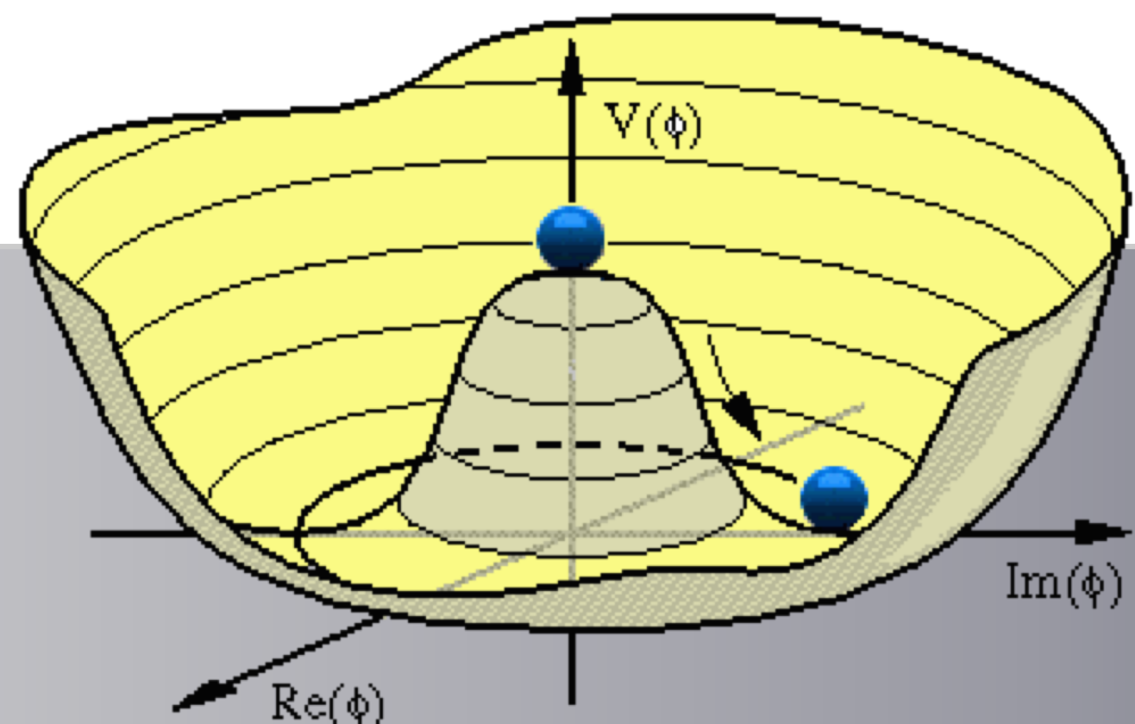
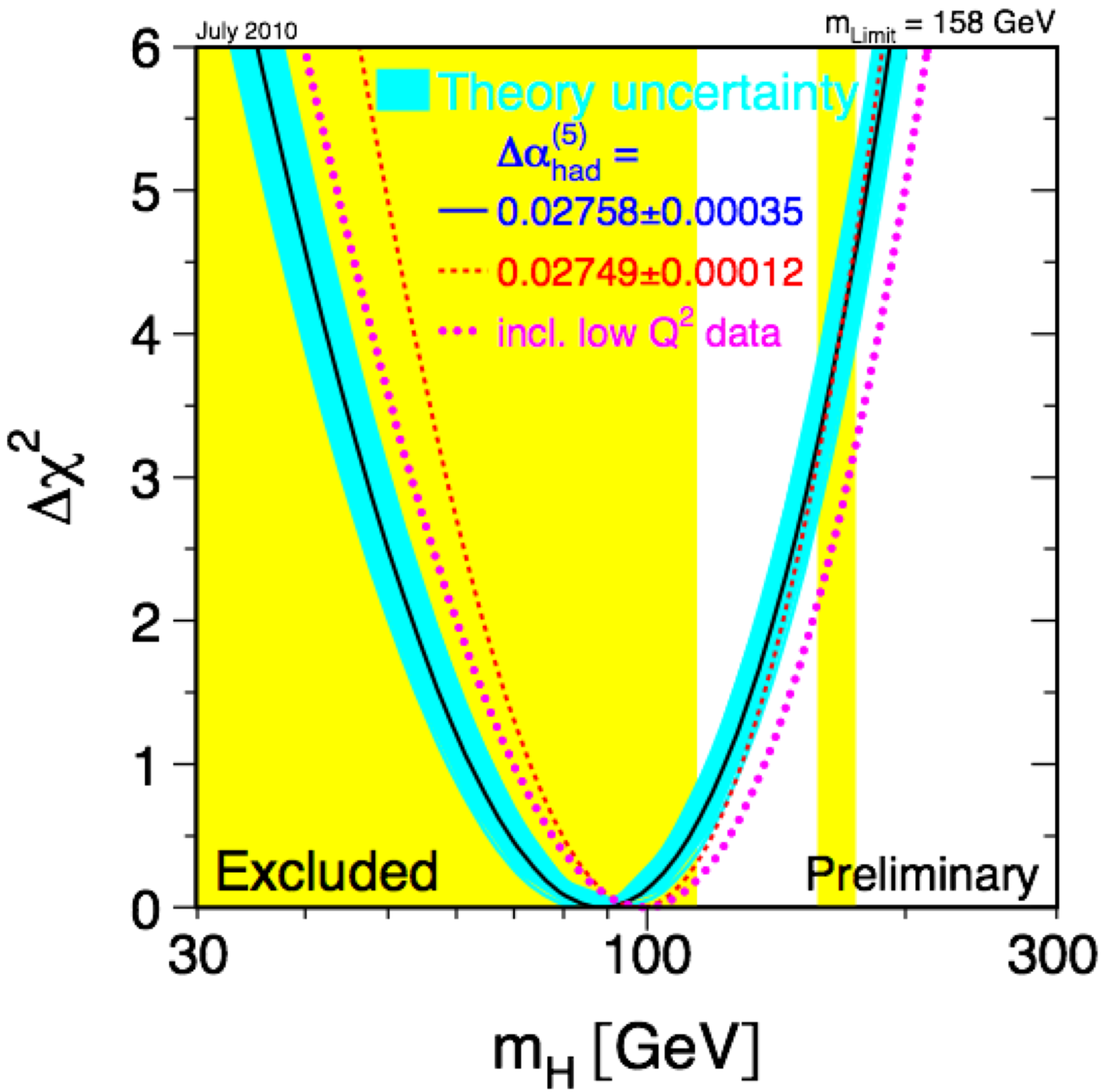
The Higgs

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



Our Knowledge about the Higgs … archeology!



EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

From direct search at LEP:

$M_H > 114$ GeV

@ 95% CL

From direct search at Tevatron:

$158 < M_H < 175$ GeV

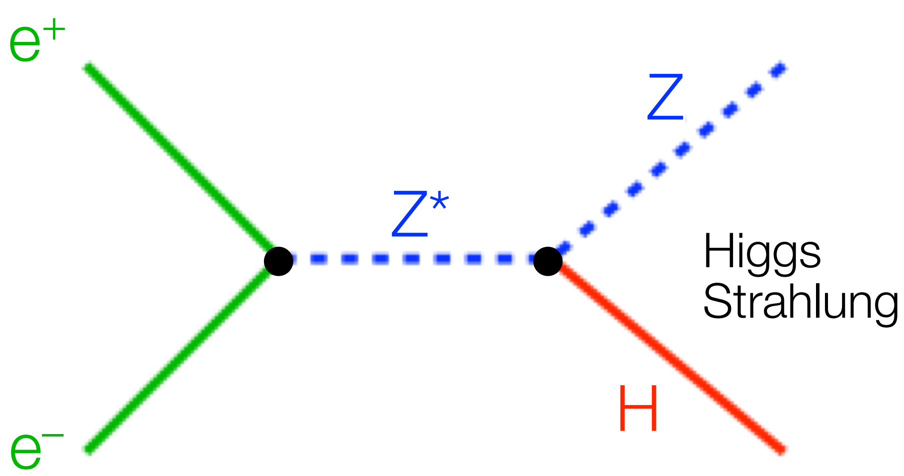
@ 95% CL

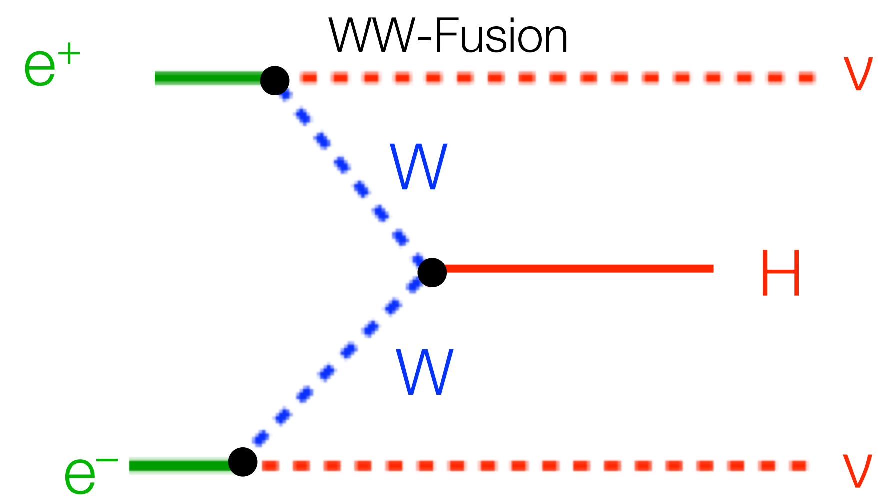
[Updated: Summer 2010]

