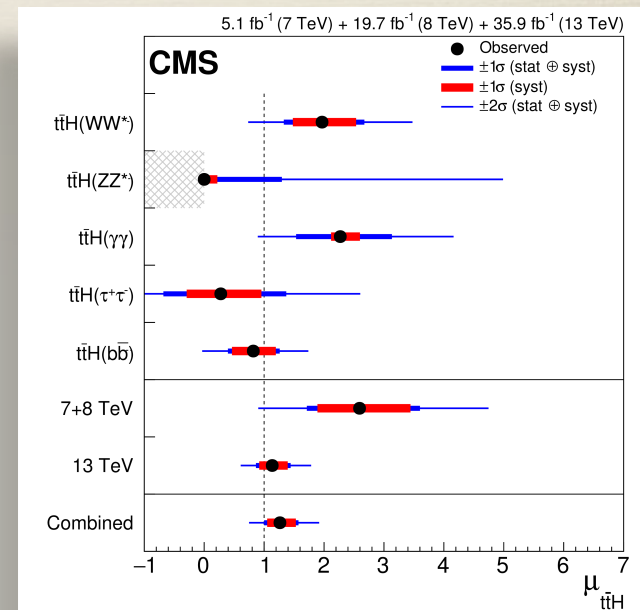
2018

Run 2 $t\bar{t}H$

ATLAS Phys. Lett. B 784 (2018) 173



CMS PRL 120 (2018) 231801

Higgs decays to WW^* , ZZ^* , $\gamma\gamma$, $\tau\tau$, bb consideredMultiple categories. Final ML fit to bins in $\log_{10}(S/B)$ Signal strength: $\mu = 1.32 + 0.28 - 0.26$ Significance: $S = 5.8(4.9 \text{ exp.})\sigma$ $\oplus$ Run 1:Significance: $S = 6.3(5.1 \text{ exp.})\sigma$ Signal strength: $\mu = 1.23 + 0.45 - 0.43$ Significance: $S = 3.2(2.8 \text{ exp.})\sigma$ $\oplus$ Run 1:Significance: $S = 5.2(4.2 \text{ exp.})\sigma$

Observation! At last 😊

2020

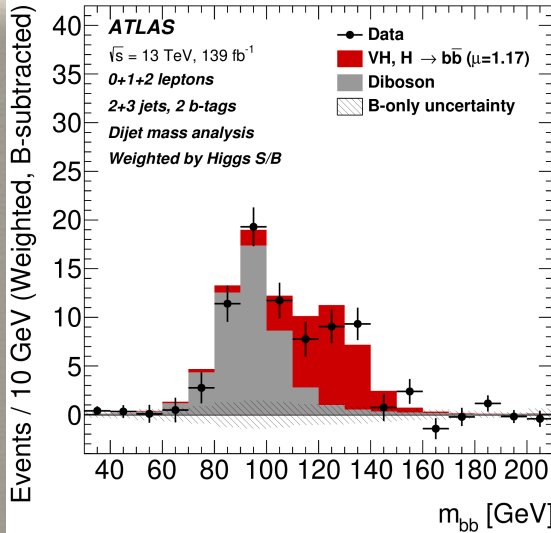
Run 2 (139 fb⁻¹) VH, H→bb

ATLAS

Resolved VH→bb arXiv:2007.02873 (2020)

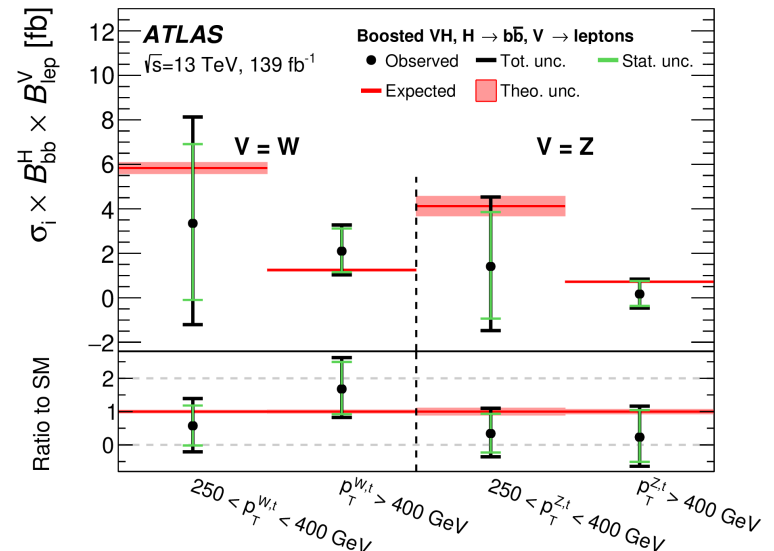
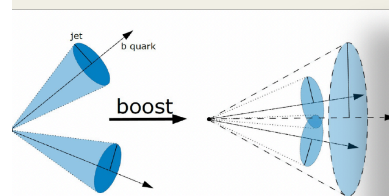
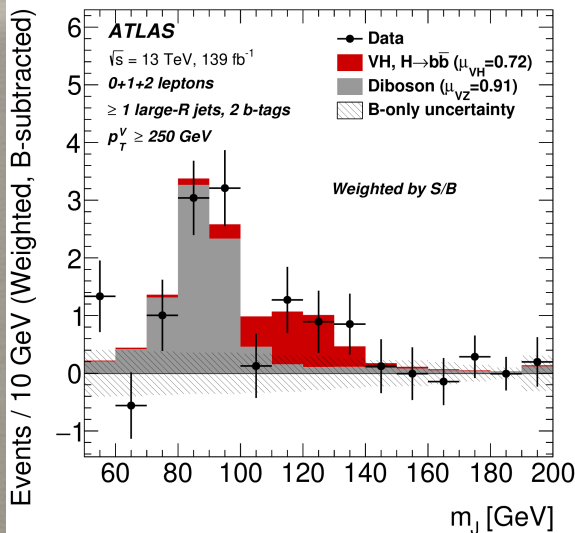
Boosted VH→bb arXiv:2008.02508 (2020)

All backgrounds except VZ subtracted



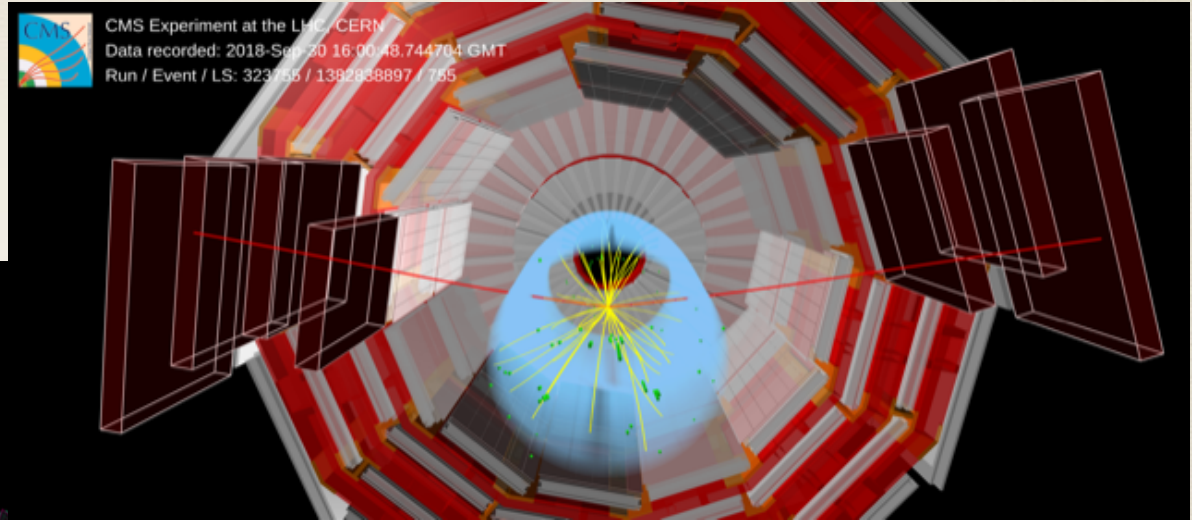
Signal strength: $\mu = 1.02 \pm 0.12 \pm 0.14$
 Significance: $S = 6.7(6.7 \text{ exp.})\sigma$
 Significance (ZH): $S = 5.3(5.1 \text{ exp.})\sigma$

Boosted analysis: measurement at high p_T - increased sensitivity to BSM physics

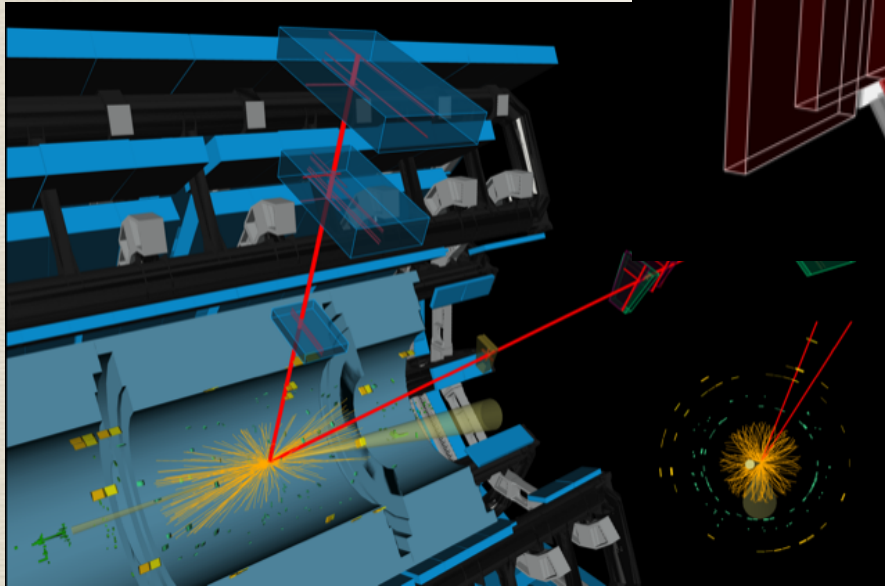


2020

Observation of $H \rightarrow \mu^+ \mu^-$ announced at ICHEP2020



ATLAS: VBF candidate



CMS: ggH 0-jets candidate

Run 2 (139 fb⁻¹)

ATLAS: [arXiv:2007.07830](https://arxiv.org/abs/2007.07830) [hep-ex]

CMS: [arXiv:2009.04363](https://arxiv.org/abs/2009.04363) [hep-ex]

