中国科学技术大学
1958
University of Science and Technology of China

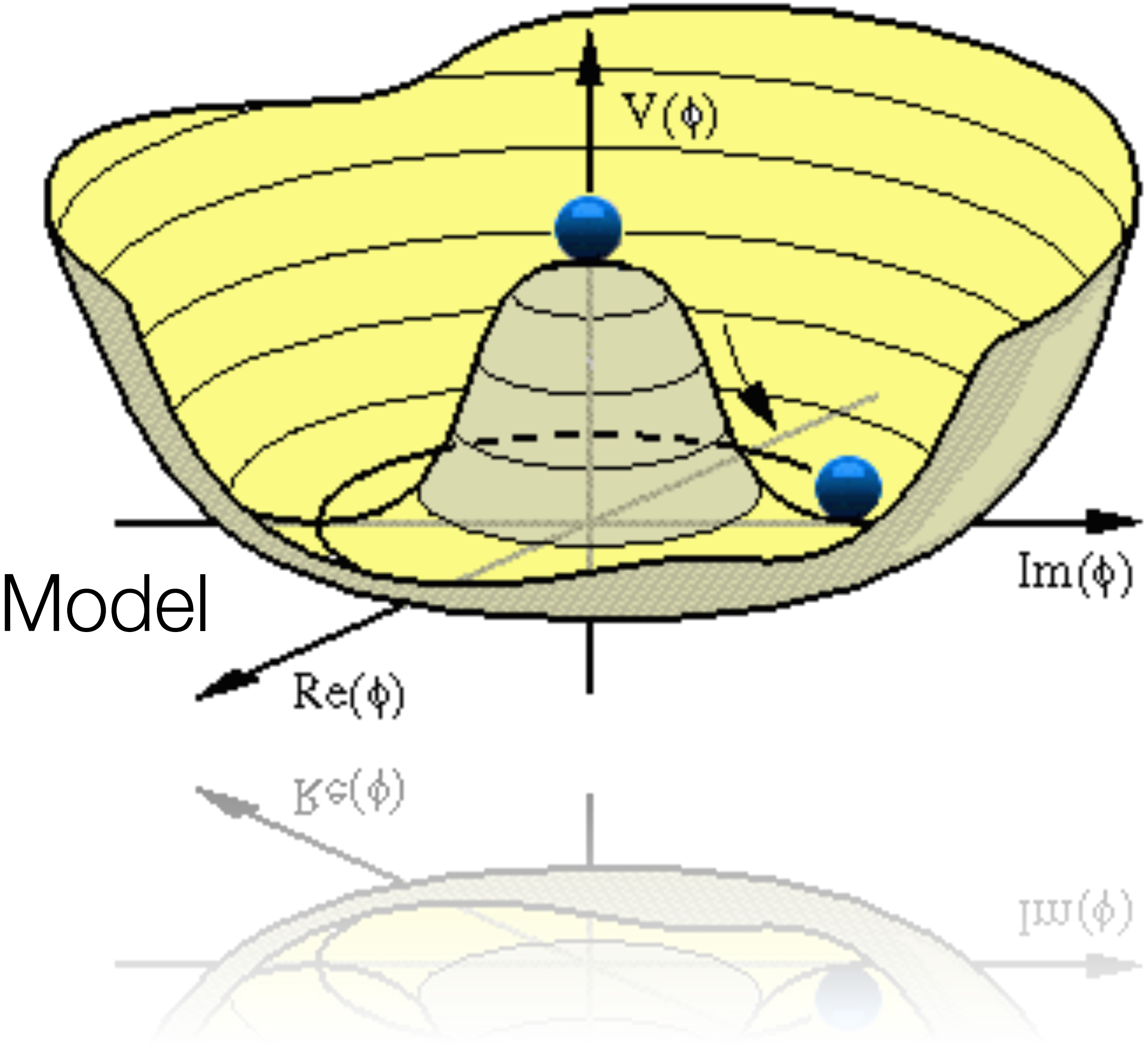
The Discovery of the Higgs at LHC

Year 2023

Collider Physics
Toni Baroncelli

The Higgs

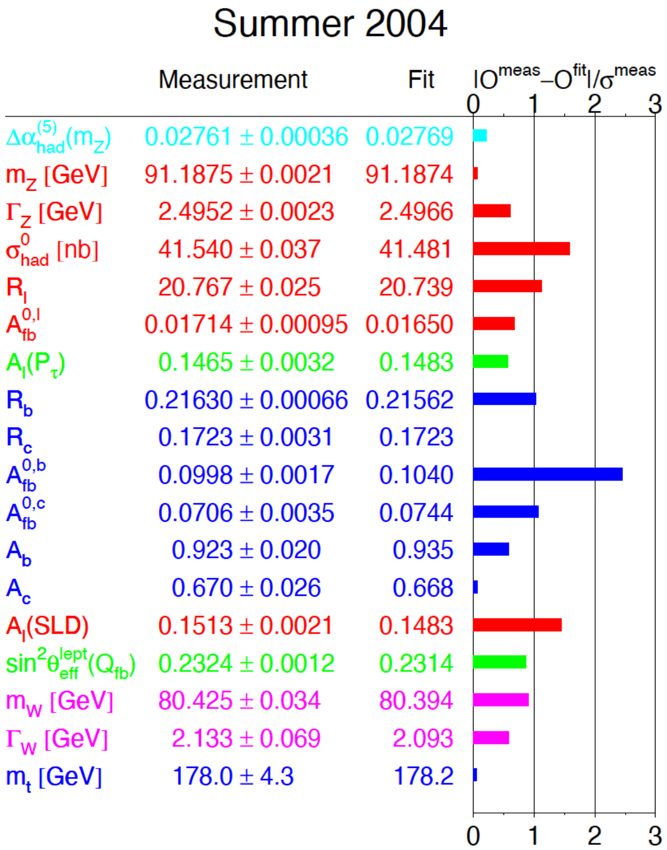
(The “once”)
Missing Piece in the Standard Model



m_t and m_H → EW fits

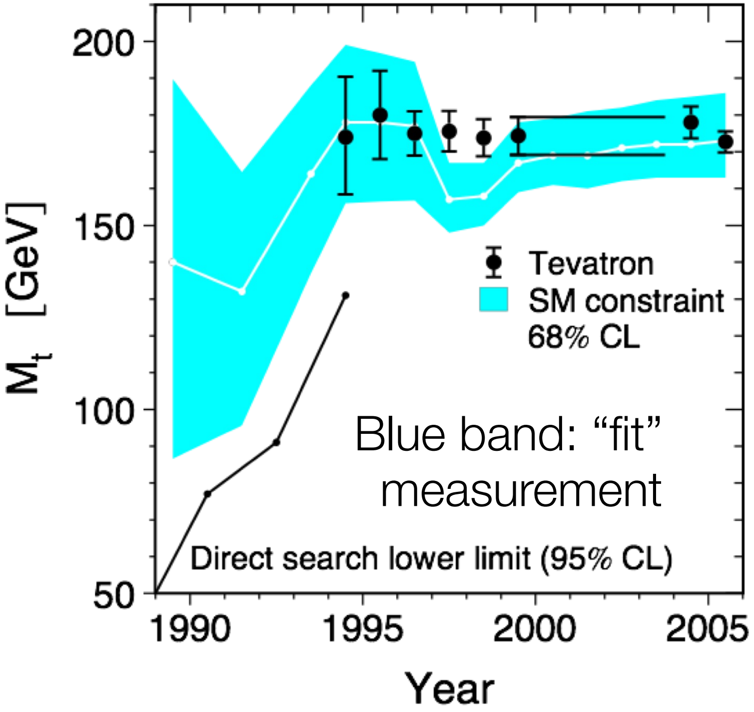
There are very many EW measurements: cross sections, asymmetries and many others.

Some diagrams contain loops where top and Higgs bosons circulate → slightly modify observables → indication on top mass and Higgs mass before their discoveries

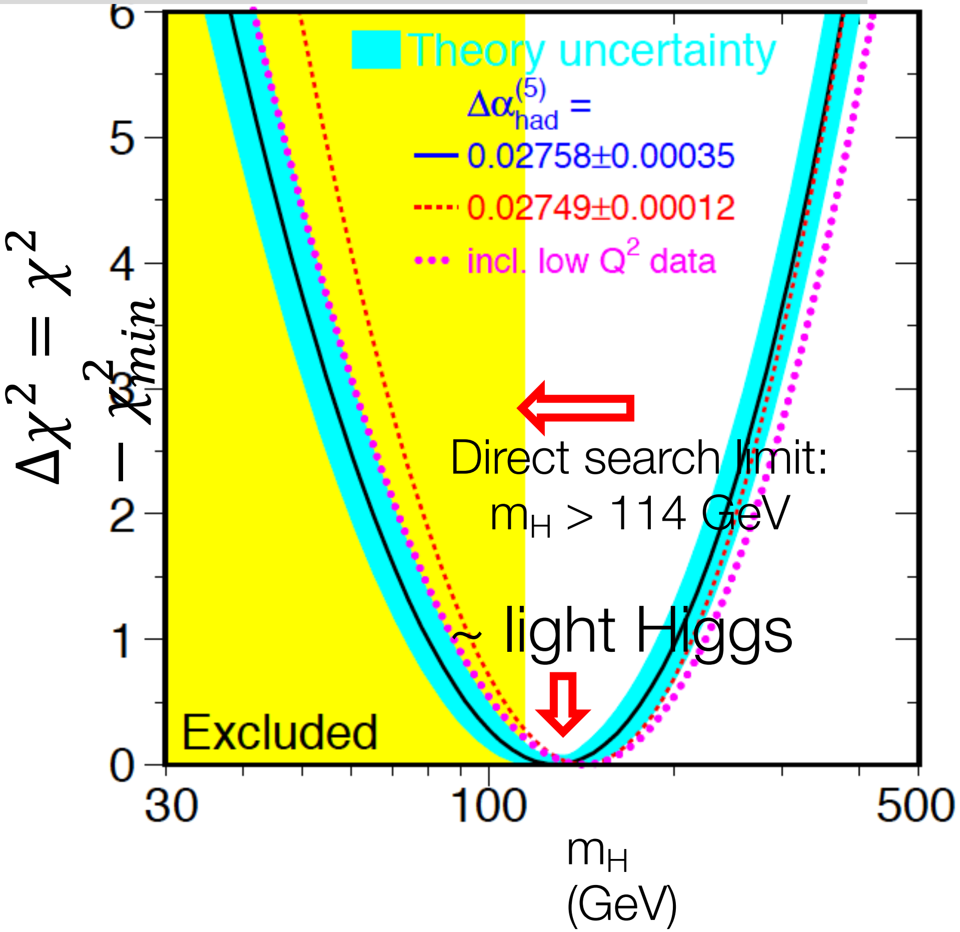


Summer 2004

	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966	
σ_{had}^0 [nb]	41.540 ± 0.037	41.481	
R_l	20.767 ± 0.025	20.739	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483	
R_b	0.21630 ± 0.00066	0.21562	
R_c	0.1723 ± 0.0031	0.1723	
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040	
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.026	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1483	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.425 ± 0.034	80.394	
Γ_W [GeV]	2.133 ± 0.069	2.093	
m_t [GeV]	178.0 ± 4.3	178.2	



Blue band: “fit” measurement



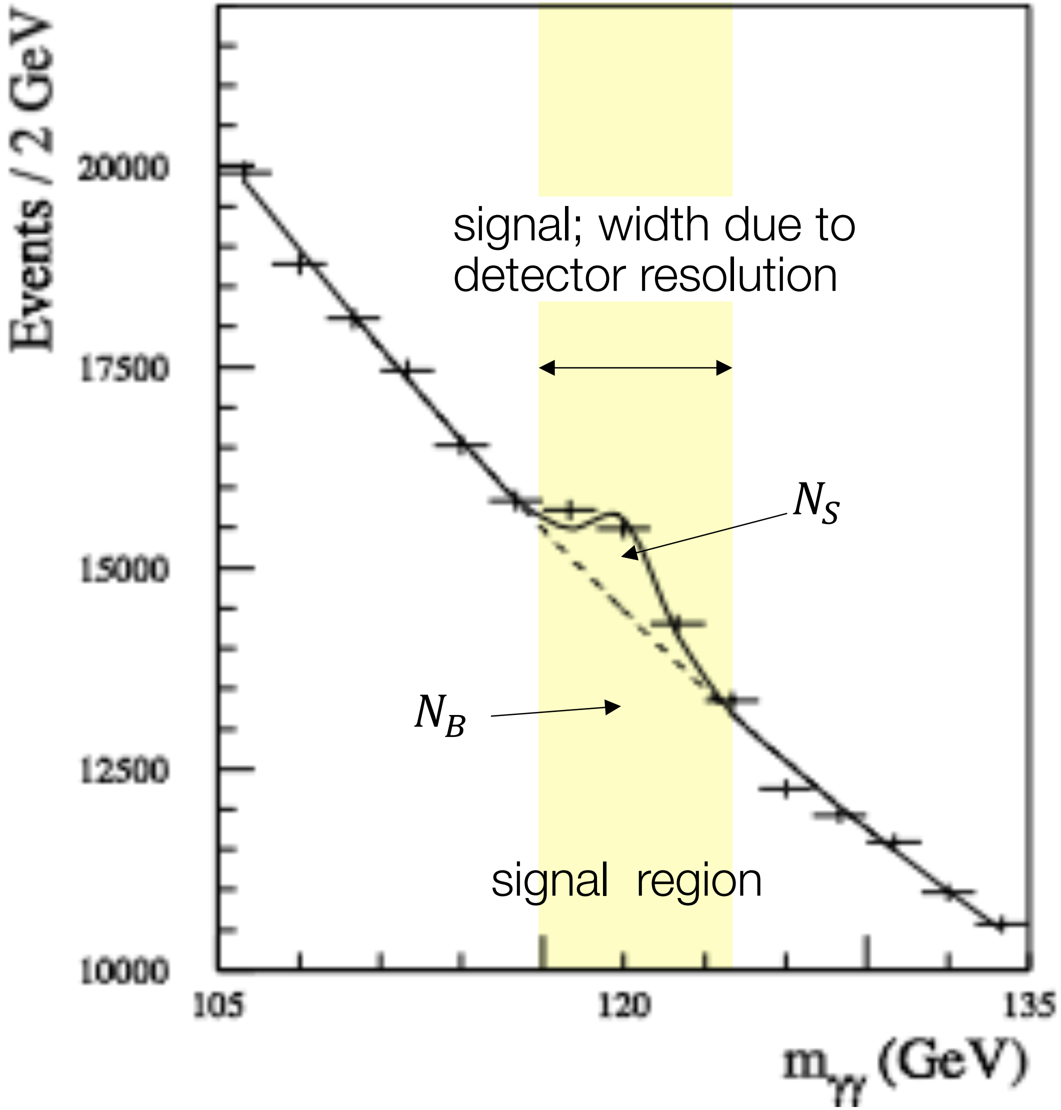
Direct search limit: m_H > 114 GeV

~ light Higgs

Higgs and the Tevatron: Reminder on Discoveries

Toni Baroncelli: The Discovery of the Higgs

The Higgs Boson was also searched for at the Tevatron. Without success!   Why?



signal; width due to detector resolution

N_S

N_B

signal region

Signal significance: $S = \frac{N_S}{\sqrt{N_B + N_S}}$

N_S: # signal events
N_B: # background events
In the "signal region"

Kinematically out of reach?

By "convention" a discovery is claimed when the significance

$$S > 5:$$

This means that the signal

$$N_S = N_{tot} - N_B$$

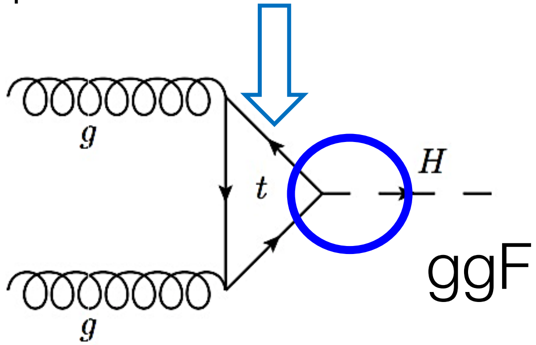
is 5 times larger than statistical uncertainty on N_B+N_S → the probability of a fluctuation is very small: the Gaussian probability that upward fluctuation by more than 5σ is observed is

$$P_{5\sigma} = 10^{-7}$$

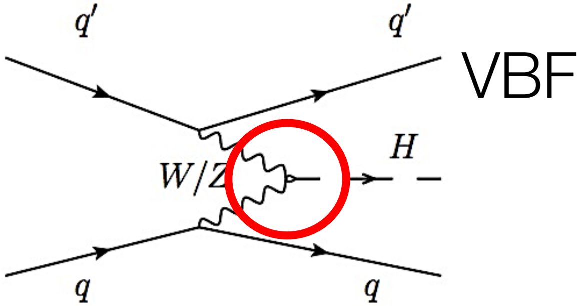
The sensitivity to a signal increases with increasing statistics

Higgs Production Mechanisms at Hadron Colliders

Loop with circulating tops, other quarks contribute much less



Gluon-gluon fusion

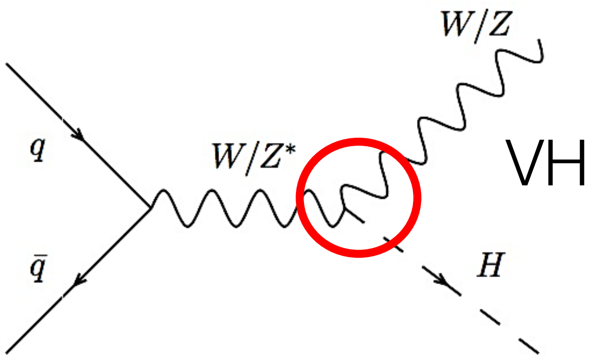


Vector bosons fusion

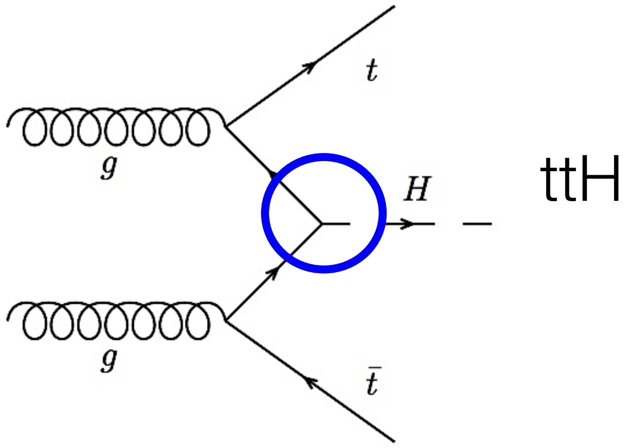
Higgs couples to massive particles, cannot couple directly to gluons and photons

○ Vertex with Higgs & bosons

○ Vertex with Higgs & fermions

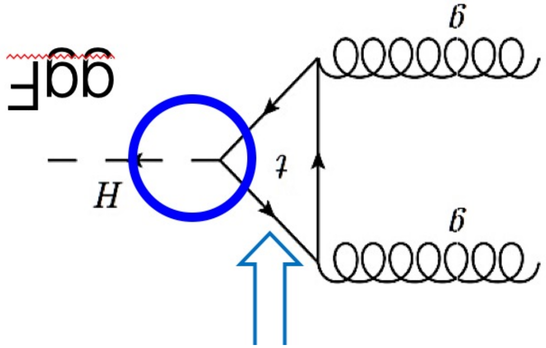


Associated production



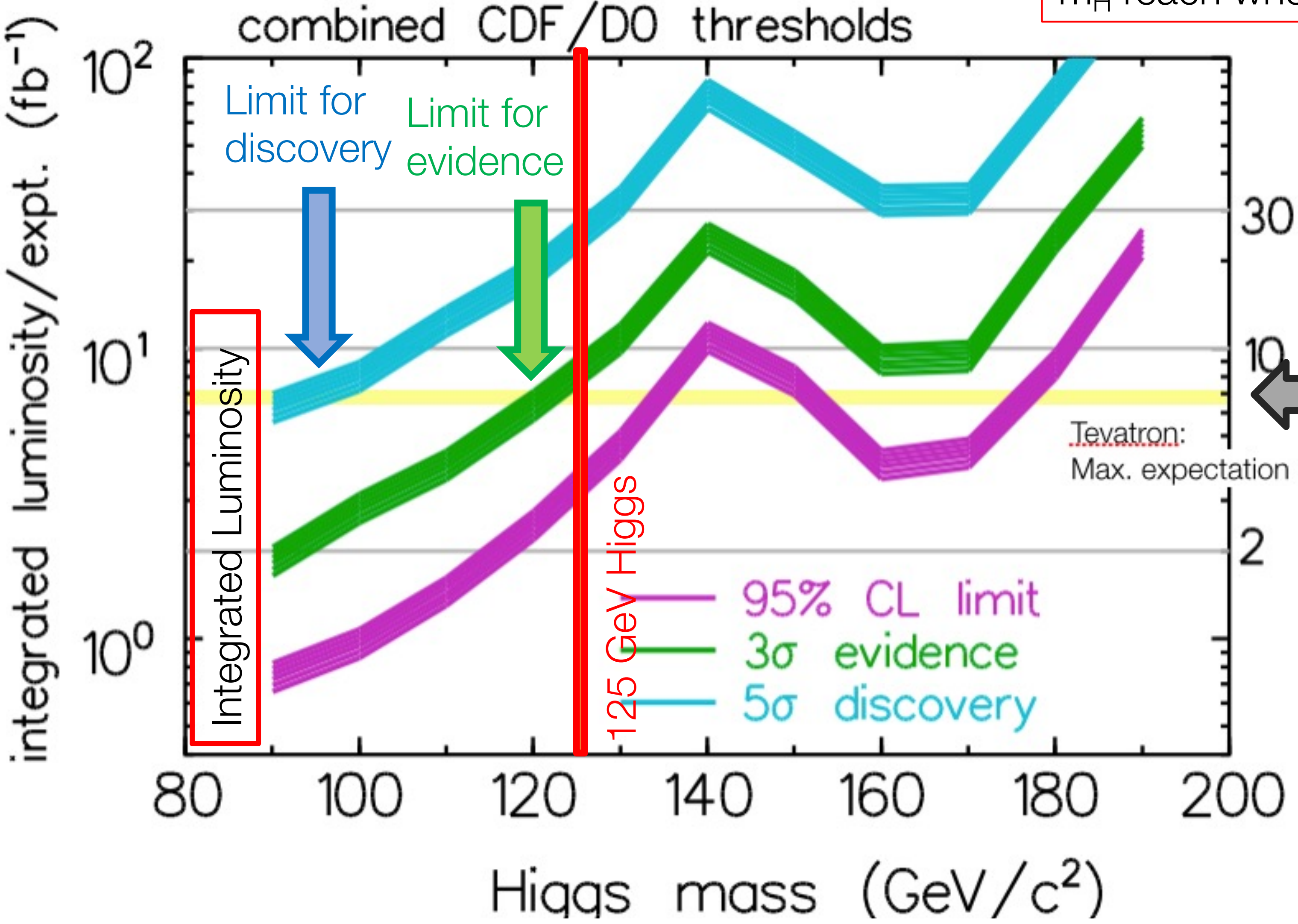
$t\bar{t}$ fusion

We will find the same vertices also in the Higgs decay!