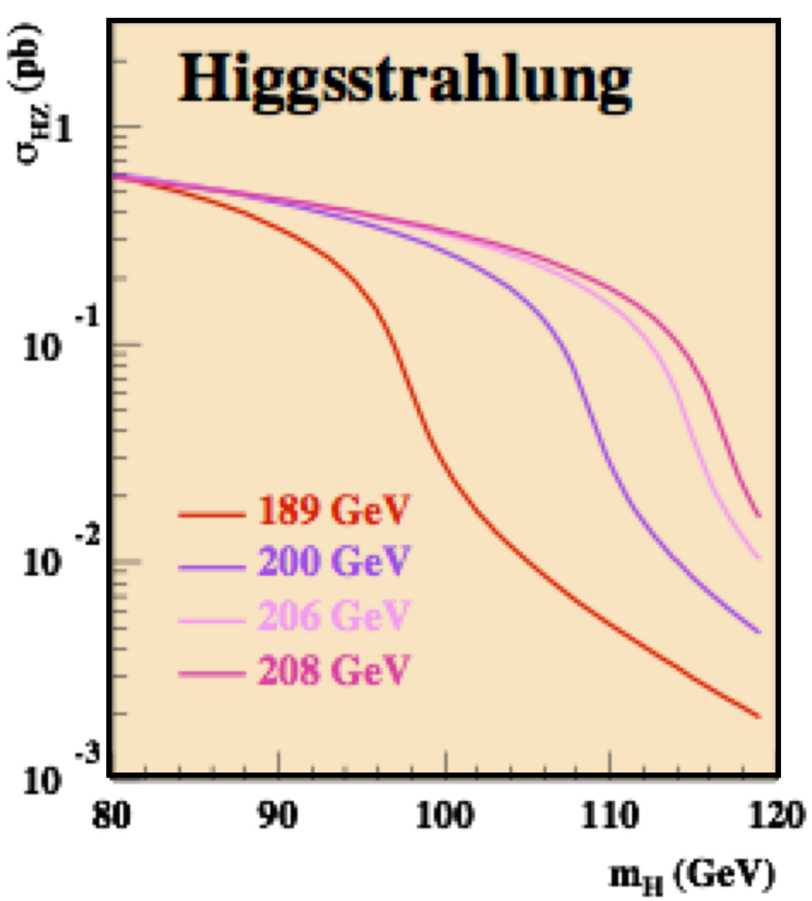
Higgs Search

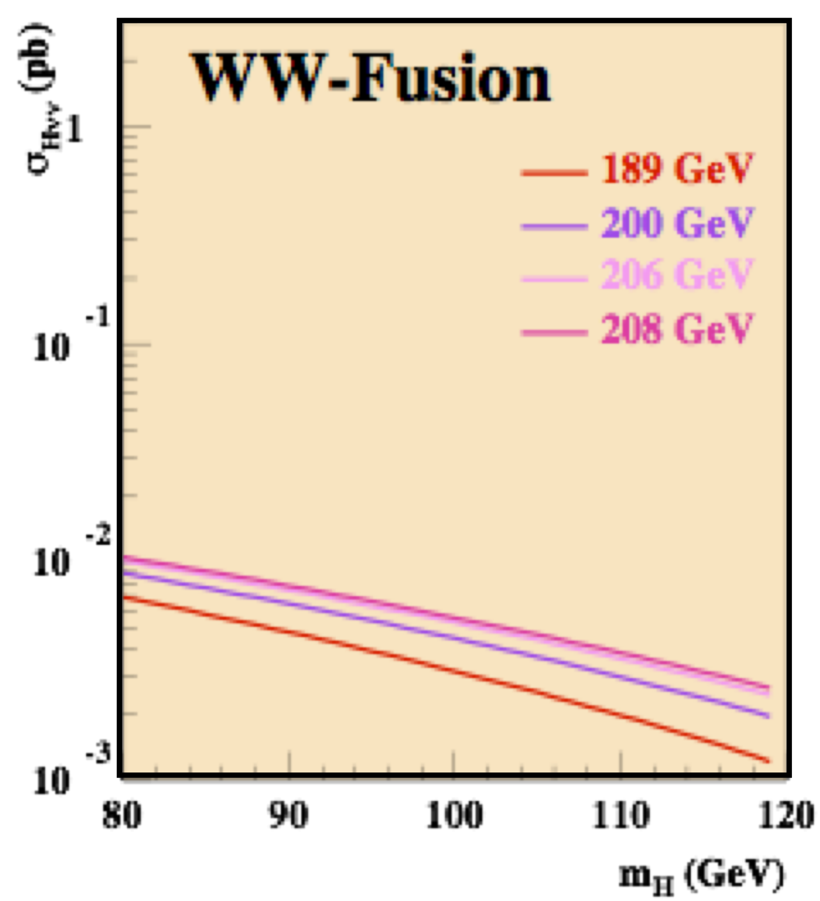
at LEP

SM Higgs Production at LEP

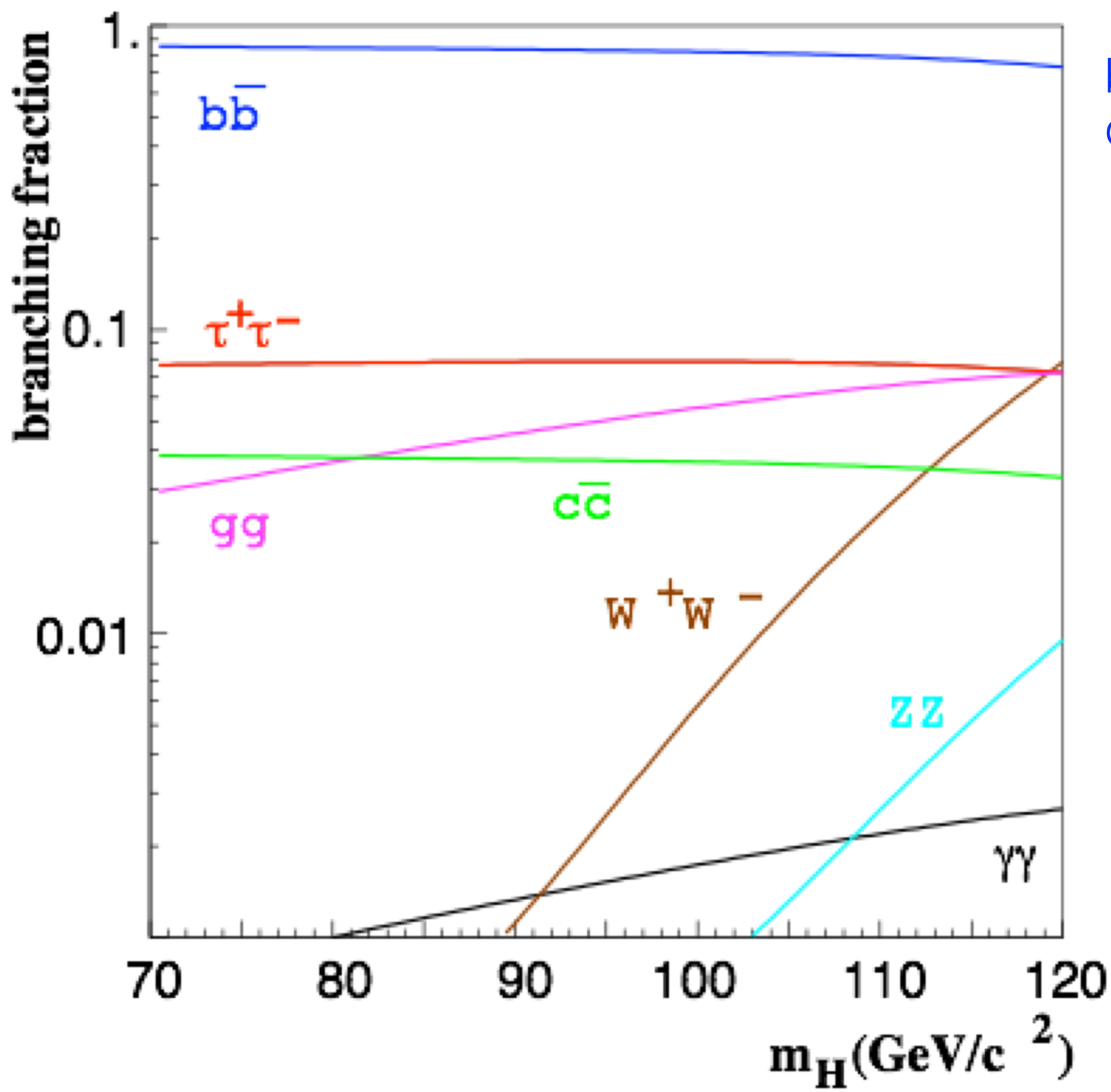






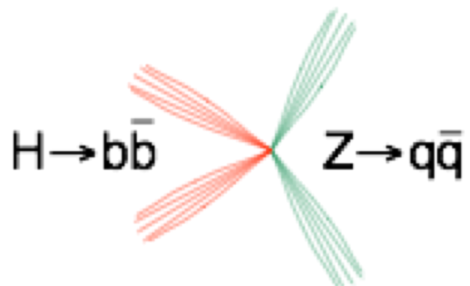


Higgs Decay at LEP Energies

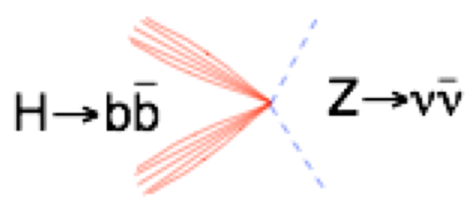


bb-decay dominant !!

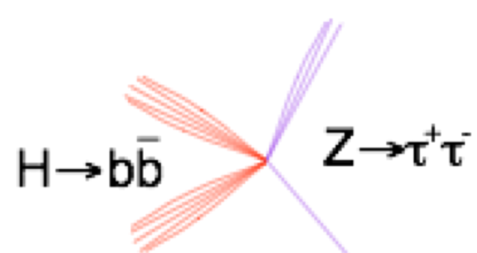
LEP Higgs Signatures



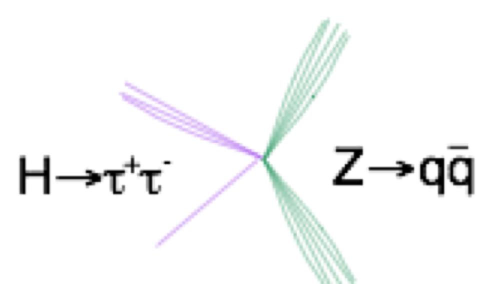
4-jets — 51%



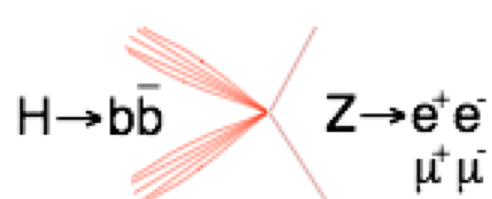
missing energy — 15%



τ-channel — 2.4%



τ-channel — 5.1%



lepton channel — 4.9%

Backgrounds

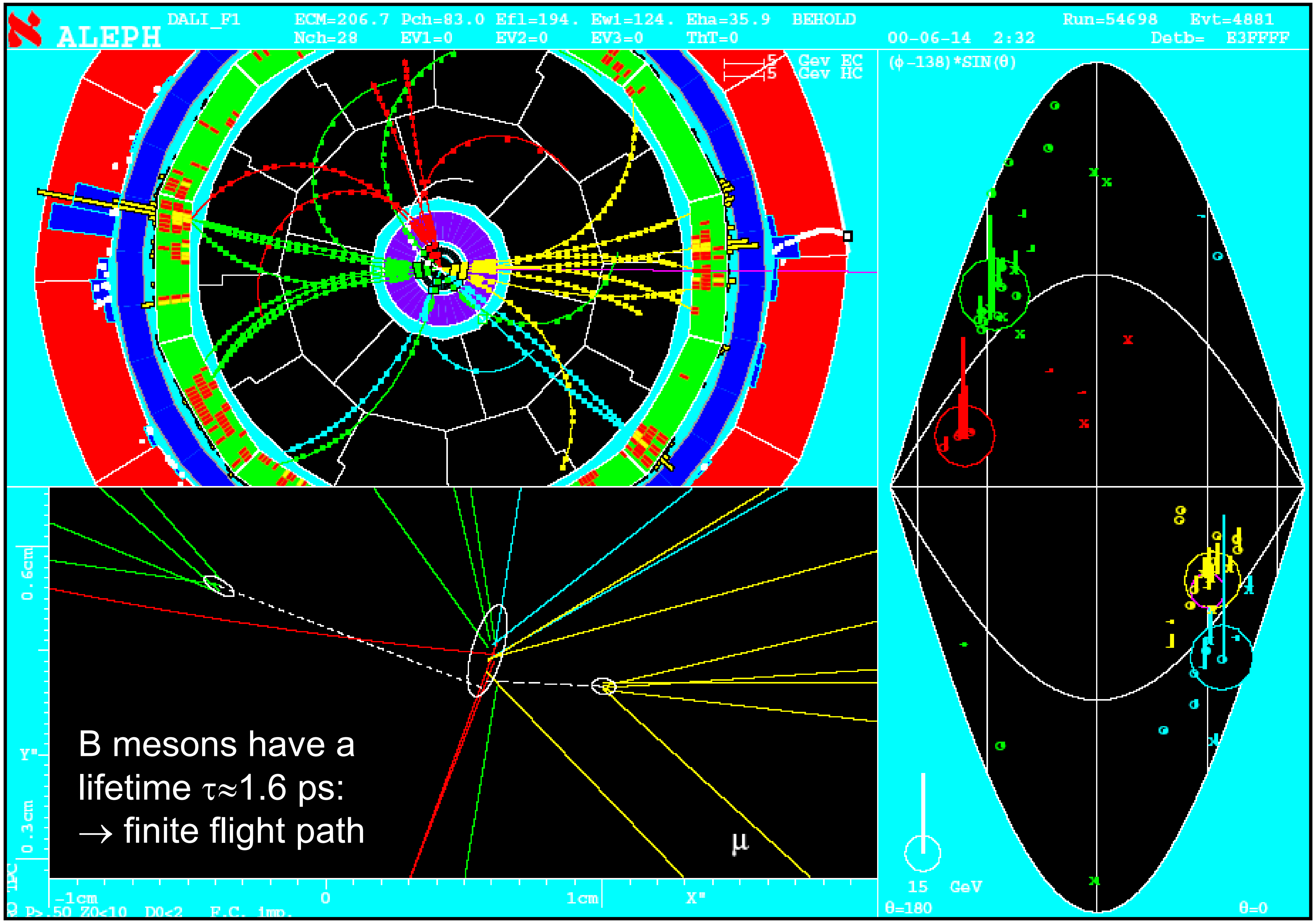
WW ➛ qqqq
ZZ ➛ qqqq
QCD 4-jets

WW ➛ qqlv
ZZ ➛ bbvv

WW ➛ qqτv
ZZ ➛ bbττ
ZZ ➛ qqττ
QCD low mult. jets

ZZ ➛ bbee
ZZ ➛ bbμμ

Higgs Candidate [M_H=114 GeV]