Submitted to: Phys. Lett. B

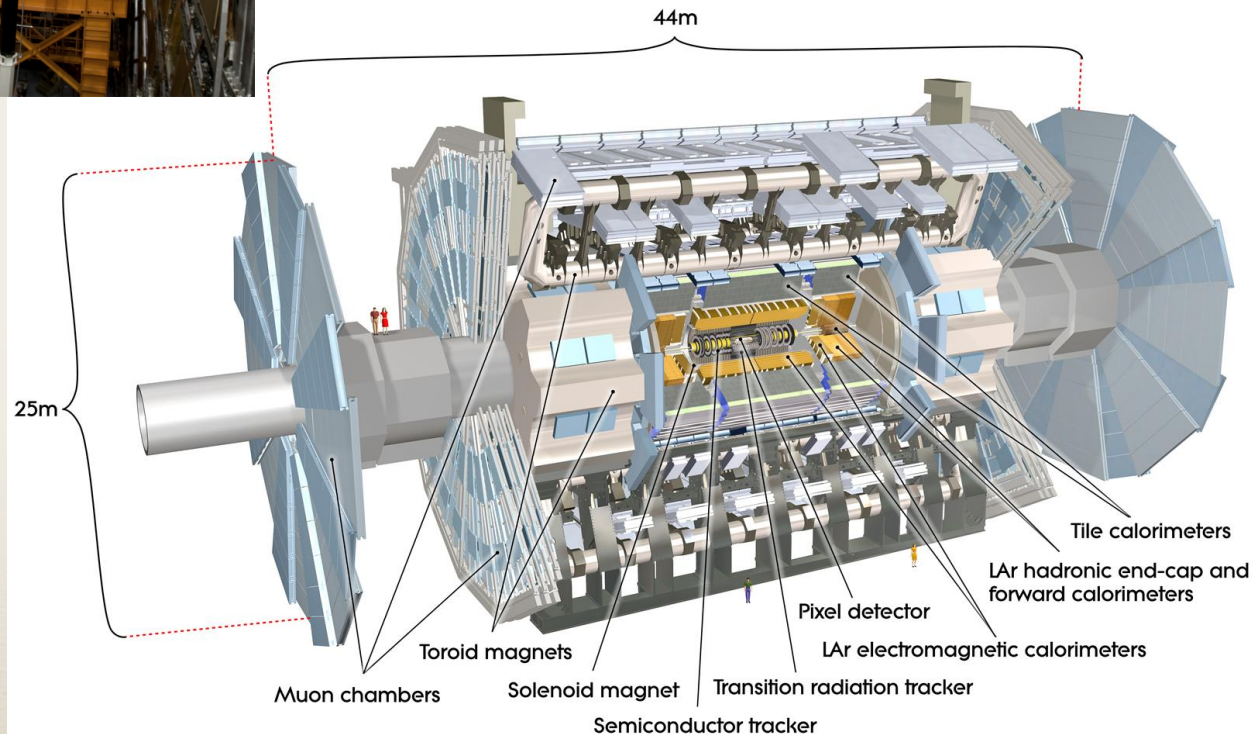
Submitted to: J. High Energy Phys.

ATLAS Detector

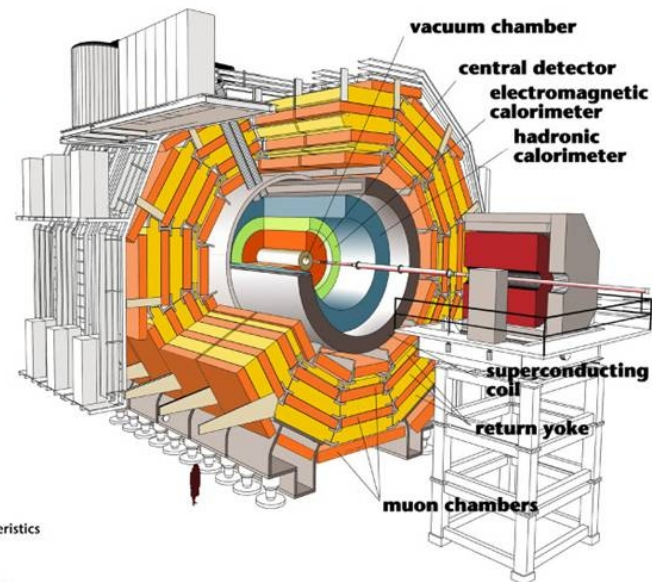
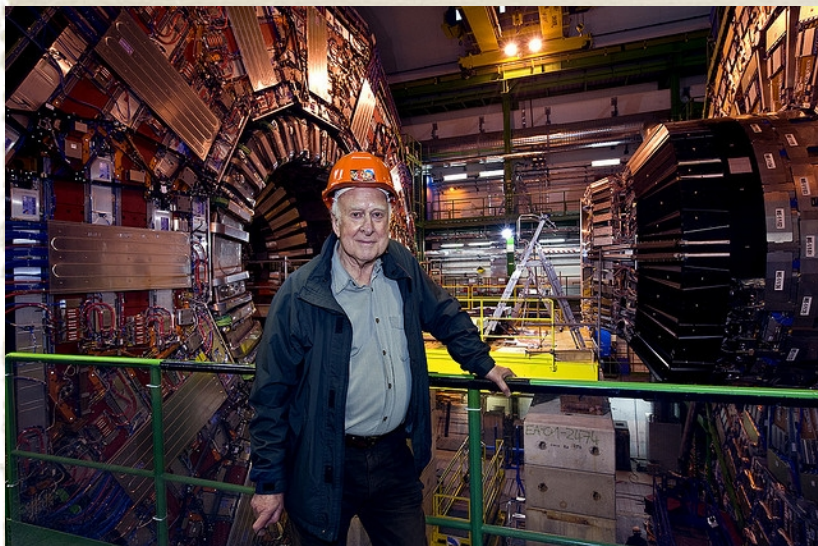


	ATLAS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10 λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03 \text{ GeV}$
Muon	$\sigma/p_T \approx 2\% \text{ @ } 50\text{GeV to } 10\% \text{ @ } 1\text{TeV}$ (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)

ATLAS Collaboration
38 Countries
175 Institutions
3000 Scientific Authors total



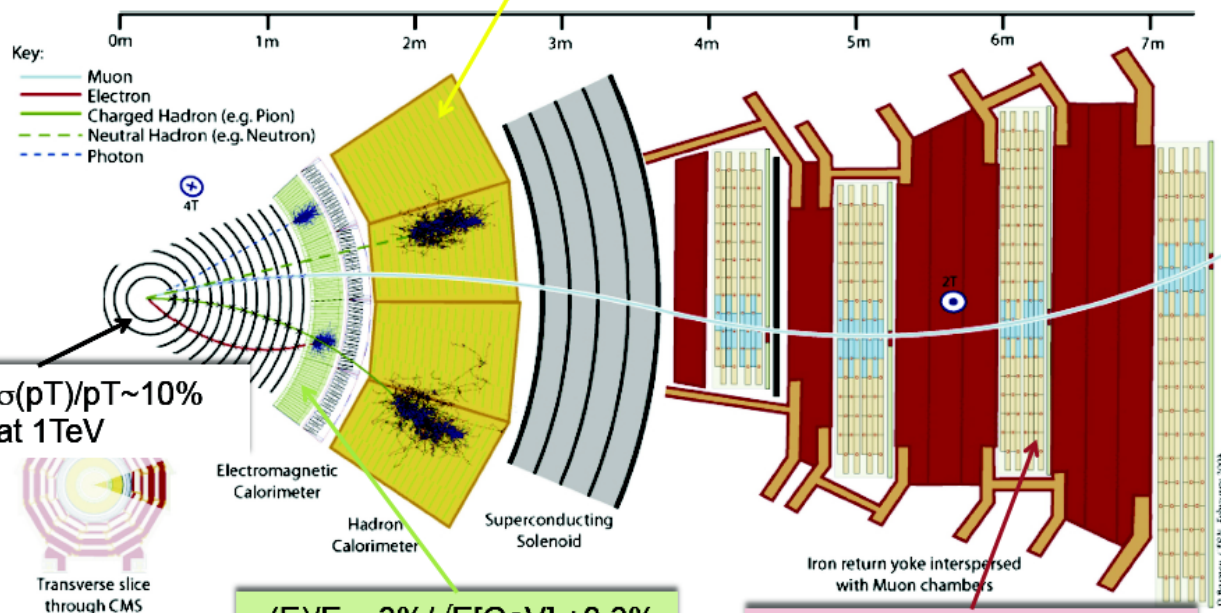
CMS Detector



Detector characteristics

Width: 22m
Diameter: 15m
Magnet: 4.4 T @ 6000 t

$$\sigma(E_T)/E_T \sim 100\%/E_T[\text{GeV}] + 5\%$$



$$\sigma(p_T)/p_T \sim 10\% \text{ at } 1\text{TeV}$$

$$\sigma(E)/E \sim 3\%/E[\text{GeV}] + 0.3\%$$

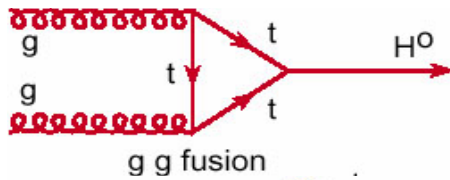
$$\sigma(p_T)/p_T \sim 1\% \text{ @ } 100\text{GeV}$$

$$\sigma(p_T)/p_T \sim 10\% \text{ @ } 1\text{TeV}$$

CMS Collaboration
42 Countries
182 Institutions
3300 Scientific Authors total

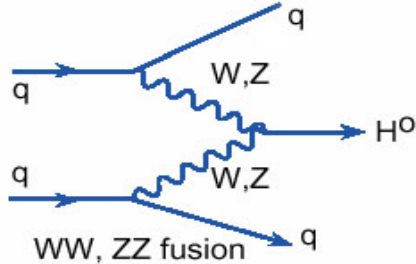
SM Higgs production @ LHC

(for 125 GeV Higgs boson @13 TeV LHC collisions)



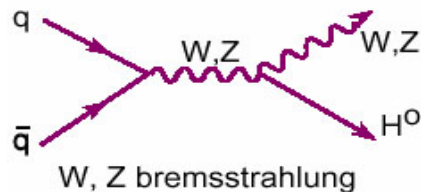
$\sim 48.6 \text{ pb}$

Dominant process. Can exploit high p_T of the Higgs due to recoil against hadronic jets.



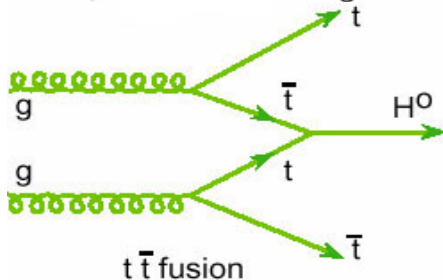
$\sim 3.8 \text{ pb}$

Clean signature with two forward jets and a rapidity gap.