Higgs Search at the Tevatron (forecast)

m_H reach when different channels are combined



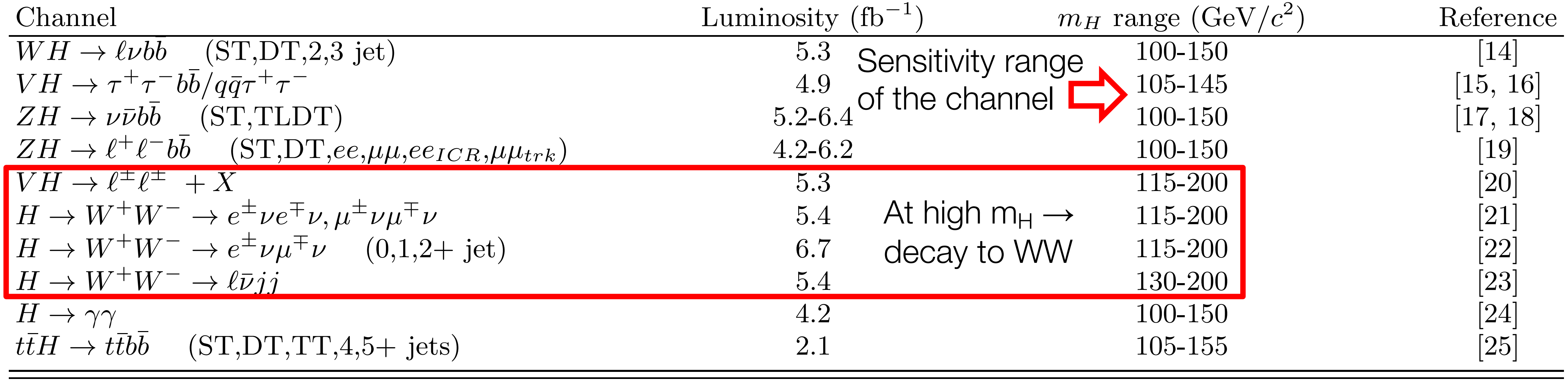
Luminosity collected at the Tevatron

- More statistics → more significant signal

Useful region → above out of reach

Higgs Decay Channels Investigated by CDF & D0

CDF

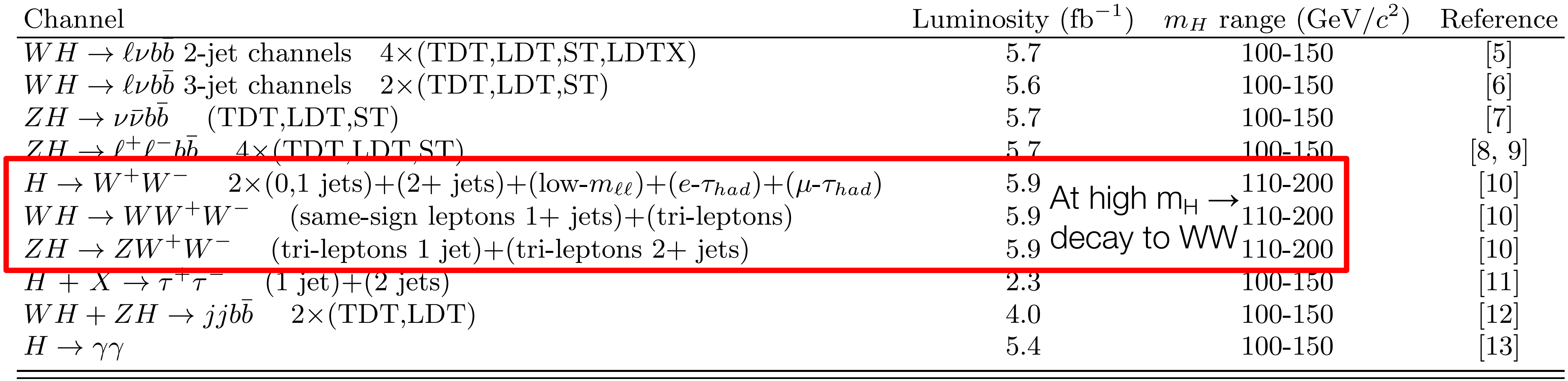


Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ (ST,DT,2,3 jet)	5.3	100-150	[14]
$VH \to \tau^+\tau^- b\bar{b}/q\bar{q}\tau^+\tau^-$	4.9	105-145	[15, 16]
$ZH \to \nu\bar{\nu}b\bar{b}$ (ST,TLDT)	5.2-6.4	100-150	[17, 18]
$ZH \to \ell^+\ell^- b\bar{b}$ (ST,DT,ee,$\mu\mu$,ee_{ICR},$\mu\mu_{trk}$)	4.2-6.2	100-150	[19]
$VH \to \ell^\pm\ell^\pm + X$	5.3	115-200	[20]
$H \to W^+W^- \to e^\pm\nu e^\mp\nu, \mu^\pm\nu\mu^\mp\nu$	5.4	115-200	[21]
$H \to W^+W^- \to e^\pm\nu\mu^\mp\nu$ (0,1,2+ jet)	6.7	115-200	[22]
$H \to W^+W^- \to \ell\bar{\nu}jj$	5.4	130-200	[23]
$H \to \gamma\gamma$	4.2	100-150	[24]
$t\bar{t}H \to t\bar{t}b\bar{b}$ (ST,DT,TT,4,5+ jets)	2.1	105-155	[25]

Sensitivity range of the channel ⇨

At high m$_H$ → decay to WW

D0



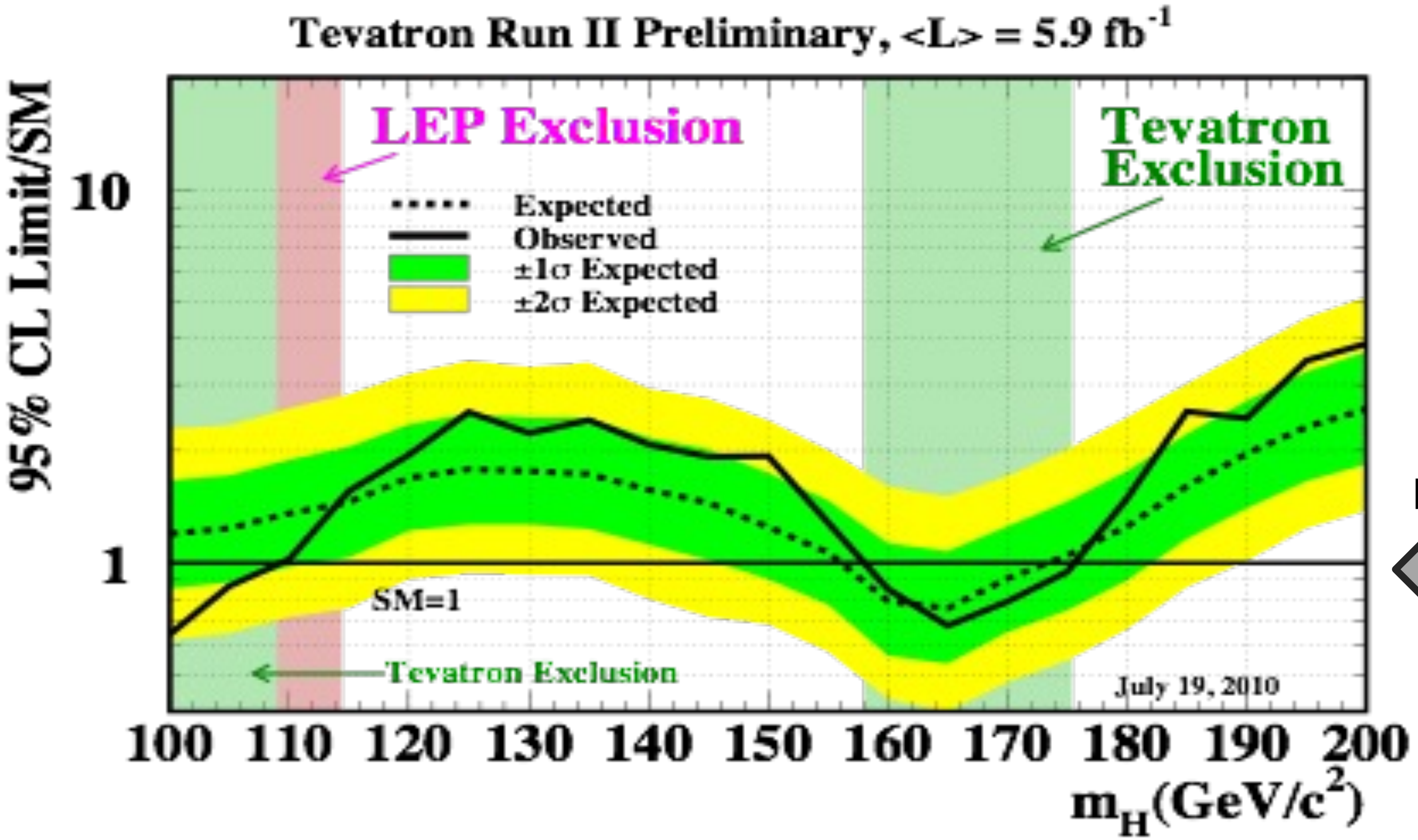
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(TDT,LDT,ST,LDTX)	5.7	100-150	[5]
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(TDT,LDT,ST)	5.6	100-150	[6]
$ZH \to \nu\bar{\nu}b\bar{b}$ (TDT,LDT,ST)	5.7	100-150	[7]
$ZH \to \ell^+\ell^- b\bar{b}$ 4×(TDT,LDT,ST)	5.7	100-150	[8, 9]
$H \to W^+W^-$ 2×(0,1 jets)+(2+ jets)+(low-$m_{\ell\ell}$)+(e-τ_{had})+(μ-τ_{had})	5.9	110-200	[10]
$WH \to WW^+W^-$ (same-sign leptons 1+ jets)+(tri-leptons)	5.9	110-200	[10]
$ZH \to ZW^+W^-$ (tri-leptons 1 jet)+(tri-leptons 2+ jets)	5.9	110-200	[10]
$H + X \to \tau^+\tau^-$ (1 jet)+(2 jets)	2.3	100-150	[11]
$WH + ZH \to jjb\bar{b}$ 2×(TDT,LDT)	4.0	100-150	[12]
$H \to \gamma\gamma$	5.4	100-150	[13]

At high m$_H$ → decay to WW

Tevatron Upper Limits on Higgs Mass

Observed and expected 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and D0 analyses :

If the experiments could be repeated 100 times, 95% of times they would get the same ‘exclusion’ result

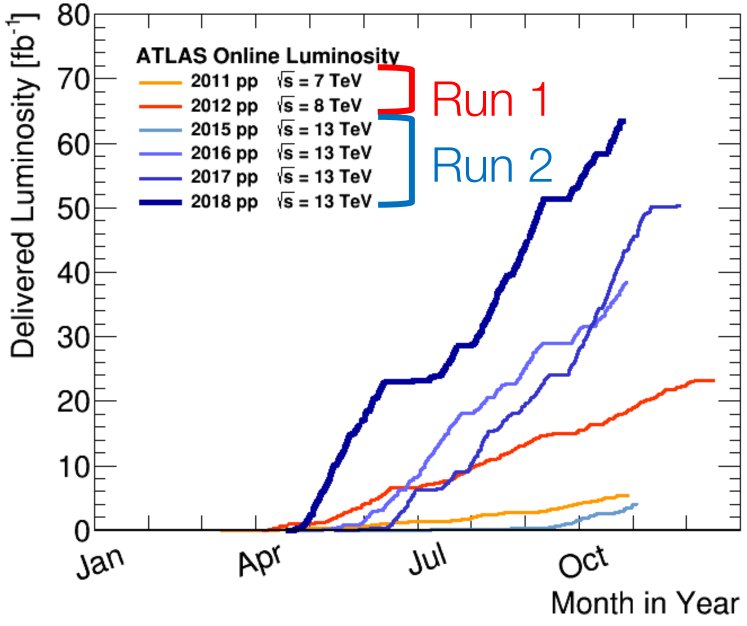


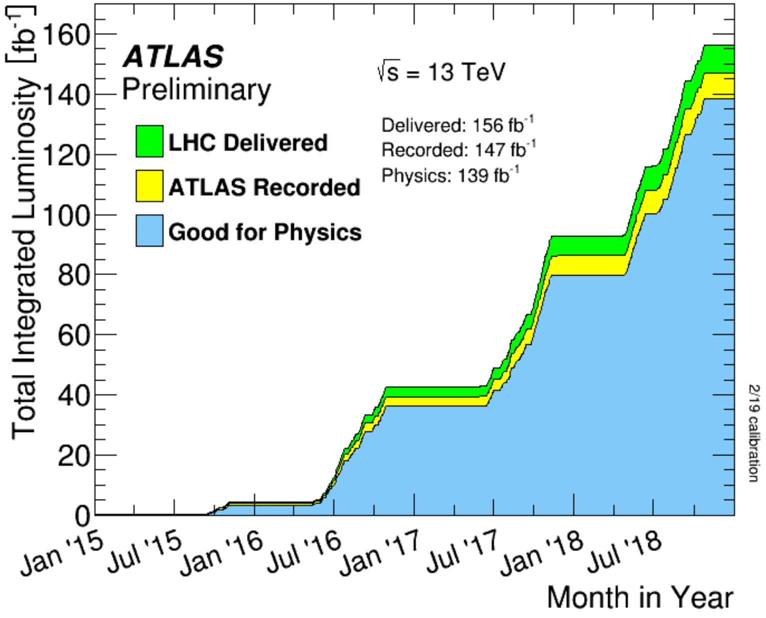
Ups ↑ and downs ↓ depend on the decay channel used in the search

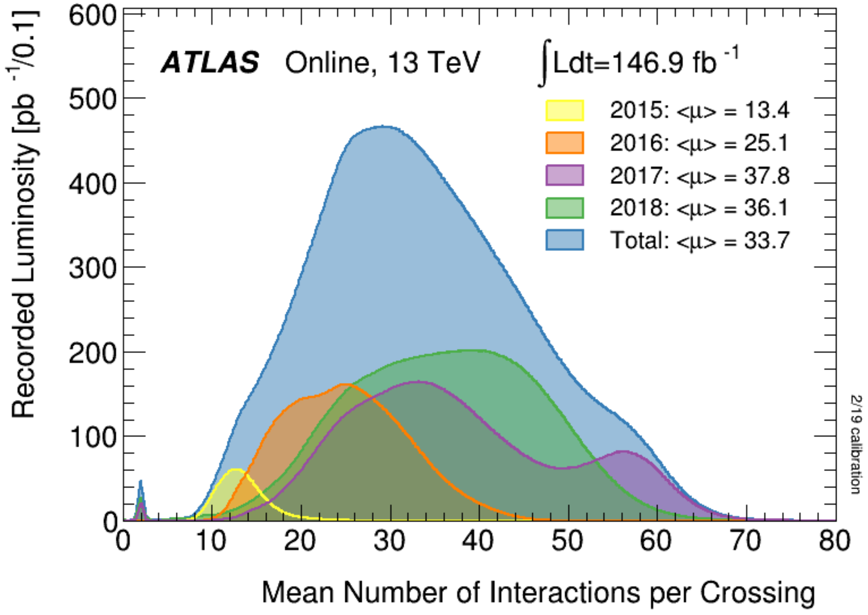
Some channels are more sensitive than others

Exclusion region → above out of reach

Delivered Luminosity by LHC in Run 1& 2







Integrated luminosity in LHC (fb^{-1})

- Run 1 (7 and 8 TeV)
- Run 2 (13 TeV)

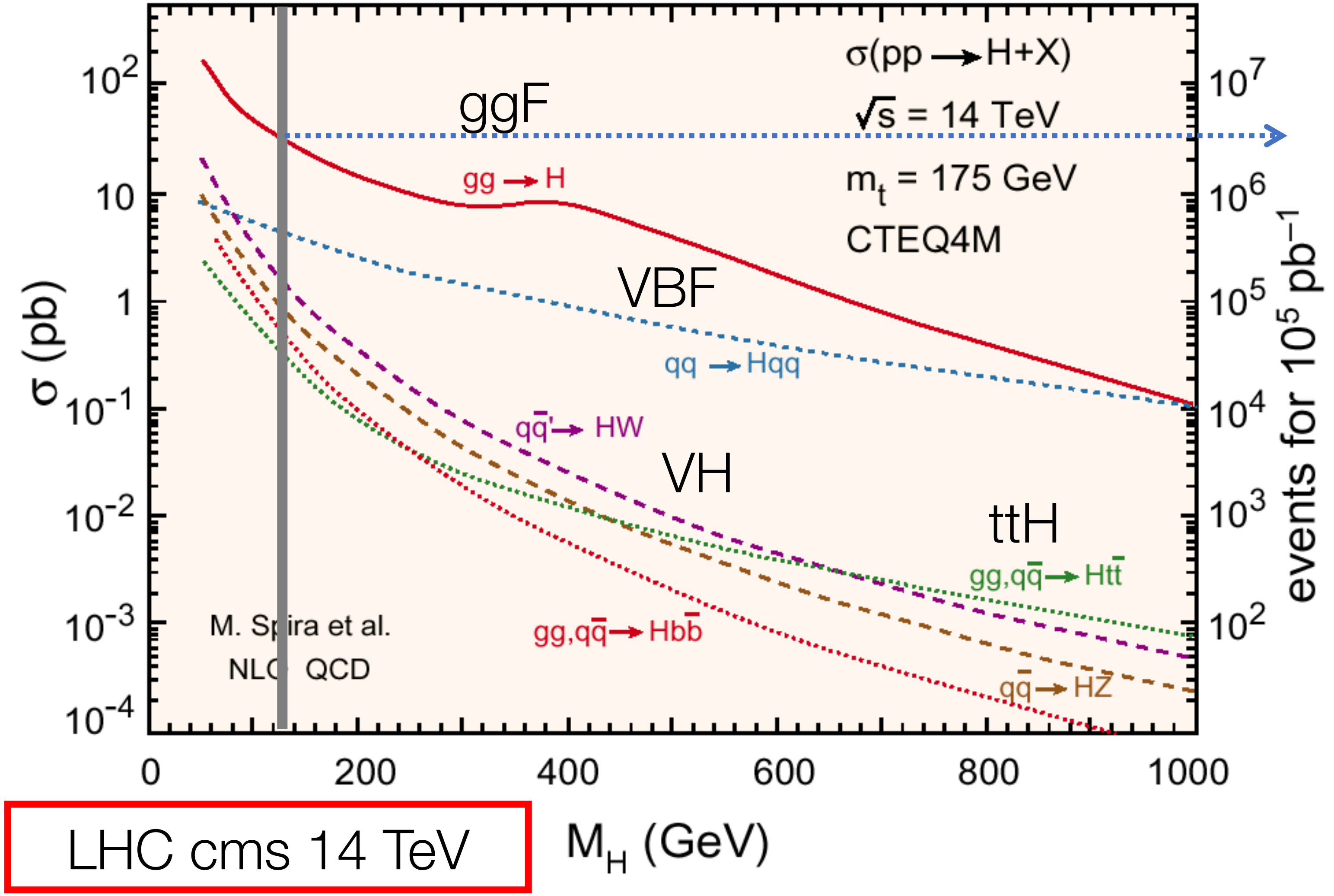
Delivered by LHC in Run 2: 156 fb^{-1}
Recorded by ATLAS: 147 fb^{-1}

Year	2010	2011	2012	2015	2016	2017	2018
Luminosity delivered (fb^{-1})	0.05	6.1	23.3	4.2	41	50	68
CMS Energy	7	7	8	13			

Higgs Search at the LHC

LHC:< 13 TeV!

Higgs production cross-section at centre-of-mass energies of 14 TeV, as a function of m_H.



LHC cms 14 TeV

M_H (GeV)

Different production mechanisms are shown

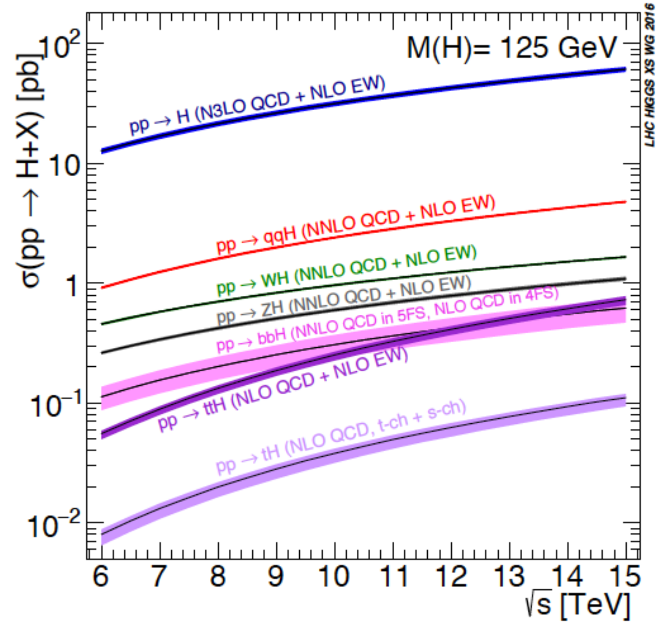
10^5 pb^{-1} = 100 fb^{-1}

'Millions' of 125 GeV Higgs produced by the ggF mechanism at 14 TeV for 100 fb^{-1} total luminosity

⇩

Acceptance and efficiency reduces this number drastically!

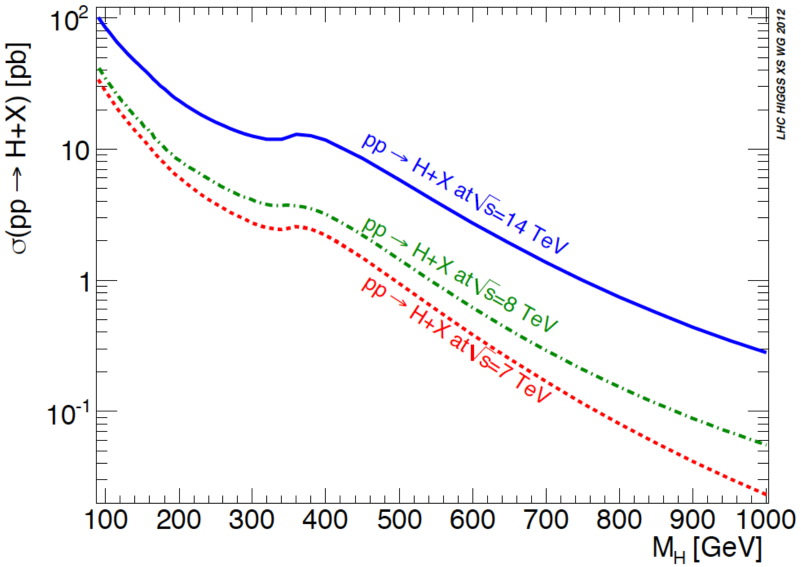
Cross Section vs √s for a 125 GeV Higgs



Calculation

$\sqrt{s}$ (TeV)	ggF	VBF	WH	ZH	$t\bar{t}H$	total	
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23	Tevatron
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1	LHC Run 1
8	$21.4^{+5\%}_{-5\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	24.2	
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1	LHC Run 2
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1	LHC Run HL

Production cross section (in pb) for $m_H = 125\,\mathrm{GeV}$

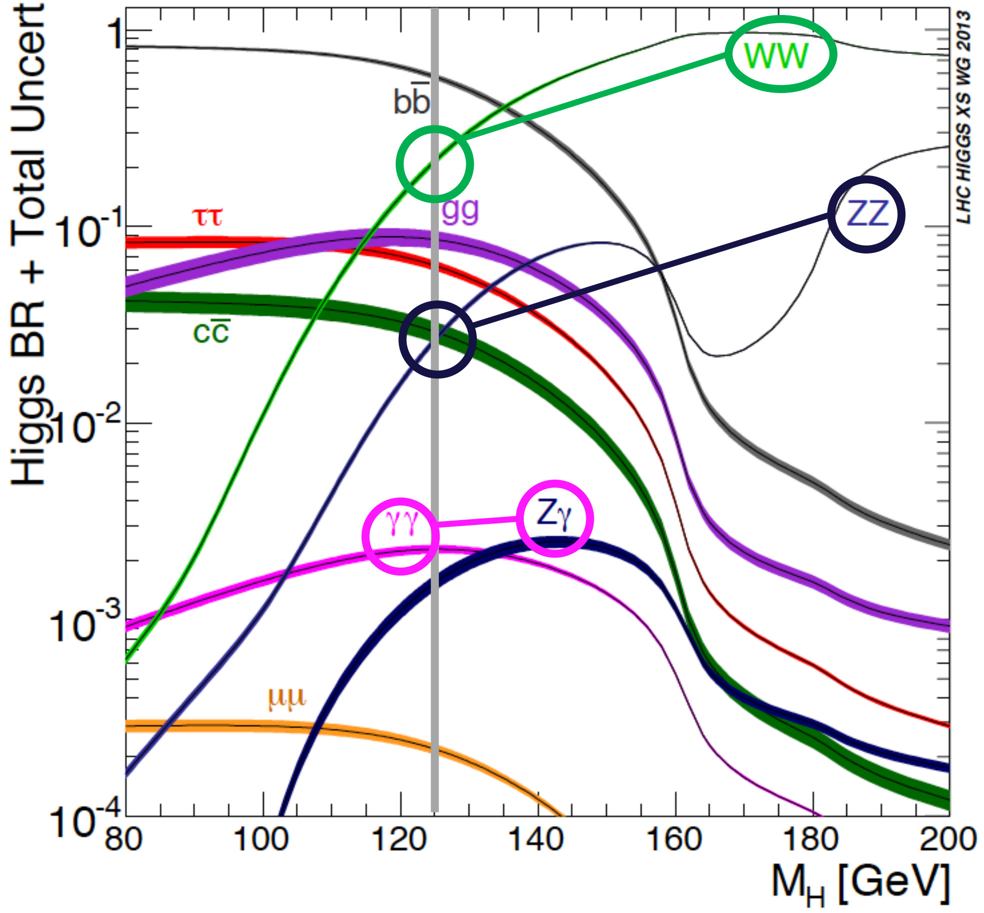


- Relative ratios between different production modes is ~ constant at LHC energies: ggF → VBF → VH → ttH
- The total cross section for the production of an Higgs of 125 GeV increases significantly with centre-of-mass energy & decreases with mass

$$\frac{\sigma^{\sqrt{s}=1.96\ TeV}_{Higgs(125\ GeV)}}{\sigma^{\sqrt{s}=13\ TeV}_{Higgs(125\ GeV)}} = 2.2\%$$

Tevatron: ggF then WH
LHC: ggF then VBF

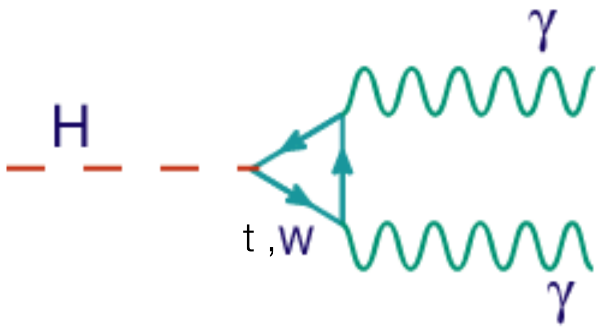
Higgs Decay Branching Fractions



Discovery driven by significance of different channels

What really counts is how well one can distinguish an Higgs signal from the background

Example: the decay of the Higgs into a pair of photons is very small (H ➛WW is ~ 100 times larger that H ➛γγ), however the distinct topology it generates made it very important in the Higgs discovery



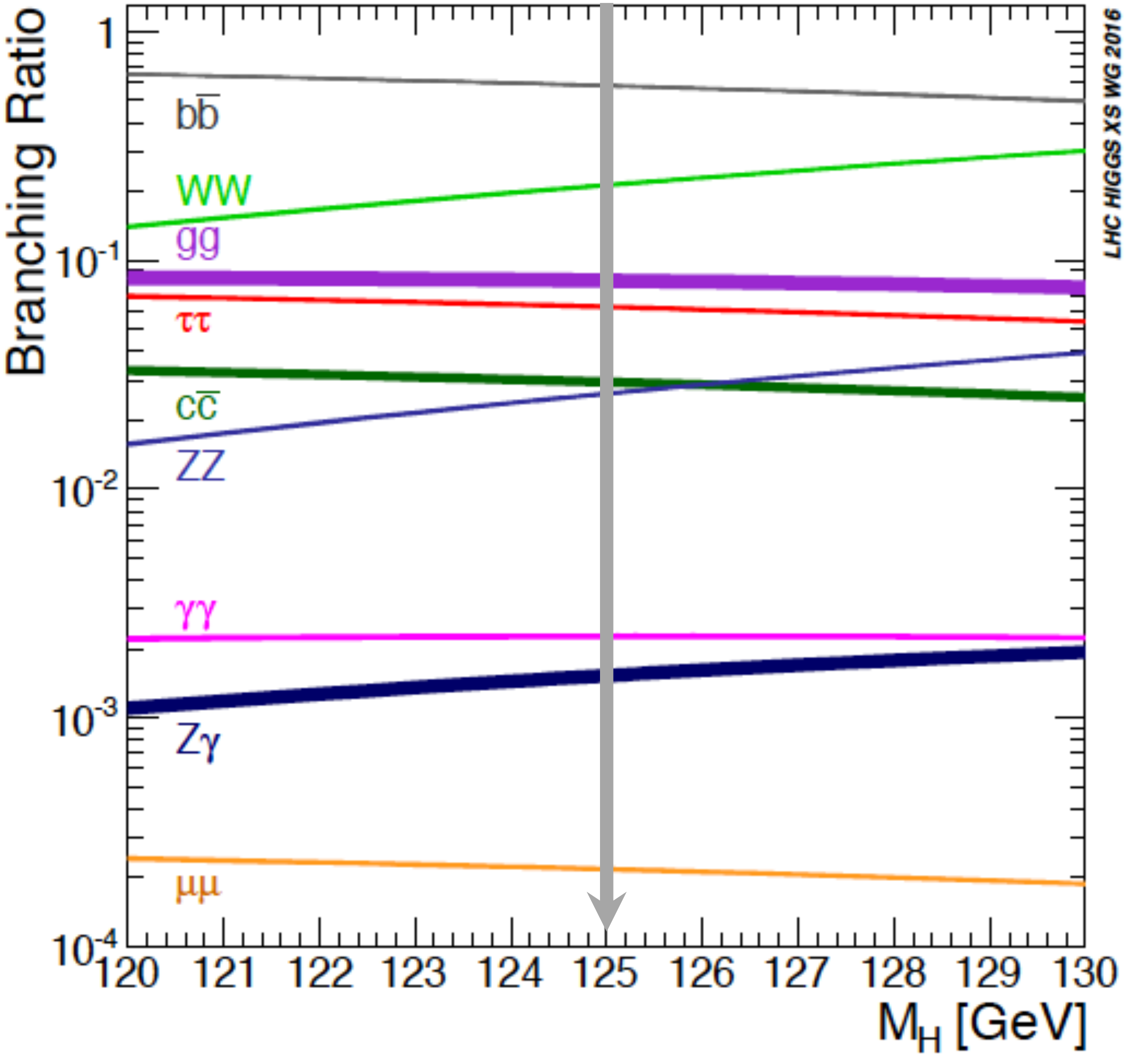
For m_H = 125 GeV: H ➛ bb, WW, gg, ττ

For m_H > 160 GeV: H ➛ WW, ZZ dominant

○ Channels used for the Higgs discovery:

- ZZ to 4 leptons
- Two photons
- Two WW to leptons and neutrinos (a bit late!)