LEP Higgs Candidates

LEP final result

Observation:
17 candidate events

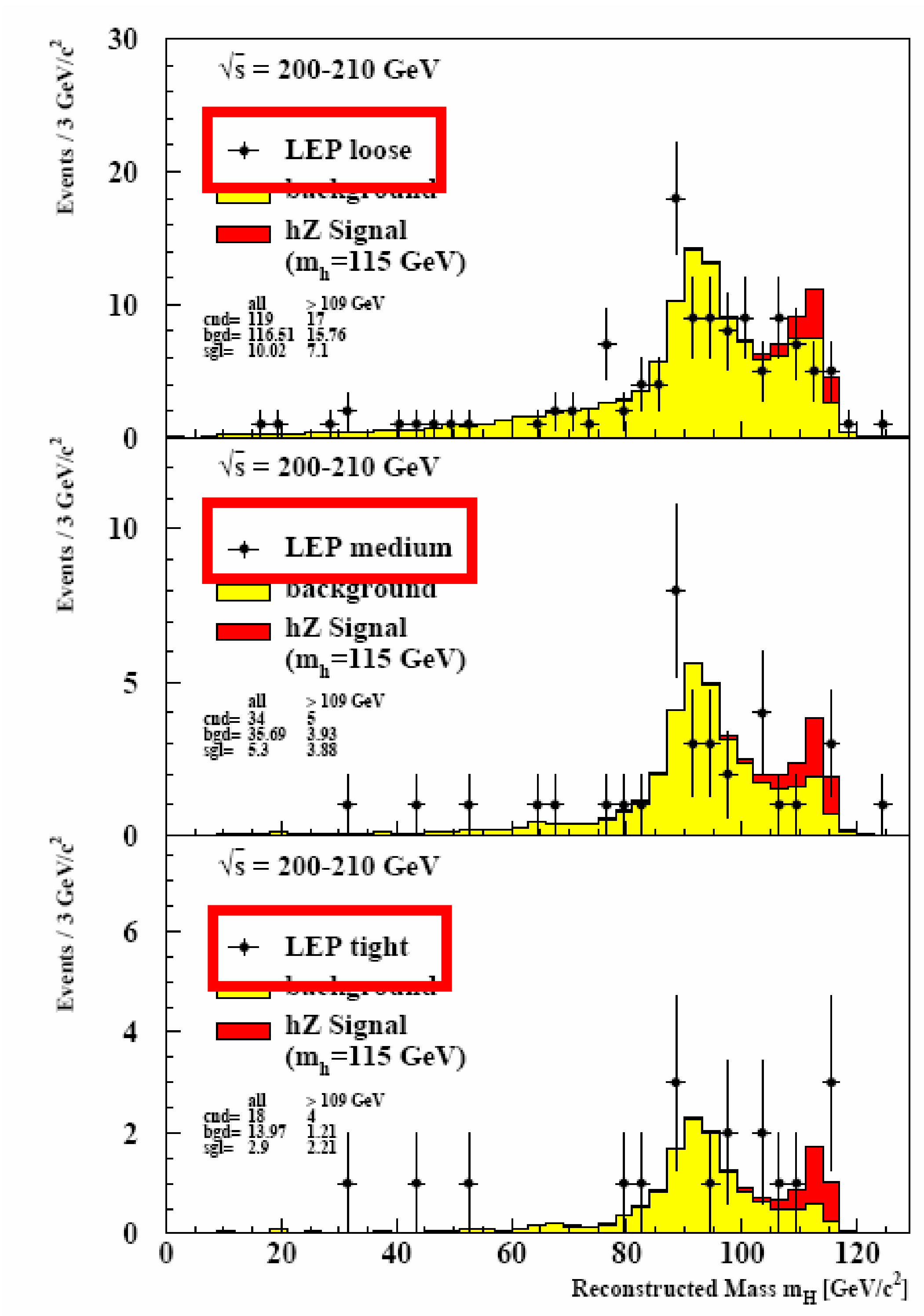
Expectation:
15.8 background events

8.4 signal events for M_H =115 GeV

	Expt	E_{cm}	channel	M^{rec} (GeV)	$\ln(1+s/b)$ @ 115 GeV	prev. rank.
1	A	206.6	4 jet	114.1	1.76	1
2	A	206.6	4 jet	114.4	1.44	2
3	A	206.4	4 jet	109.9	0.59	3
4	L	206.4	Emiss	115.0	0.53	4
5	A	205.1	Lept.	117.3	0.49	7
6	A	206.5	Tau	115.2	0.45	8
7	O	206.4	4 jet	108.2	0.43	5
8	A	206.4	4 jet	114.4	0.41	9
9	L	206.4	4 jet	108.3	0.30	12
10	D	206.6	4 jet	110.7	0.28	
11	A	207.4	4 jet	102.8	0.27	14
12	D	206.6	4 jet	97.4	0.23	11
13	O	201.5	Emiss	111.2	0.22	
14	L	206.0	Emiss	110.1	0.21	17
15	A	206.5	4 jet	114.2	0.19	
16	D	206.6	4 jet	108.2	0.19	
17	L	206.6	4 jet	109.6	0.18	

Observation consistent with background !

Final LEP Result



Reconstructed Mass m_H [GeV]

Invariant mass of Higgs candidates

LEP Summary:

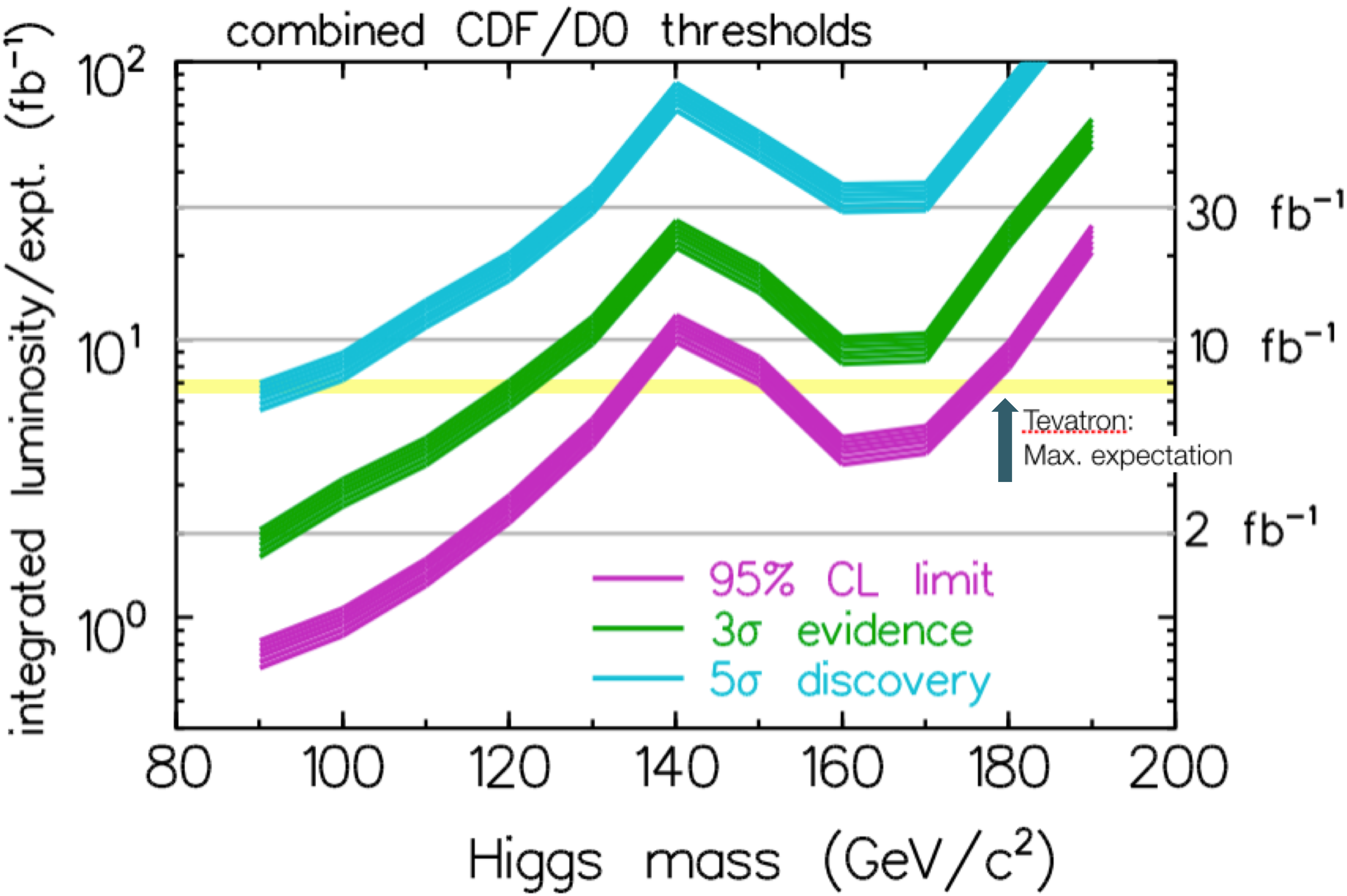
No signal above background

$M_H > 114.4$ GeV @ 95% CL

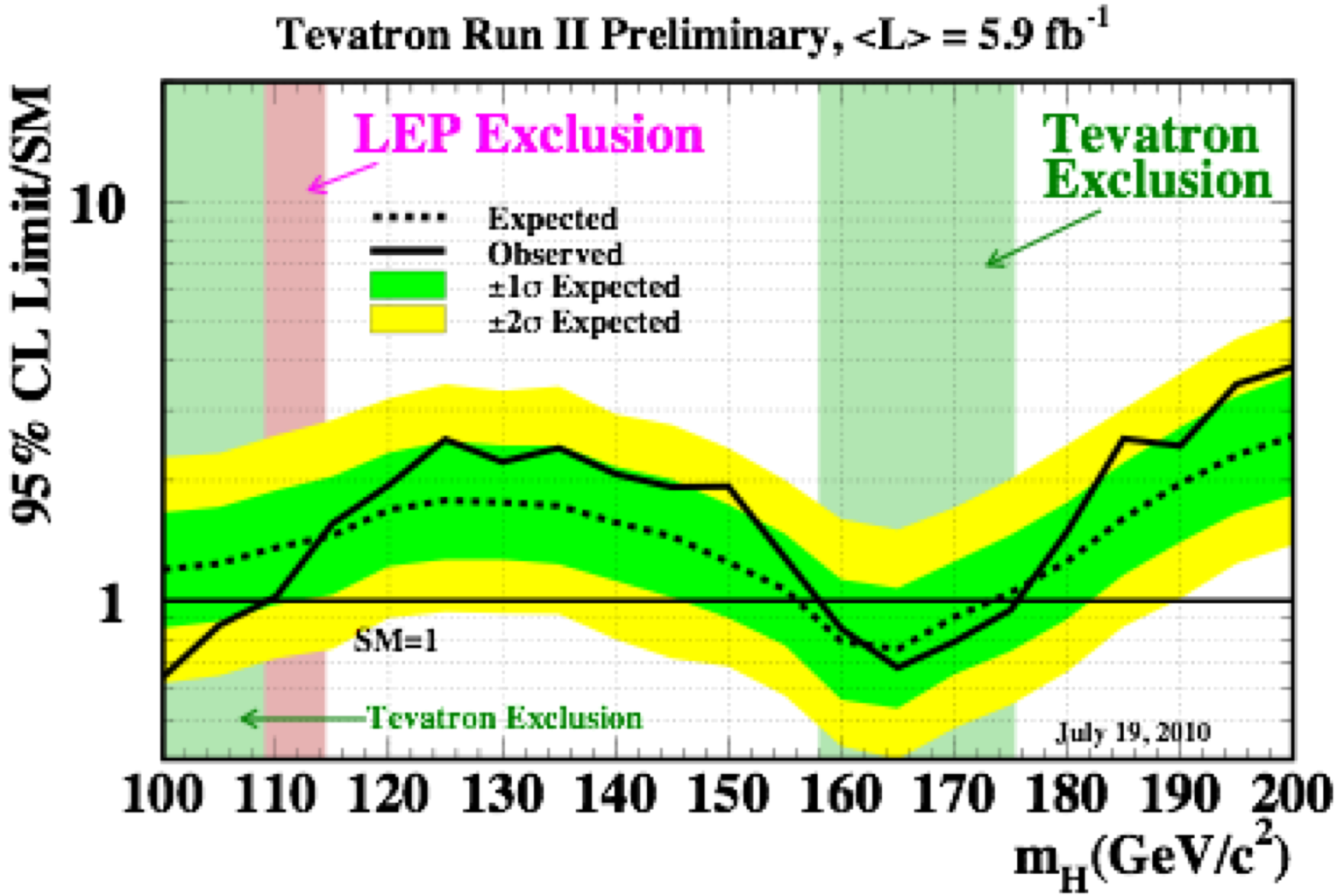
Higgs Search

at Tevatron

Tevatron: Higgs Discovery Potential



Tevatron: Recent Results (@2010!)



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 ...