$\sim 2.2 \text{ pb}$

Smaller contribution to significance.
W/Z $\rightarrow$ leptons considered



$\sim 0.5 \text{ pb}$

The smallest contribution
Use b -tagged jets and leptons

Analysis strategy for $H \rightarrow \mu^+ \mu^-$

- ❑ Similar strategy based on optimal combination of multiple selection categories adopted by both experiments.
- ❑ Separate analyses in each production mode allow optimization for different background compositions and signal purity.
- ❑ The dominant backgrounds come from $Z/\gamma \rightarrow \mu^+ \mu^-$ DY, diboson and $t\bar{t}$ production.
- ❑ Define mutually exclusive categories motivated by Higgs production modes and kinematics:
 - **VBF**: tagged by 2 forward jets in opposite hemispheres with large rapidity difference. Usually gives the highest significance
 - **ggH**: target ggF topology, further classified according to the multivariate discriminant (BDT).
 - **VH**: target H associated production with W/Z, tagged by the leptonic W/Z decay.
 - **t $\bar{t}$ H**: tagged by the presence of b -jets (and additional leptons)

Basic selections

ATLAS (139 fb⁻¹)

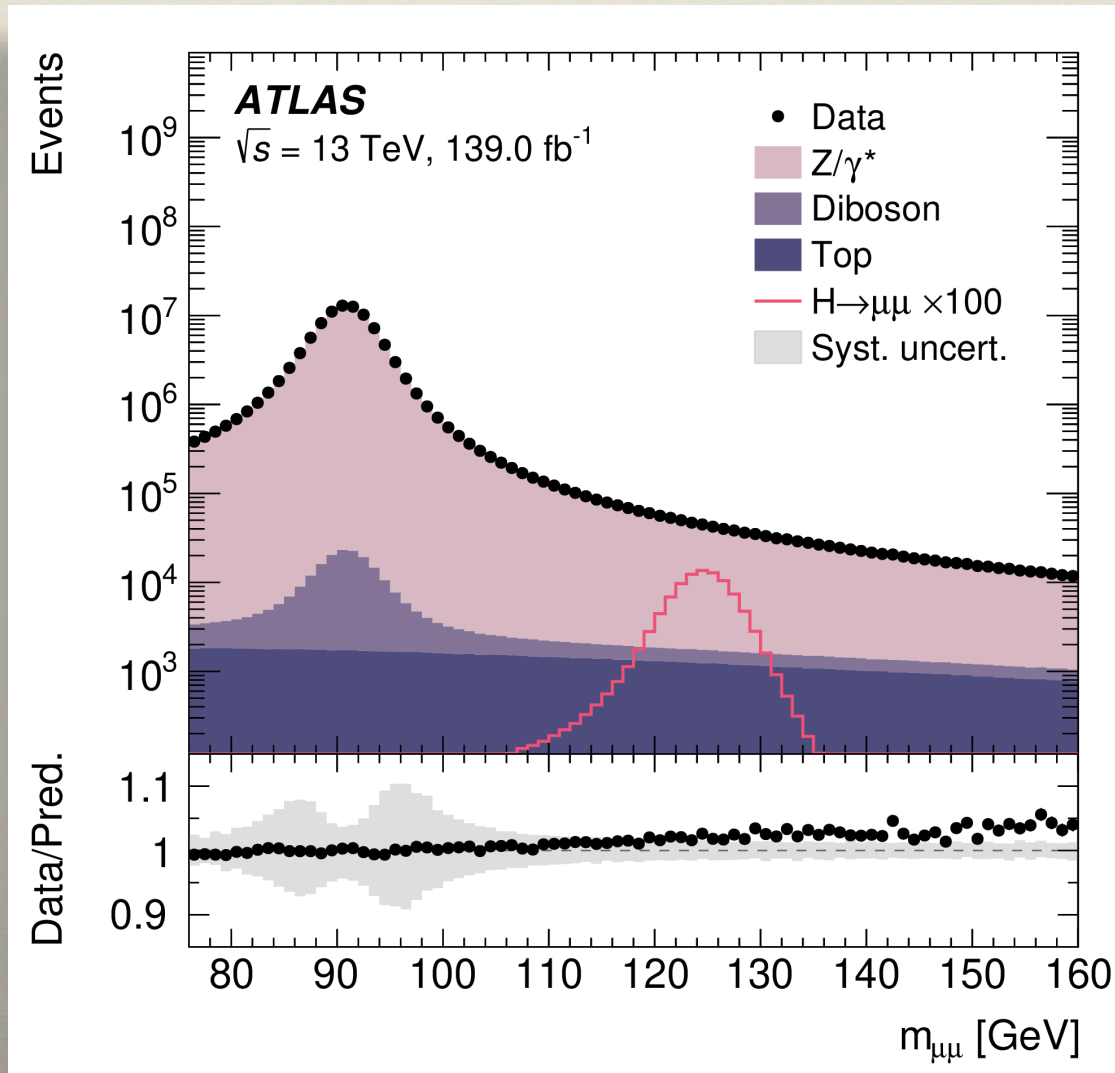
- Single muon trigger
26 GeV(isolated)/50 GeV
- Two OS muons
 $p_T > 27/15 \text{ GeV}$, $|\eta| < 2.7$
- Central jets:
 $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$
- Forward jets:
 $p_T > 30 \text{ GeV}$, $2.4 < |\eta| < 4.5$
- $110 < m_{\mu\mu} < 160 \text{ GeV}$
- Additional photon added to $m_{\mu\mu}$ if:
 $\Delta R(\gamma, \mu) < 0.2$ & $p_T^\gamma < 8 \text{ GeV}$ (FSR)

CMS (137 fb⁻¹)

- Single muon trigger
27(24) GeV
- Two OS muons
 $p_T > 29(26)/20 \text{ GeV}$, $|\eta| < 2.4$
- Jets:
 $p_T > 25 \text{ GeV}$, $|\eta| < 4.7$
- $110 < m_{\mu\mu} < 150 \text{ GeV}$
- Additional photon added to $m_{\mu\mu}$ if:
 $\Delta R(\gamma, \mu) < 0.5$ & $p_T^\gamma / p_T^\mu < 0.4$ (FSR)

Looking for a needle in a haystack!

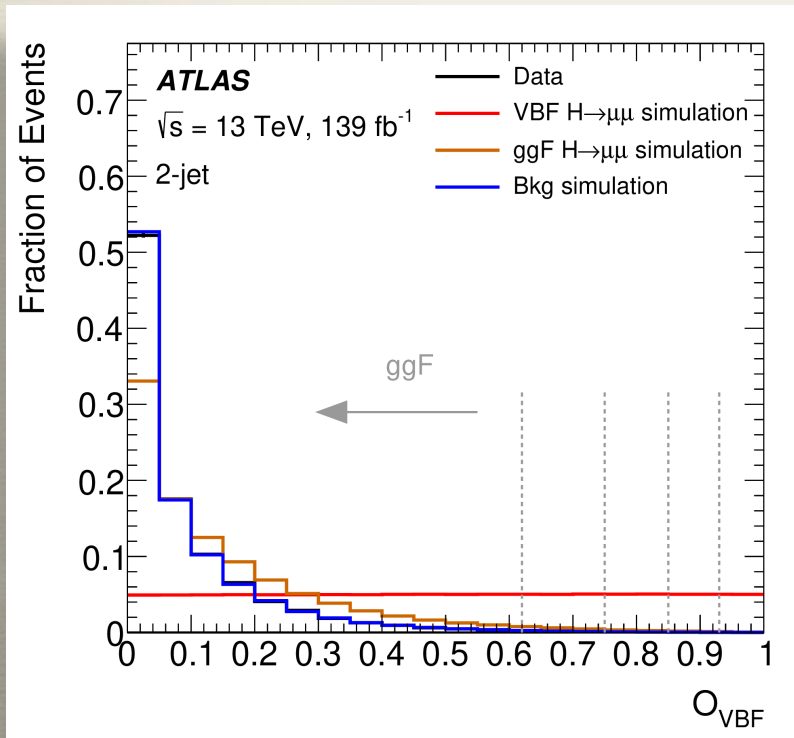
$m_{\mu\mu}$ after preselection



VBF category

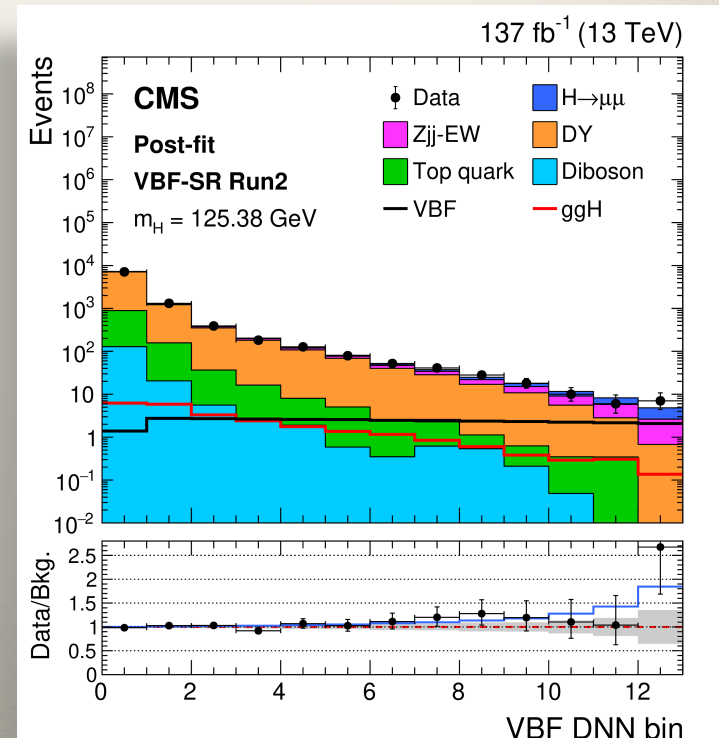
ATLAS

- Two jets
- Veto: b -jets & additional leptons
- BDT (O_{VBF}) based on 17 variables which include $\mu\mu$ and jj kinematics
- 4 categories with S/B ranging from 18% to 2.8%



CMS

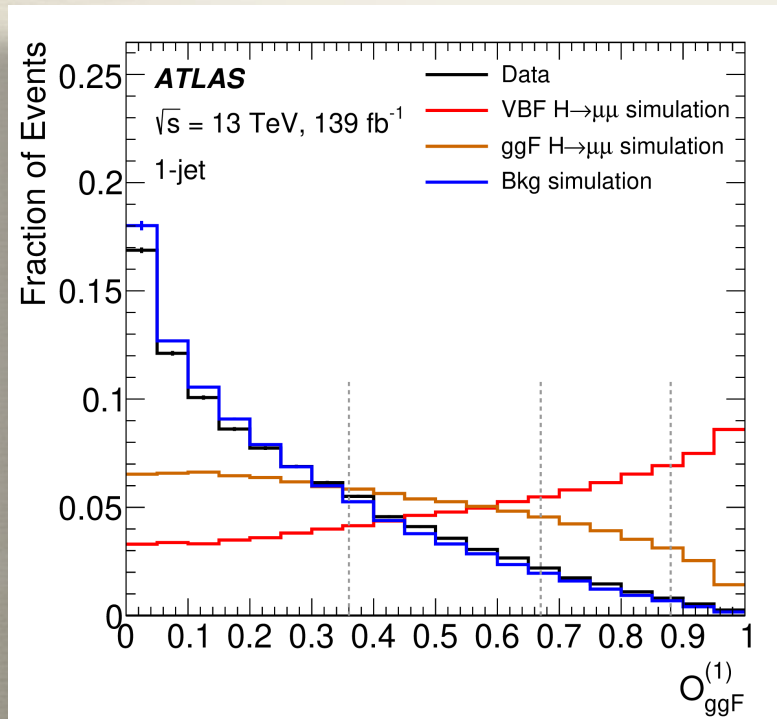
- Two jets
- $m_{jj} > 400 \text{ GeV}, |\Delta \eta_{jj}| > 2.5$
- SR: $115 < m_{\mu\mu} < 135 \text{ GeV}$
- SB: $110 < m_{\mu\mu} < 115$ & $135 < m_{\mu\mu} < 150 \text{ GeV}$
- DNN classifier with 17 variables
- $N_{\text{soft track-jet}}, H_{\text{T soft track-jet}}, L(q/g)$



ggH category

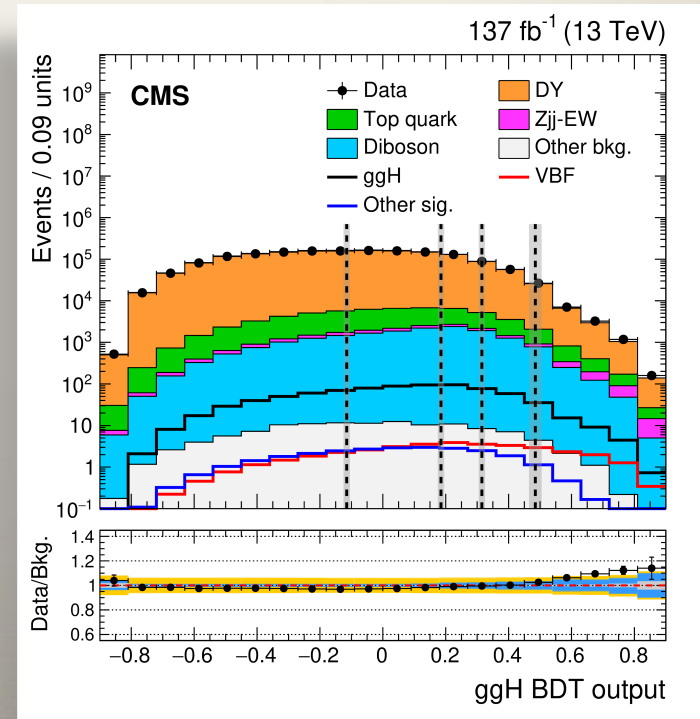
ATLAS

- Three jet categories (0-2),
- BDT ($O_{ggF}^{(0-2)}$) based on up to 17 variables which include $\mu\mu$ and optionally jet kinematics
- 3x4 categories with S/B ranging from 1.7% to 0.07%