Zooming the Branching Ratios of the Higgs



$m_H = 125$ GeV

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	$2.27 \times \boxed{10^{-3}}$	$+5.0\%$ -4.9%
$H \to ZZ$	$2.62 \times \boxed{10^{-2}}$	$+4.3\%$ -4.1%
$H \to W^+W^-$	$2.14 \times \boxed{10^{-1}}$	$+4.3\%$ -4.2%
$H \to \tau^+\tau^-$	6.27×10^{-2}	$+5.7\%$ -5.7%
$H \to b\bar{b}$	5.84×10^{-1}	$+3.2\%$ -3.3%
$H \to Z\gamma$	1.53×10^{-3}	$+9.0\%$ -8.9%
$H \to \mu^+\mu^-$	2.18×10^{-4}	$+6.0\%$ -5.9%

The Story of the Higgs (Discovery) in one Slide

- Indirect bounds on m_H from global EW fits : two decades at LEP, SLC, Tevatron suggest a ~light Higgs

$$m_H = 89^{+35}_{-26}\ \text{GeV}$$

- Direct and model-independent search at LEP up to 209 GeV cms gave a 95% CL lower bound on m_H

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

- Direct search after LEP shutdown in 2000 at Tevatron ppbar collider using 10fb-1 gave

⇒ a] excluded intervals 90-109 GeV and 149-182 GeV
b] broad excess at the level of 3 σ in the interval $115<m_H<140$ GeV with a maximum at 125 GeV

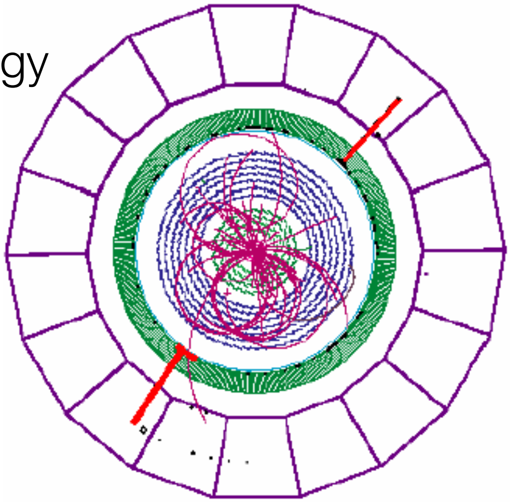
- LHC run in 2011 (7 TeV, 5 fb^{-1}), 2012 (8 TeV, 20 fb^{-1}) gave evidence for a new particle decaying to $\gamma\gamma$ and ZZ with rates as predicted by SM. Evidence for decays to W^+W^- but no evidence for bbar and $\tau^+\tau^-$
- LHC July 2012 : ATLAS & CMS claim a discovery of a new particle with a mass of about 125 GeV

Most Promising Higgs Decay Channels

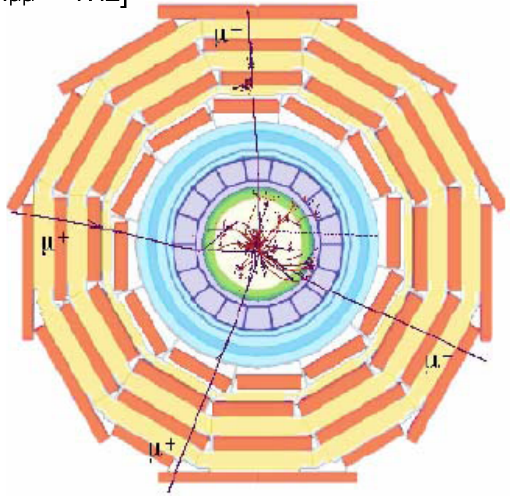
Channel	LHC Potential
gg ➛ H ➛ bb	Huge QCD background (gg ➛ bb); extremely difficult
gg ➛ H ➛ ττ	Higgs with low p_T, hard to discriminate from background; problematic
gg ➛ H ➛ γγ	Small rate, large combinatorial background, but excellent determination of m_H (CMS: crystal calorimeter)
gg ➛ H ➛ WW	Large rate, but 2 neutrinos in leptonic decay, Higgs spin accessible via lepton angular correlations
gg ➛ H ➛ ZZ	ZZ ➛ 4μ: “gold-plated” channel for high-mass Higgs (ATLAS: muon spectrometer)

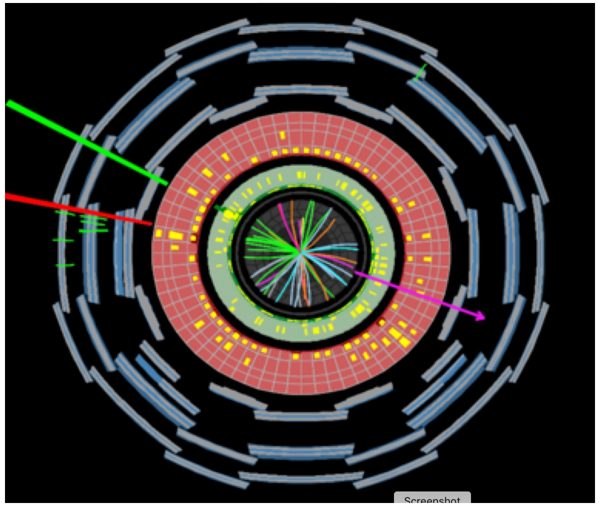
Topologies!

Two high-energy photons

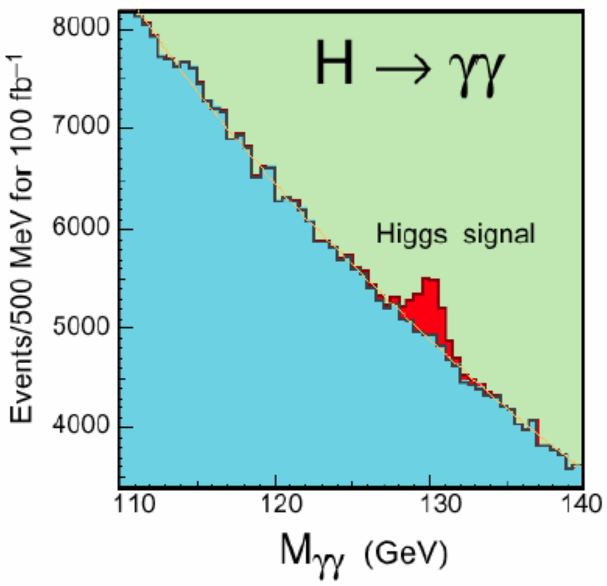


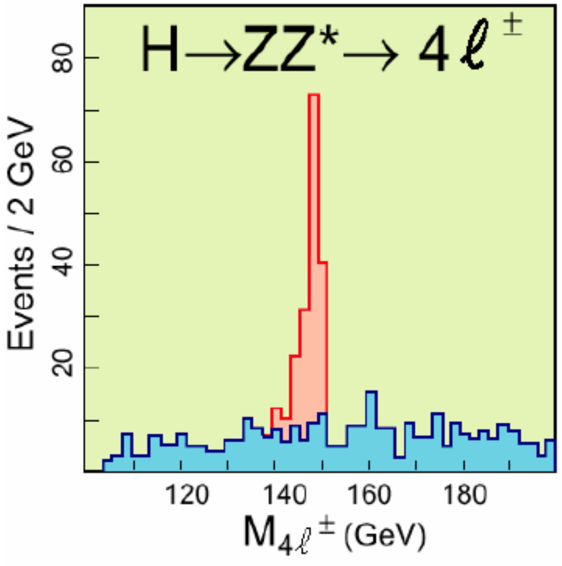
4 muons [$M_{\mu\mu} = M_Z$]

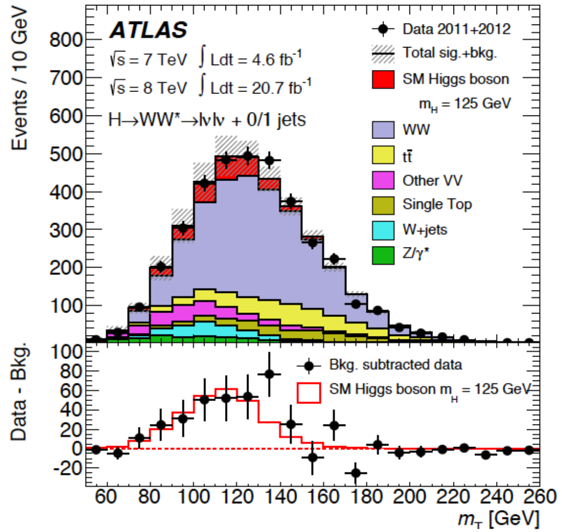




Electron + muon + MET







Complications of Real Life: Background

1. Choose channels with low SM background

   not possible: H ➛ bb ... without associated production ...(VH mode,V=W,Z)

   possible: H ➛ γγ ... despite of small branching ratio .

   H ➛ ZZ ... with one Z decaying leptonically

   H ➛ WW ... large signal and large background

2. Optimize detector resolution

   Example:mass resolution σ_m worsen by a factor of 2;

   N_S doesn't change; signal region has to be increased by a factor 2

   → number N_B of background events increases by factor of 2

   $S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$

thus:

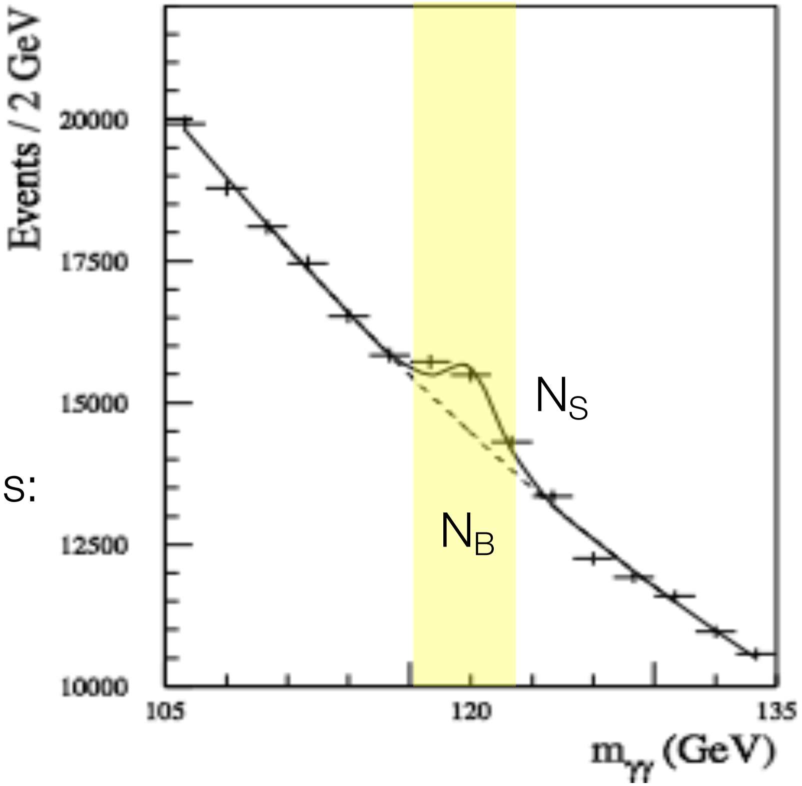
$$S \sim \frac{1}{\sqrt{\sigma_m}}$$

3. Recorded luminosity $\mathcal{L}$

   Signal: $N_S \sim \mathcal{L}$

   Background: $N_B \sim \mathcal{L}$

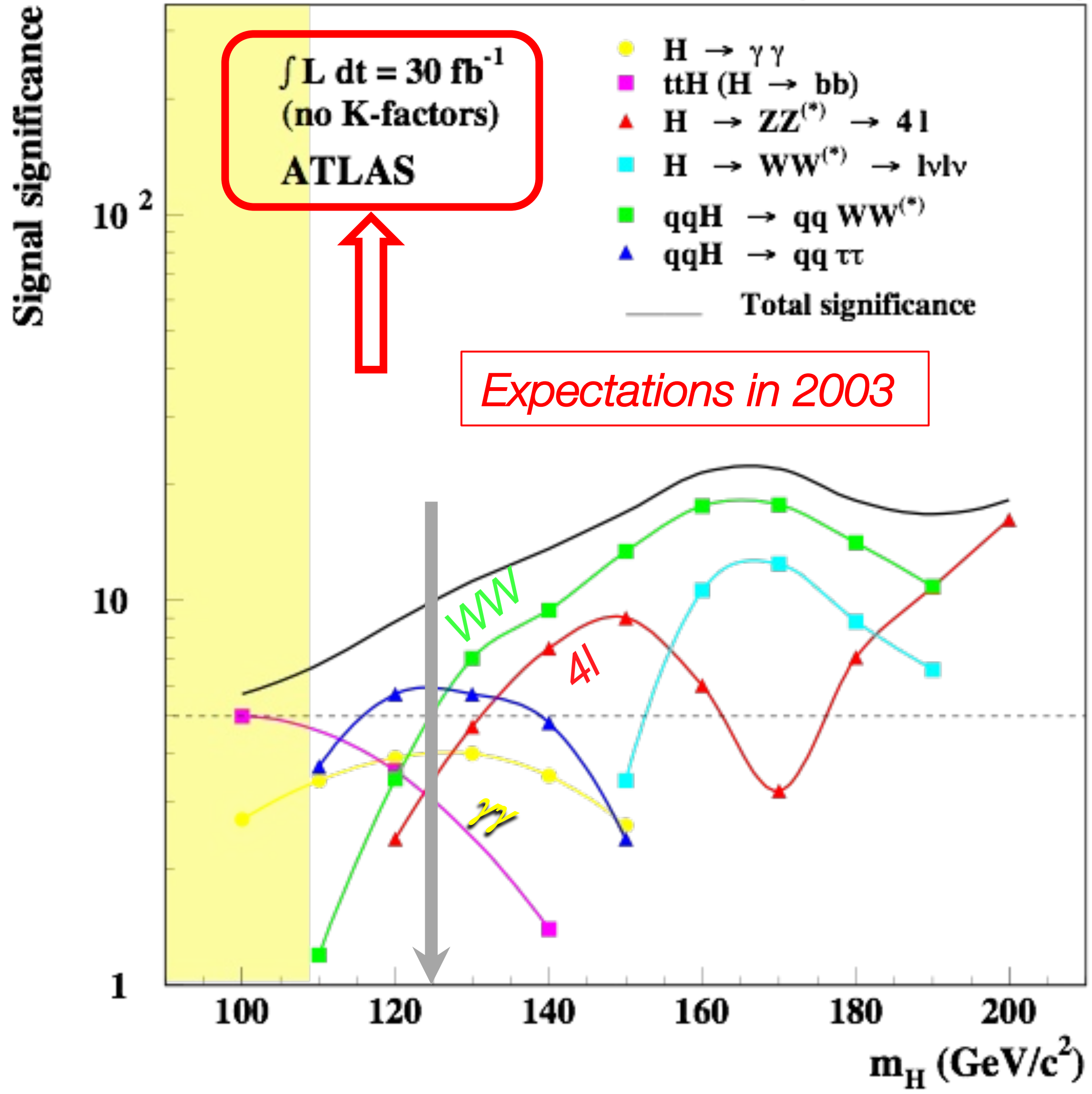
$$S \sim \sqrt{\mathcal{L}}$$



Decay channel	Mass resolution
$H \to \gamma\gamma$	1–2%
$H \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	1–2%
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$	20%
$H \to b\bar{b}$	10%
$H \to \tau^+\tau^-$	15%

(Pre-Discovery) Discovery Potential

[ATL-PHYS-2003-005]



Statement in 2003

- Full mass range can already be covered after a few years at low luminosity
- Several channels available over a large range of masses

- *Low mass discovery requires combination of three of the most demanding channels*

- Comparable situation for the CMS experiment

Significance = 5 σ
→ Discovery

Prediction almost correct:

- γγ, ZZ to 4 leptons, WW to lνlν (higgs to qqττ not used)
- Combination of channels

Higgs Terms in the Lagrangian

Toni Baroncelli: The Discovery of the Higgs

$$\mathcal{L} = -\boxed{g_{Hff}\bar{f}fH +} \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4 + \delta_V V_\mu V^\mu\left(\boxed{g_{HVV}H +} \frac{g_{HHVV}}{2}H^2\right)$$

linear quadratic

$$\boxed{g_{Hf\bar{f}} = \frac{m_f}{v},} \quad \boxed{g_{HVV} = \frac{2m_V^2}{v}} \quad g_{HHVV} = \frac{2m_V^2}{v^2}$$

$$g_{HHH} = \frac{3m_H^2}{v}, \quad g_{HHHH} = \frac{3m_H^2}{v^2}$$

V = W± or Z δW = 1, δZ = 1/2

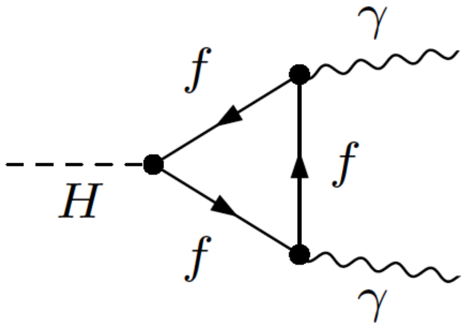
- The dominant mechanisms for Higgs boson production and decay involve the coupling of H to W, Z and/or the third generation quarks and leptons.

Coupling to bosons (W or Z) ∝ m_V^2

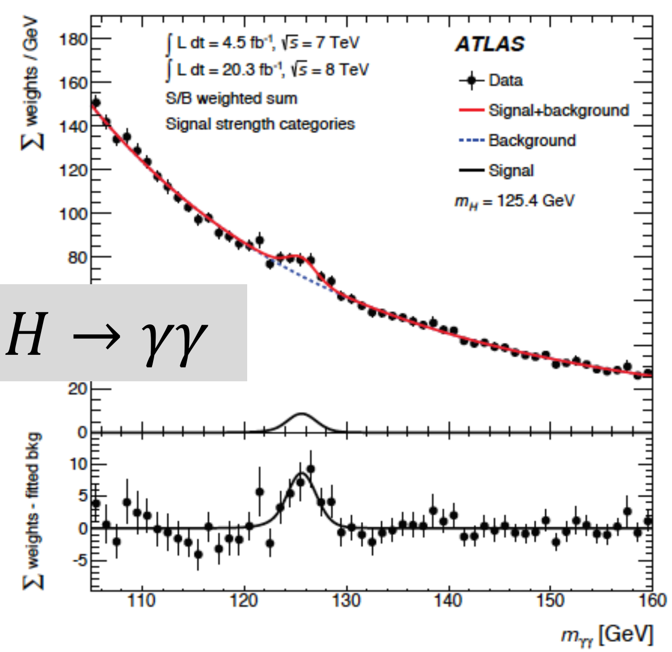
Coupling to fermions ∝ m_f

- The Higgs coupling to photons is generated by loops
  - ➢ virtual W^+W^- pair provides the dominant contribution
  - ➢ virtual tt pair is subdominant.

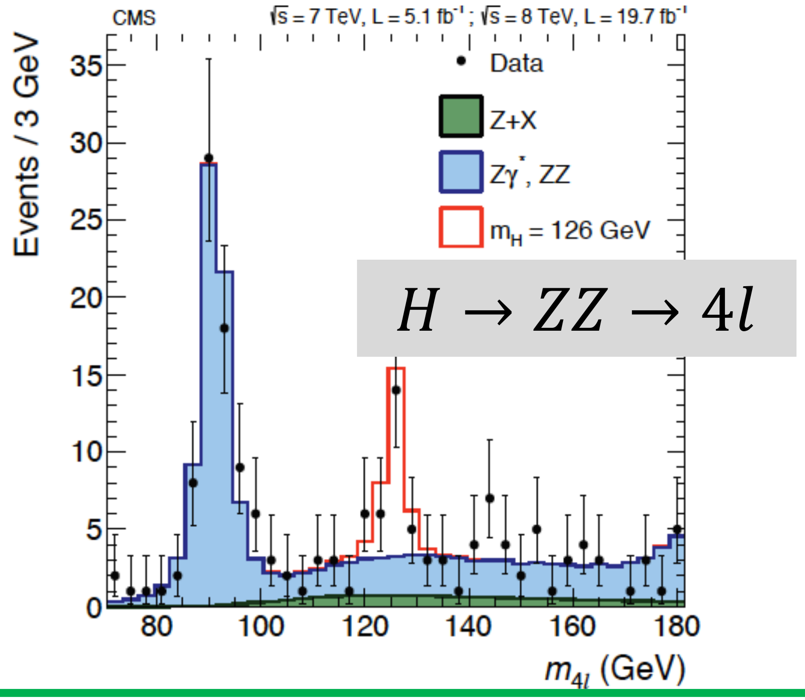
- The Higgs coupling to gluons, is induced by a one-loop graph: H couples to a virtual tt pair.



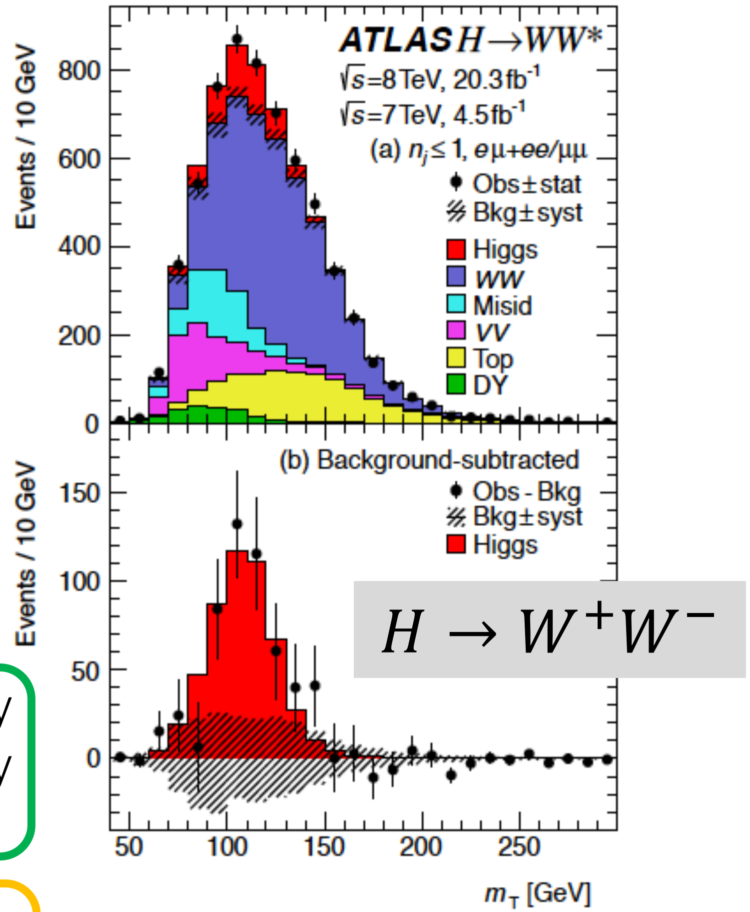
Summary of LHC Run-1 Results (7 TeV + 8 TeV)



$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ \rightarrow 4l$



$H \rightarrow W^+W^-$

- In the H → γγ and H → ZZ → 4l channels, all final state particles can be very precisely measured and the reconstructed m_H resolution is excellent (typically 1-2%).

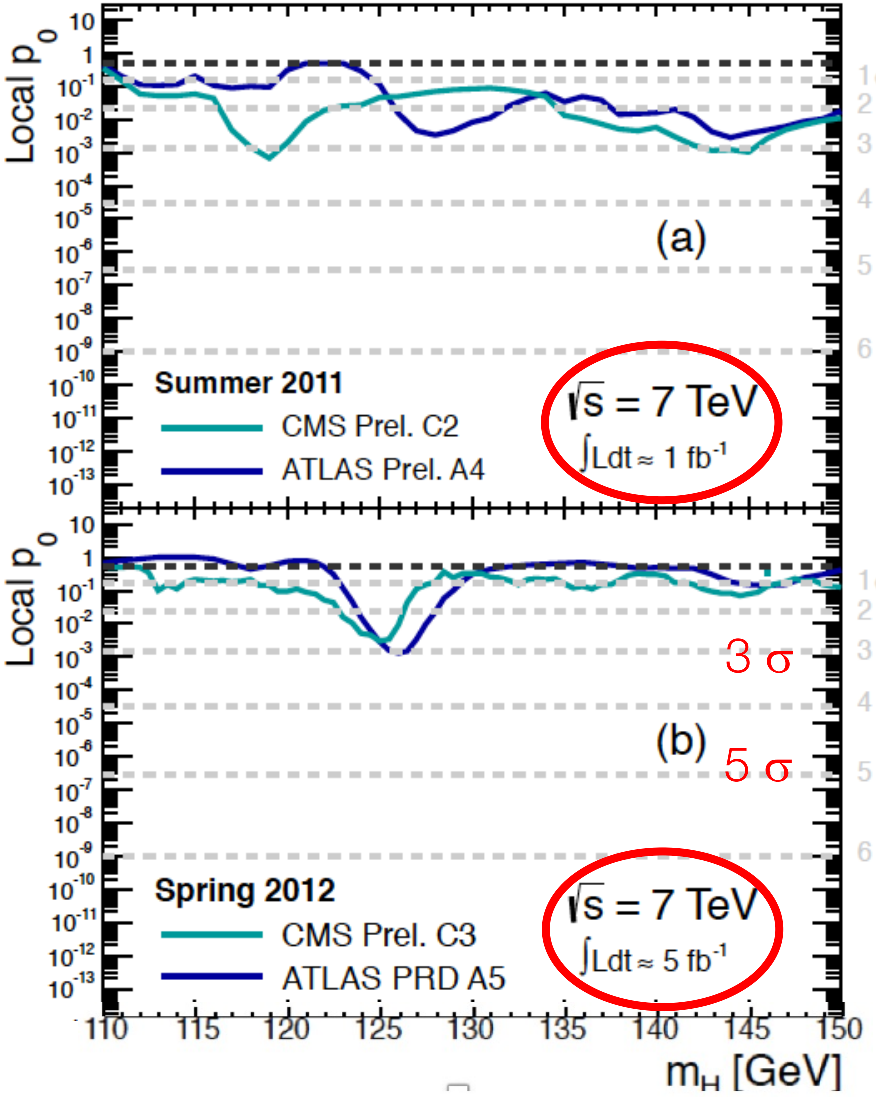
- the $H \rightarrow W^+W^- \rightarrow l^+\nu_l l^-\overline{\nu_l}$ channel has relatively large branching fraction, but the m_H resolution is poor (approximately 20%) due to the presence of neutrinos.