Tevatron: Explored Channels

CDF

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ (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]

D0

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ 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]

Production via: qq ➛ W/Z H (associate production), gg ➛ H (gluon fusion) and qq ➛qqH (vector boson fusion)

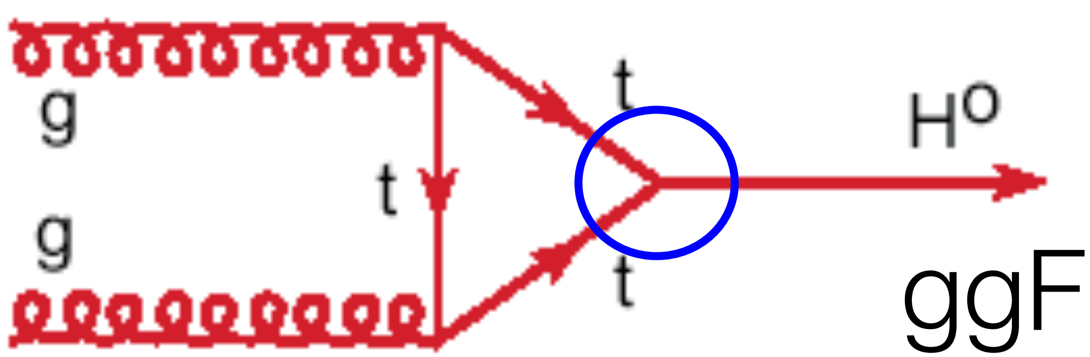
Higgs Search

at the LHC

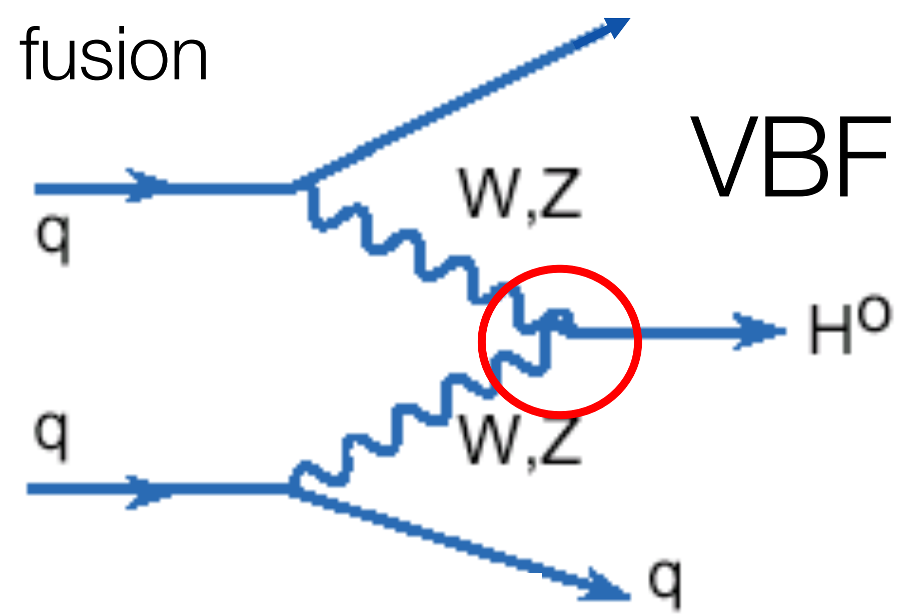
Higgs Production Mechanisms

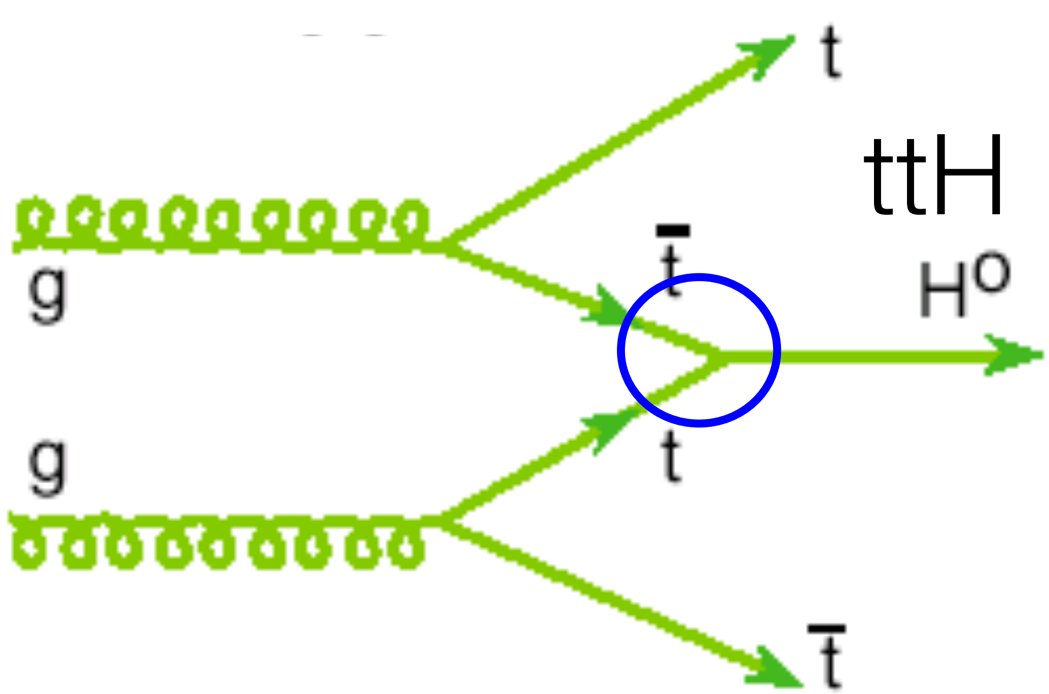
Gluon fusion

Other quarks contribution suppressed by m_q^2

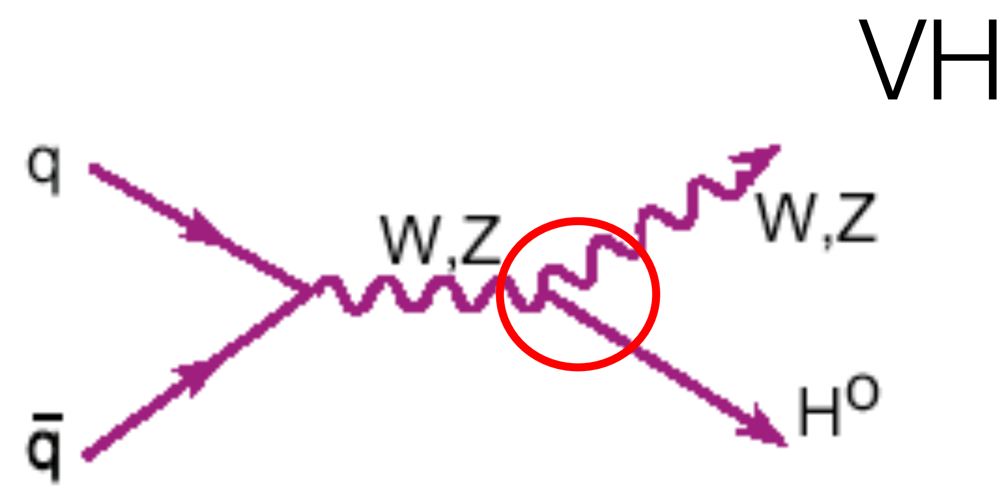


Vector boson fusion



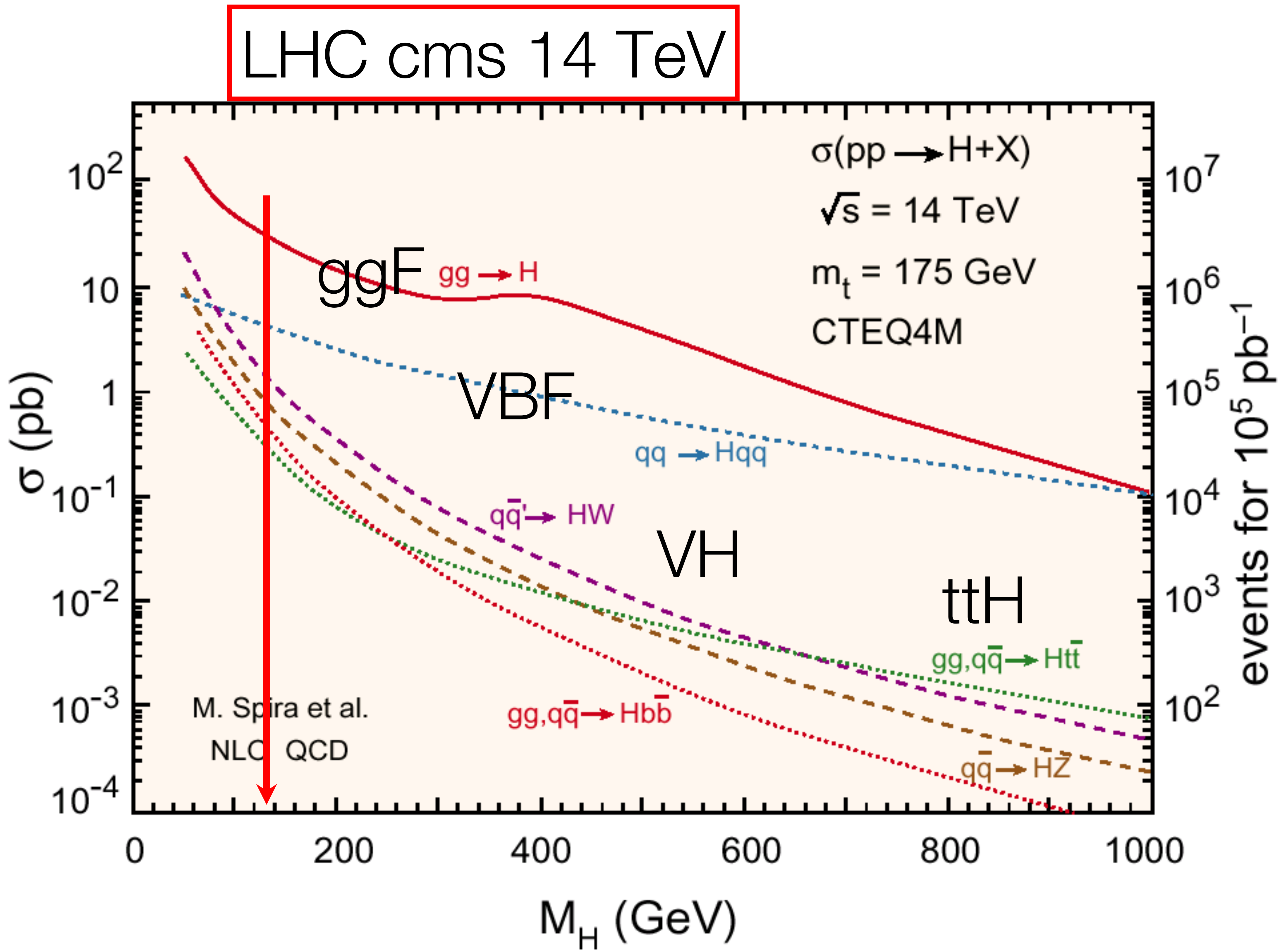


$t\bar{t}$-fusion



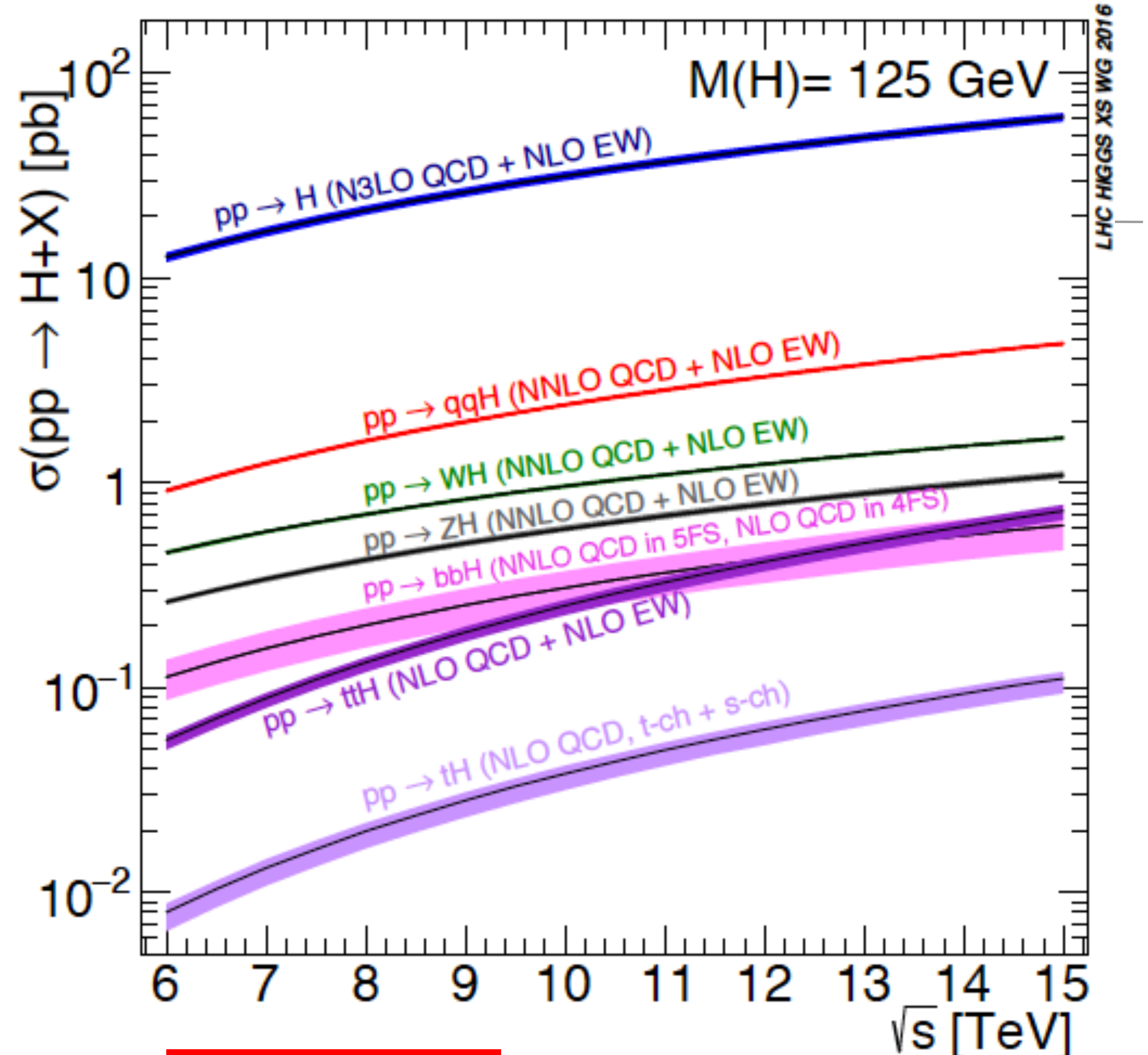
Associated production

Higgs Production Cross Sections



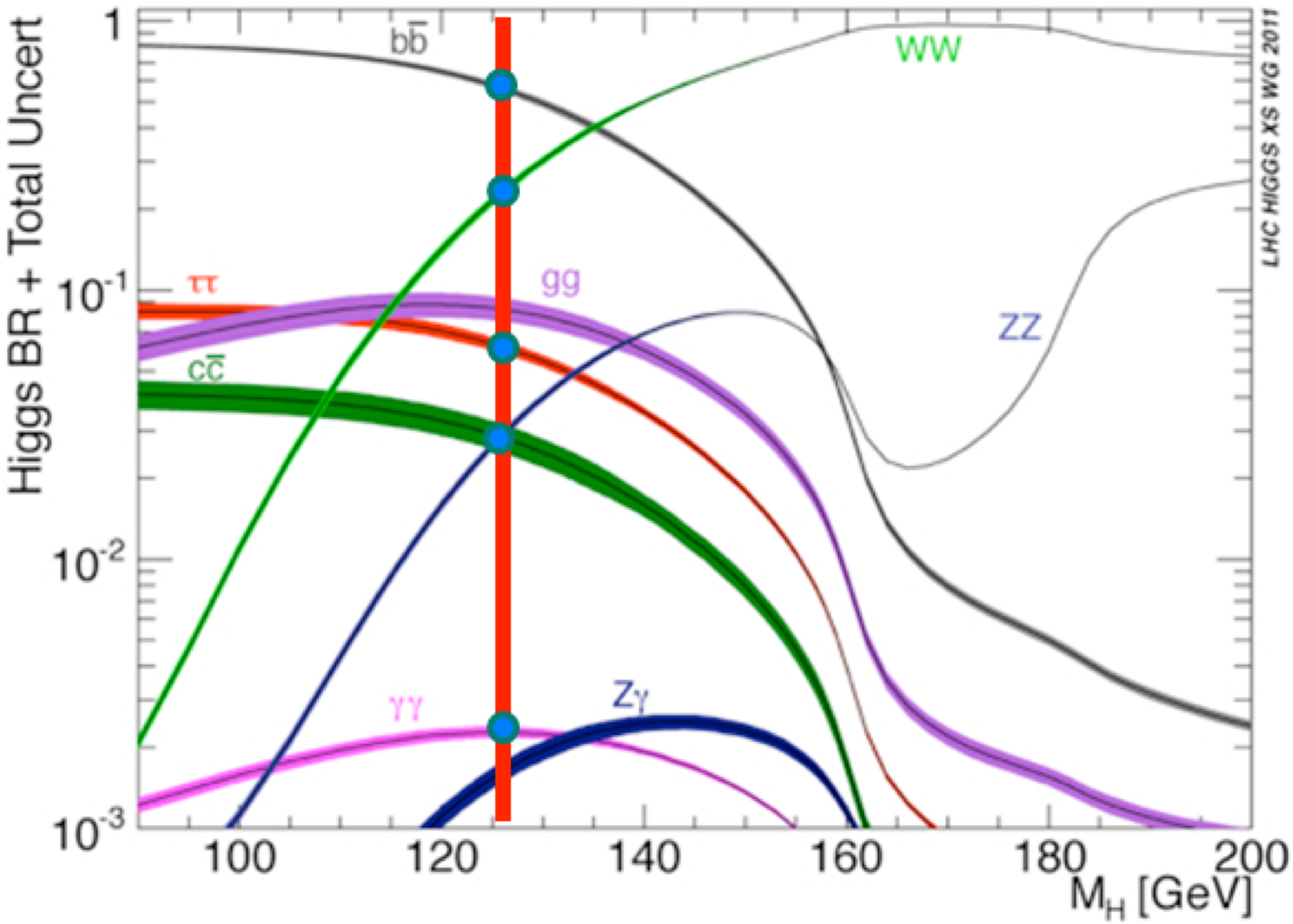