CMS

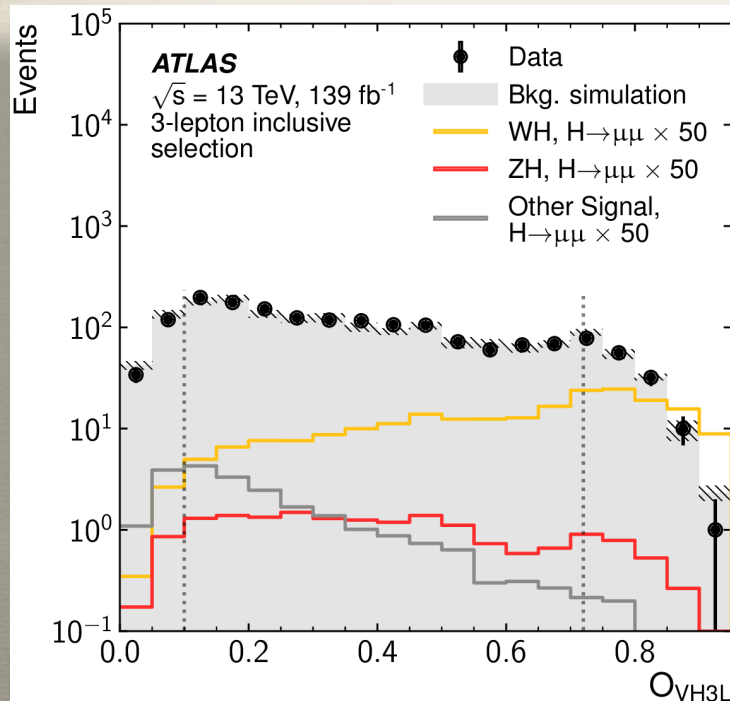
- Veto: b -jets & additional leptons
- $N_{\text{jets}} > 1$: $m_{jj} < 400 \text{ GeV}$ or $|\Delta\eta_{jj}| < 2.5$
- BDT based on up to 21 variables
- 5 categories defined based on the BDT discriminant



VH category

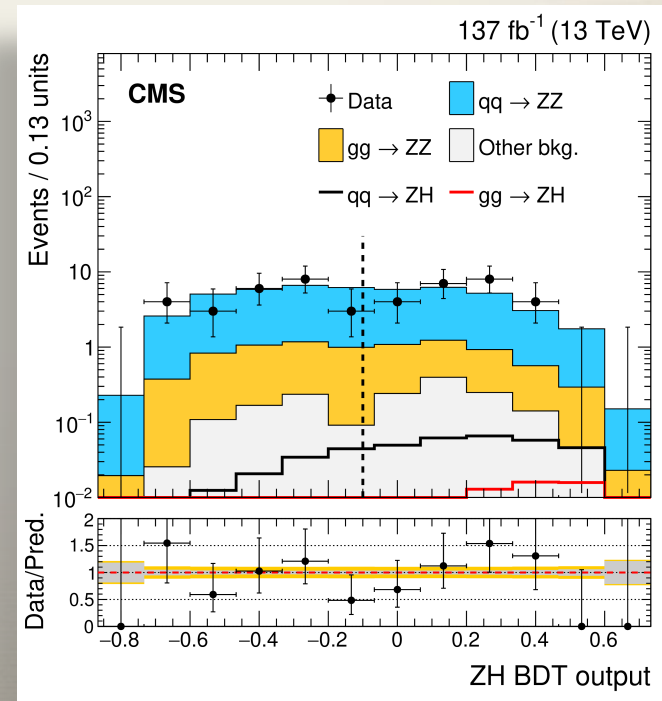
ATLAS

- Veto: b -jets
- Additional isolated $\mu(e)$ $p_T > 10(15)$
- Two separate BDT's targeting WH and ZH final states
- 2 WH and 1 ZH signal categories defined with S/B ranging from 3.7% to 0.8%



CMS

- Veto: b -jets
- Additional isolated $\mu(e)$ $p_T > 20$ GeV
- Two separate BDT's targeting WH and ZH final states
- 3 WH and 2 ZH signal categories defined



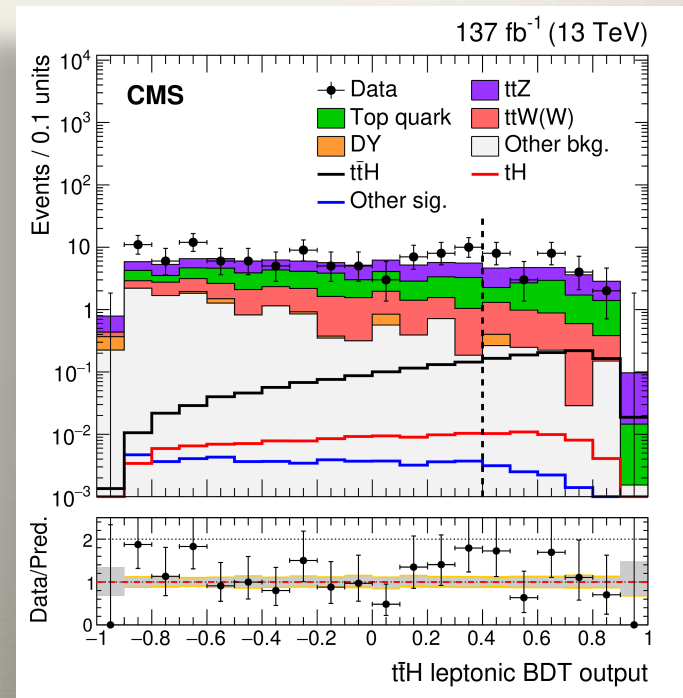
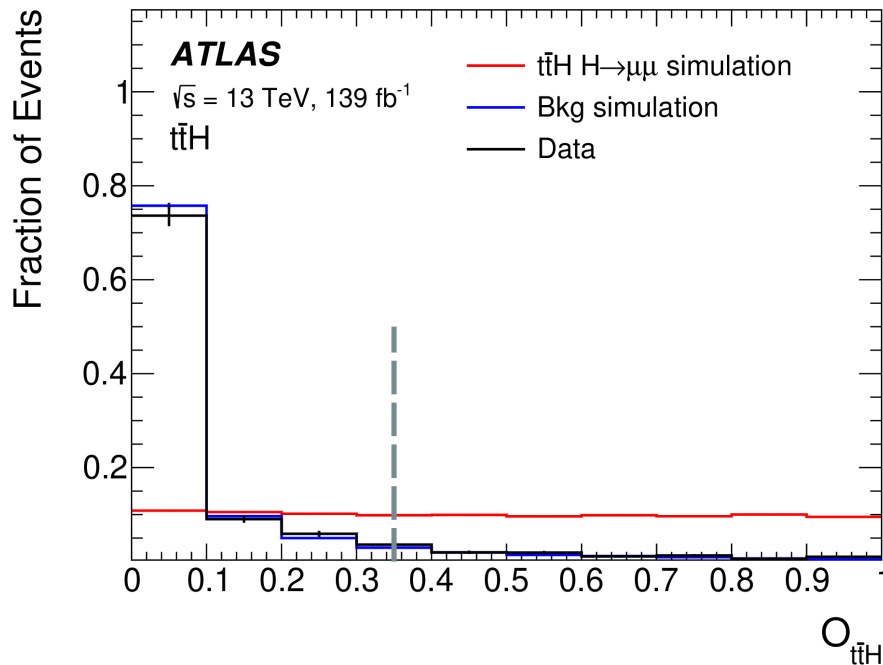
ttH category

ATLAS

- At least one b -jet (85% WP)
- Additional isolated $\mu(e)$ $p_T > 15$ GeV
- BDT taking 12 inputs, including multiplicity of b -jets
- ttH category optimizes expected significance, with S/B of 8%

CMS

- At least 1(2) b -jets med(loose) WP
- 0(1,2) additional leptons
- $N_{\text{jets}} \geq 3(2)$
- $100 < m_{\text{j}jj} < 300$
- Hadronic(leptonic) BDT score define 3(2) further sub-categories



SM Yields & Signal Resolution

ATLAS

$m_{\mu\mu} \in 120\text{--}130\text{ GeV}$:

- VBF: 18.6 / 369
- ggF: 843.0 / 441185
- VH: 4.7 / 412
- ttH: 1.2 / 15

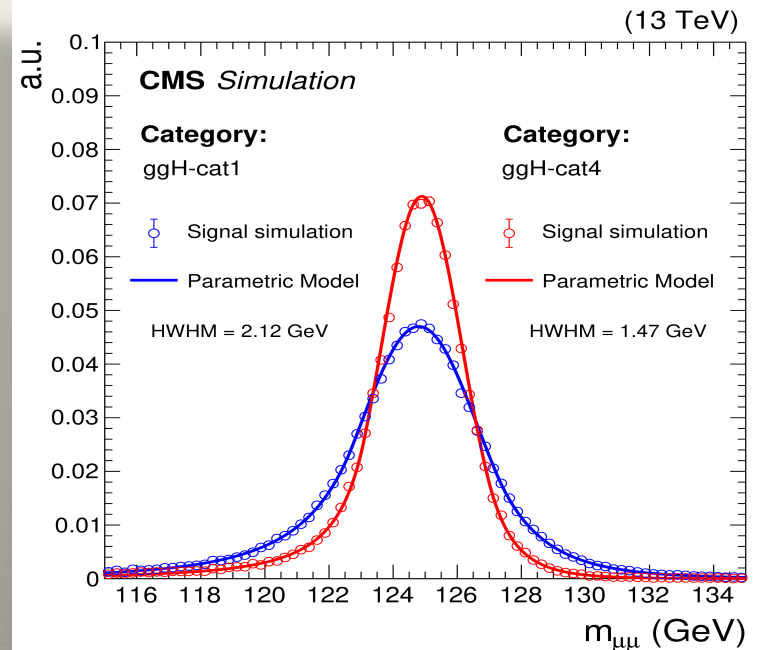
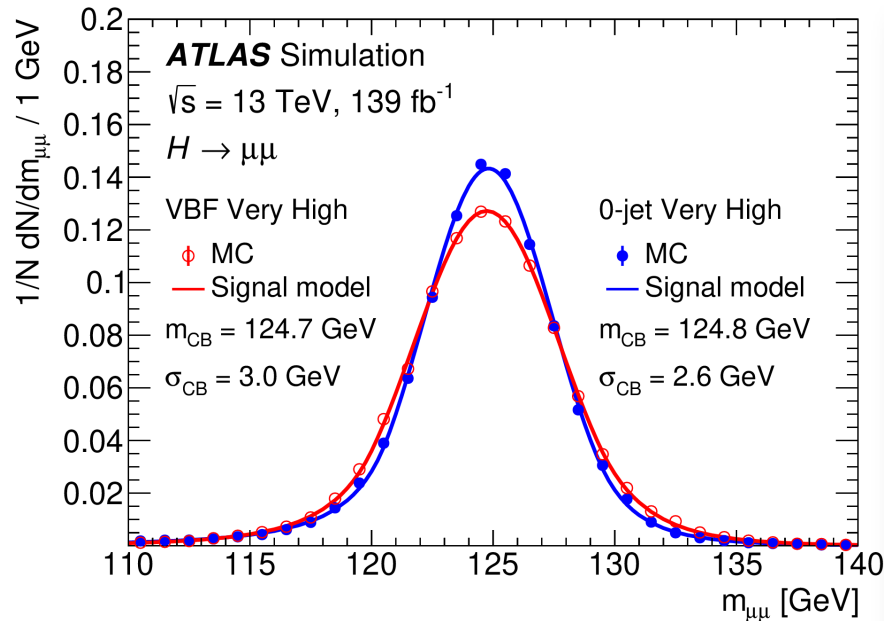
(~52% overall efficiency)