Past History: a Few Important Facts

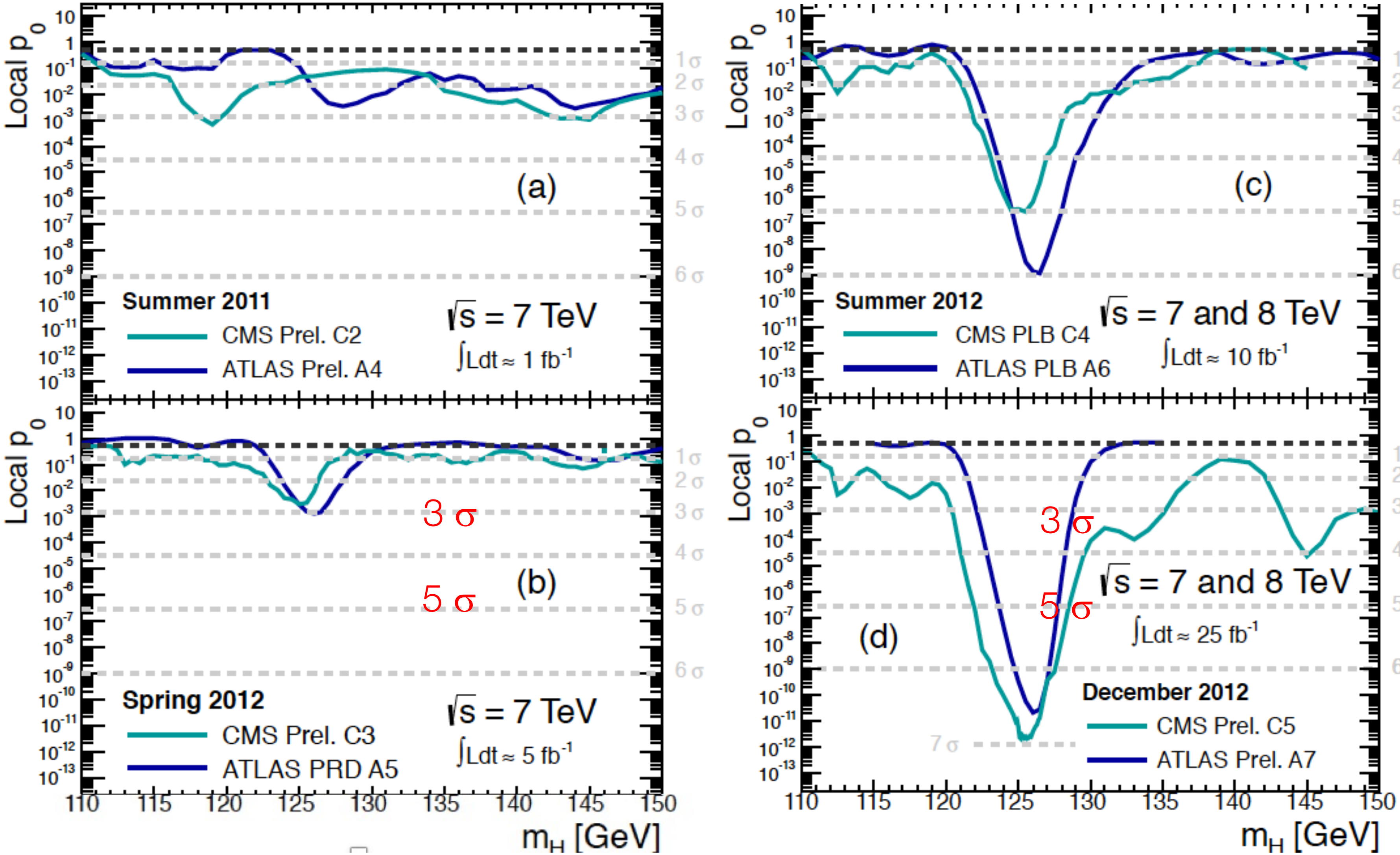
- On July 4, 2012 the observation at the LHC of a narrow resonance with a mass of about 125 GeV was announced.
- *Initial strategy: integrate all production modes for one decay channel*
- The observed decay channels indicated → is a boson.
- Decays rates to γγ and ZZ consistent with the Standard Model (SM) Higgs boson.
- There were indications that the new particle also decays to W^+W^-.

The significance of these observations are quantified by a p-value, the probability for an experiment to give a result compatible with background only.

ATLAS / CMS observed a significance of 5.9 /4.9 σ at a mass m_H = 126.5GeV / 125.5



Recent History: a Few Important Facts



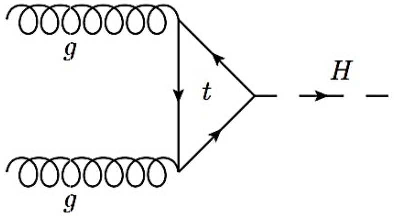
p_0 = probability that the excess can be described by background only

A p_0 of 2.87×10^{-7} corresponds to 5σ excess over the background-only prediction.

Topologies of Production Mechanisms

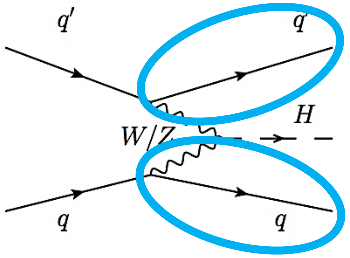
ggf, gluon-fusion process :

- largest cross section
- Loop with heavy top quark. *No very distinctive feature in the topology!*



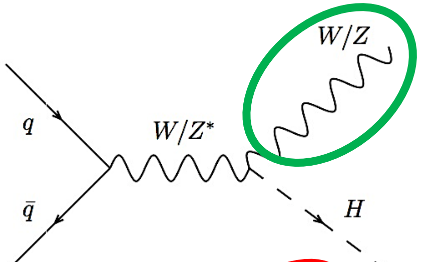
VBF, vector boson fusion :

- second-largest cross section
- scattering of $qq'(q\bar{q})$, mediated by the exchange of a W or Z boson.
- The scattered quarks give two hard jets in the forward and backward regions with a large dijet mass (≥ 400GeV) and separated by $\Delta\eta_{jj} \geq 3.5$ → one jet very forward + 1 jet very backward.



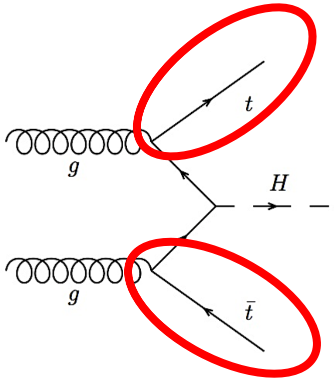
VH, associated production with W and Z gauge bosons :

- Third cross-section
- W and Z leptonic decay(s) → MET & high p_T leptons → clean signatures.



ttH: Higgs radiation off top quarks

- High p_T leptons, MET, b-tagged jets. Complex topology with many decay channels



Improve Initial Discovery

Is the observed resonance the Higgs boson predicted by the SM?
→ more analysis

Higgses produced in ATLAS & CMS in LHC RunI				
Production Mode	ggF	VBF	WH+ZH	ttH
Higgs events	500.000	40.000	20.000	3.000

Production →

Five modes;
ggF vbf WH ZH ttH

Higgs

→ Decay

Three main modes

You see this!

There are three main decay channels: the γγ, ZZ, WW

3 x 5 = 15 combinations → too many for an (initial) search, not enough statistics!

Strategy was:

- define categories for each production mode and for each decay mode ***(→ check with SM!)***
- optimise the search using characteristics of the (production-decay) topology of the event
- *then integrate over all production modes and give results for 3 decay channels only (WW arrived a bit later)*

Events selected for the discovery were very few: between 1 and 100 for each production-decay category.

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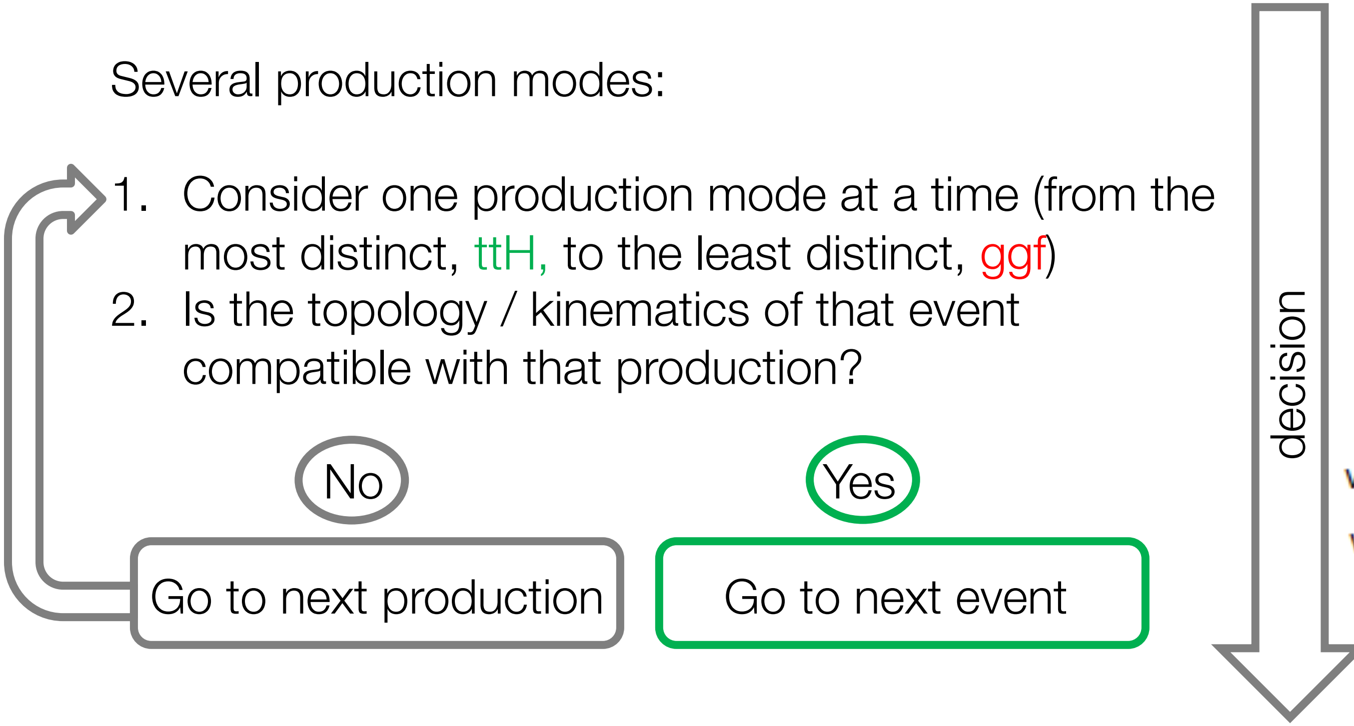
Categorisation

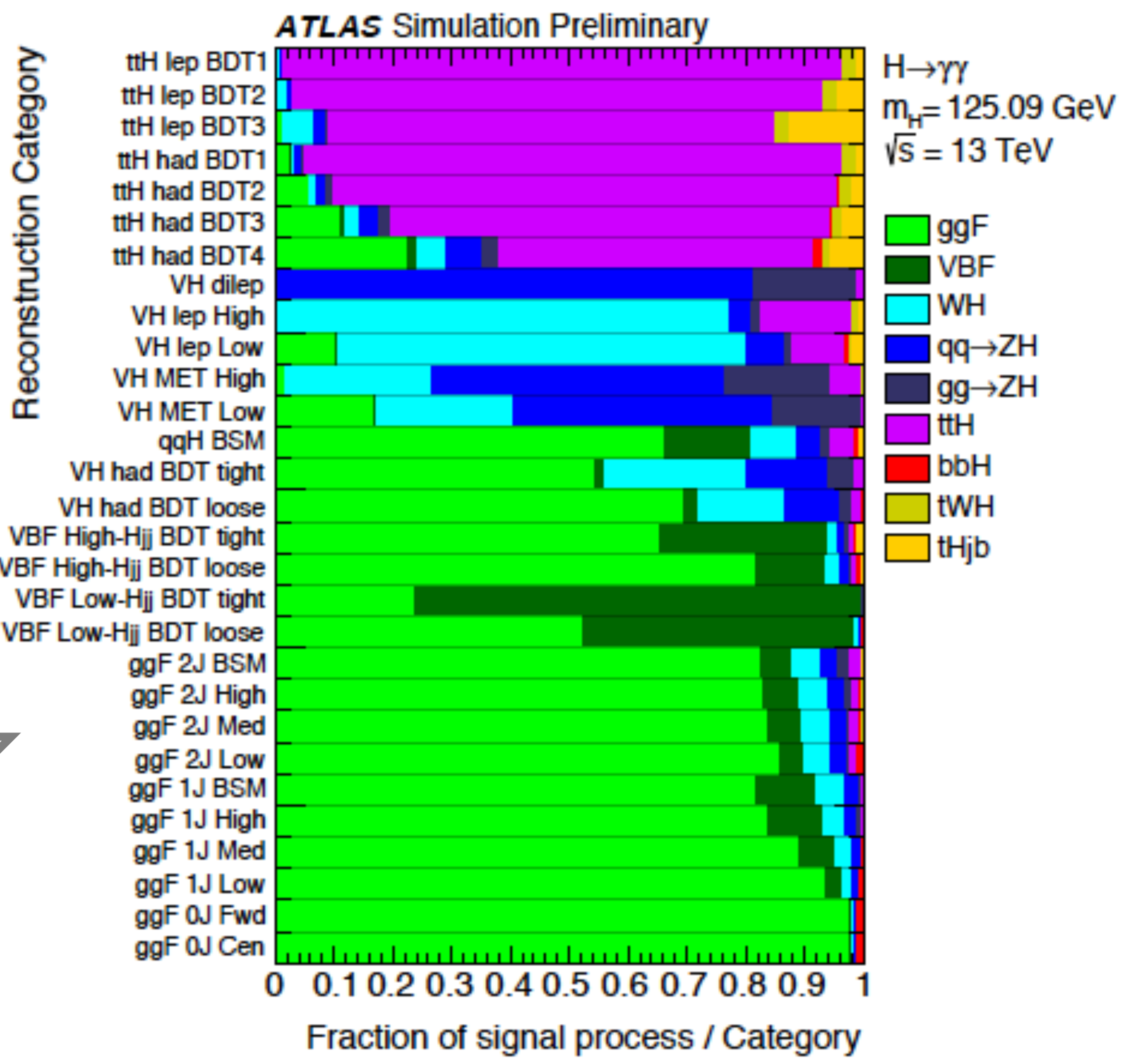
Example: $H \rightarrow \gamma\gamma$

Several production modes:



1. Consider one production mode at a time (from the most distinct, ttH, to the least distinct, ggf)
2. Is the topology / kinematics of that event compatible with that production?

- Attribution to one category is exclusive!
- There is some wrong attribution
- Composition of one category studied by MC



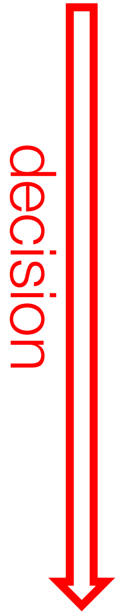
Of the Categorisation

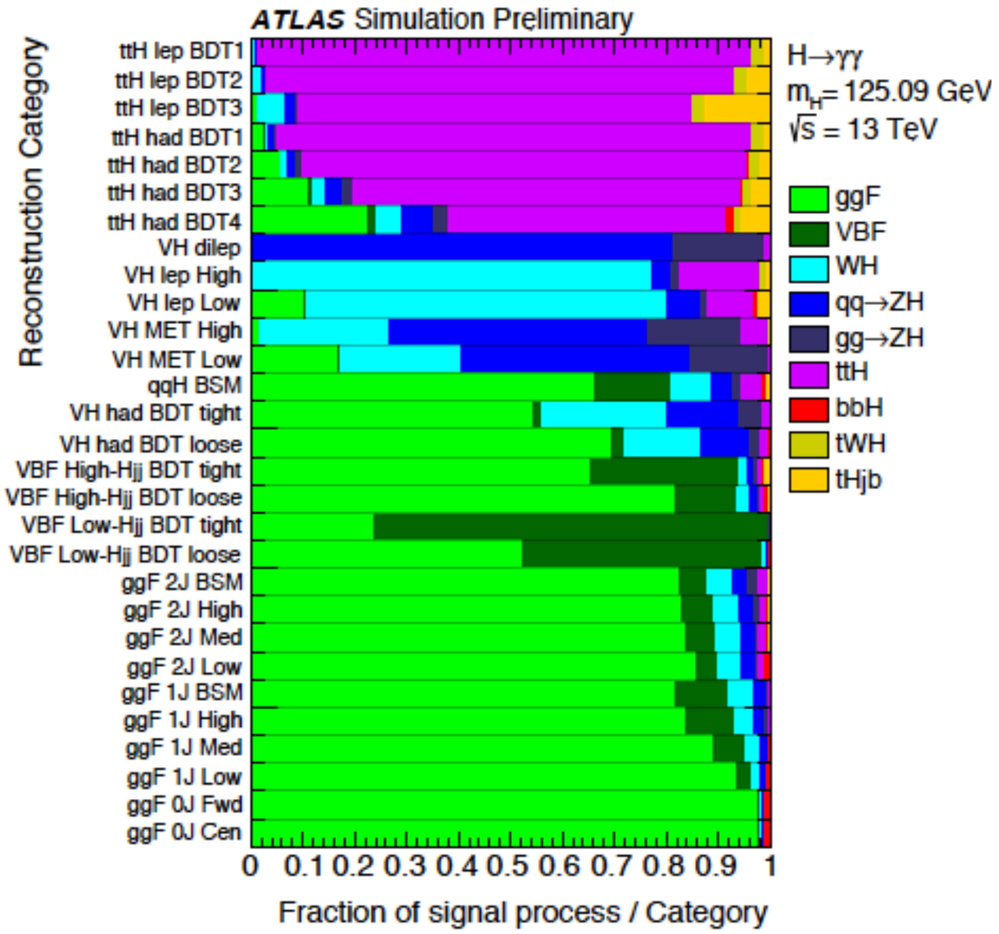
Initial discovery was based on a low sample of events → limited sensitivity to SM Higgs predictions

- Selection: decay modes only, integrate production modes
- Peak in the mass → a resonance, not necessarily a Higgs

- Later in time → more statistics → Need to check if also production modes are in agreement with SM

Start with most distinctive and finish with least distinctive

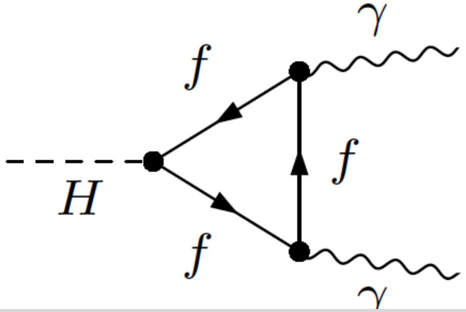




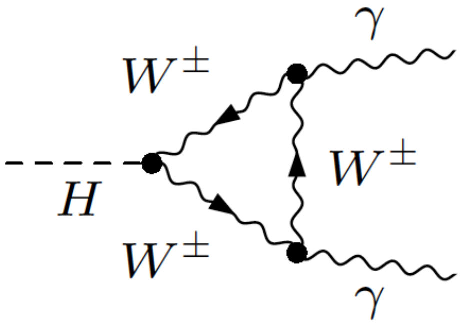
- Separate production processes with topological characteristics → categorisation.
- One category ~ mostly one production mode (but also others) → not a measurement of that production cross-section.

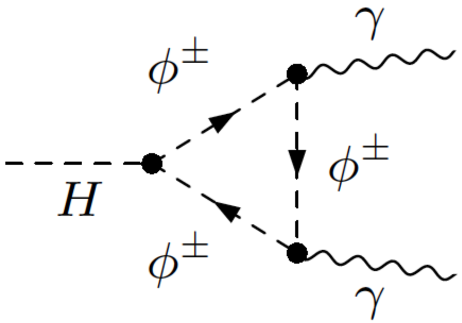
- Simulations are used to determine the relative contributions of the various Higgs production modes in a particular category.

Higgs Decay to Two Photons

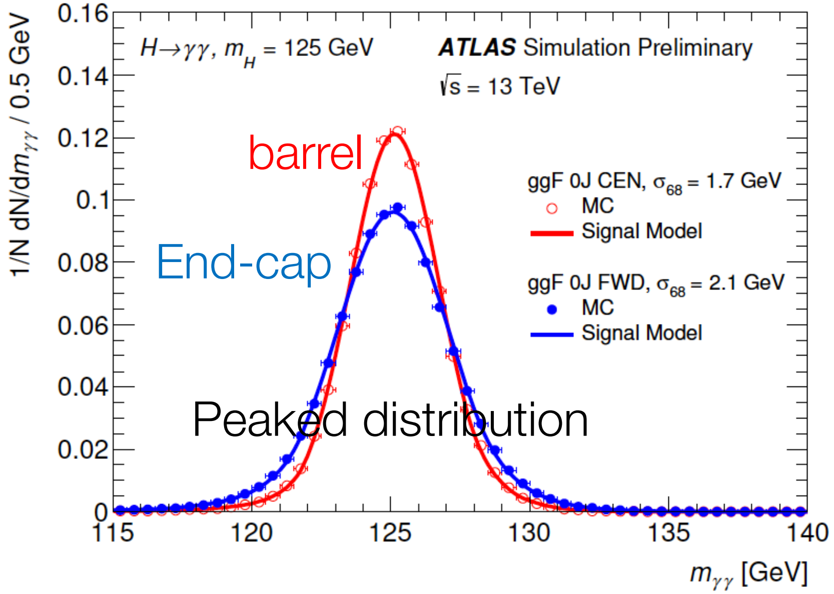


~Only top quarks contribute, contributions from light fermions negligible





Method: look for a peak in the invariant mass of two high p_T photons over a smoothly falling background distribution.

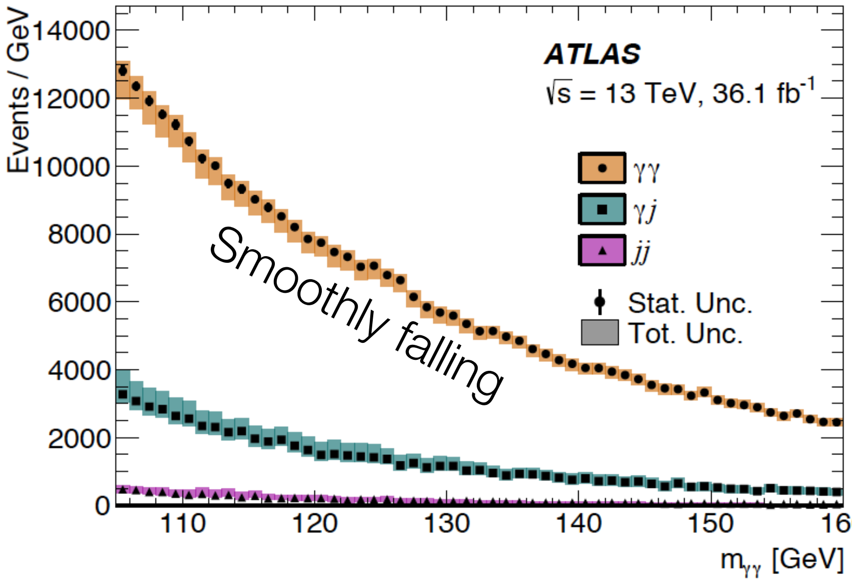


barrel

End-cap

Peaked distribution

Gaussian central part + power law tails on both sides.



Smoothly falling

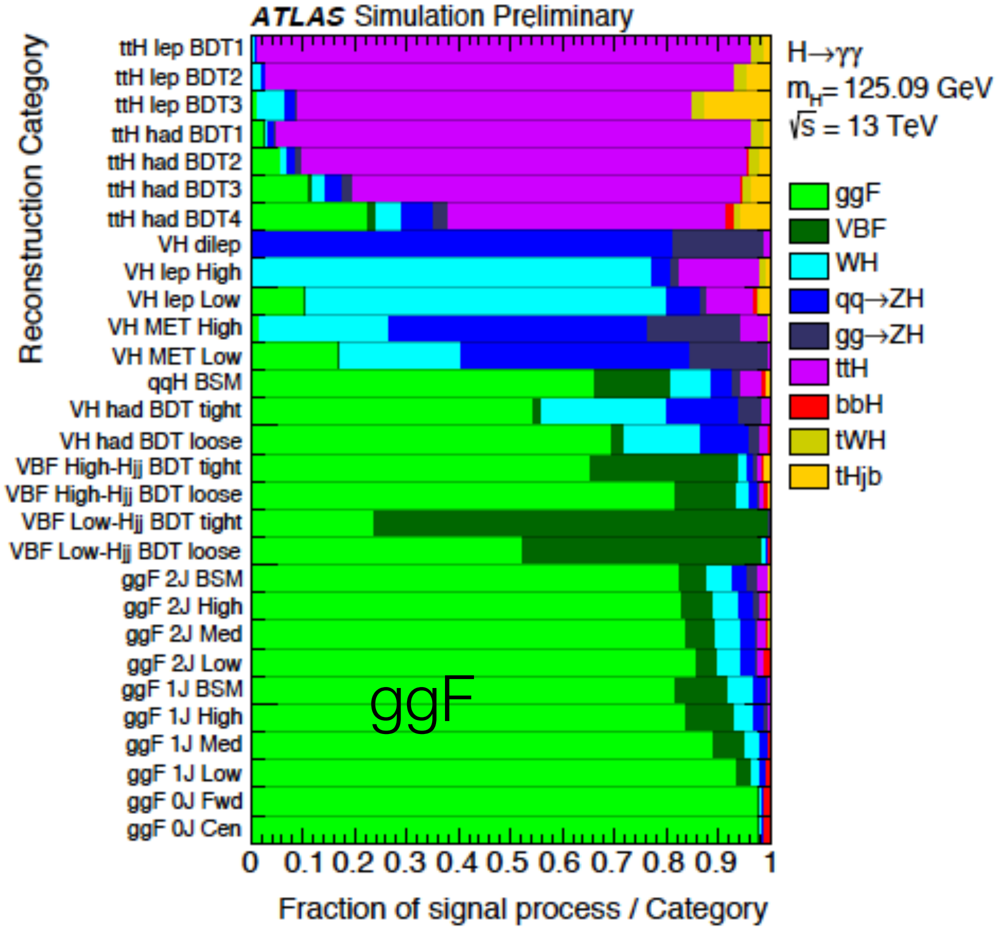
Fits to large control samples of data or simulated background events

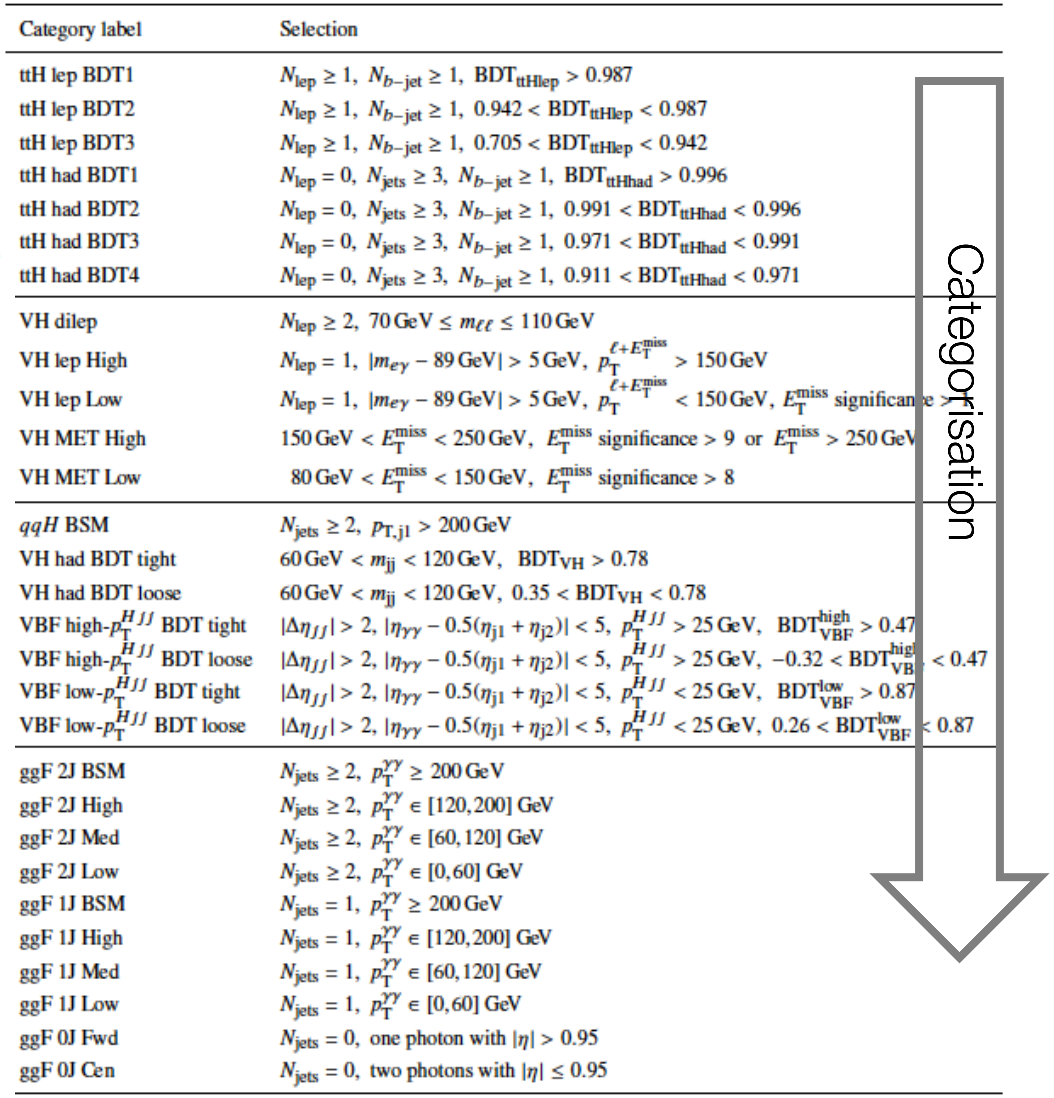
29 Categories in Higgs → $\gamma\gamma$

Summary of the 29 event reconstruction categories for the measurement of production mode cross sections.