Higgs Production

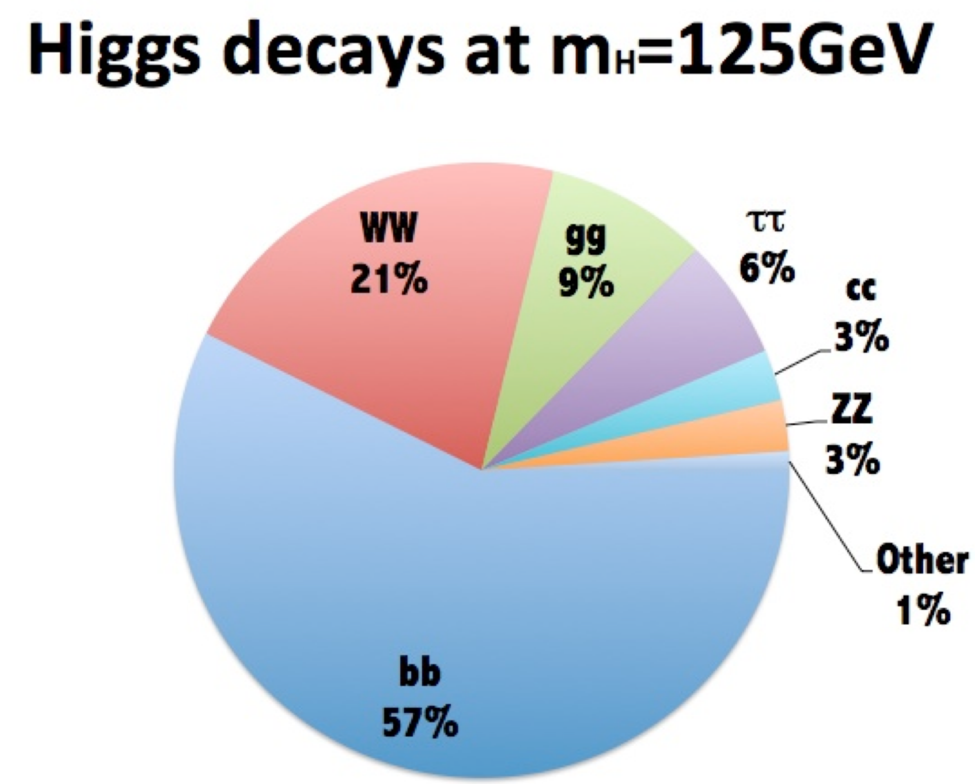
Higgs mass = 125 GeV



$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\mathrm{GeV}$					
	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
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1
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
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1

Higgs Boson Decays



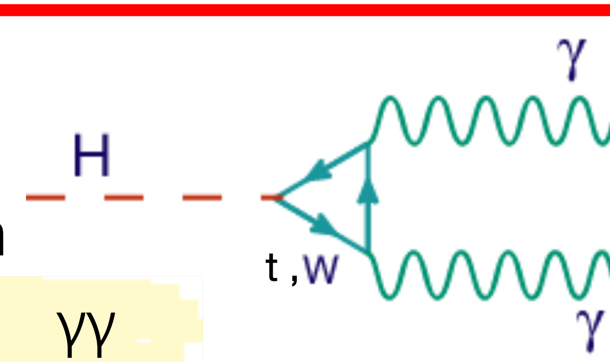


Discovery driven by significance of different channels

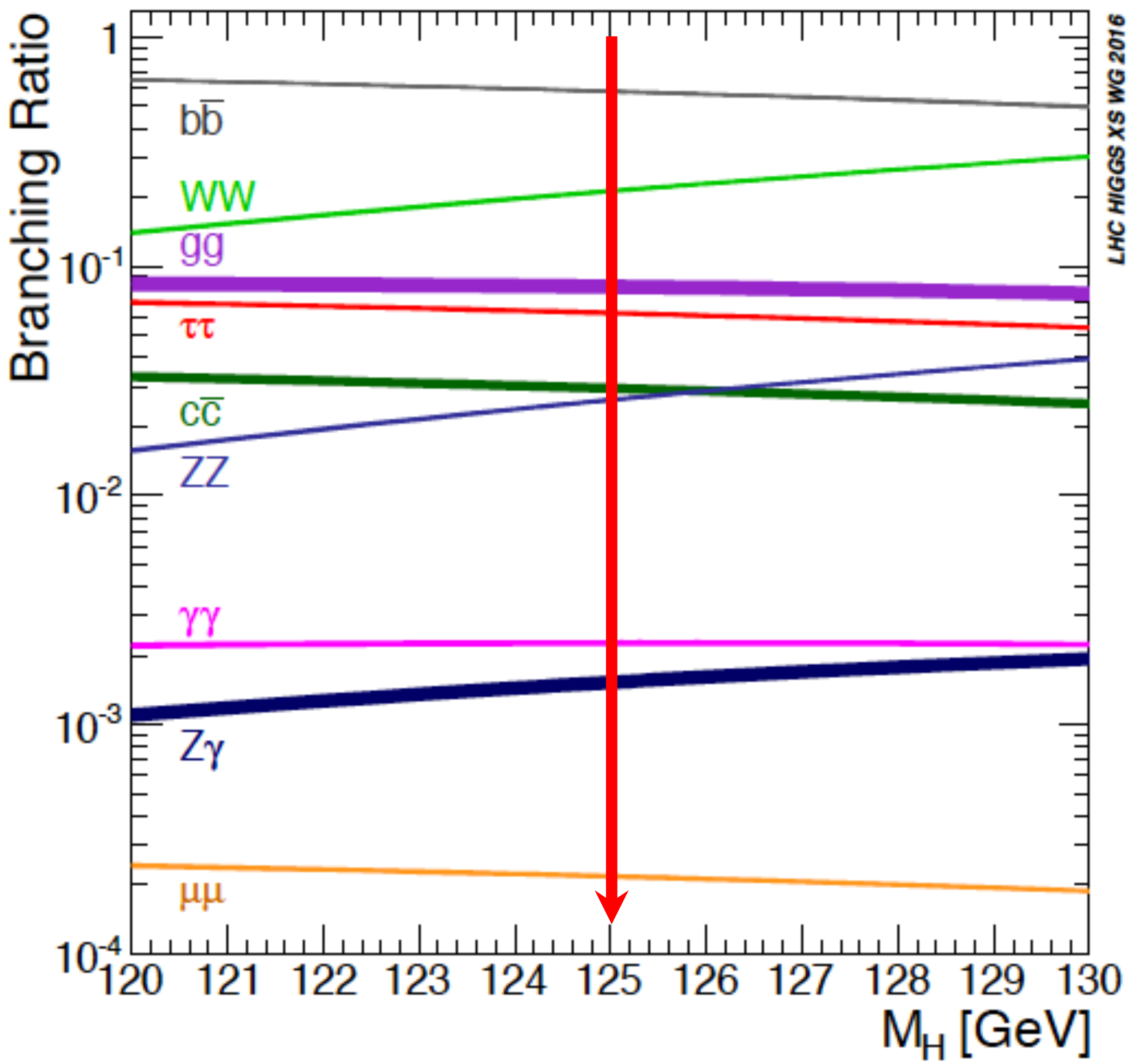
For M < 135 GeV: H ➛ bb, ττ dominant

For M > 135 GeV: H ➛ WW, ZZ dominant

Tiny but used in discovery: H ➛ γγ



Zooming the Branching Ratios of the Higgs



m_H = 125 GeV

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-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}	$^{+6.0\%}_{-5.9\%}$