CMS

$m_{\mu\mu} \in 115\text{--}135\text{ GeV}$:

- VBF: 48.0 / 9420 (28.5/530)
- $m_{\mu\mu} \in 125.38\text{ GeV} \pm \text{HWHM}$:
- ggF: 890.8 / 155310
- VH: 4.1 / 65
- ttH: 11.9 / 4403 (2.0/11)

(~58% overall efficiency)



Fitting Signal Yields

Simultaneous binned maximum-likelihood fit to all categories with signal strength POI: $\mu = \sigma \times B(H \rightarrow \mu\mu)_{\text{obs}} / \sigma \times B(H \rightarrow \mu\mu)_{\text{SM}}$

ATLAS

❖ All categories:
to $m_{\mu\mu}$ in the range 110–160 GeV

Signal model: DS Crystall Ball (Gauss + power law tails)

Background model:
DY line-shape convolved with a Gaussian multiplied by empirical:

Function	Expression
PowerN	$m_{\mu\mu}^{(a_0 + a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \dots + a_N m_{\mu\mu}^N)}$
EpolyN	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \dots + a_N m_{\mu\mu}^N)$

CMS

❖ VBF:
to 13 bins of DNN discriminator, simultaneously in SR & SB, data-taking periods. DNN is trained in the SR, evaluated in SR and SB (with $m_{\mu\mu}=125$)

❖ ggH , VH , ttH :
to $m_{\mu\mu}$ in the range 110–150 GeV

Signal model: DS Crystall Ball

Background model:
DY line-shape/mBW/third order Bernstein poly modulated by a third/second order polynomial

Uncertainties

The measurement is statistically dominated.

Systematics considered include:

1. Experimental uncertainties (efficiencies, energy scales, resolutions, etc.),
2. Background modeling (parametric background model),
3. Theory uncertainties on signal yield,
4. Luminosity.

ATLAS

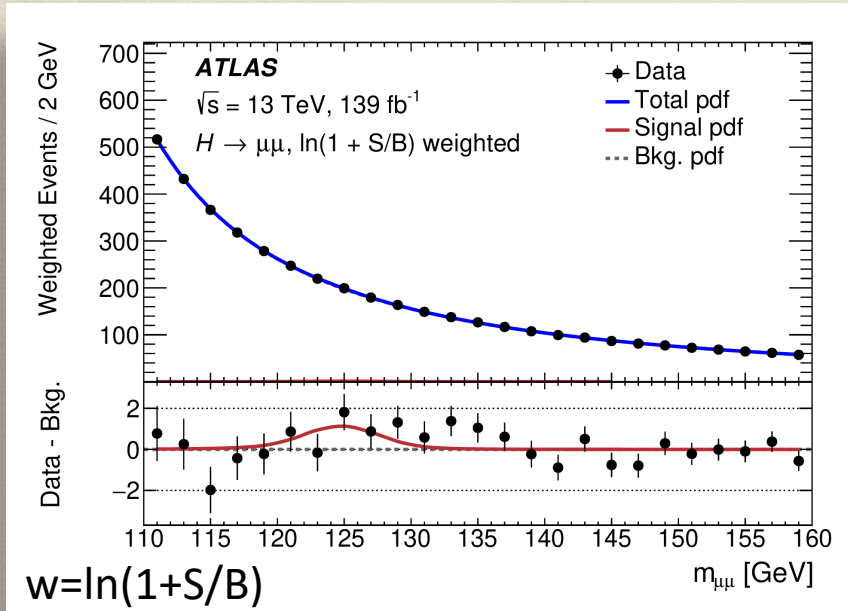
- Systematic uncertainties estimated via spurious-signal tests, i.e. signal obtained with signal-plus-background fits to the background-only MC.

CMS

- Systematic uncertainties modelled as nuisance parameters in the binned maximum-likelihood fit.
- Bias observed on pseudo-data fits to $m_{\mu\mu}$.

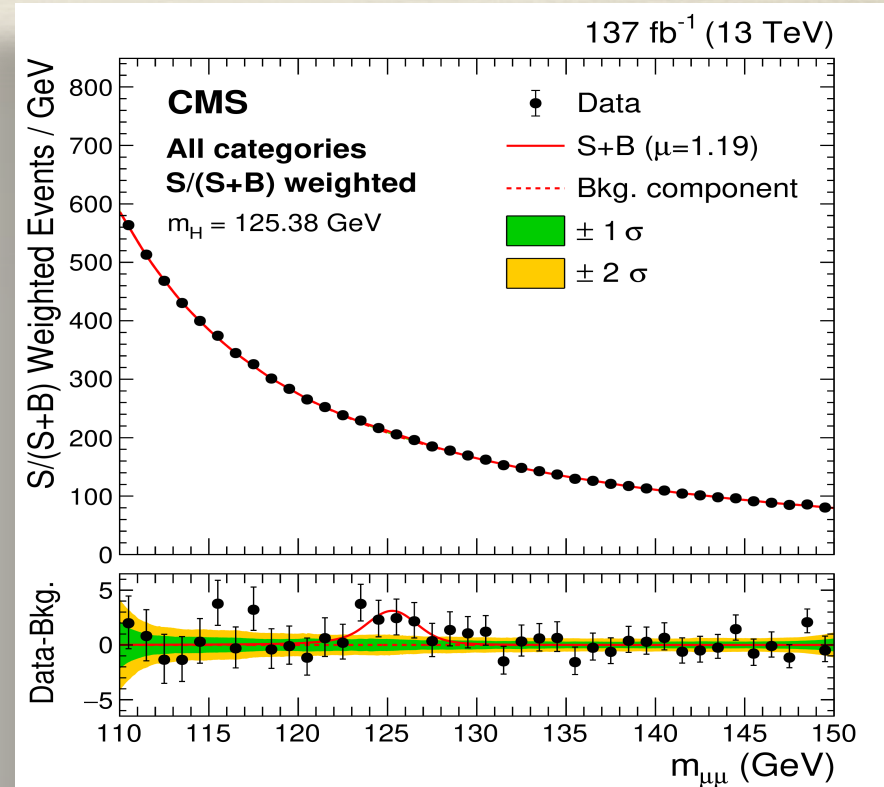
Results

ATLAS



Best fit signal strength: $\mu = 1.2 \pm 0.6$
 Obs. (exp.) significance: $S = 2.0\sigma$ (1.7σ)

CMS

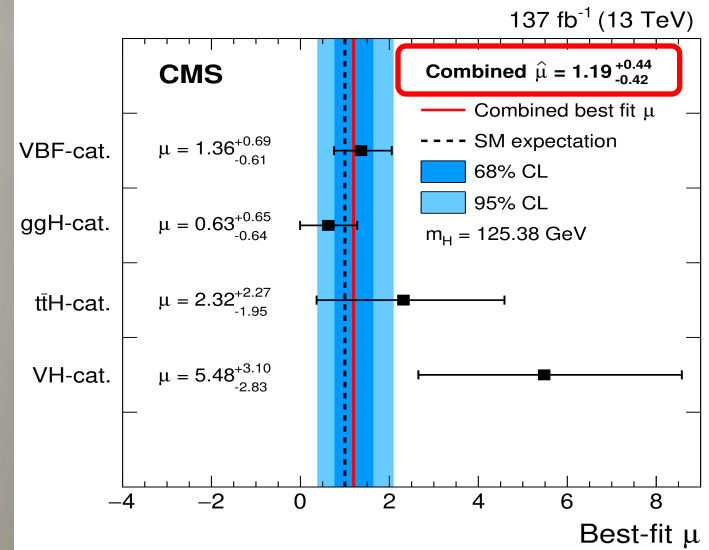
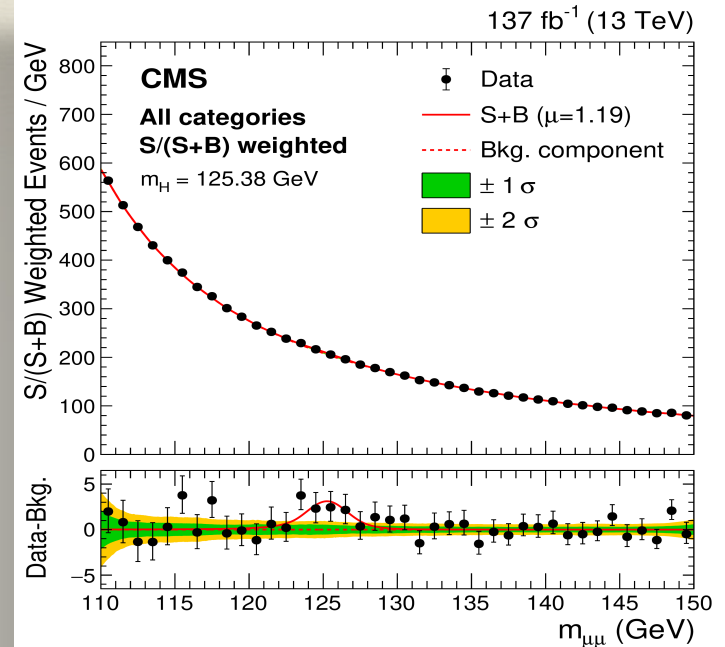
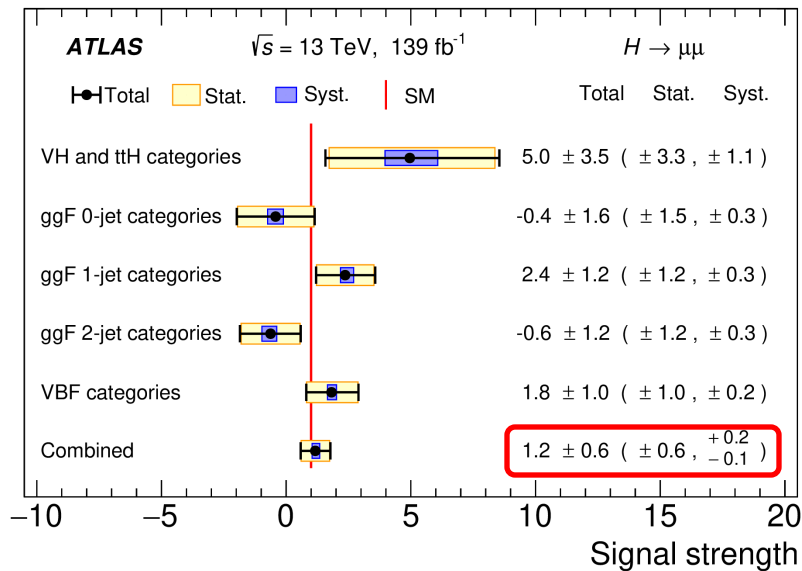
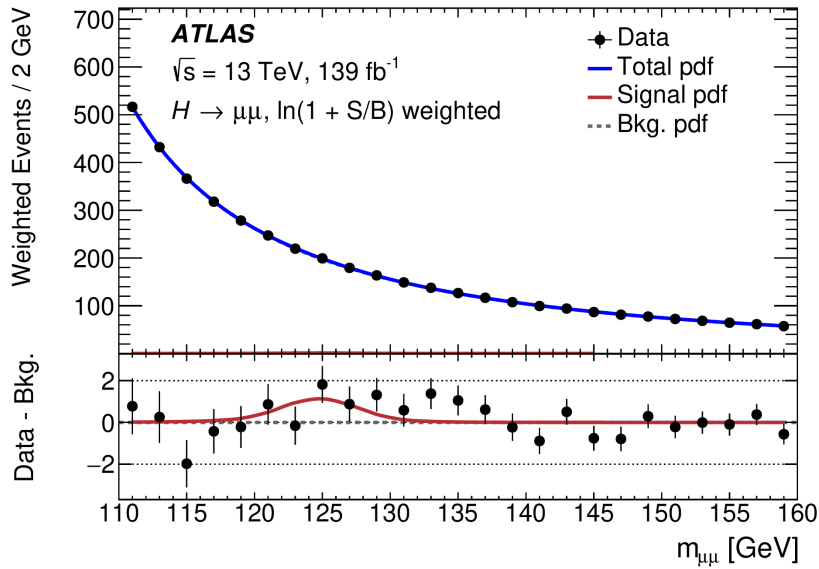