Each event is assigned to the first category whose requirements are satisfied, using the descending order given in the table.

As a result, the event populations of categories are mutually exclusive.





Category label	Selection
ttH lep BDT1	$N_{\text{lep}} \geq 1,\ N_{b-\text{jet}} \geq 1,\ \text{BDT}_{\text{ttHlep}} > 0.987$
ttH lep BDT2	$N_{\text{lep}} \geq 1,\ N_{b-\text{jet}} \geq 1,\ 0.942 < \text{BDT}_{\text{ttHlep}} < 0.987$
ttH lep BDT3	$N_{\text{lep}} \geq 1,\ N_{b-\text{jet}} \geq 1,\ 0.705 < \text{BDT}_{\text{ttHlep}} < 0.942$
ttH had BDT1	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{b-\text{jet}} \geq 1,\ \text{BDT}_{\text{ttHhad}} > 0.996$
ttH had BDT2	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{b-\text{jet}} \geq 1,\ 0.991 < \text{BDT}_{\text{ttHhad}} < 0.996$
ttH had BDT3	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{b-\text{jet}} \geq 1,\ 0.971 < \text{BDT}_{\text{ttHhad}} < 0.991$
ttH had BDT4	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{b-\text{jet}} \geq 1,\ 0.911 < \text{BDT}_{\text{ttHhad}} < 0.971$
VH dilep	$N_{\text{lep}} \geq 2,\ 70\,\text{GeV} \leq m_{\ell\ell} \leq 110\,\text{GeV}$
VH lep High	$N_{\text{lep}} = 1,\ \lvert m_{e\gamma} - 89\,\text{GeV}\rvert > 5\,\text{GeV},\ p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} > 150\,\text{GeV}$
VH lep Low	$N_{\text{lep}} = 1,\ \lvert m_{e\gamma} - 89\,\text{GeV}\rvert > 5\,\text{GeV},\ p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} < 150\,\text{GeV},\ E_{\text{T}}^{\text{miss}}$ significance >
VH MET High	$150\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 250\,\text{GeV},\ E_{\text{T}}^{\text{miss}}$ significance > 9 or $E_{\text{T}}^{\text{miss}} > 250\,\text{GeV}$
VH MET Low	$80\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 150\,\text{GeV},\ E_{\text{T}}^{\text{miss}}$ significance > 8
qqH BSM	$N_{\text{jets}} \geq 2,\ p_{\text{T,j1}} > 200\,\text{GeV}$
VH had BDT tight	$60\,\text{GeV} < m_{\text{jj}} < 120\,\text{GeV},\ \text{BDT}_{\text{VH}} > 0.78$
VH had BDT loose	$60\,\text{GeV} < m_{\text{jj}} < 120\,\text{GeV},\ 0.35 < \text{BDT}_{\text{VH}} < 0.78$
VBF high-p_{T}^{HJJ} BDT tight	$\lvert\Delta\eta_{JJ}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5,\ p_{\text{T}}^{HJJ} > 25\,\text{GeV},\ \text{BDT}_{\text{VBF}}^{\text{high}} > 0.47$
VBF high-p_{T}^{HJJ} BDT loose	$\lvert\Delta\eta_{JJ}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5,\ p_{\text{T}}^{HJJ} > 25\,\text{GeV},\ -0.32 < \text{BDT}_{\text{VB}}^{\text{hig}} < 0.47$
VBF low-p_{T}^{HJJ} BDT tight	$\lvert\Delta\eta_{JJ}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5,\ p_{\text{T}}^{HJJ} < 25\,\text{GeV},\ \text{BDT}_{\text{VBF}}^{\text{low}} > 0.87$
VBF low-p_{T}^{HJJ} BDT loose	$\lvert\Delta\eta_{JJ}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5,\ p_{\text{T}}^{HJJ} < 25\,\text{GeV},\ 0.26 < \text{BDT}_{\text{VBF}}^{\text{low}} < 0.87$
ggF 2J BSM	$N_{\text{jets}} \geq 2,\ p_{\text{T}}^{\gamma\gamma} \geq 200\,\text{GeV}$
ggF 2J High	$N_{\text{jets}} \geq 2,\ p_{\text{T}}^{\gamma\gamma} \in [120, 200]\,\text{GeV}$
ggF 2J Med	$N_{\text{jets}} \geq 2,\ p_{\text{T}}^{\gamma\gamma} \in [60, 120]\,\text{GeV}$
ggF 2J Low	$N_{\text{jets}} \geq 2,\ p_{\text{T}}^{\gamma\gamma} \in [0, 60]\,\text{GeV}$
ggF 1J BSM	$N_{\text{jets}} = 1,\ p_{\text{T}}^{\gamma\gamma} \geq 200\,\text{GeV}$
ggF 1J High	$N_{\text{jets}} = 1,\ p_{\text{T}}^{\gamma\gamma} \in [120, 200]\,\text{GeV}$
ggF 1J Med	$N_{\text{jets}} = 1,\ p_{\text{T}}^{\gamma\gamma} \in [60, 120]\,\text{GeV}$
ggF 1J Low	$N_{\text{jets}} = 1,\ p_{\text{T}}^{\gamma\gamma} \in [0, 60]\,\text{GeV}$
ggF 0J Fwd	$N_{\text{jets}} = 0$, one photon with $\lvert\eta\rvert > 0.95$
ggF 0J Cen	$N_{\text{jets}} = 0$, two photons with $\lvert\eta\rvert \leq 0.95$

Categorisation

The $m_{\gamma\gamma}$ distribution with ~80fb^{-1}

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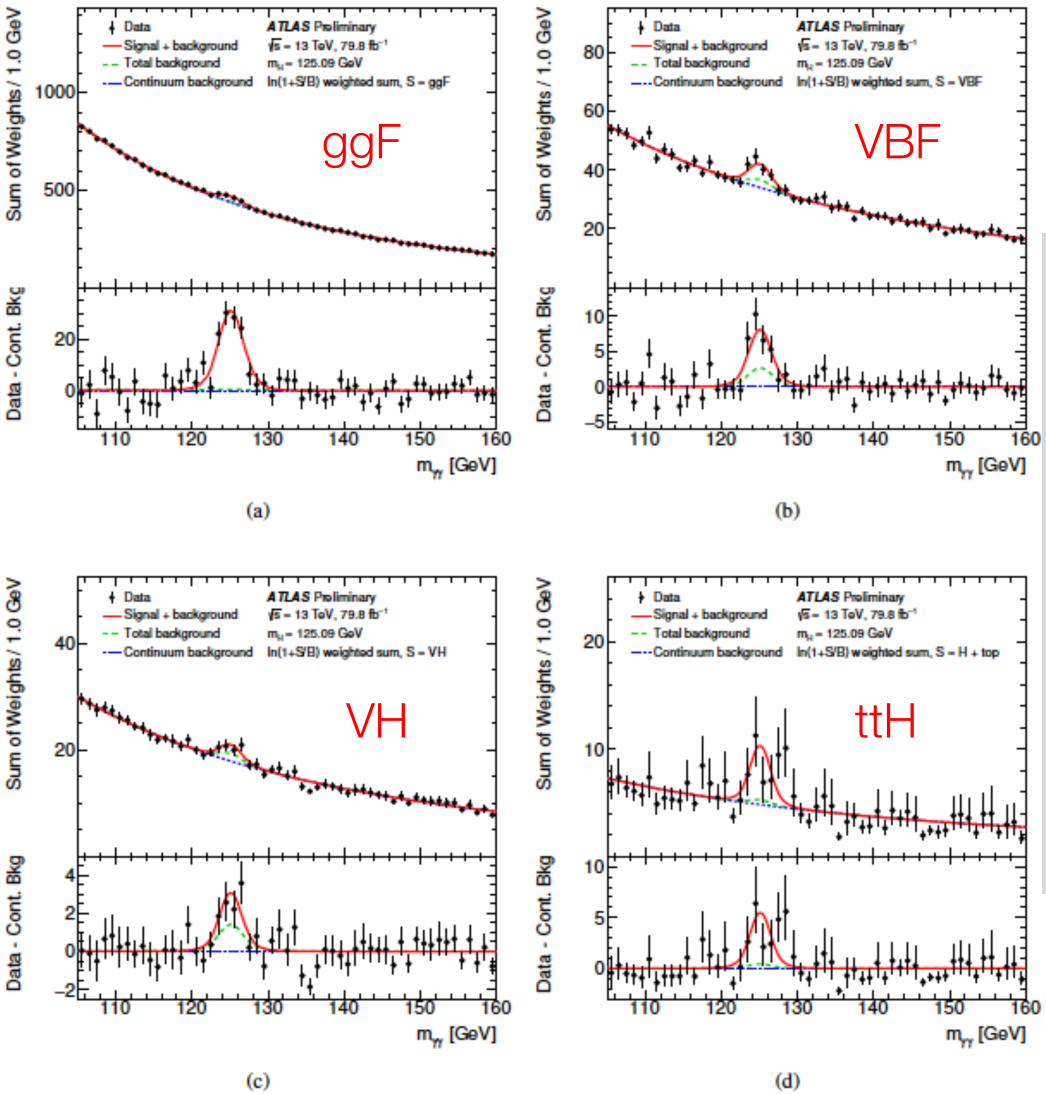
$m_{\gamma\gamma}$ in the four production categories



(a) (b) (c) (d)

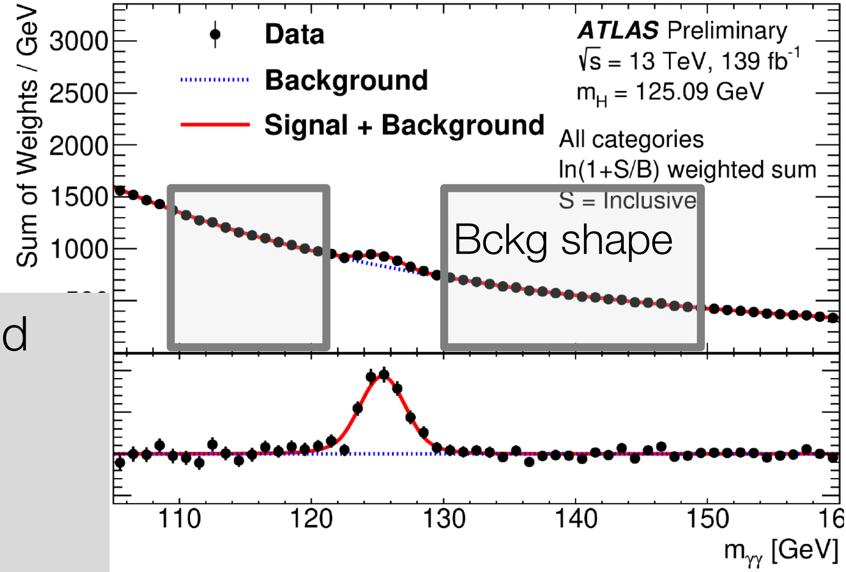
Cumulated $m_{\gamma\gamma}$ distribution for the H → γγ decay

Signal-strength is defined as the ratio between the observed and the SM expected cross section

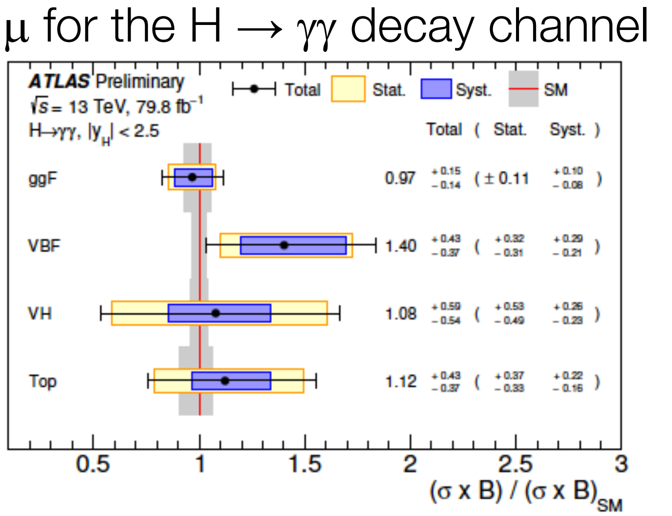
$$\mu = \frac{\sigma^{measured} \times BR^{measured}}{\sigma^{SM} \times BR^{SM}}$$

This observables tells how well data are in agreement with SM

Signal consists of between 150 and 200 H→ γγ decay candidates



μ for the H → γγ decay channel



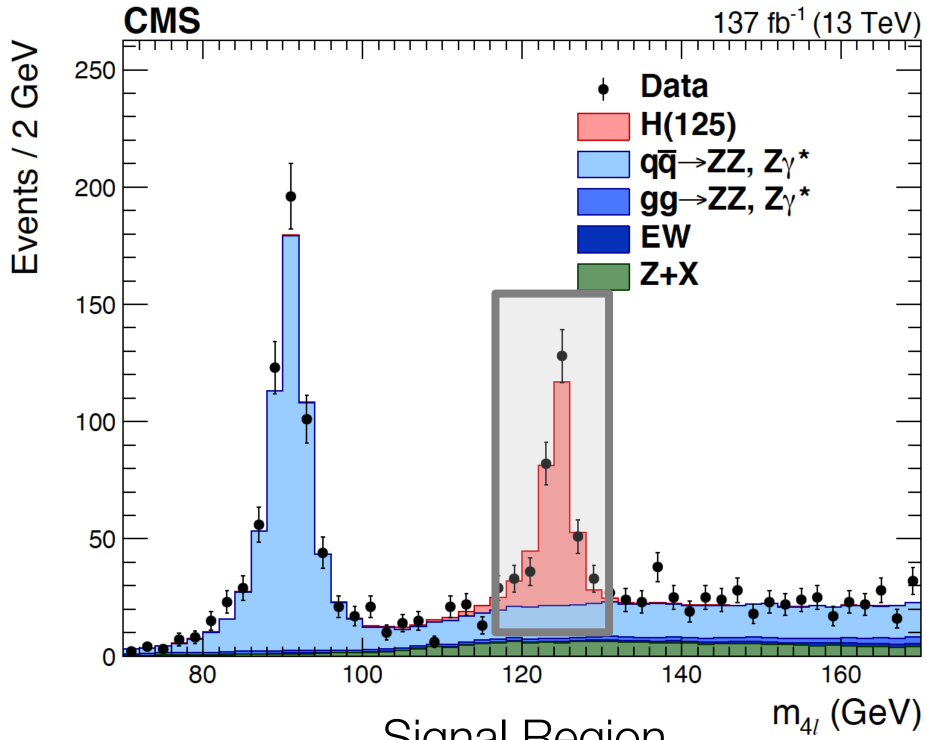
Higgs decay to ZZ → 4 leptons (80 fb^{-1})

Method: $H \rightarrow ZZ^{*} \rightarrow l^{+}\, l^{-}\, l'^{+}\, l'^{-}$ look for a narrow mass peak over a continuous background.

$$H \rightarrow ZZ^{*} \rightarrow 4\ell \text{ decay } (4\mu,\, 2e2\mu,\, 2\mu 2e,\, 4e)$$

Different event-observables → the probability for the event to be signal-like or background-like → Neural Network

Event selection to magnify the ratio S/B

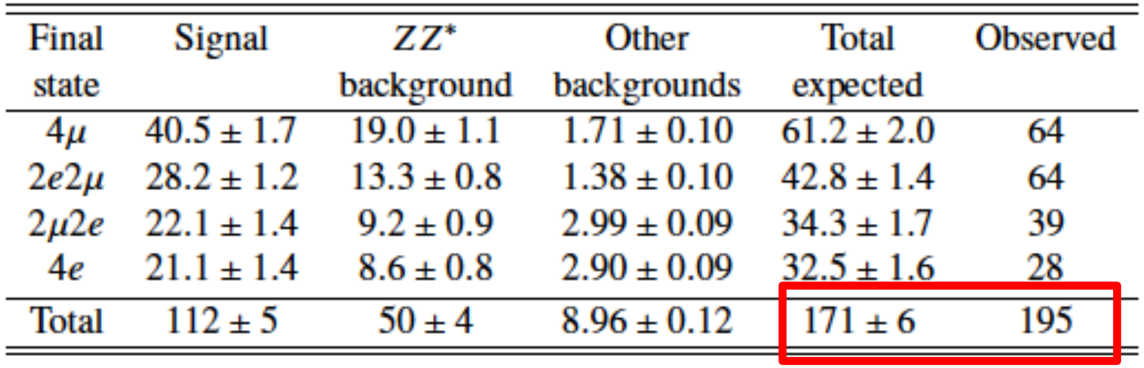


Signal Region

Number of expected and observed events in the four decay channels after the event selection, in the mass range

$$115 \text{ GeV} < m_{4l} < 130 \text{ GeV}.$$

The sum of the expected number of SM Higgs boson events and the estimated background yields is compared to the data.



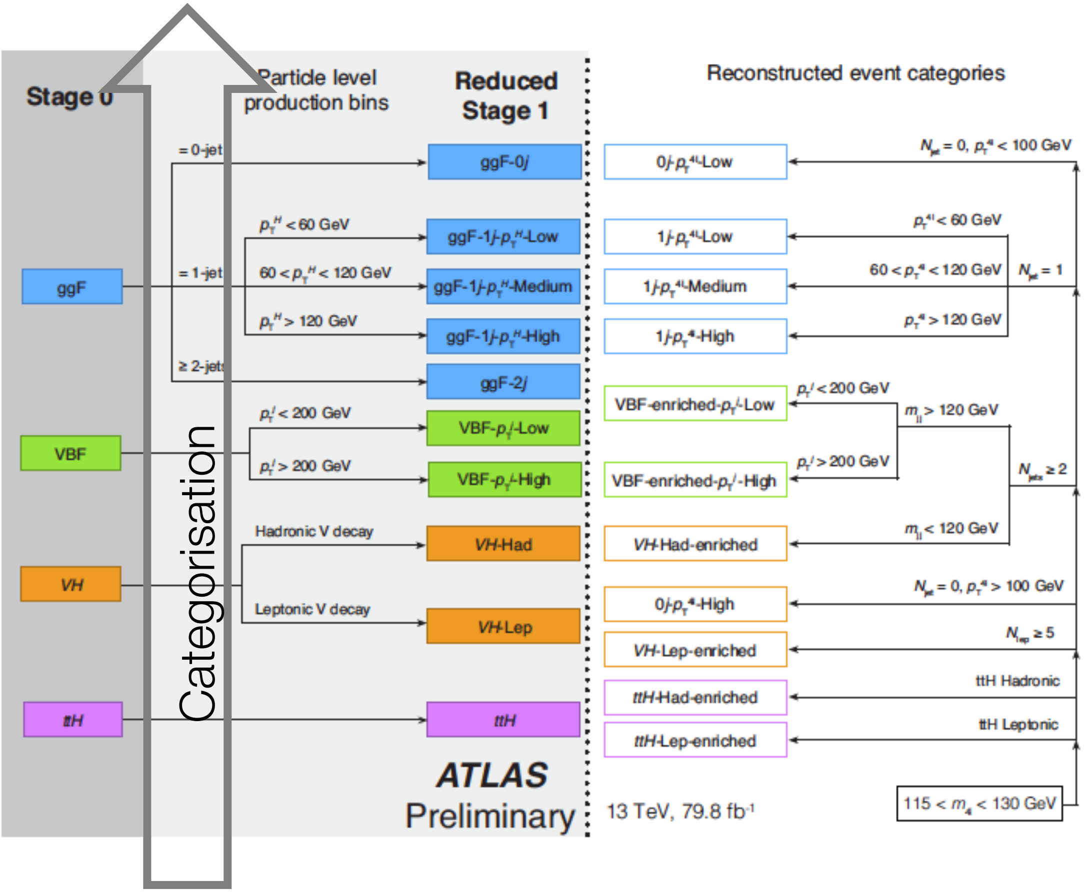
Final state	Signal	ZZ^{*} background	Other backgrounds	Total expected	Observed
4μ	40.5 ± 1.7	19.0 ± 1.1	1.71 ± 0.10	61.2 ± 2.0	64
$2e2\mu$	28.2 ± 1.2	13.3 ± 0.8	1.38 ± 0.10	42.8 ± 1.4	64
$2\mu 2e$	22.1 ± 1.4	9.2 ± 0.9	2.99 ± 0.09	34.3 ± 1.7	39
$4e$	21.1 ± 1.4	8.6 ± 0.8	2.90 ± 0.09	32.5 ± 1.6	28
Total	112 ± 5	50 ± 4	8.96 ± 0.12	171 ± 6	195

Agreement data/MC to 1.7 σ

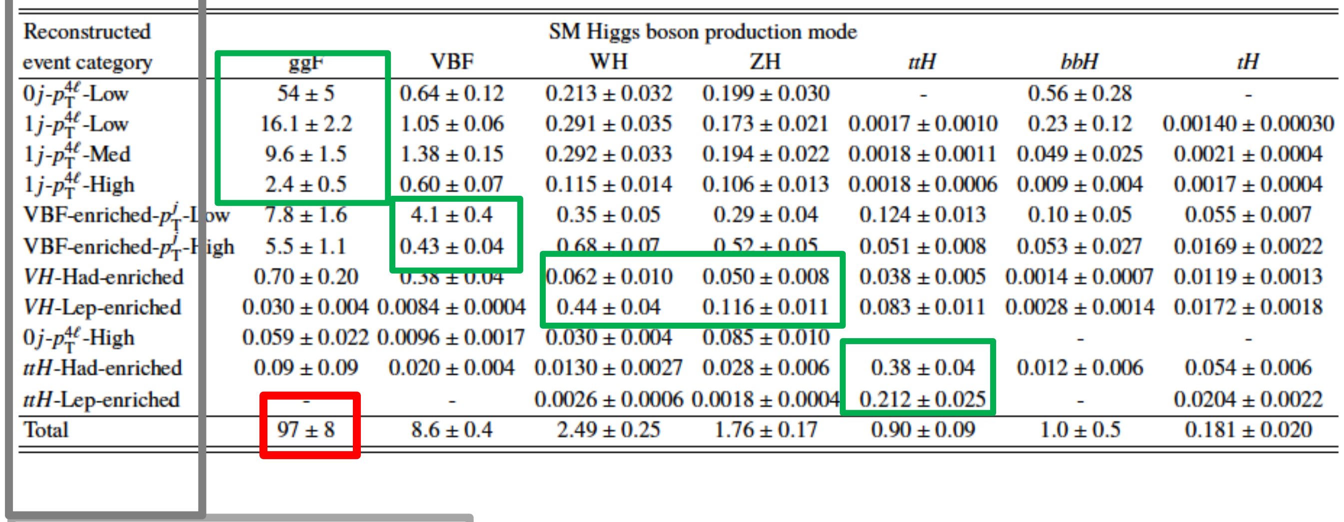
Composition of the Signal

A categorisation ~similar to what was used for the $H \rightarrow \gamma\gamma$ decay is also used for the $H \rightarrow 4l$ decay

Simulated signal composition for ~80 fb-1 of luminosity at 13 TeV: The ggF component, as expected, dominates.