LHC Higgs diary

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

$$mH = 89 +35 -26 \text{ GeV}$$

- Direct and model-independent search at LEP up 20 209 GeV cms yelded a 95% CL lower bound on mH of 114.4GeV

- 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 std in the interval 115<mH<140 GeV with a maximum at 125 GeV

- LHC run in 2011 (7 TeV, 5 fb^{-1}), 2012 (8 TeV, 20 fb^{-1}) 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 $\tau^+\tau^-$

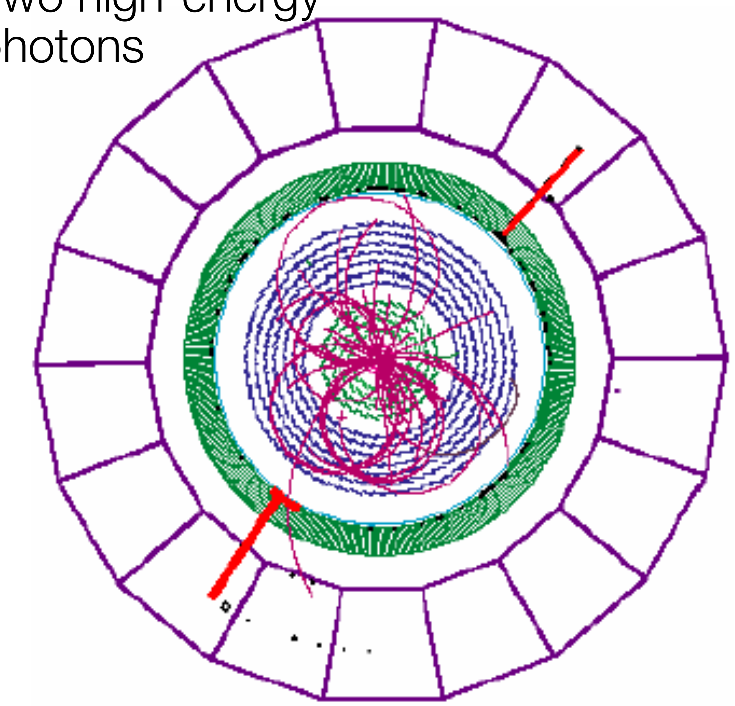
- LHC July 2012 : ATLAS & CMS claim a discovery of a new particle with a mass of about 125 GeV

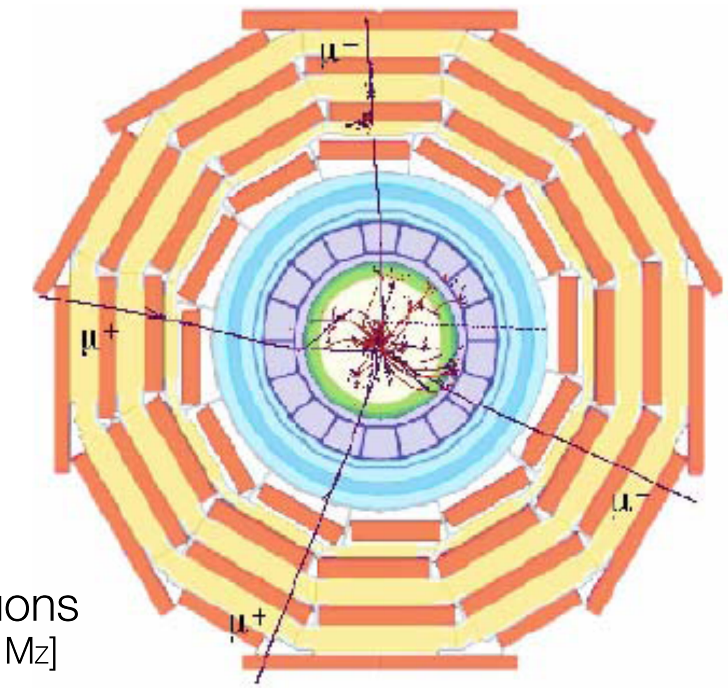
Direct Higgs Channels

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

Higgs Searches @ LHC: Examples

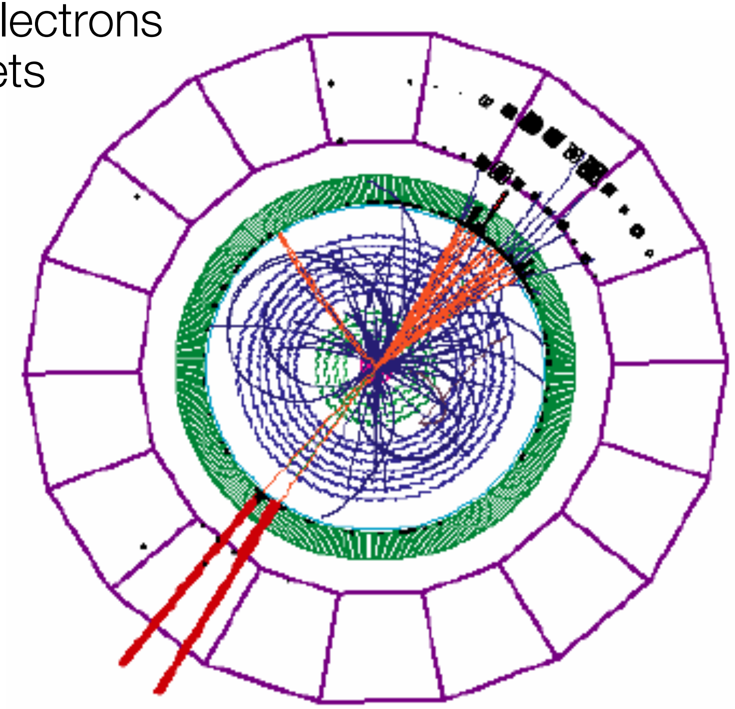
Two high-energy photons

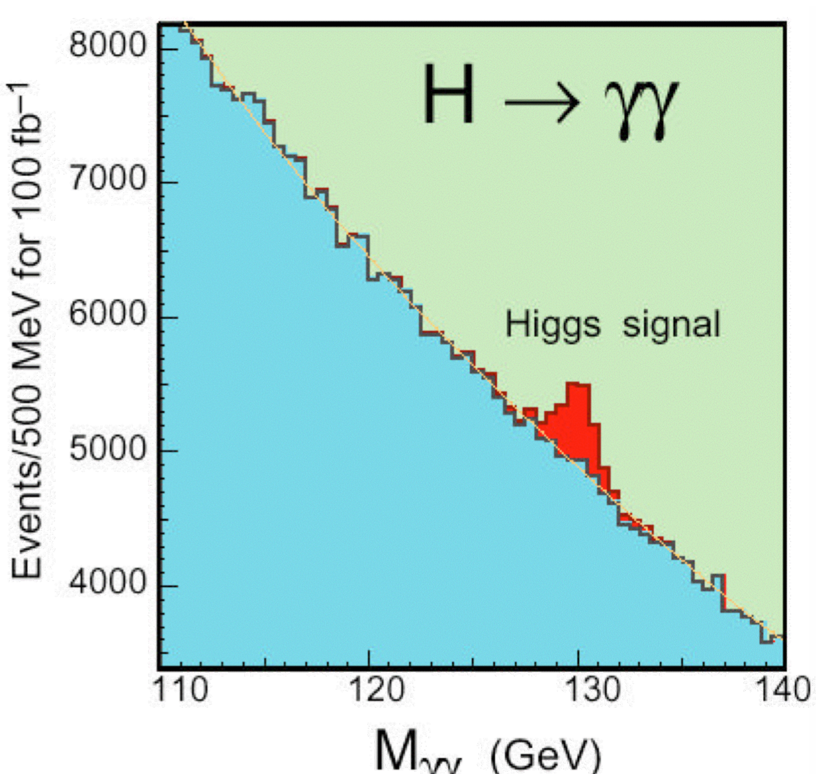


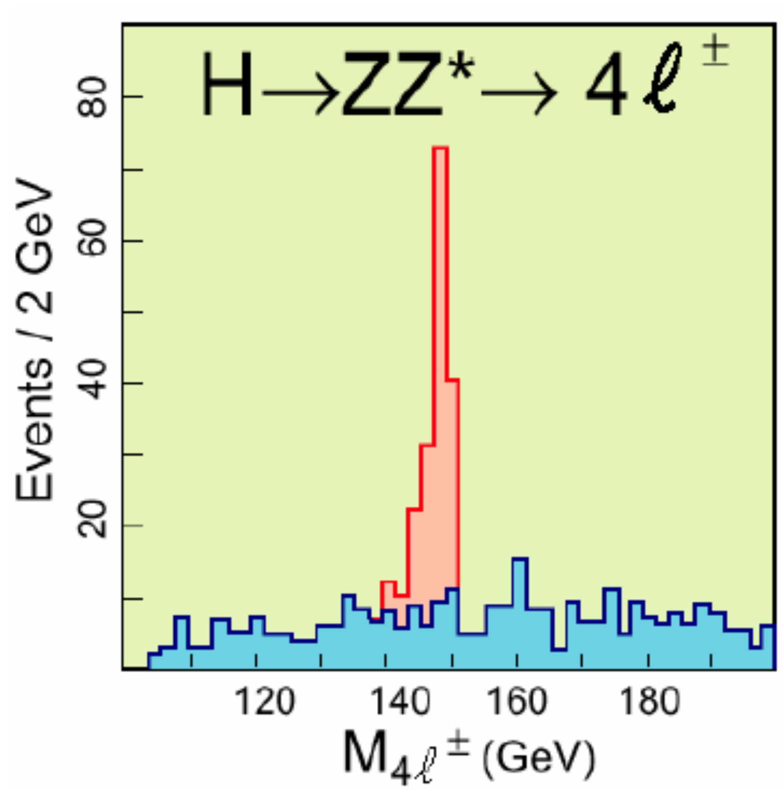


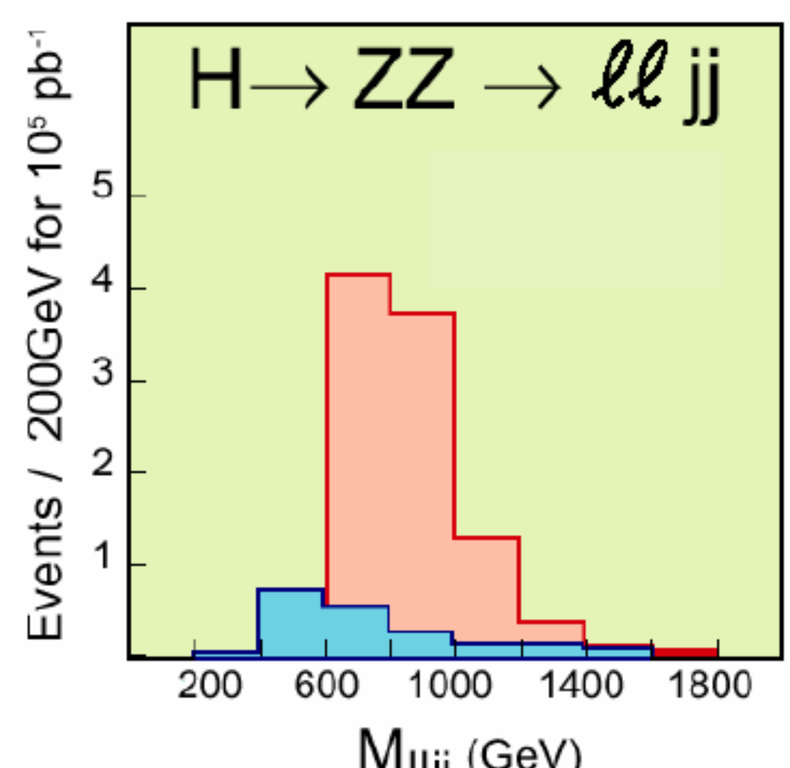
4 muons
[$M_{\mu\mu} = M_Z$]