Best fit signal strength: $\mu = 1.19 \pm 0.41 \pm 0.16$
 Obs. (exp.) significance: $S = 2.95\sigma$ (2.46σ)
 $\oplus$ Run 1 (*Phys. Lett. B* **744** (2015) 184)
 Best fit signal strength: $\mu = 1.19 \pm 0.40 \pm 0.15$
 Obs. (exp.) significance: $S = 2.98\sigma$ (2.48σ)

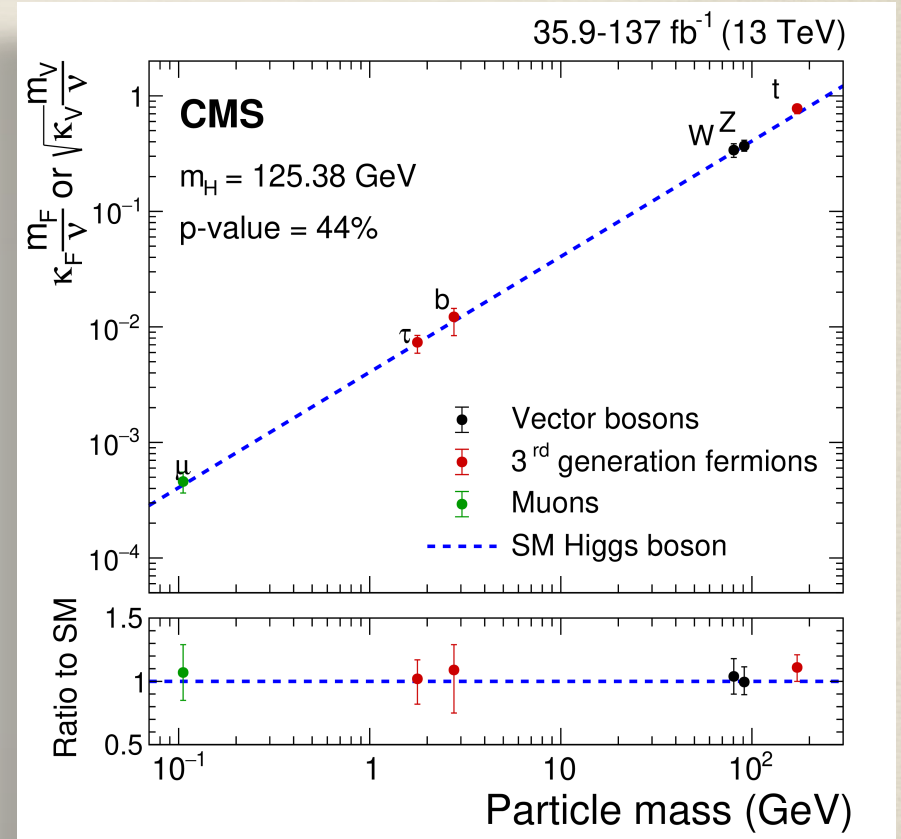
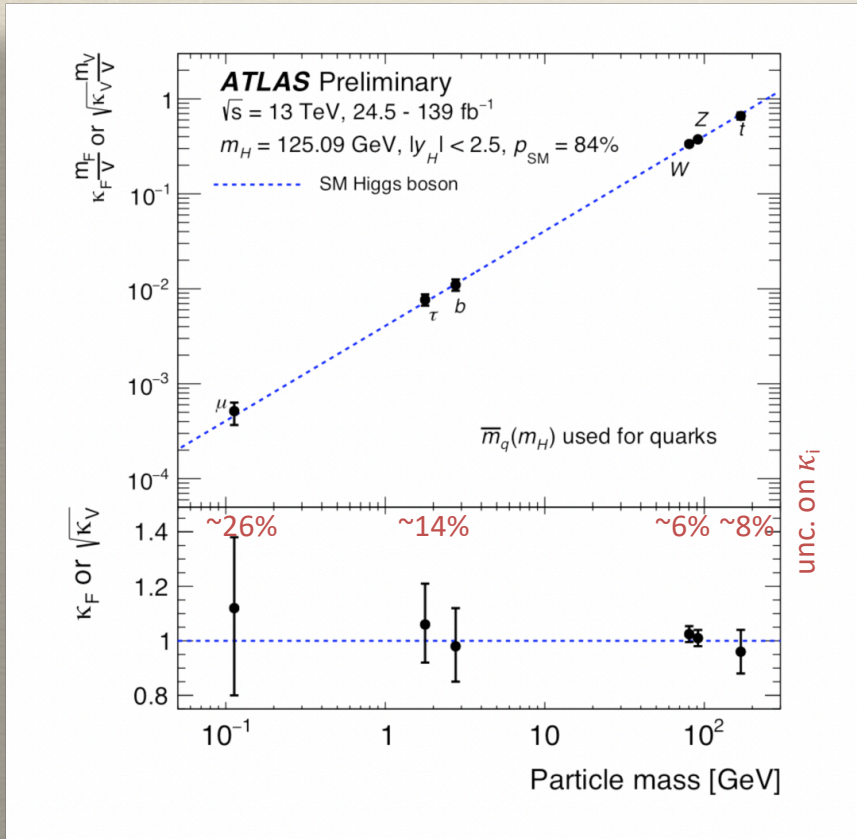
ATLAS

Results

CMS



Where are we now?



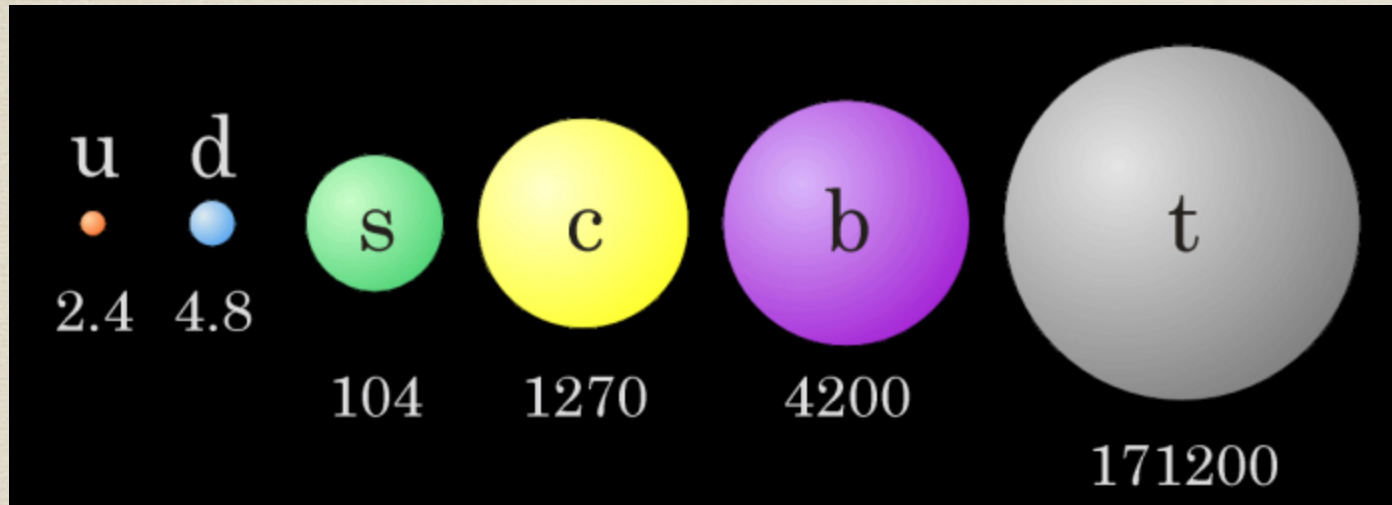
Excellent agreement of couplings across three orders of magnitude of particle mass!

CONCLUSIONS

- ❖ Yukawa Higgs sector being explored since 2012.
- ❖ It could hint to a richer scalar structure.
- ❖ No indirect evidence for leptonic couplings.
- ❖ Due to mass hierarchy 2-nd generation particularly challenging. Most promising: muon.
- ❖ First evidence for $H \rightarrow \mu\mu$ at ICHEP2020
- ❖ The measurement is statistically limited
- ❖ With 3000 fb^{-1} @ 14 TeV, $\sigma(\mu\mu) < 0.2$.
- ❖ HL LHC will allow to explore leptonic Yukawa sector in much detail.
- ❖ So far SM minimal Higgs sector holds strong!

THANK YOU.

This is not the end of the story...



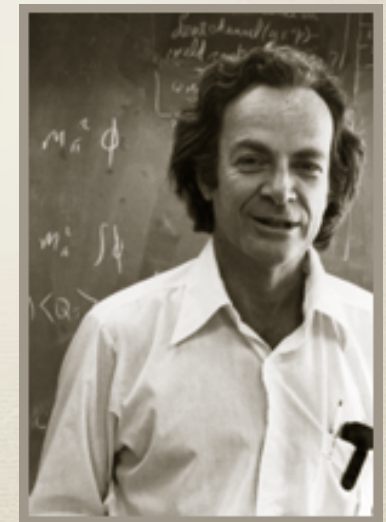
Three generations of matter (fermions)

	I	II	III	
mass →	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²
	-1	-1	-1	±1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	e electron	μ muon	τ tau	W[±] W boson

Gauge bosons

- ▶ Do you want to be famous?
- ▶ Do you want to be a king?
- ▶ Do you want more than the Nobel Prize?