Simulation-based categories (= truth)



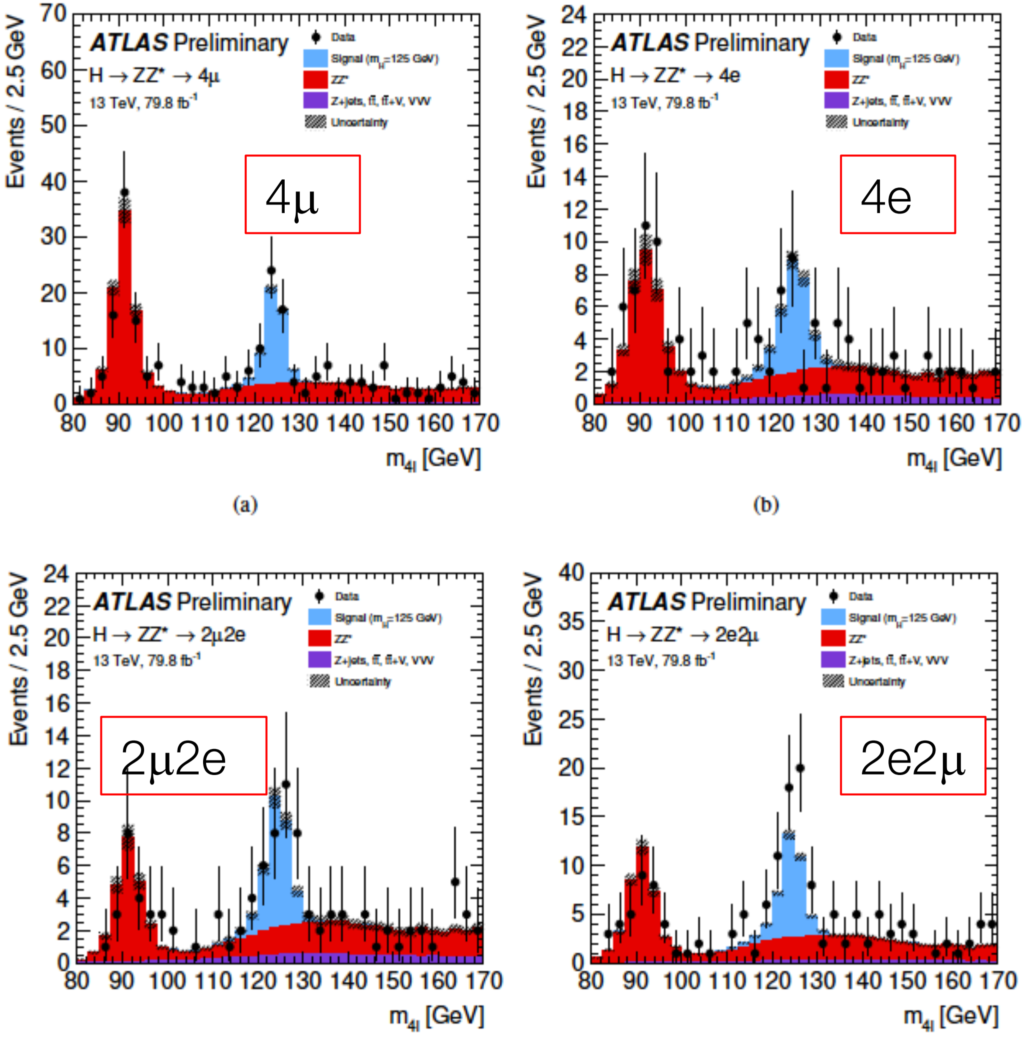
Reconstructed event category	SM Higgs boson production mode ggF	VBF	WH	ZH	ttH	bbH	tH
$0j$-$p_T^{4\ell}$-Low	54 ± 5	0.64 ± 0.12	0.213 ± 0.032	0.199 ± 0.030	-	0.56 ± 0.28	-
$1j$-$p_T^{4\ell}$-Low	16.1 ± 2.2	1.05 ± 0.06	0.291 ± 0.035	0.173 ± 0.021	0.0017 ± 0.0010	0.23 ± 0.12	0.00140 ± 0.00030
$1j$-$p_T^{4\ell}$-Med	9.6 ± 1.5	1.38 ± 0.15	0.292 ± 0.033	0.194 ± 0.022	0.0018 ± 0.0011	0.049 ± 0.025	0.0021 ± 0.0004
$1j$-$p_T^{4\ell}$-High	2.4 ± 0.5	0.60 ± 0.07	0.115 ± 0.014	0.106 ± 0.013	0.0018 ± 0.0006	0.009 ± 0.004	0.0017 ± 0.0004
VBF-enriched-p_T^j-Low	7.8 ± 1.6	4.1 ± 0.4	0.35 ± 0.05	0.29 ± 0.04	0.124 ± 0.013	0.10 ± 0.05	0.055 ± 0.007
VBF-enriched-p_T^j-High	5.5 ± 1.1	0.43 ± 0.04	0.68 ± 0.07	0.52 ± 0.05	0.051 ± 0.008	0.053 ± 0.027	0.0169 ± 0.0022
VH-Had-enriched	0.70 ± 0.20	0.38 ± 0.04	0.062 ± 0.010	0.050 ± 0.008	0.038 ± 0.005	0.0014 ± 0.0007	0.0119 ± 0.0013
VH-Lep-enriched	0.030 ± 0.004	0.0084 ± 0.0004	0.44 ± 0.04	0.116 ± 0.011	0.083 ± 0.011	0.0028 ± 0.0014	0.0172 ± 0.0018
$0j$-$p_T^{4\ell}$-High	0.059 ± 0.022	0.0096 ± 0.0017	0.030 ± 0.004	0.085 ± 0.010		-	-
ttH-Had-enriched	0.09 ± 0.09	0.020 ± 0.004	0.0130 ± 0.0027	0.028 ± 0.006	0.38 ± 0.04	0.012 ± 0.006	0.054 ± 0.006
ttH-Lep-enriched	-	-	0.0026 ± 0.0006	0.0018 ± 0.0004	0.212 ± 0.025	-	0.0204 ± 0.0022
Total	97 ± 8	8.6 ± 0.4	2.49 ± 0.25	1.76 ± 0.17	0.90 ± 0.09	1.0 ± 0.5	0.181 ± 0.020

Reconstruction-based categories

Categorisation works!

A correspondence is determined between reconstruction and simulation categories

Details of the Results



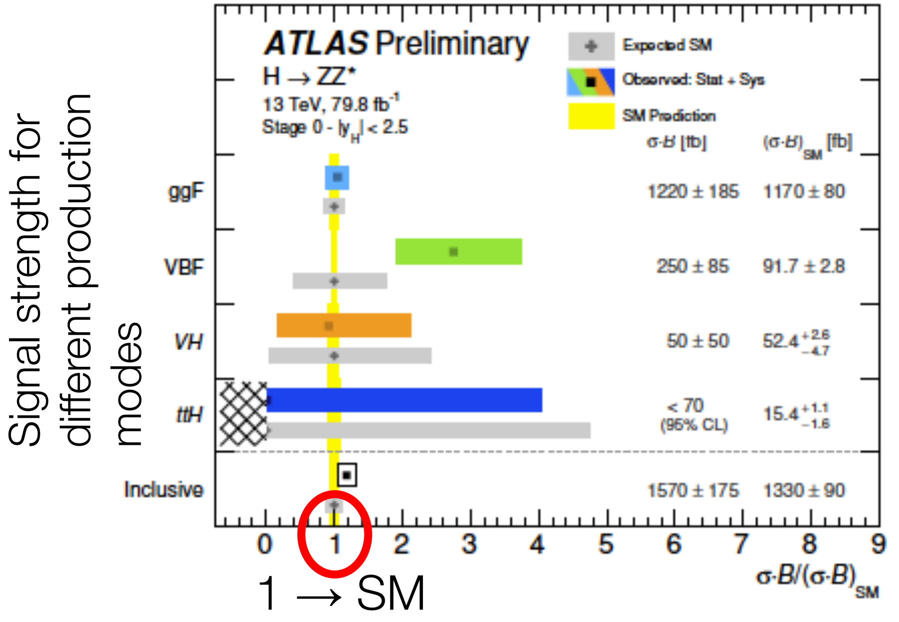
(a) (b)

(c) (d)

Cross section [fb]	Data (± (stat.) ± (syst.))			Standard Model prediction	p-value [%]
$\sigma_{4\mu}$	0.97	±0.17	±0.05	0.886 ± 0.039	62
σ_{4e}	0.61	±0.21	±0.07	0.886 ± 0.039	25
$\sigma_{2\mu 2e}$	0.88	±0.21	±0.08	0.786 ± 0.035	66
$\sigma_{2e2\mu}$	1.37	±0.22	±0.07	0.786 ± 0.035	0.3

The signal strength μ has also been calculated:

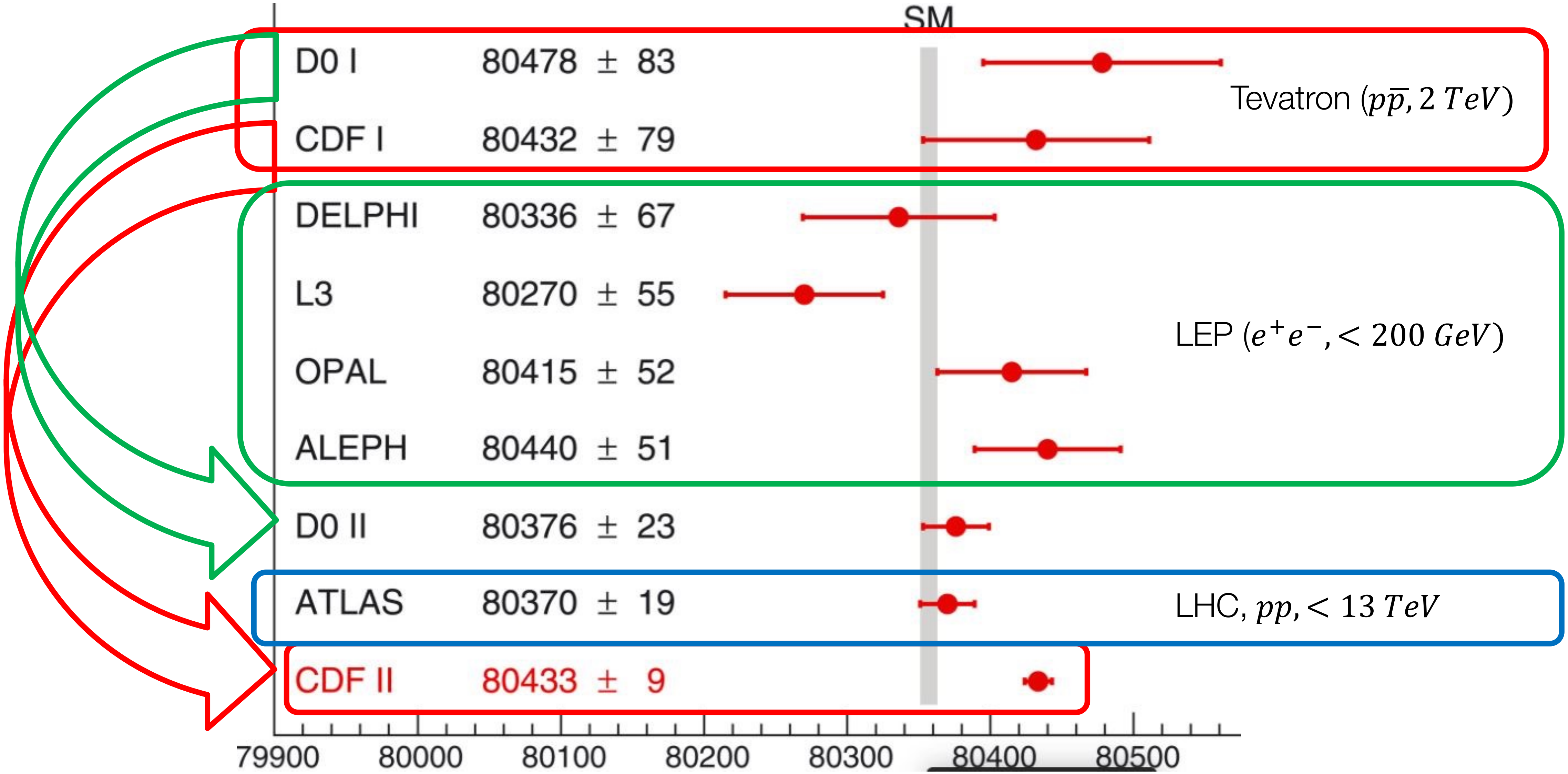
Integrated $\mu = 1.19 \pm 0.12(\text{stat.}) \pm 0.06(\text{exp.})^{+0.08}_{-0.07}(\text{th.}) = 1.19^{+0.16}_{-0.15}.$



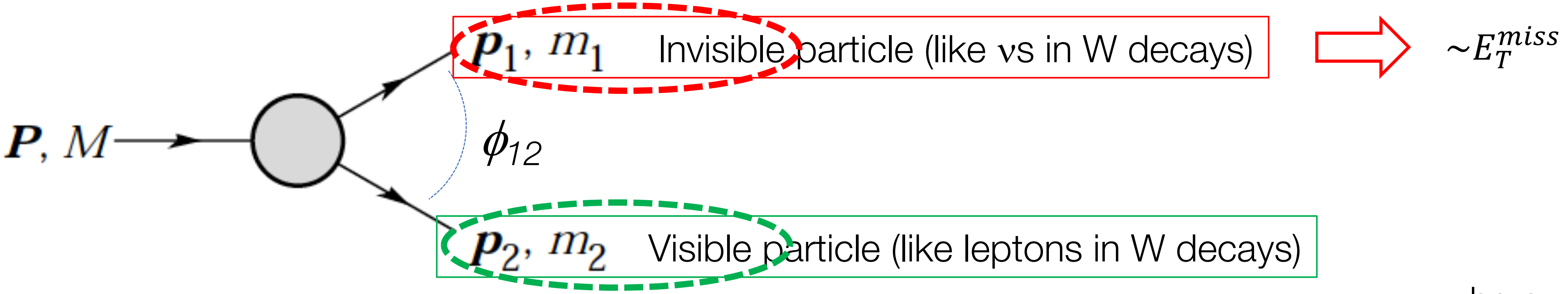
Signal strength for different production modes

1 → SM

W mass measurement at Colliders



W Mass Measurements at Hadron Colliders



Invisible particle (like νs in W decays) ⇒ $\sim E_T^{miss}$

Visible particle (like leptons in W decays)

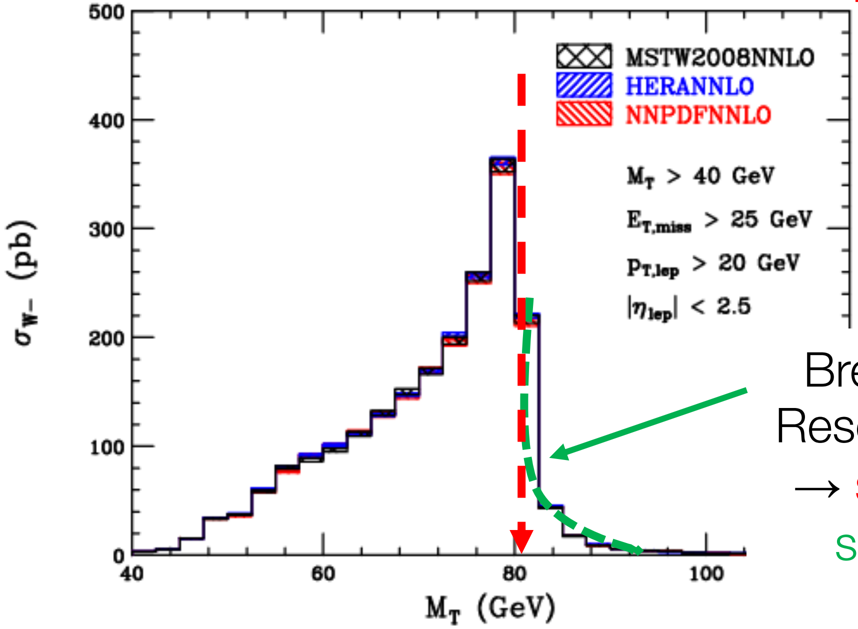
The mass of the parent particle can be constrained with the observable M_T defined by

$$M_T^2 \equiv [E_T(1)+E_T(2)]^2 - [\boldsymbol{p}_T(1)+\boldsymbol{p}_T(2)]^2$$
$$= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1)\cdot\boldsymbol{p}_T(2)]$$

where

$$p_T(1) = E_T^{miss}$$

For m1~m2~0→ $M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1-\cos\phi_{12})$



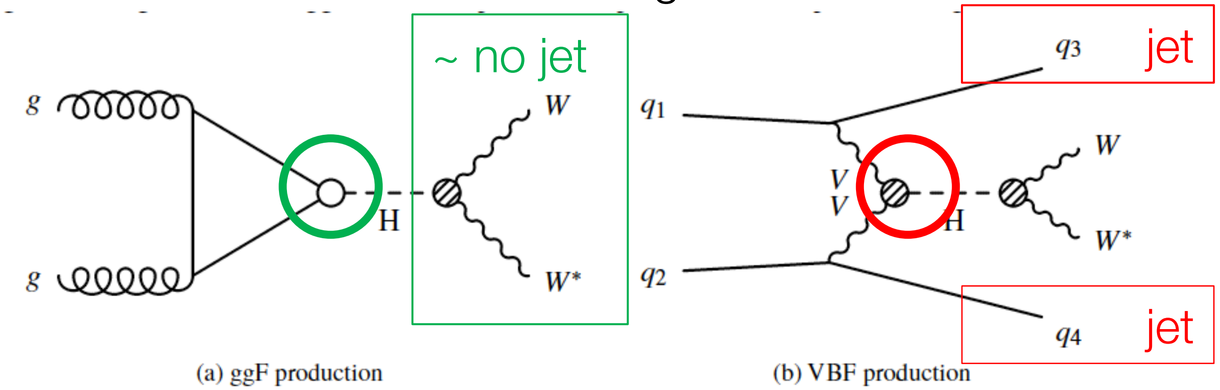
Breit-Wigner+ Resolution effect
→ sharp fall →
smooth fall

Important characteristic: the end point of this distribution is $M_T^{max} = M$

Also the distribution of the p_T of the lepton has memory of m_W: the end-point is $m_W/2$

Higgs → WW → $e\nu\ \mu\nu$ (36 fb^{-1})

Dominant diagrams



(a) ggF production

(b) VBF production

Coupling to fermions

Coupling to bosons

Event selection

2 OFOS leptons ($e\nu_e\ \mu\nu_\mu$) → no Z decay!

Category	$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF
Preselection	Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge $p_T^{\text{lead}} > 22$ GeV , $p_T^{\text{sublead}} > 15$ GeV $m_{\ell\ell} > 10$ GeV $p_T^{\text{miss}} > 20$ GeV		
Background rejection	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$ $\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$ $p_T^{\ell\ell} > 30$ GeV	max $(m_T^\ell) > 50$ GeV $m_{\tau\tau} < m_Z - 25$ GeV	
$H \to WW^* \to e\nu\mu\nu$ topology	$m_{\ell\ell} < 55$ GeV $\Delta\phi_{\ell\ell} < 1.8$		central jet veto outside lepton veto
Discriminant variable BDT input variables	m_T		BDT $m_{jj}, \Delta y_{jj}, m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_T, \sum_\ell C_\ell, \sum_{\ell,j} m_{\ell j}, p_T^{\text{tot}}$

Background is computed using simulation. Control regions in data (orthogonal to the signal region) are used to normalise the MC predictions for most important backgrounds:

- Non resonant WW
- Top pairs production
- Di-bosons (WZ and ZZ) and Drell-Yan

CR	$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF
WW	$55 < m_{\ell\ell} < 110$ GeV $\Delta\phi_{\ell\ell} < 2.6$ $N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$	$m_{\ell\ell} > 80$ GeV $\lvert m_{\tau\tau} - m_Z \rvert > 25$ GeV max $(m_T^\ell) > 50$ GeV	
$t\bar{t}/Wt$	$N_{b\text{-jet},(20\text{ GeV}<p_T<30\text{ GeV})} > 0$ $\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$ $p_T^{\ell\ell} > 30$ GeV $\Delta\phi_{\ell\ell} < 2.8$	$N_{b\text{-jet},(p_T>30\text{ GeV})} = 1$ $N_{b\text{-jet},(20\text{ GeV}<p_T<30\text{ GeV})} = 0$ max $(m_T^\ell) > 50$ GeV $m_{\tau\tau} < m_Z - 25$ GeV	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 1$ central jet veto outside lepton veto
Z/γ^*	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$ $m_{\ell\ell} < 80$ GeV no p_T^{miss} requirement $\Delta\phi_{\ell\ell} > 2.8$	max $(m_T^\ell) > 50$ GeV $m_{\tau\tau} > m_Z - 25$ GeV	central jet veto outside lepton veto $\lvert m_{\tau\tau} - m_Z \rvert \leq 25$ GeV

Results: m_T as proxy of m_H

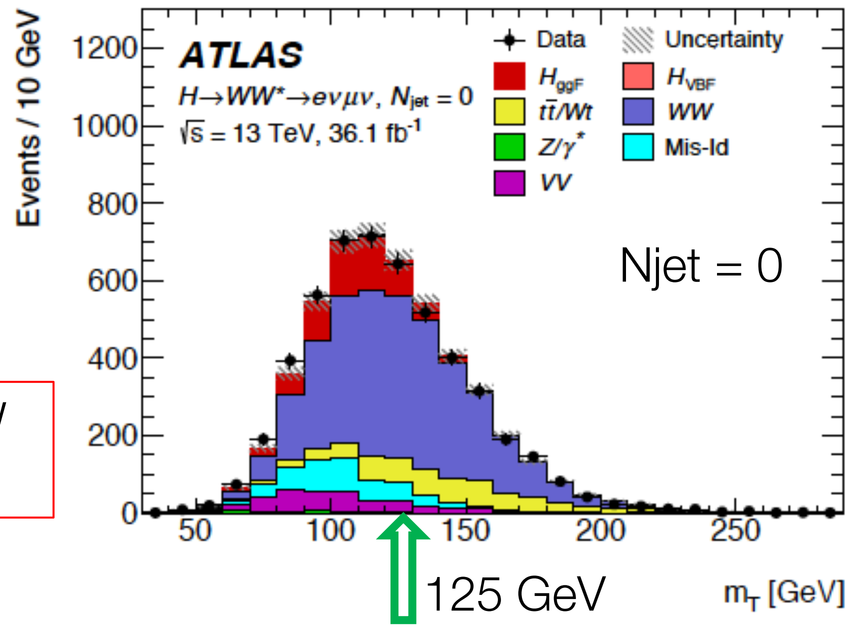
Process	$N_{\text{jet}} = 0$ ggF	$N_{\text{jet}} = 1$ ggF	$N_{\text{jet}} \geq 2$ VBF Inclusive	 BDT: [0.86, 1.0]
H_{ggF}	639 ± 110	285 ± 51	42 ± 16	6 ± 3
H_{VBF}	7 ± 1	31 ± 2	28 ± 16	16 ± 6
WW	3016 ± 203	1053 ± 206	400 ± 60	11 ± 2
VV	333 ± 38	208 ± 32	70 ± 12	3 ± 1
$t\bar{t}/Wt$	588 ± 130	1397 ± 179	1270 ± 80	14 ± 2
Mis-Id	447 ± 77	234 ± 49	90 ± 30	6 ± 2
Z/γ^*	27 ± 11	76 ± 24	280 ± 40	4 ± 1
Total	5067 ± 80	3296 ± 61	2170 ± 50	60 ± 10
Observed	5089	3264	2164	60

ggF populates mostly the Njet=0 and Njet=1 region

VBF populates mostly the Njet>1 region

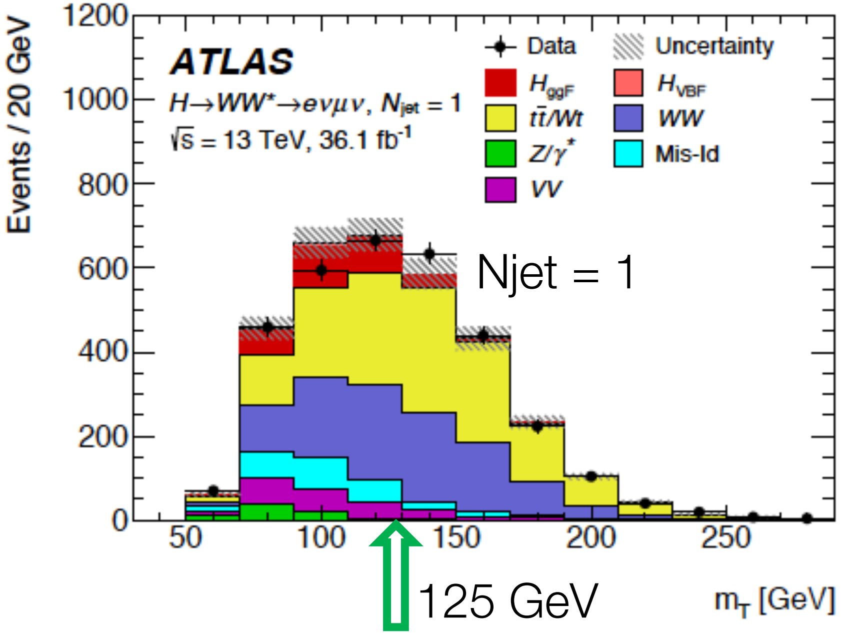
BDT (Boosted Decision Tree) is an analysis technique that combines many different variables in one unique indicator ranging between -1 and 1: the more negative (positive) values are the more background-like (signal-like) is the event

~ 1000 H → WW events selected



Njet = 0

125 GeV

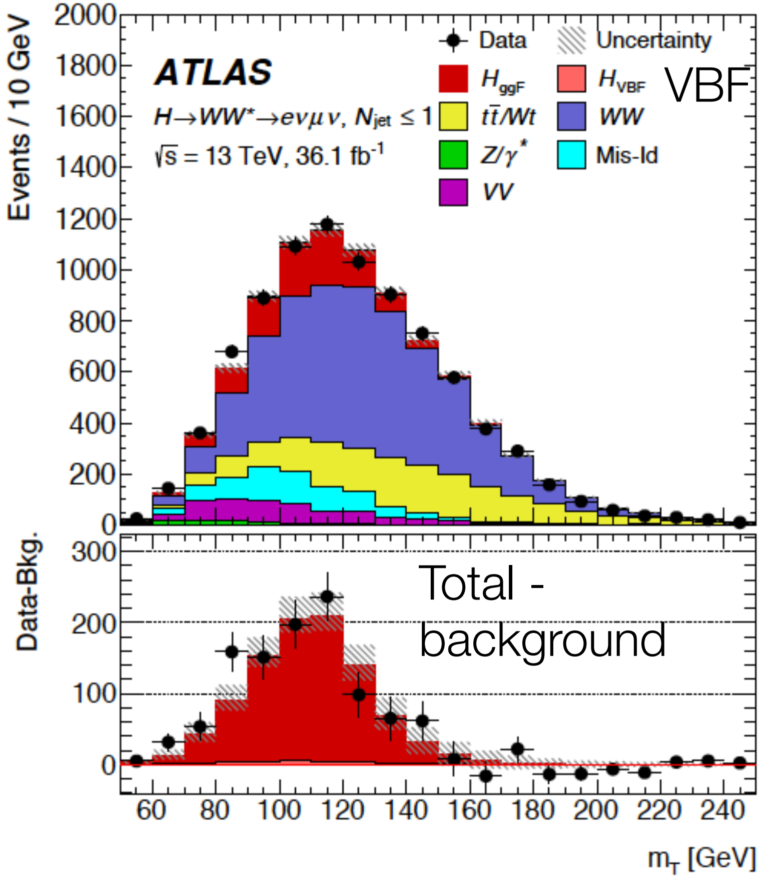


Njet = 1

125 GeV

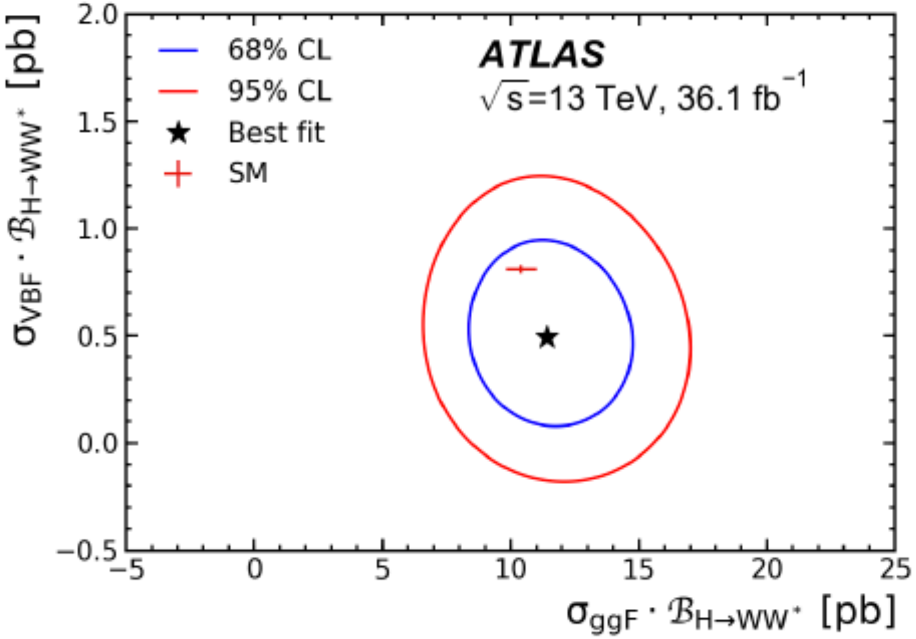
Higgs to WW: Results

Combined m_T distribution for $N_{jet} < 2$.