2 electrons
2 jets

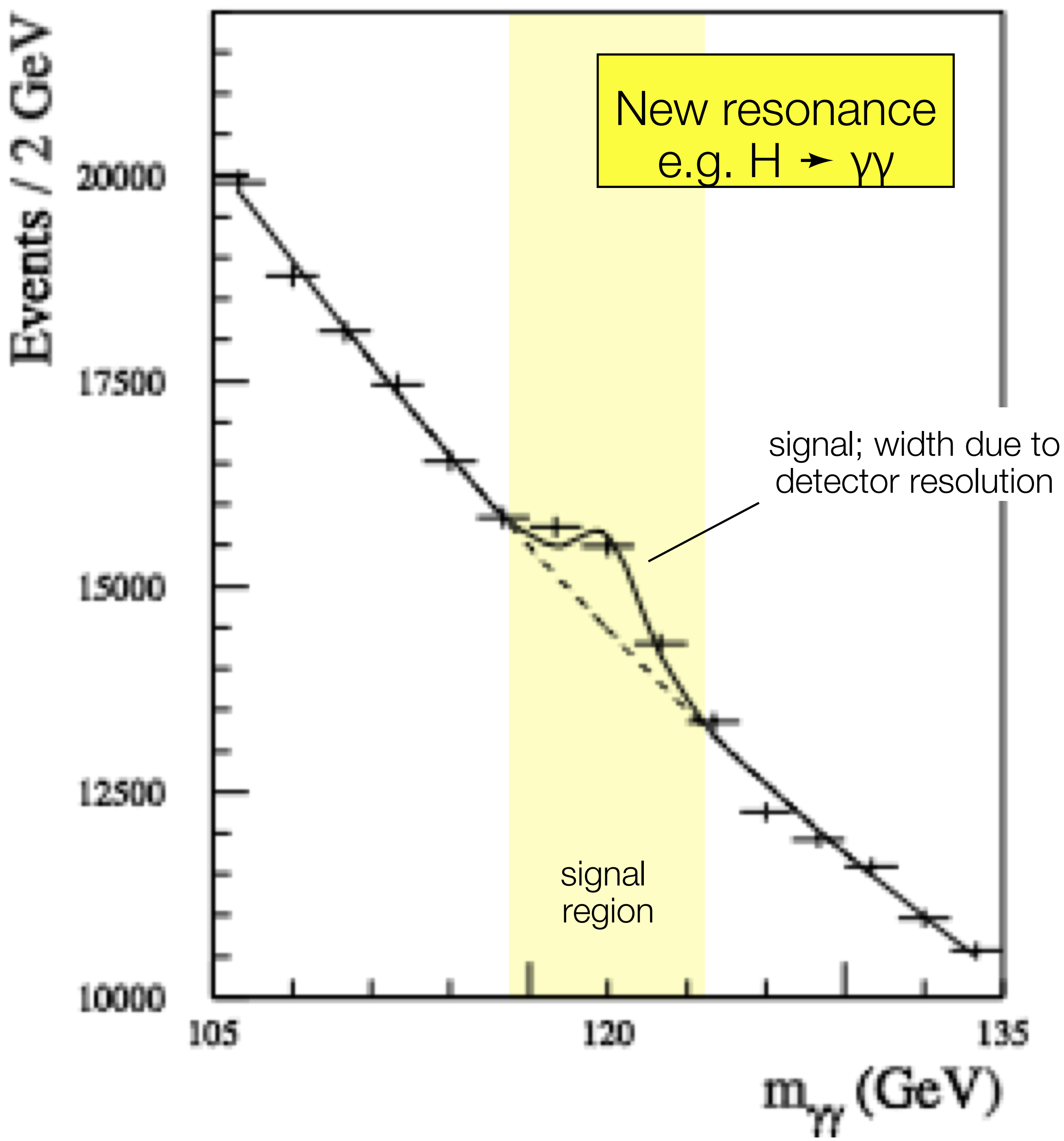








How to Make a Discovery



+ categorize events in classes

Signal significance:

$$S = \frac{N_S}{\sqrt{N_B + N_S}}$$

N_S: # signal events
N_B: # background events

... in peak region

$S > 5$:

Signal $N_S = N_{tot} - N_B$ is 5 times larger than statistical uncertainty on $N_B + N_S$ ...

Gaussian probability that upward fluctuation by more than 5σ is observed ...

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

Discovery!

Maximizing the Significance S

1. Choose channels with low SM background

not possible: $H \to bb$ ... without associated production ...

possible: $H \to \gamma\gamma$ ... despite of small branching ratio ...

$H \to ZZ$ ... with at least one Z decaying leptonically ...

$ttH \to ttbb$ ... via additional top selection ...

2. Optimize detector resolution

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

thus: peak region has to be increased by a factor 2 and number N_B of background events increases by factor of 2

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

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

3. Maximize luminosity L

Signal: $N_S \sim L$

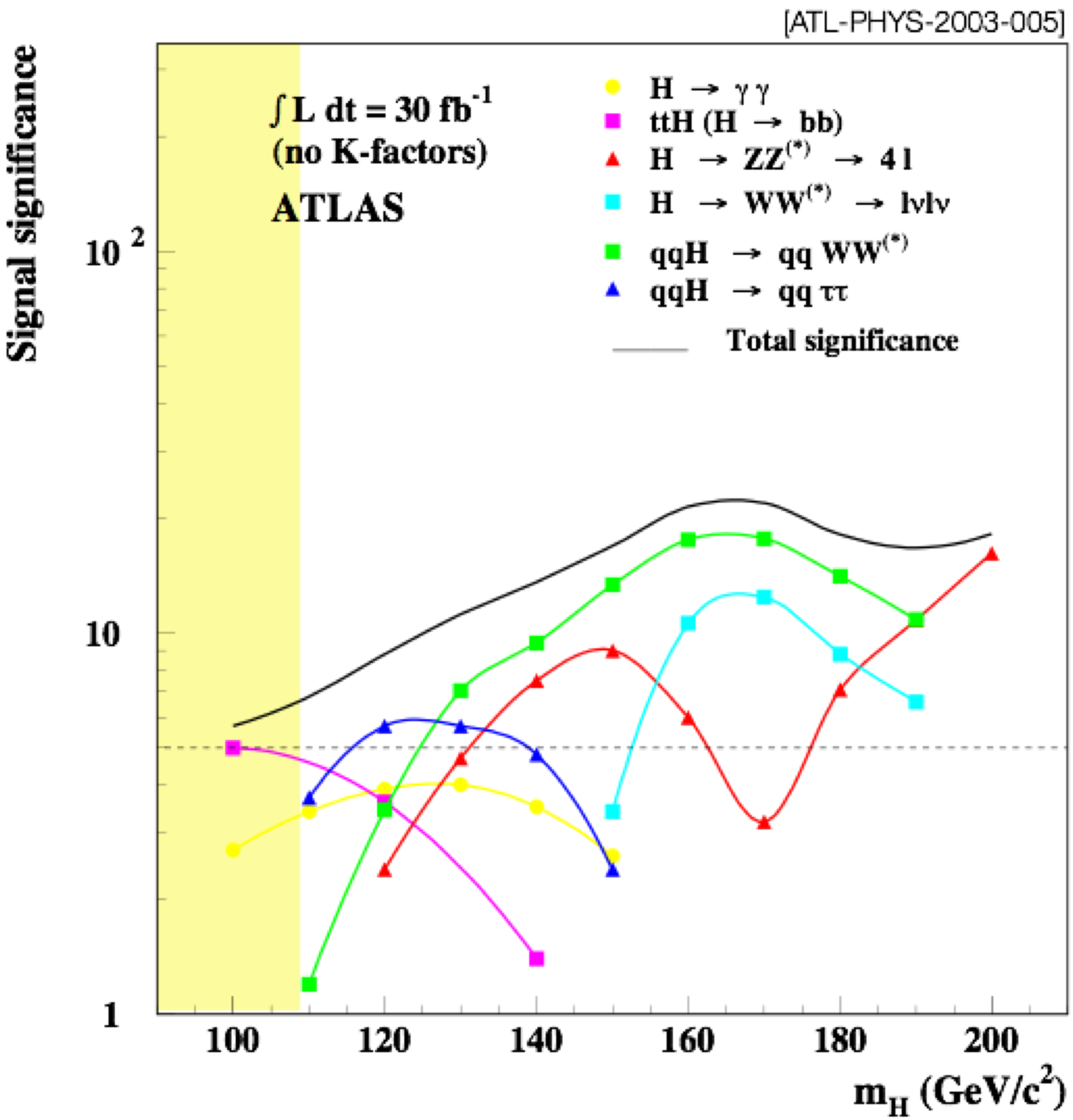
Background: $N_B \sim L$

} ➛

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

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%

LHC: Higgs Discovery Potential



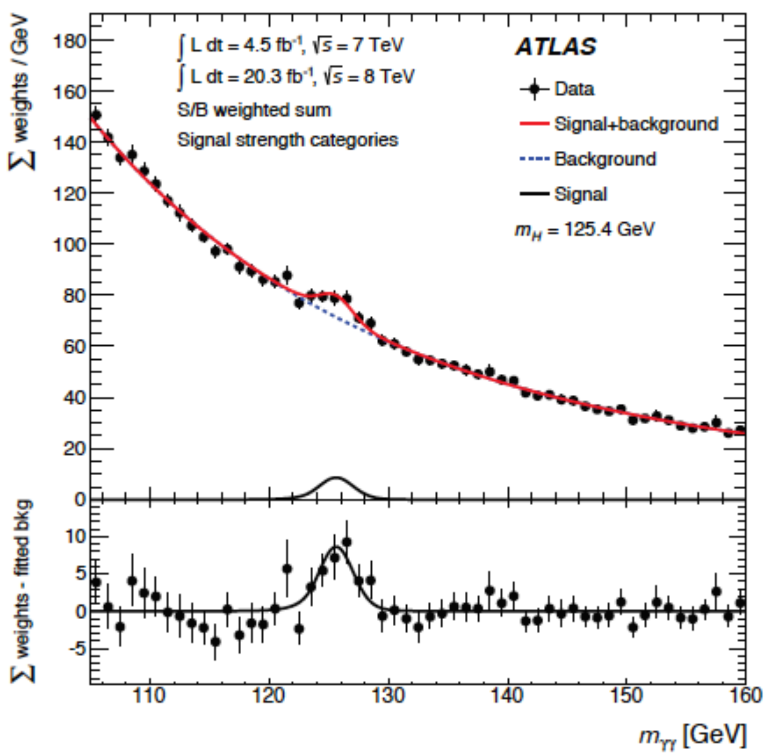
Full mass range can already be covered after a few years at low luminosity

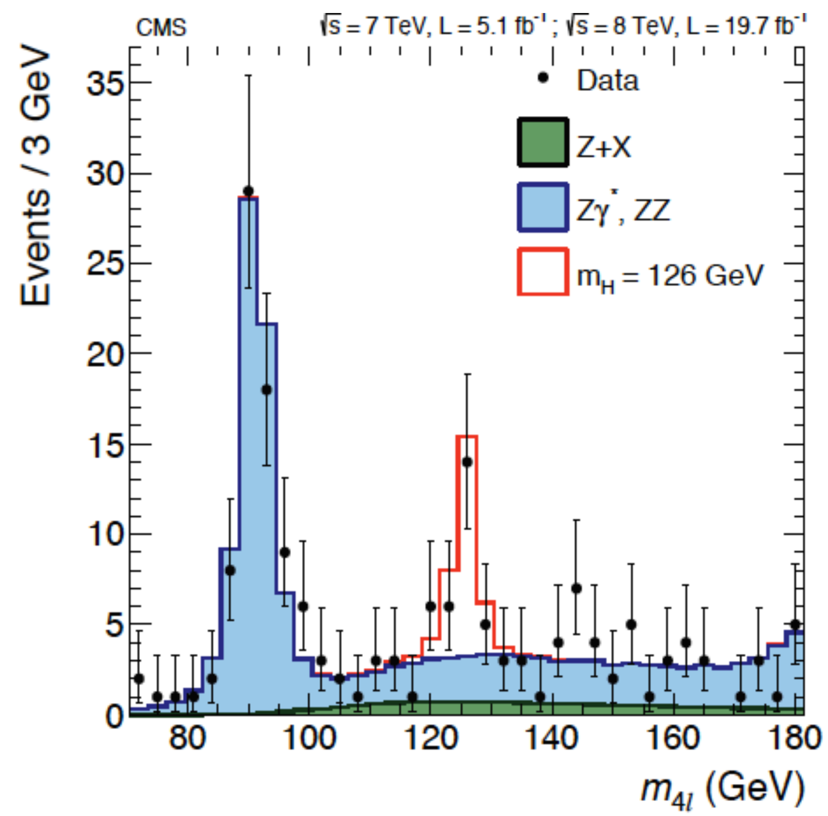
Several channels available over a large range of masses