- Then solve the mass problem -
R.P. Feynman



BONUS MATERIAL

ATLAS selections

Selection	
Common preselection	Primary vertex
	Two opposite-charge muons
	Muons: $ \eta < 2.7$, $p_T^{\text{lead}} > 27 \text{ GeV}$, $p_T^{\text{sublead}} > 15 \text{ GeV}$ (except VH 3-lepton)
Fit Region	$110 < m_{\mu\mu} < 160 \text{ GeV}$
Jets	$p_T > 25 \text{ GeV}$ and $ \eta < 2.4$
	or with $p_T > 30 \text{ GeV}$ and $2.4 < \eta < 4.5$
$t\bar{t}H$ Category	at least one additional e or μ with $p_T > 15 \text{ GeV}$, at least one b -jet (85% WP)
VH 3-lepton Categories	$p_T^{\text{sublead}} > 10 \text{ GeV}$, one additional e (μ) with $p_T > 15(10) \text{ GeV}$, no b -jets (85% WP)
VH 4-lepton Category	at least two additional e or μ with $p_T > 8, 6 \text{ GeV}$, no b -jets (85% WP)
$ggF + VBF$ Categories	no additional μ , no b -jets (60% WP)

ATLAS event yields

Category	ggF	VBF	WH	ZH	$t\bar{t}H$
VBF Very High	6.6%	93.3%	0.0%	0.0%	0.0%
VBF High	12.8%	87.1%	0.0%	0.0%	0.0%
VBF Medium	21.3%	78.5%	0.1%	0.1%	0.0%
VBF Low	34.8%	64.8%	0.2%	0.2%	0.0%
2-jet Very High	82.0%	15.7%	1.2%	1.0%	0.2%
2-jet High	79.3%	16.0%	2.7%	1.8%	0.3%
2-jet Medium	80.7%	10.4%	5.4%	3.0%	0.5%
2-jet Low	78.2%	6.6%	8.8%	4.9%	1.5%
1-jet Very High	78.2%	21.2%	0.3%	0.3%	0.0%
1-jet High	88.2%	10.4%	0.9%	0.6%	0.0%
1-jet Medium	91.4%	6.1%	1.6%	0.9%	0.0%
1-jet Low	92.4%	3.8%	2.6%	1.2%	0.0%
0-jet Very High	94.1%	2.5%	1.4%	2.0%	0.0%
0-jet High	98.3%	1.0%	0.4%	0.3%	0.0%
0-jet Medium	99.1%	0.6%	0.2%	0.1%	0.0%
0-jet Low	99.5%	0.3%	0.1%	0.1%	0.0%
VH4L	0.0%	0.0%	0.1%	99.5%	0.4%
VH3LH	0.3%	0.1%	96.9%	2.6%	0.1%
VH3LM	4.2%	1.0%	80.8%	8.6%	5.3%
$t\bar{t}H$	0.1%	0.0%	1.5%	0.4%	98.0%

CMS selections

VBF

Observable	VBF-SB	VBF-SR
Number of loose (medium) b-tagged jets	≤ 1 (0)	
Number of selected muons	$= 2$	
Number of selected electrons	$= 0$	
Jet multiplicity ($p_T > 25 \text{ GeV}$, $ \eta < 4.7$)	≥ 2	
Leading jet p_T	$\geq 35 \text{ GeV}$	
Dijet mass (m_{jj})	$\geq 400 \text{ GeV}$	
Pseudorapidity separation ($ \Delta\eta_{jj} $)	≥ 2.5	
Dimuon invariant mass	$110 < m_{\mu\mu} < 115 \text{ GeV}$ or $135 < m_{\mu\mu} < 150 \text{ GeV}$	$115 < m_{\mu\mu} < 135 \text{ GeV}$

ggH

Observable	Selection
Number of loose (medium) b-tagged jets	≤ 1 (0)
Number of selected muons	$= 2$
Number of selected electrons	$= 0$
VBF selection veto	if $N_{\text{jets}} \geq 2$ $m_{jj} < 400 \text{ GeV}$ or $ \Delta\eta_{jj} < 2.5$ or $p_T(j_1) < 35 \text{ GeV}$

VH

Observable	WH leptonic		ZH leptonic	
	$\mu\mu\mu$	$\mu\mu e$	4μ	$2\mu 2e$
Number of loose (medium) b-tagged jets	≤ 1 (0)	≤ 1 (0)	≤ 1 (0)	≤ 1 (0)
Number of selected muons	$= 3$	$= 2$	$= 4$	$= 2$
Number of selected electrons	$= 0$	$= 1$	$= 0$	$= 2$
Lepton charge ($q(\ell)$)	$\sum q(\ell) = \pm 1$		$\sum q(\ell) = 0$	
Low-mass resonance veto	$m_{\ell\ell} > 12 \text{ GeV}$			
$N(\mu^+\mu^-)$ pairs with $110 < m_{\mu\mu} < 150 \text{ GeV}$	≥ 1	$= 1$	≥ 1	$= 1$
$N(\mu^+\mu^-)$ pairs with $ m_{\mu\mu} - m_Z < 10 \text{ GeV}$	$= 0$	$= 0$	$= 1$	$= 0$
$N(e^+e^-)$ pairs with $ m_{ee} - m_Z < 20 \text{ GeV}$	$= 0$	$= 0$	$= 1$	$= 1$

ttH

Observable	ttH hadronic	ttH leptonic
Number of b quark jets	> 0 medium or > 1 loose b-tagged jets	
Number of leptons ($N(\ell = \mu, e)$)	$= 2$	$= 3$ or 4
Lepton charge ($q(\ell)$)	$\sum q(\ell) = 0$	$N(\ell) = 3$ (4) $\rightarrow \sum q(\ell) = \pm 1$ (0)
Jet multiplicity ($p_T > 25 \text{ GeV}$, $ \eta < 4.7$)	≥ 3	≥ 2
Leading jet p_T	$> 50 \text{ GeV}$	$> 35 \text{ GeV}$
Z boson veto	—	$ m_{\ell\ell} - m_Z > 10 \text{ GeV}$
Low-mass resonance veto	—	$m_{\ell\ell} > 12 \text{ GeV}$
Jet triplet mass	$100 < m_{jjj} < 300 \text{ GeV}$	—

CMS event yields

VBF

Event category	Total signal	ggH (%)	VBF (%)	Other (%)	HWHM (GeV)	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	S/ $\sqrt{B}$ @HWHM
ggH-cat1	268	93.7	2.9	3.4	2.12	86 360	86 632	0.20	0.60
ggH-cat2	312	93.5	3.4	3.1	1.75	46 350	46 393	0.46	0.98
ggH-cat3	131	93.2	4.0	2.8	1.60	12 660	12 738	0.70	0.80
ggH-cat4	126	91.5	5.5	3.0	1.47	8260	8377	1.03	0.96
ggH-cat5	53.8	83.5	14.3	2.2	1.50	1680	1711	2.16	0.91

ggH

DNN bin	Total signal	VBF (%)	ggH (%)	Bkg. $\pm \Delta B$	Data	S/(S+B) (%)	S/ $\sqrt{B}$
1-3	19.5	30	70	8890 ± 67	8815	0.22	0.21
4-6	11.6	57	43	394 ± 8	388	2.86	0.58
7-9	8.43	73	27	103 ± 4	121	7.56	0.83
10	2.30	85	15	15.1 ± 1.4	18	13.2	0.59
11	2.15	88	12	9.1 ± 1.2	10	19.1	0.71
12	2.10	87	13	5.8 ± 1.1	6	26.6	0.87
13	1.87	94	6	2.6 ± 0.9	7	41.8	1.16

VH

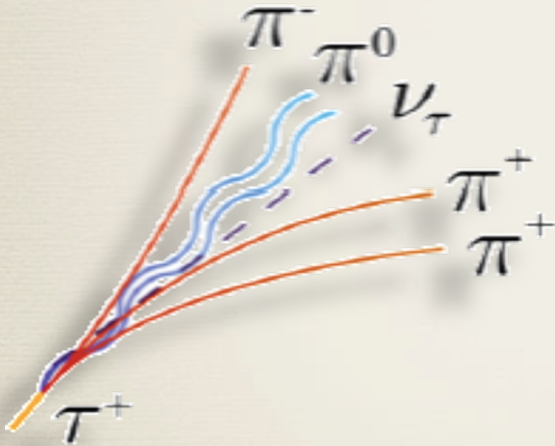
Event category	Total signal	WH (%)	qqZH (%)	ggZH (%)	$t\bar{t}H+tH$ (%)	HWHM (GeV)	Bkg. fit function	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	S/ $\sqrt{B}$ @HWHM
WH-cat1	0.82	76.2	9.6	1.6	12.6	2.00	BWZ γ	32.0	34	1.54	0.09
WH-cat2	1.72	80.1	9.1	1.5	9.3	1.80	BWZ	23.1	27	4.50	0.23
WH-cat3	1.14	85.7	6.7	1.8	4.8	1.90	BWZ	5.48	4	12.6	0.35
ZH-cat1	0.11	—	82.8	17.2	—	2.07	BWZ	2.05	4	3.29	0.05
ZH-cat2	0.31	—	79.6	20.4	—	1.80	BWZ	2.19	4	8.98	0.14

$t\bar{t}H$

Event category	Total signal	$t\bar{t}H$ (%)	ggH (%)	VH (%)	Other (%)	HWHM (GeV)	Bkg. fit function	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	S/ $\sqrt{B}$ @HWHM
$t\bar{t}H$ had-cat1	6.87	32.3	40.3	17.2	10.2	1.85	Bern(2)	4298	4251	1.07	0.07
$t\bar{t}H$ had-cat2	1.62	84.3	3.8	5.6	6.2	1.81	Bern(2)	82.0	89	1.32	0.12
$t\bar{t}H$ had-cat3	1.33	94.0	0.3	1.3	4.4	1.80	S-Exp	12.3	12	6.87	0.26
$t\bar{t}H$ lep-cat1	1.06	85.8	—	4.7	9.5	1.92	Exp	9.00	13	7.09	0.22
$t\bar{t}H$ lep-cat2	0.99	94.7	—	1.0	4.3	1.75	Exp	2.08	4	24.5	0.47

τ lepton basics

- Mass: 1.777 GeV/c²
the heaviest lepton
- $c\tau$: $\sim 87\mu\text{m}$
short lifetime
- decays via weak interactions



First observed in 1977 by Martin Perl et al. (SLAC-LBL)

Most important decay modes

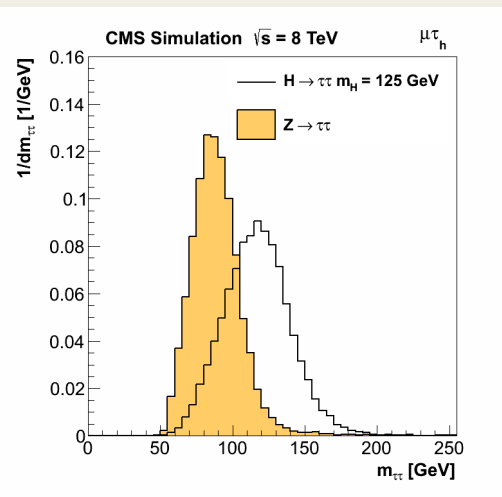
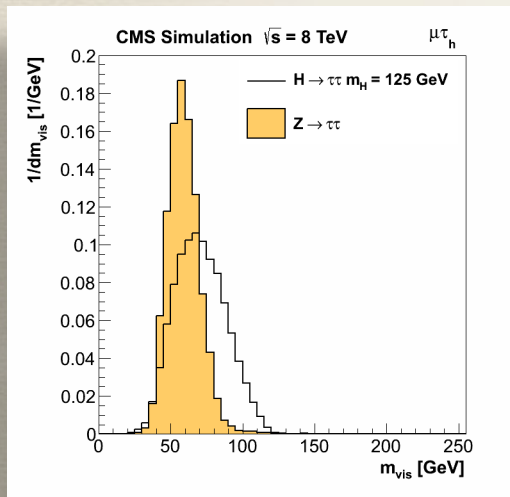
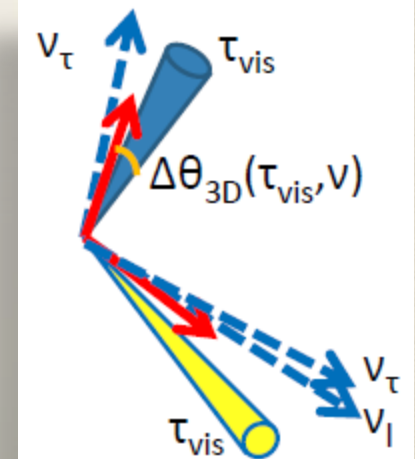
Decay Mode	Branching Fraction
Leptonic modes $\sim 35\%$	
$\tau^\pm \rightarrow e^\pm \nu_e \nu_\tau$	18%
$\tau^\pm \rightarrow \mu^\pm \nu_\mu \nu_\tau$	17%
Hadronic modes $\sim 65\%$	
1 prong (1 charged particle)	46%
$\tau^\pm \rightarrow \pi^\pm \nu_\tau$	11%
$\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_\tau$	26%
$\tau^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \nu_\tau$	9%
3 prong (3 charged particles)	14%
$\tau^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp \nu_\tau$	9%
$\tau^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp \pi^0 \nu_\tau$	5%