VBF ~ invisible

Total - background



$$\mu_{\mathrm{ggF}} = 1.10^{+0.10}_{-0.09}(\text{stat.})^{+0.13}_{-0.11}(\text{theo syst.})^{+0.14}_{-0.13}(\text{exp syst.}) = 1.10^{+0.21}_{-0.20}$$

$$\mu_{\mathrm{VBF}} = 0.62^{+0.29}_{-0.27}(\text{stat.})^{+0.12}_{-0.13}(\text{theo syst.}) \pm 0.15(\text{exp syst.}) = 0.62^{+0.36}_{-0.35}.$$

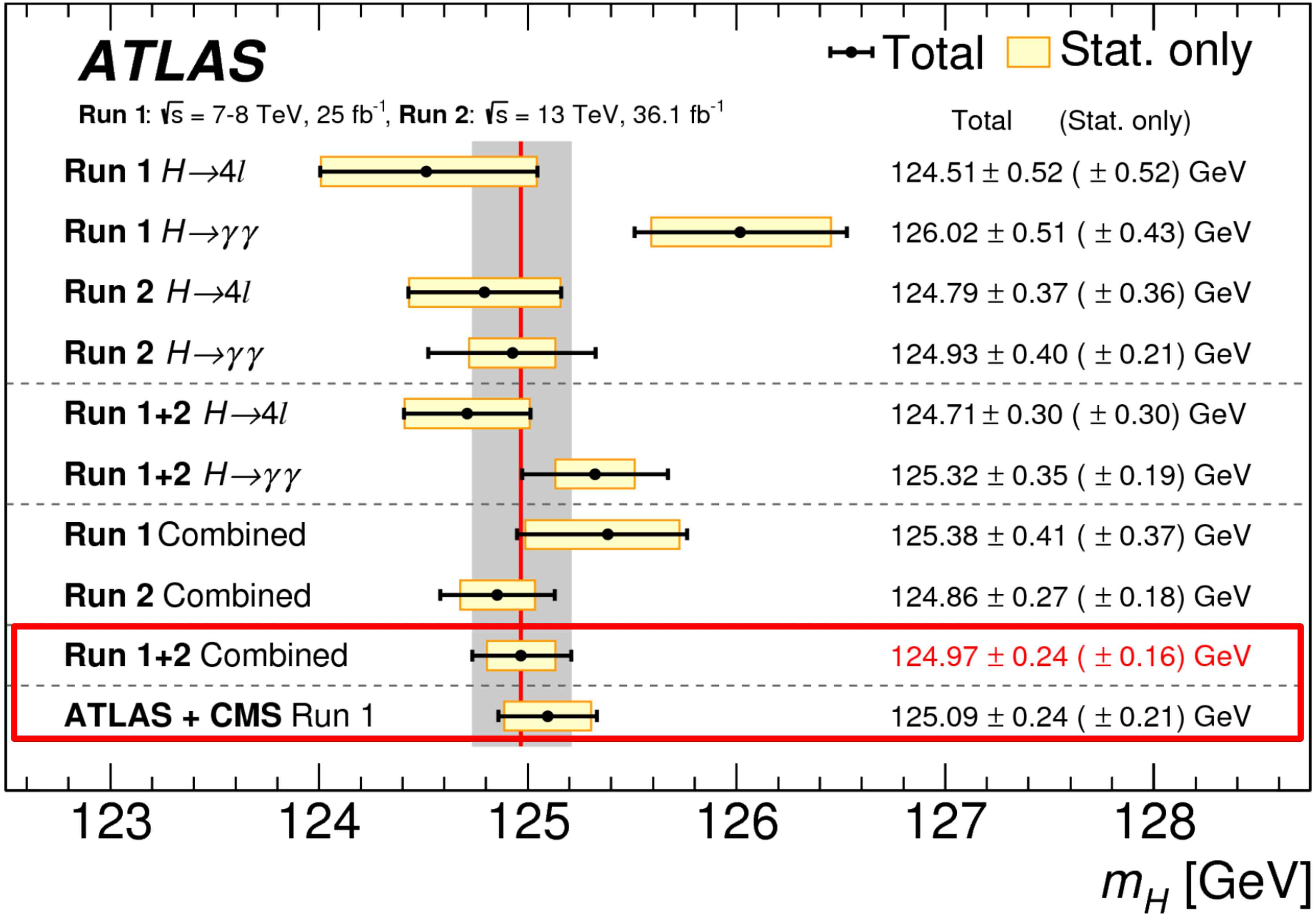
Difference between the data and the estimated background for a SM Higgs boson with mH = 125 GeV.

The signal is fitted to the data with a floating signal strength → expect **$\mu = 1$** for SM Higgs

Higgs mass: Results (@ Run 1& Run 2)

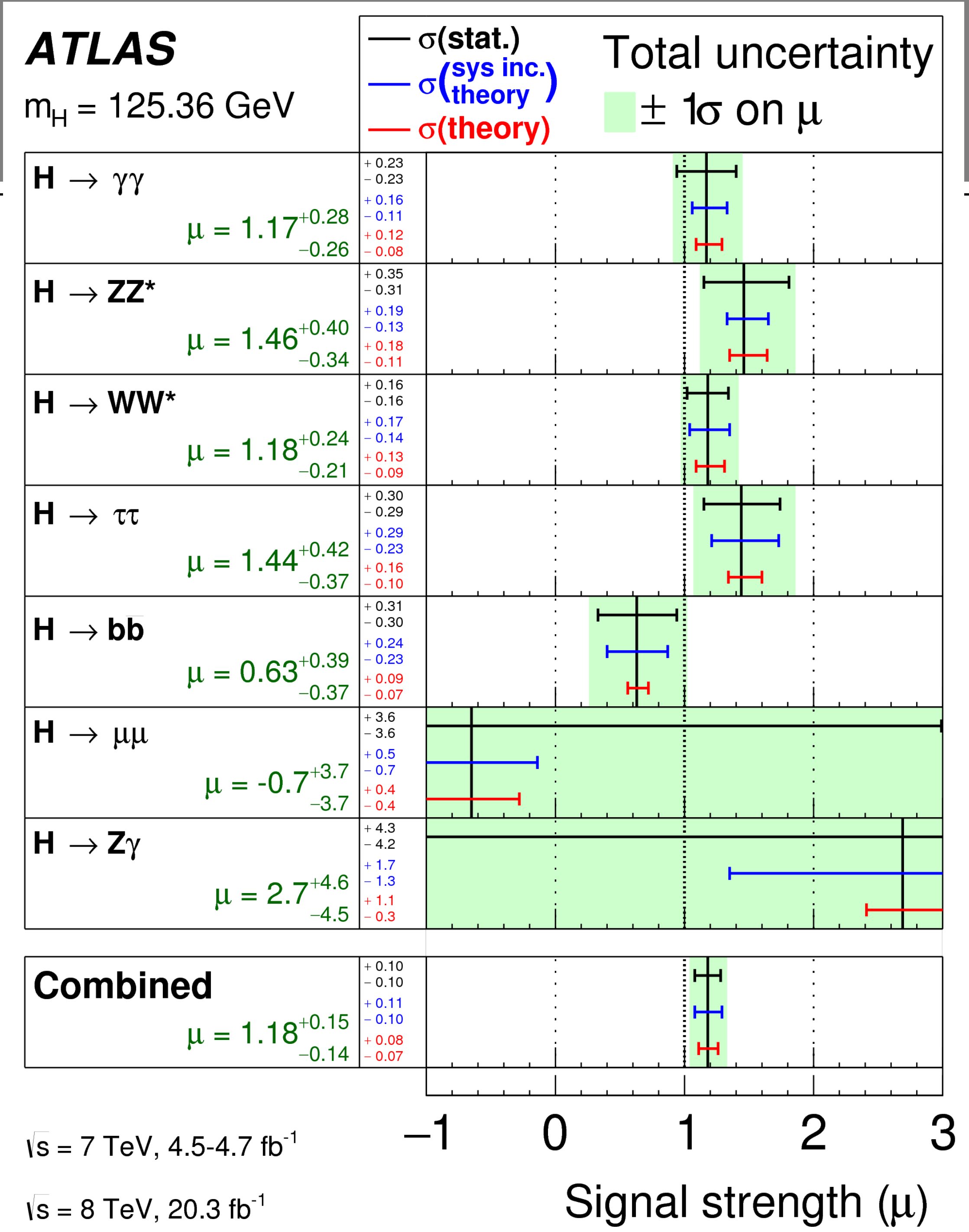
Higgs decays to two photons and four leptons: well reconstructed m_H channels.

ATLAS & CMS

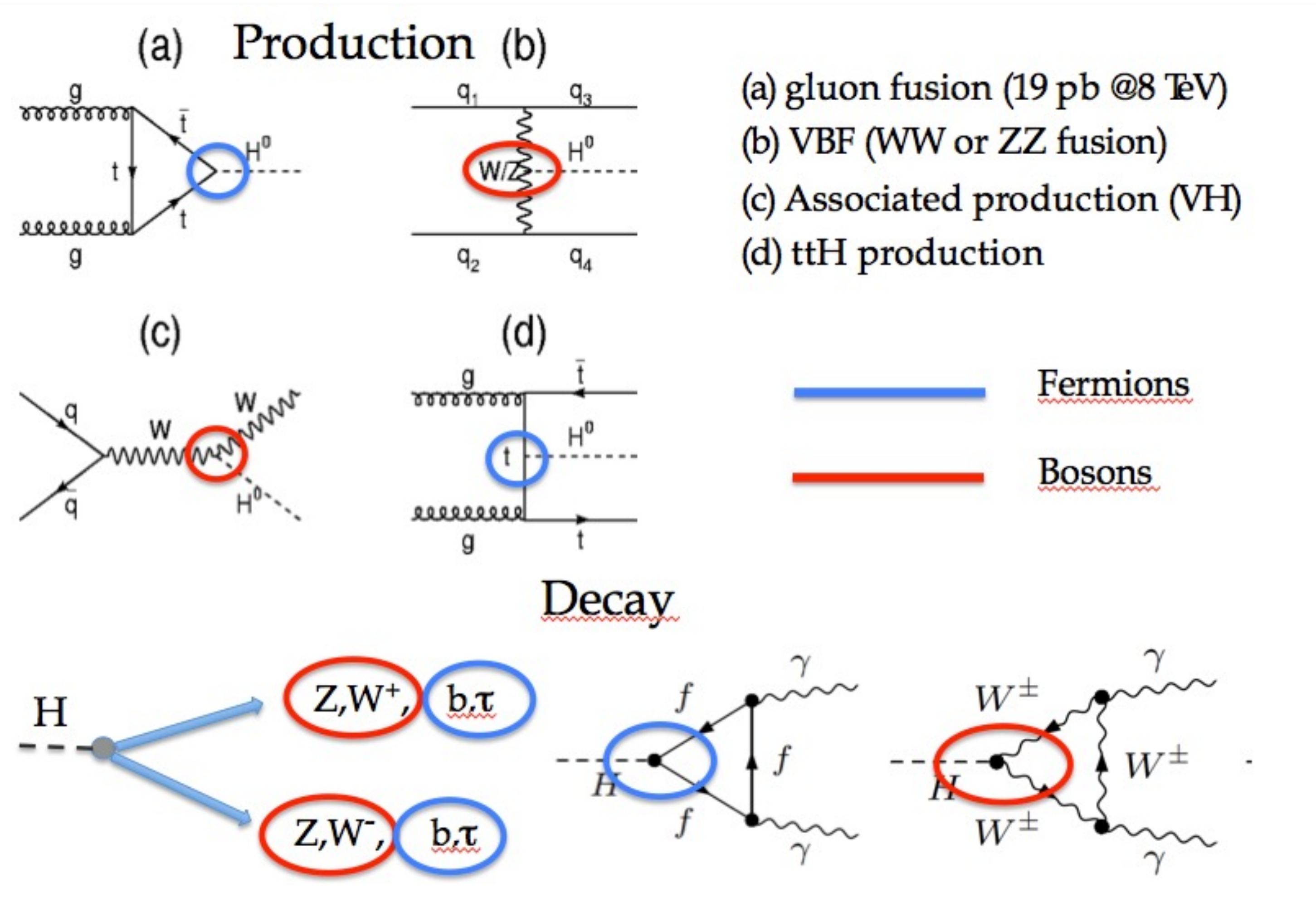


ATLAS

Higgs μ



Correlation Between Production and Decay of the Higgs



(a) gluon fusion (19 pb @8 TeV)
(b) VBF (WW or ZZ fusion)
(c) Associated production (VH)
(d) ttH production

Same vertices in Higgs production and decay → in the SM they are dependent.

Use

$$\mu = \frac{\sigma^{measured} \times BR^{measured}}{\sigma^{SM} \times BR^{SM}}$$

→ if one vertex is modified by a correction factor in production the same correction factor has to modify also the corresponding vertex in decay

Use all possible measurements in the different categories and parametrise the correction factor with the signal strengths

One unique μ

The combination will give a better indication of how well SM describes data

The Analysis Model

$$n_s^c = \left(\sum_{i,f} \underset{\text{production}}{\enclose{circle}{\mu_i}} \cdot \sigma_i^{SM} \cdot A_{if}^c \cdot \varepsilon_{if}^c \cdot \underset{\text{decay}}{\enclose{circle}{\mu_f}} \cdot BR_f^{SM}\right) \cdot \mathcal{L}^c$$

$n_s^c = number\ of\ events\ selected\ in\ one\ category\ c$

Category is a sample of events selected by analysis cuts

- μ_i is the ratio between the observed cross section and the one predicted by the SM
- The production index i ∈ {ggH, VBF, VH, ttH} and the decay index f ∈ {γγ,WW, ZZ, bb, ττ}
- σ_i^{SM} and BR_f^{SM} production cross sections, decay branching fractions for a SM Higgs
- A_{if}^c and ε_{if}^c are the signal acceptance and the reconstruction efficiency for given production and decay mode in the category c.
- $\mathcal{L}^c$ is the integrated luminosity used for that specific category.

Combination = fit μ_i and μ_i → best agreement between data and (modified) SM prediction in different categories.

Includes Signal Regions and Control Regions

There are different ways of combination → different assumptions (~ simplifications)

How Complex is the Fit?

$$n_s^c = \left(\sum_{i,f} \mu_i \cdot \sigma_i^{SM} \cdot A_{if}^c \cdot \varepsilon_{if}^c \cdot \mu_f \cdot BR_f^{SM}\right) \cdot \mathcal{L}^c$$

i ∈ {ggH, VBF, VH, ttH}
f ∈ {γγ,WW, ZZ, bb, τ τ}
5 values of i (VH=WH+WZ)
5 values of f

	$\gamma\gamma$	ZZ (4ℓ)	WW $(\ell\nu\ell\nu)$	$\tau^+\tau^-$	$b\bar{b}$
ggF (high p_T^H)	A	A	—	A	—
ggF (incl. or low p_T^H)	A - C	A - C	A - C		
ggF 1-jet	—	C	A - C	C	—
VBF	A - C	A - C	A - C	A - C	C
WH (1-ℓ)	A - C	A	A - C	C	A - C
WH (two jets)	A - C	A - C	A - C	—	—
ZH (0-ℓ)	A - C	A	—	—	A - C
ZH (2-ℓ)	A - C	A	A - C	C	A - C
ZH (two jets)	A - C	A - C	A - C	—	—
ttH (1-ℓ)	A - C	—	A - C	A - C	A - C
ttH (2-ℓ)	—	—	A - C	A - C	A - C
ttH (hadronic)	A - C	—	—	—	A

A=ATLAS, C=CMS

Possible ways of fitting:

1. *i x f* makes 25 free parameters
2. One reference process (characterised by σ_{ref} and BR_{ref}) + ${}^{\sigma_f}/_{\sigma_{ref}}$ + ${}^{BR_f}/_{BR_{ref}}$ (→ 1 + 4 + 4 parameters)
3. Further assumptions (see later)
4. Effective Lagrangian, introduce vertex modifiers

Signal Strenght (μ)

Production mechanism	*ggF*	*VBF*	*WH/ZH*	*ttH*
Events produced at the LHC	500 K	40 K	20 K	3 K
Selected events	O(500)	O(500)	O(50)	
Events produced at the Tevatron	10 K		2 K	

For each decay channel “c” we define categories to maximise the sensitivity of the analysis to one particular production mode.
However a mixture of different mechanisms in one category is inevitable.
→ This implies the cross section of one category is not the cross section of only one production mechanism.

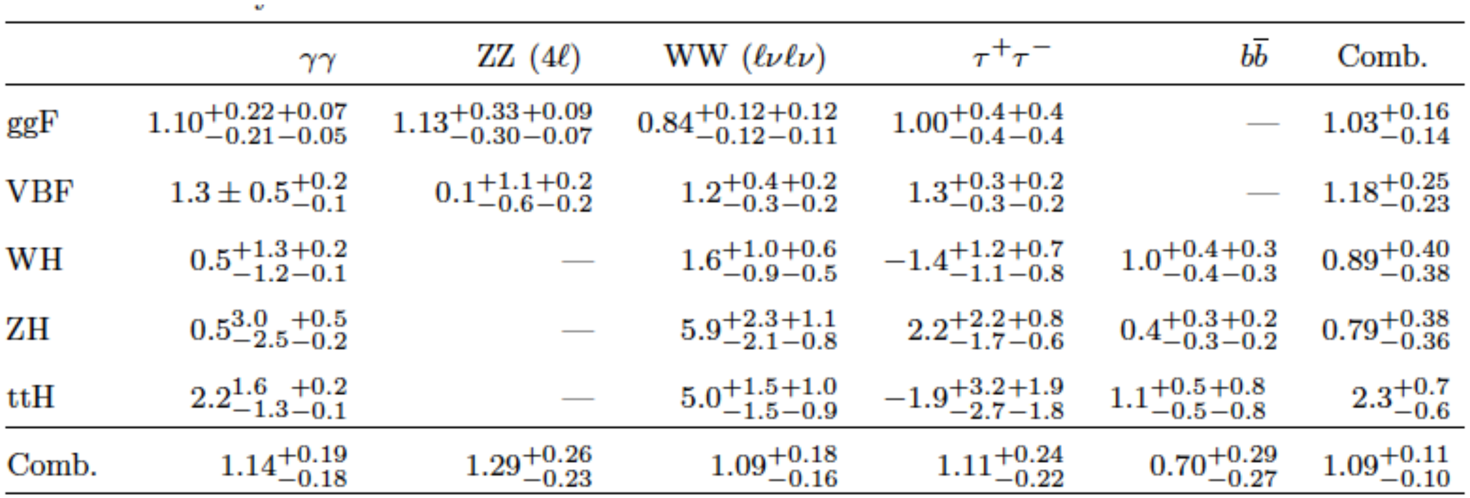
$$n_s^c = \left(\boxed{\sum_{i,f}} \mu_i \cdot \sigma_i^{SM} \cdot A_{if}^c \cdot \varepsilon_{if}^c \cdot \mu_f \cdot BR_f^{SM} \right) \cdot \mathcal{L}^c$$

Where m_c is ration between measured & expected events in that category and

i = ggf, VBF, VH, tth and f=gg,WW,ZZ,bb,tt

Measurement of μ_c gives an indication of how well SM describes data

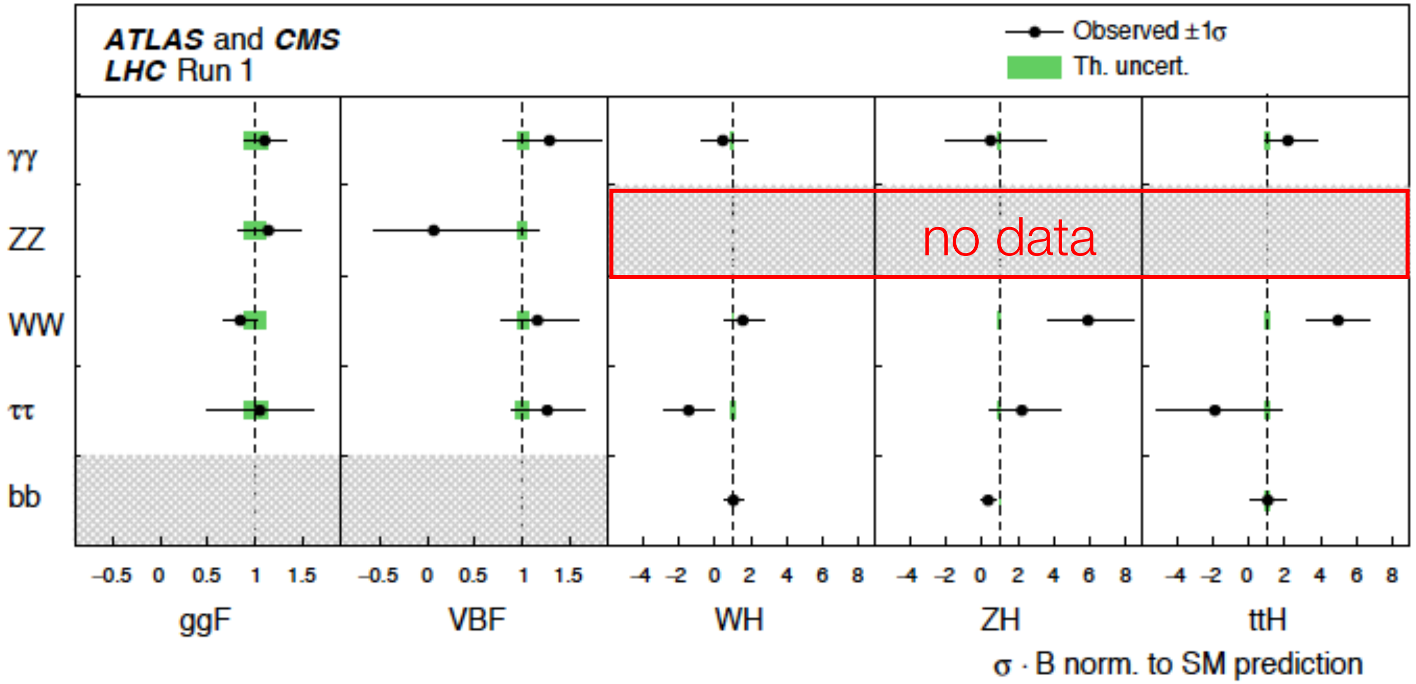
Fit type 1 most general case



	$\gamma\gamma$	ZZ (4ℓ)	WW $(\ell\nu\ell\nu)$	$\tau^+\tau^-$	$b\bar{b}$	Comb.
ggF	$1.10^{+0.22+0.07}_{-0.21-0.05}$	$1.13^{+0.33+0.09}_{-0.30-0.07}$	$0.84^{+0.12+0.12}_{-0.12-0.11}$	$1.00^{+0.4+0.4}_{-0.4-0.4}$	—	$1.03^{+0.16}_{-0.14}$
VBF	$1.3 \pm 0.5^{+0.2}_{-0.1}$	$0.1^{+1.1+0.2}_{-0.6-0.2}$	$1.2^{+0.4+0.2}_{-0.3-0.2}$	$1.3^{+0.3+0.2}_{-0.3-0.2}$	—	$1.18^{+0.25}_{-0.23}$
WH	$0.5^{+1.3+0.2}_{-1.2-0.1}$	—	$1.6^{+1.0+0.6}_{-0.9-0.5}$	$-1.4^{+1.2+0.7}_{-1.1-0.8}$	$1.0^{+0.4+0.3}_{-0.4-0.3}$	$0.89^{+0.40}_{-0.38}$
ZH	$0.5^{3.0\ +0.5}_{-2.5-0.2}$	—	$5.9^{+2.3+1.1}_{-2.1-0.8}$	$2.2^{+2.2+0.8}_{-1.7-0.6}$	$0.4^{+0.3+0.2}_{-0.3-0.2}$	$0.79^{+0.38}_{-0.36}$
ttH	$2.2^{1.6\ +0.2}_{-1.3-0.1}$	—	$5.0^{+1.5+1.0}_{-1.5-0.9}$	$-1.9^{+3.2+1.9}_{-2.7-1.8}$	$1.1^{+0.5+0.8}_{-0.5-0.8}$	$2.3^{+0.7}_{-0.6}$
Comb.	$1.14^{+0.19}_{-0.18}$	$1.29^{+0.26}_{-0.23}$	$1.09^{+0.18}_{-0.16}$	$1.11^{+0.24}_{-0.22}$	$0.70^{+0.29}_{-0.27}$	$1.09^{+0.11}_{-0.10}$

$$\text{Signal Strenght } \mu = {(\sigma \cdot B)_{obs}}\Big/{(\sigma \cdot B)_{SM}}$$

- *No significant deviation from the SM*
- *25 – 5 = 20 parameters determined*



Fit Type 2: Fewer Parameters

Take the Higgs produced via ggF and decaying to ZZ as reference

i = production, f = decay

$$\mu_i = \frac{\sigma_i}{\sigma_{ggF}\sigma_i^{SM}} \boxed{\times \mu_{gg\to H\to ZZ}}$$

$$\mu_f = \frac{\mathrm{BR}_i}{\boxed{\mathrm{BR}_{ZZ}}\mathrm{BR}_i^{SM}}$$

$$\mu_{gg\to H\to ZZ} = \boxed{\mu_{ggF} \times \mu_{ZZ}} \times \sigma_i^{SM} \times \mathrm{BR}_f^{SM}$$

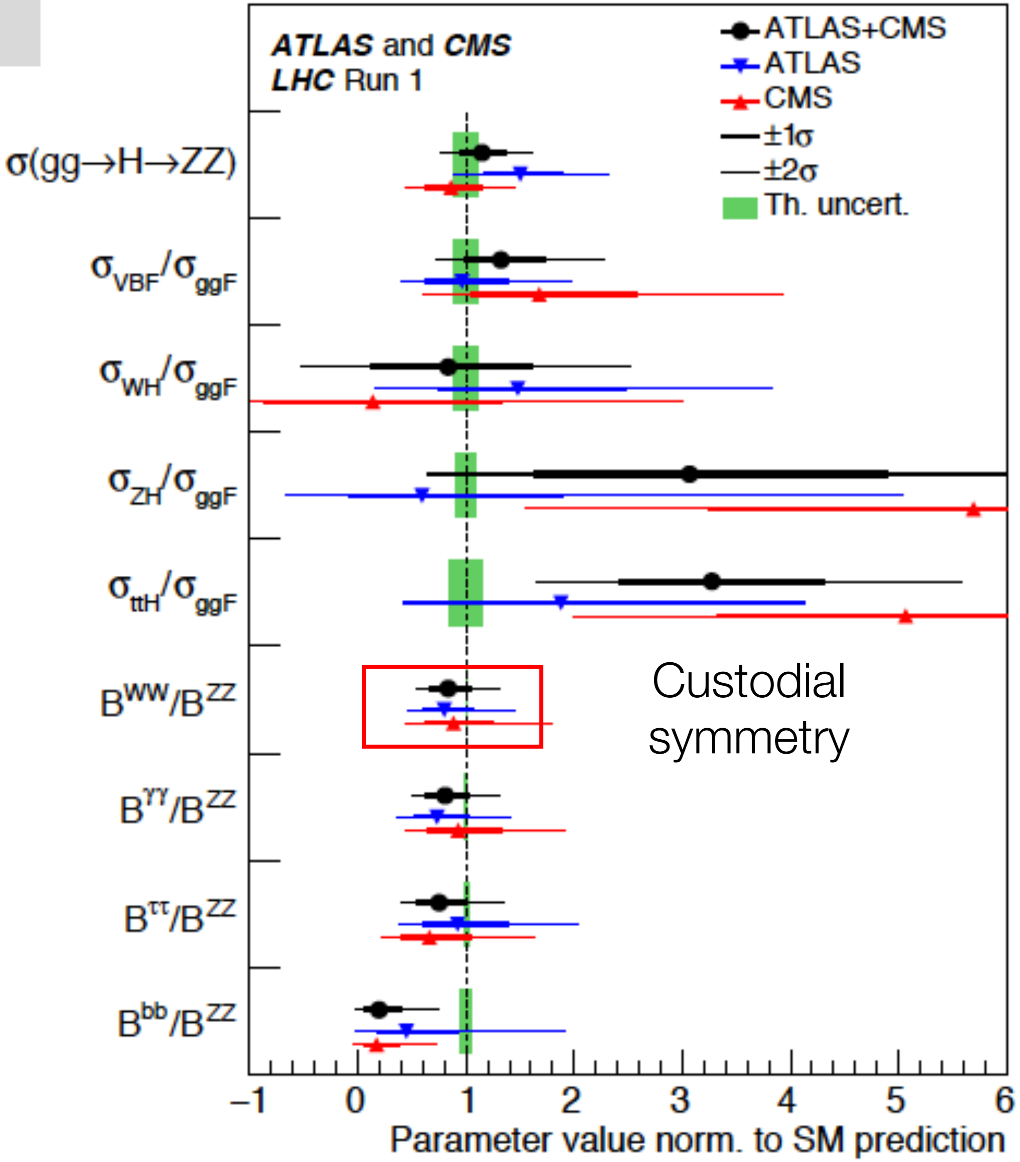
Then, the master formula applies for all i and f indices except when **both i = ggF and f = ZZ**

→ 8 + 1 parameters

Improved precision in the fit, due to fewer parameters, shows no deviation from SM (assumption production and decay independent)

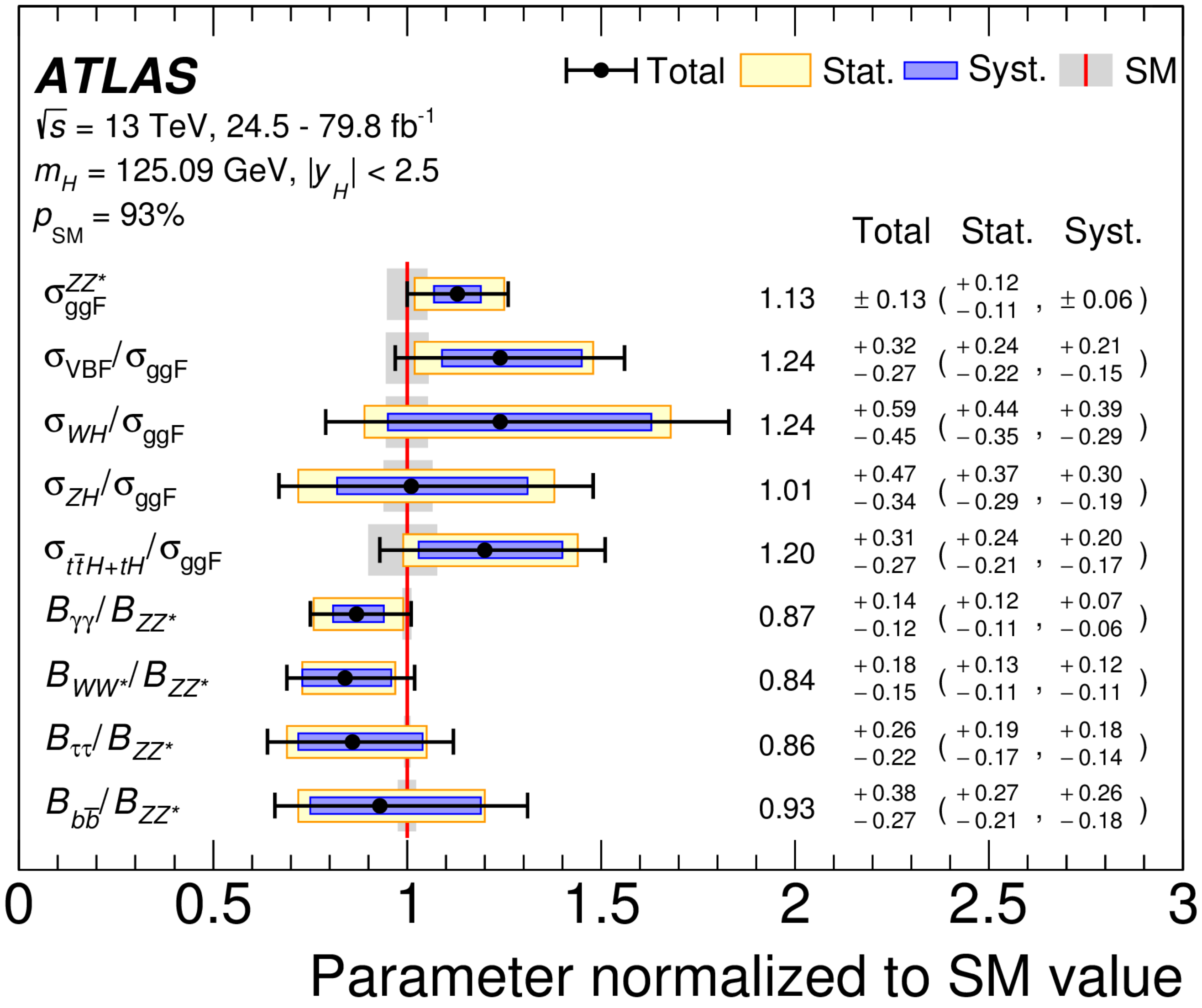
Finally if all deviations are included in a single parameter

$$\mu = 1.09 \pm 0.07 \pm 0.04(expt) \pm 0.03(th.bkg) \pm 0.07(th.sig)$$

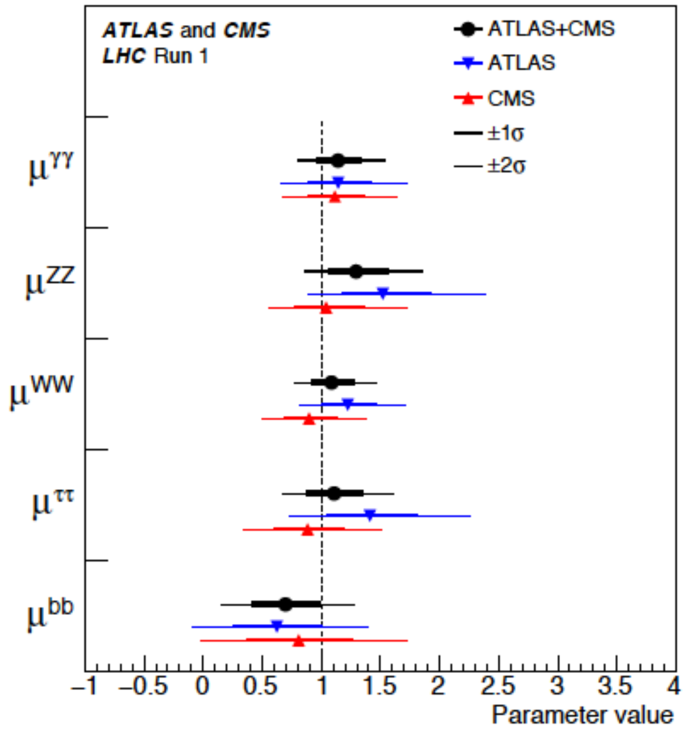


Custodial symmetry

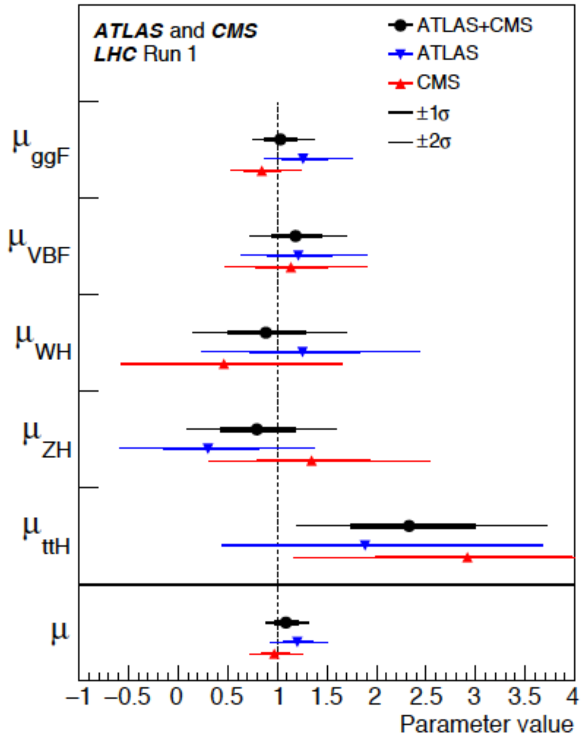
ATLAS Recent Results: references



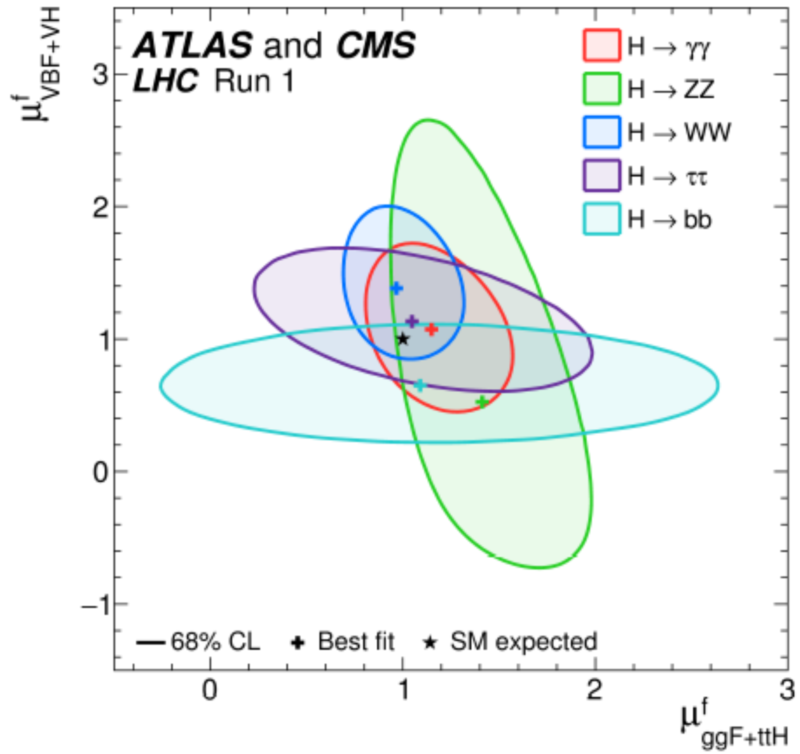
More Simplifications.. Fewer Parameters



Assume all production cross sections are SM ones → fit only modifiers of BR's



Assume all BRs are SM ones → fit only modifiers of production cross-sections



One more assumption: vertices VBF & VH scale with one μ and ggF and ttH with another μ

No (significant) deviation observed so far, need more statistics ! → LHC at High Luminosity

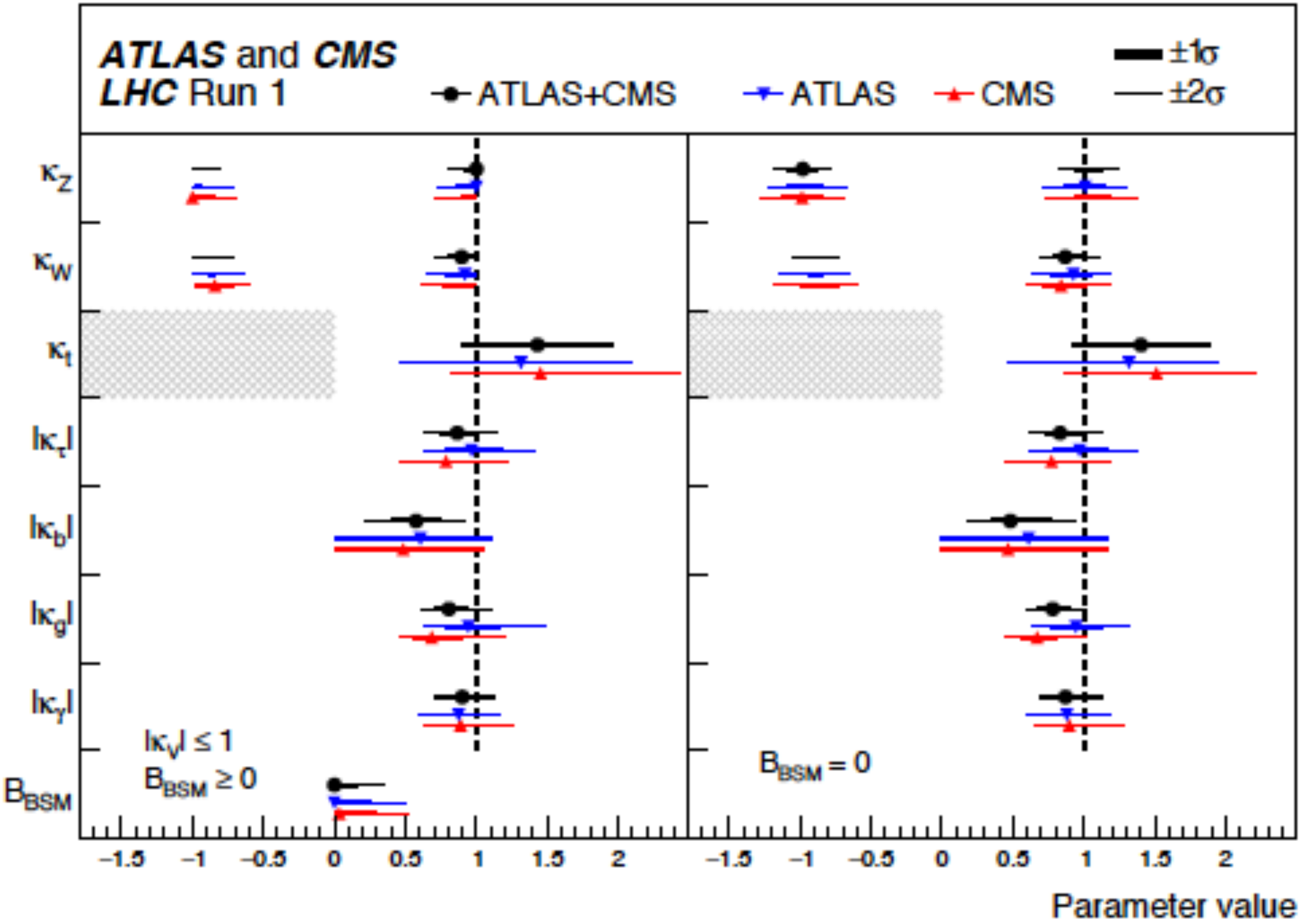
Toni Baroncelli: The Discovery of the Higgs

A Different Approach

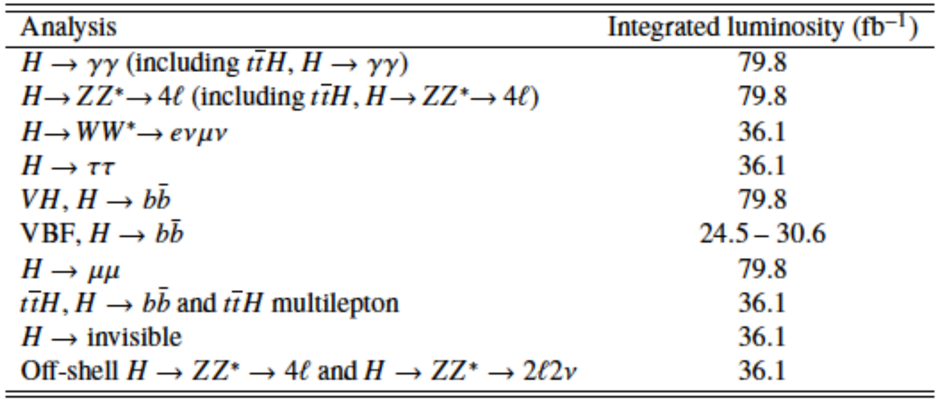
Elaborate even more: introduce modifiers k_x of vertices in the Lagrangian.
In this way production and decay vertices are treated in the same way.

$$
\begin{aligned}
\mathcal{L} = \; & \boxed{\kappa_3} \frac{m_H^2}{2v} H^3 + \boxed{\kappa_Z} \frac{m_Z^2}{v} Z_\mu Z^\mu H + \boxed{\kappa_W} \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
& + \boxed{\kappa_g} \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \boxed{\kappa_\gamma} \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \boxed{\kappa_{Z\gamma}} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\
& + \boxed{\kappa_{VV}} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu} \right) H \\
& - \left(\boxed{\kappa_t} \sum_{f=u,c,t} \frac{m_f}{v} f \bar{f} + \boxed{\kappa_b} \sum_{f=d,s,b} \frac{m_f}{v} f \bar{f} + \boxed{\kappa_\tau} \sum_{f=e,\mu,\tau} \frac{m_f}{v} f \bar{f} \right) H .
\end{aligned}
$$

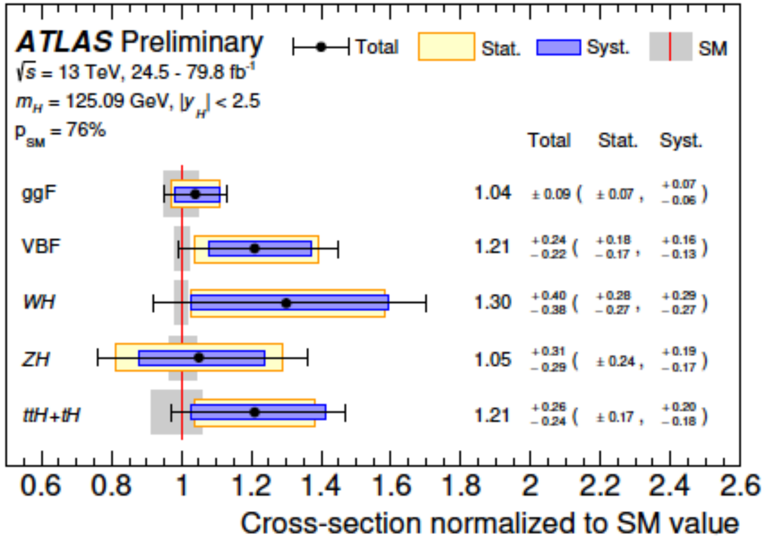
Final Result



Latest Results by ATLAS

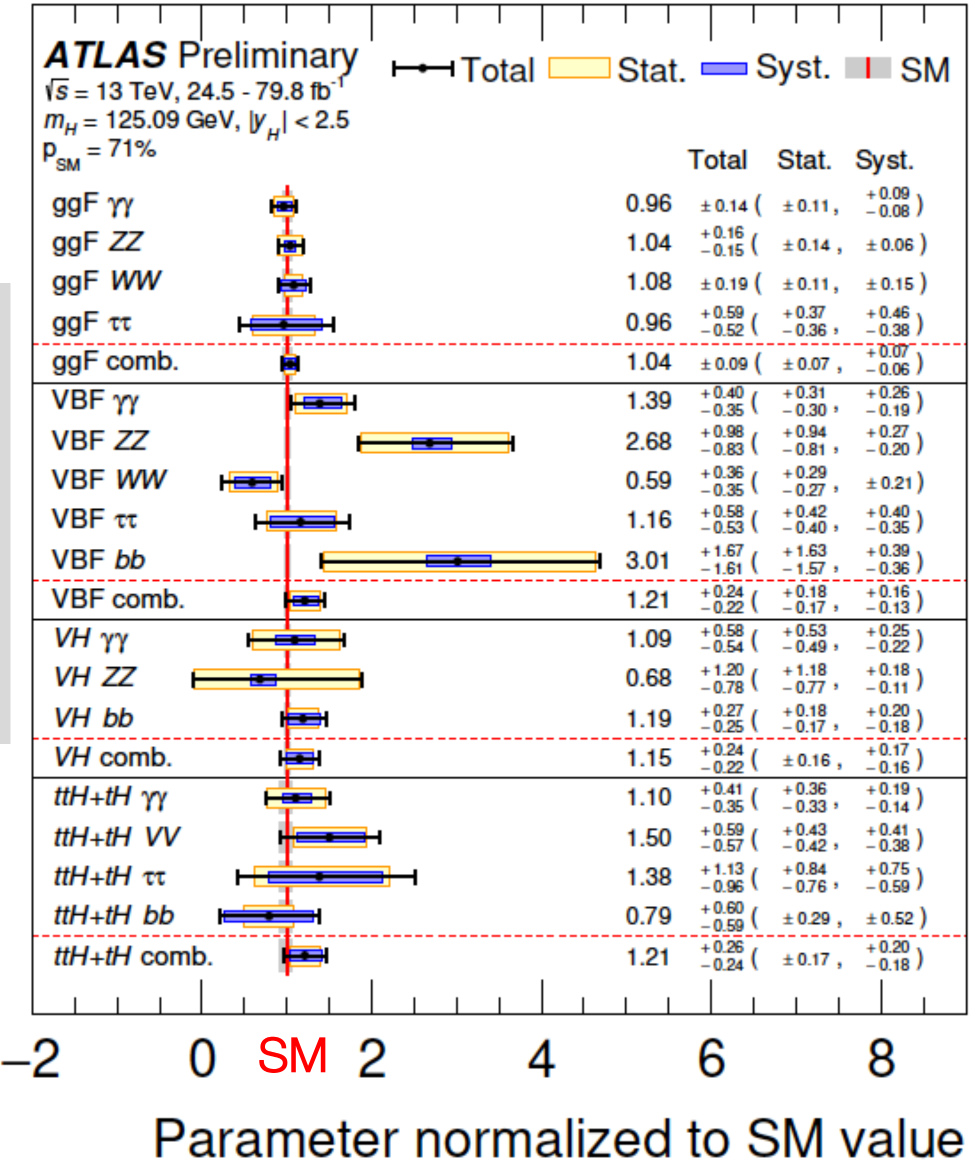


Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H, H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H, H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
$VH, H \to b\bar{b}$	79.8
VBF, $H \to b\bar{b}$	24.5 – 30.6
$H \to \mu\mu$	79.8
$t\bar{t}H, H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$H \to$ invisible	36.1
Off-shell $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$	36.1



$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$$

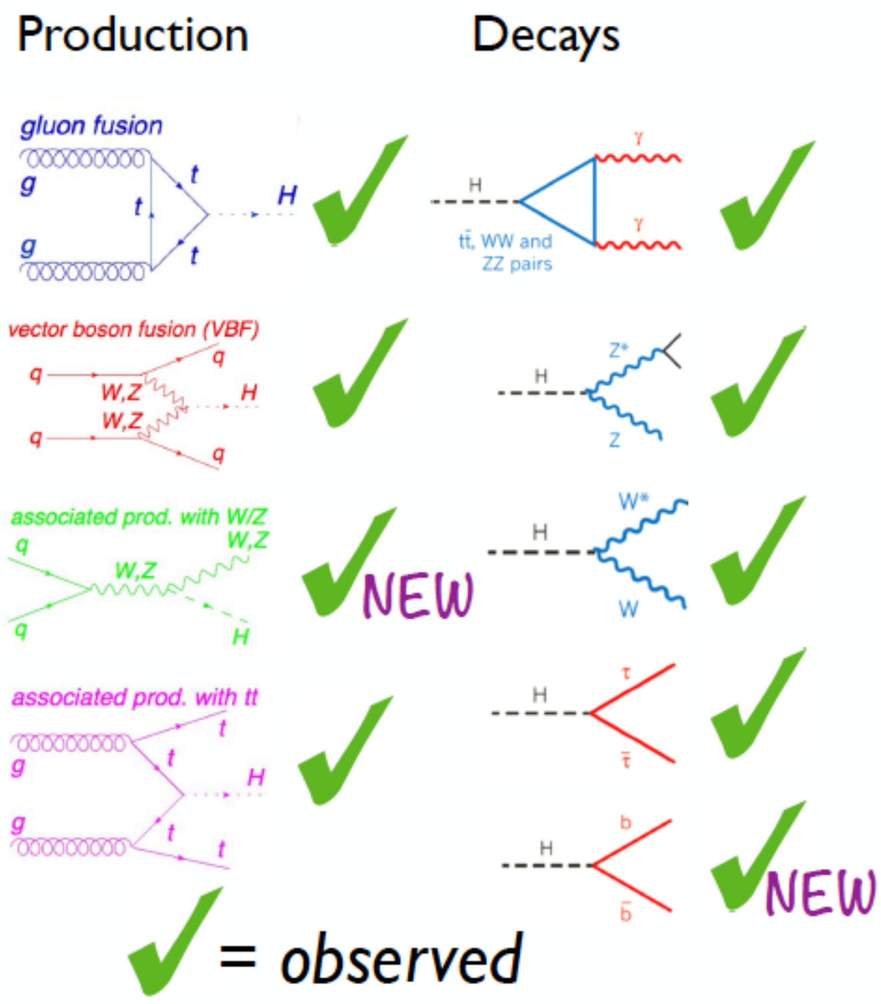
$$(\sigma \cdot B)_{obs} \big/ (\sigma \cdot B)_{SM}$$



Conclusions by Giacinto Piacquadio – ICHEP 2018

ATLAS and CMS

Conclusions



- Thanks to the first 36-80 fb^{-1} of Run-2 data:
  - The bosonic decay channels entered a precision era (~3x improvement w.r.t. Run-1)
  - Direct observation achieved for all main production and decay modes!
  - Direct confirmation of coupling to all 3rd generation fermions (top-quark, **bottom-quark**, taus)
  - Sensitivity to double Higgs production approaching 10 x SM

Higgs to 2 Higgses

- Higgs physics an important indirect probe for New Physics: so far no deviations from SM…
- But still at the beginning of a long journey! Only analyzed <3% of the final LHC luminosity.

Higgs Discovery at LHC Part

Collider Physics
Toni Baroncelli
Haiping Peng
USTC

End of Higgs Discovery at LHC Part