Invariant mass of the $\tau\tau$ system

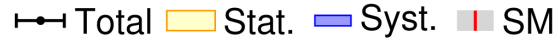
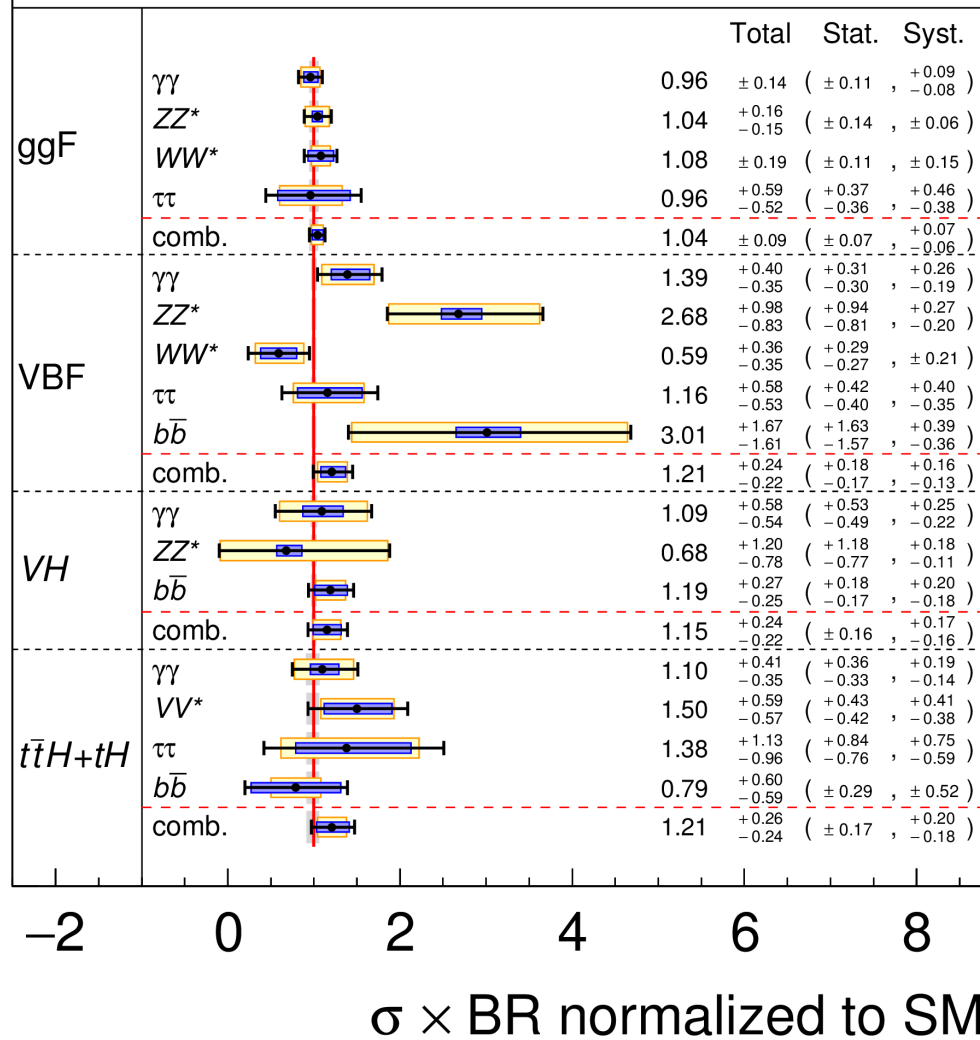
MMC (ATLAS: **NIM A 654 (2011)**) and SVFit (CMS: **HIG-13-004**)

- There are 6 to 8 parameters describing invisible neutrinos and 4 constraints ($2 \times m_\tau, \cancel{E}_{Tx}, \cancel{E}_{Ty}$)
- Find max. likelihood solution accounting for the distributions of the $\tau\tau$ kinematics and $\cancel{E}_T$ resolution.

$$\mathcal{L} = -\log(\mathcal{P}(\Delta R_1, p_{\tau 1}) \times \mathcal{P}(\Delta R_2, p_{\tau 2}) \times \mathcal{P}(\Delta \cancel{E}_{Tx}) \times \mathcal{P}(\Delta \cancel{E}_{Ty}))$$



$\sigma(m_{\tau\tau}) \leq 20\%$
(depending on the channel and kinematics)

ATLAS $\sqrt{s} = 13 \text{ TeV}, 24.5 - 79.8 \text{ fb}^{-1}$ $m_H = 125.09 \text{ GeV}, |y_H| < 2.5$ $p_{\text{SM}} = 71\%$

 Total Stat. Syst. SM


2HDM Models

❖ Generic class implementing a second Higgs doublet.

❖ Variants depend on specific coupling scheme:

Type I: One doublet couples to vector bosons, the other couples to fermions.

Type II: one doublet couples to up-type quarks, the other to down-type quarks and leptons:
„MSSM -like”

Lepton-specific: couplings to quarks as in the Type I model and to leptons as in Type II.

Flipped: couplings to quarks as in the Type II model and to leptons as in Type I.

$$\tan \beta \equiv v_2/v_1 \qquad g_{hVV}^{2\text{HDM}}/g_{hVV}^{\text{SM}} = \sin(\beta - \alpha)$$

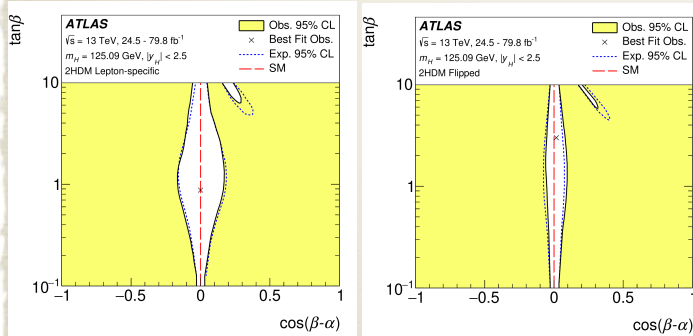
$$v_1^2 + v_2^2 = \bar{v}^2 \approx (246 \text{ GeV})^2 \qquad g_{HVV}^{2\text{HDM}}/g_{HVV}^{\text{SM}} = \cos(\beta - \alpha)$$

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

2HDM Models

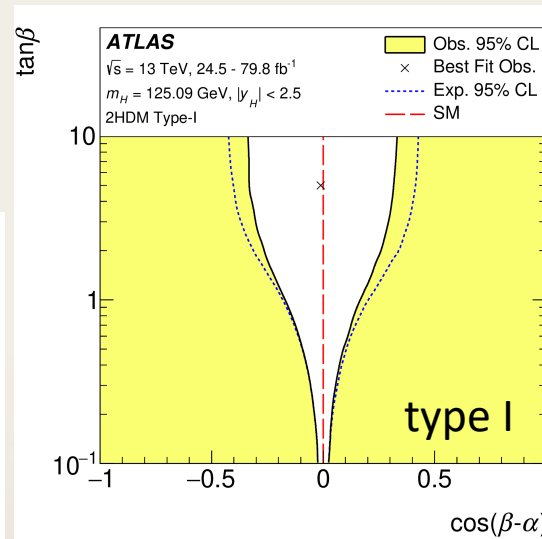
- ❖ „Decoupling”: A , H^0 , $H^\pm$ much heavier than the light h .
- ❖ h looks pretty much like a SM Higgs („Alignment”)
- ❖ Decoupling is not necessary.
- ❖ $\cos(\beta-\alpha) \rightarrow 0$ realizes Alignment.

Inverted coupling to down-type fermions (τ, b)

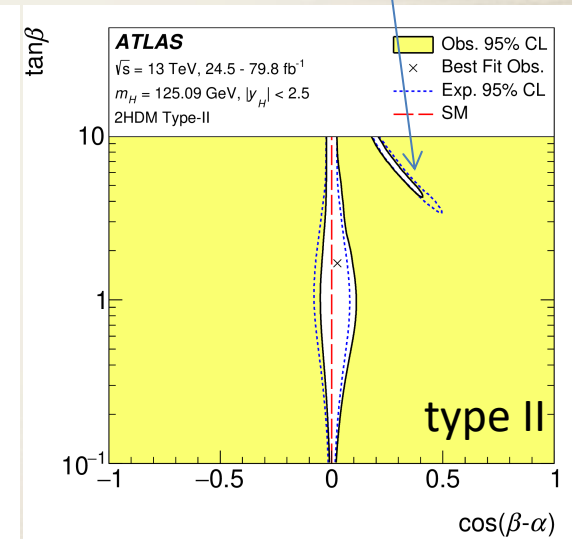


type III
(lepton specific)

type IV
(flipped)



type I



type II

“Alignment”

h recovers properties of the SM Higgs

Brout-Englert-Higgs-Hagen-Guralnik-Kibble field and... the Higgs boson (1964)



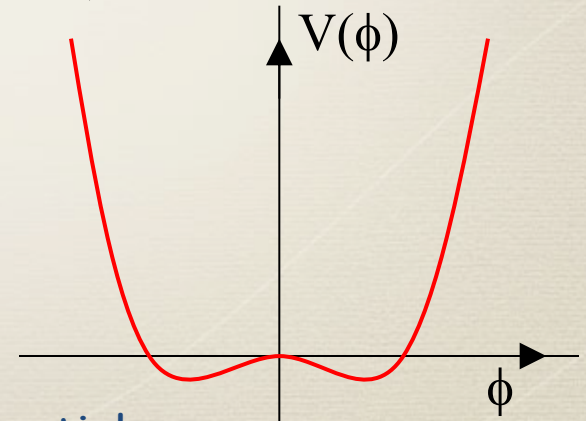
T.Kibble G.Guralnik R.C.Hagen F.Englert R.Brout & P.Higgs

$$\mathcal{L}_{Higgs} = D_\mu \phi^\dagger D^\mu \phi - V_{Higgs}$$

$$V_{Higgs} = \frac{1}{2} \mu^2 (\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$v = \sqrt{-\mu^2 / |\lambda|} \sim 246 \text{ GeV}$$



Vacuum state (174 GeV)

physical Higgs particle