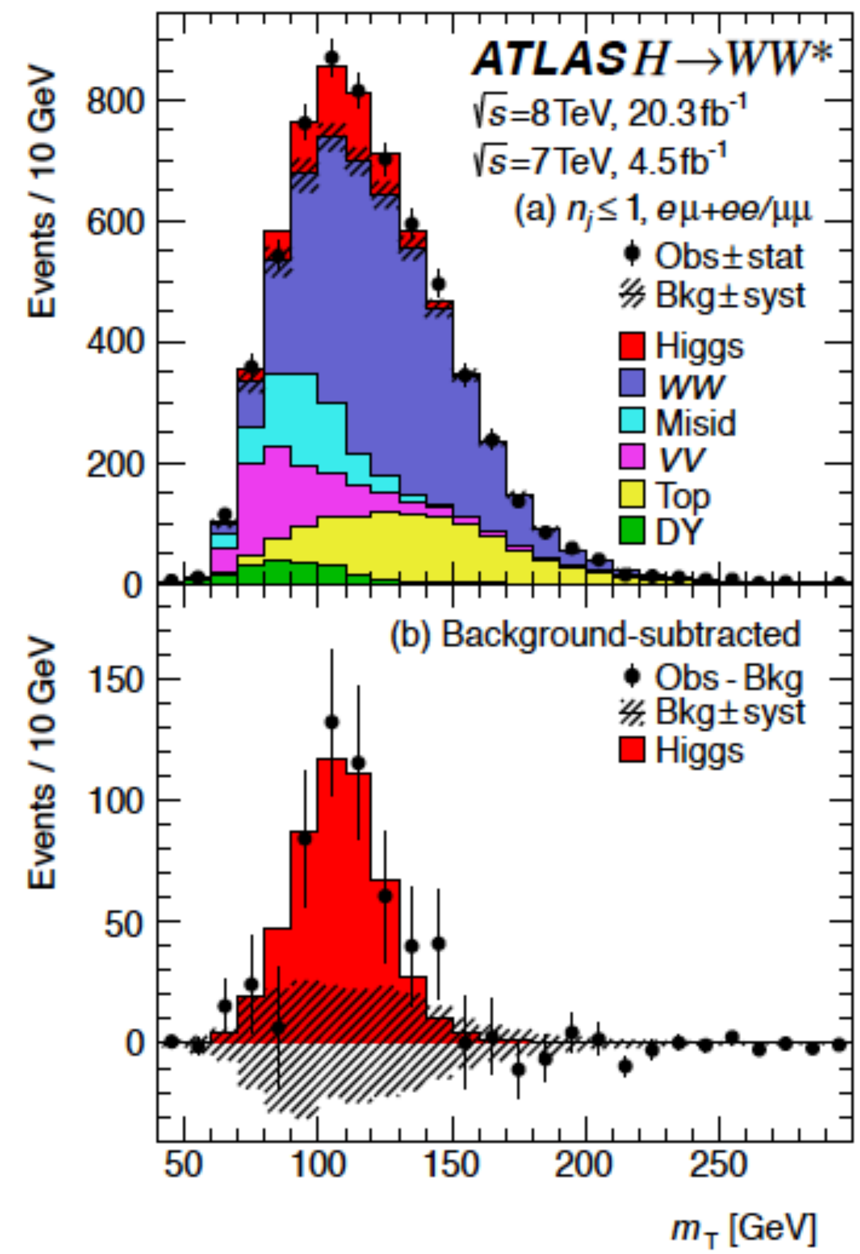
Low mass discovery requires combination of three of the most demanding channels

Comparable situation for the CMS experiment

A snap-shot of ~recent results







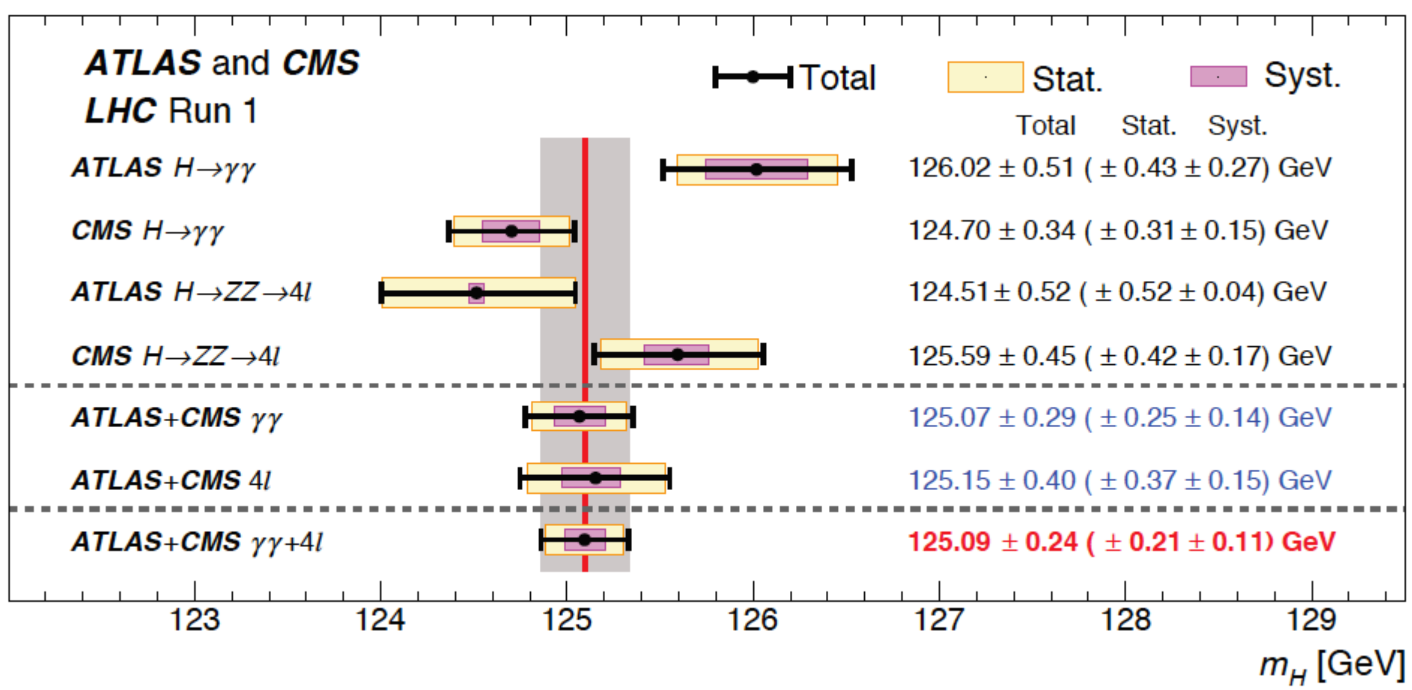


Figure 11.4: A compilation of the CMS and ATLAS mass measurements in the $\gamma\gamma$ and ZZ channels, the combined result from each experiment and their combination. From Ref. [134]

Higgs terms in the SM Lagrangian

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

V = W± or Z and
δW = 1, δZ = 1/2

linear

$$g_{Hf\bar{f}} = \frac{m_f}{v},$$

quadratic

$$g_{HVV} = \frac{2m_V^2}{v}, \qquad g_{HHVV} = \frac{2m_V^2}{v^2}$$

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

As a result, 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. The Higgs boson coupling to gluons, is induced at leading order by a one-loop graph in which H couples to a virtual tt pair. Likewise, the Higgs boson coupling to photons is also generated via loops, although in this case the one-loop graph with a virtual W+W− pair provides the dominant contribution and the one involving a virtual tt pair is subdominant.

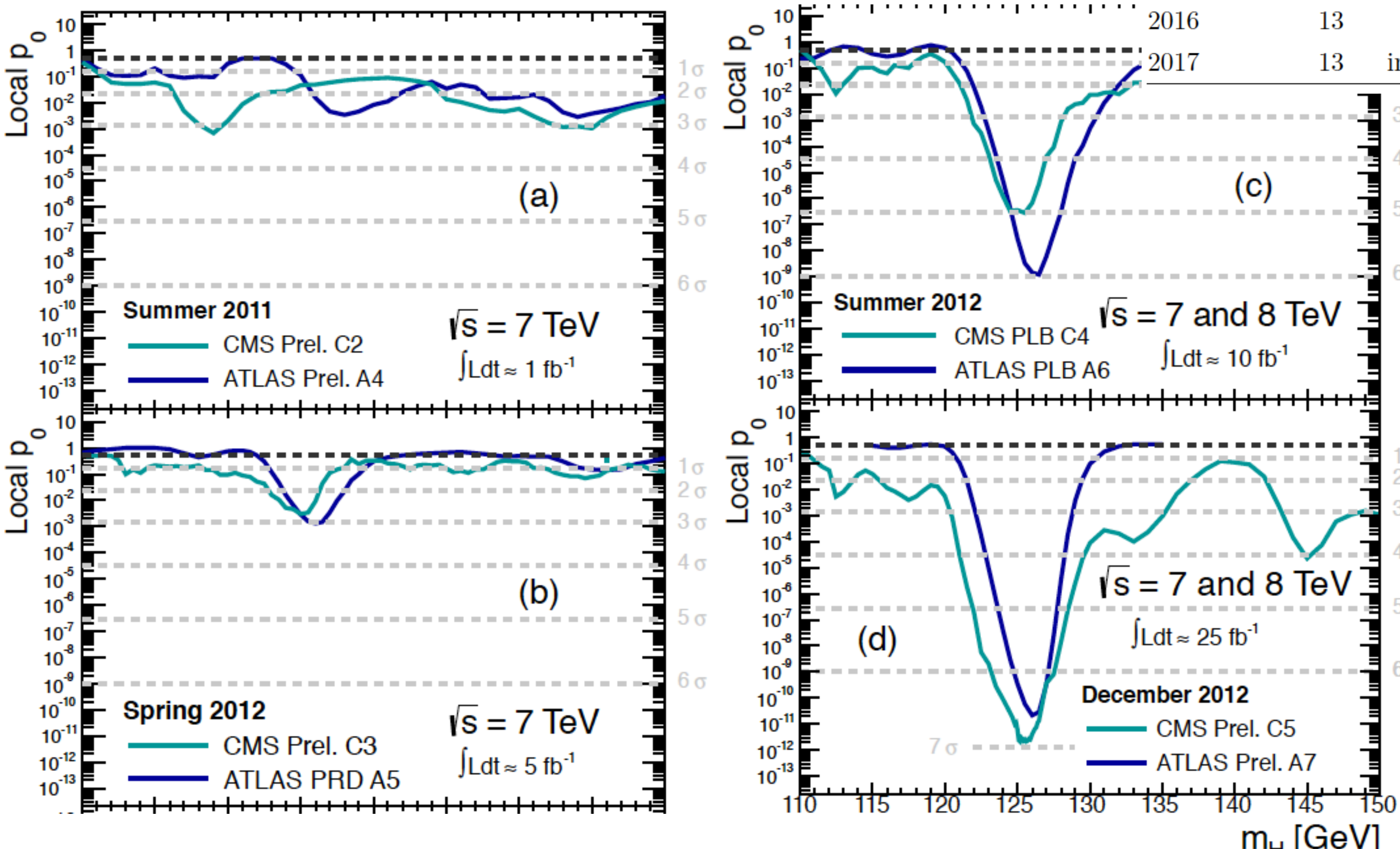
Recent history

The announcement on July 4, 2012 of the observation [1,2] at the LHC of a narrow resonance with a mass of about 125GeV has provided an important new direction in the decades-long search for the SM Higgs boson. The analyzed data corresponded to integrated luminosities of up to 4.8 (5.1) fb^{-1} at $\sqrt{s}$ = 7TeV in 2011 and 5.9 (5.3) at $\sqrt{s}$ = 8TeV in 2012 recorded by the ATLAS and CMS experiments, respectively. The observed decay channels indicated that the new particle is a boson. The evidence was strong that the new particle decays to $\gamma\gamma$ and ZZ with rates consistent with those predicted for the Standard Model (SM) Higgs boson. There were indications that the new particle also decays to W^+W^-. Although the experiments searched for decays to $b\bar{b}$ and $\tau^+\tau^-$, no statistically significant signal was found. The significance of these observations are quantified by a p-value, the probability for a background only experiment to give a result at least as signal-like as that observed in the data. For example, a p-value of 2.87×10^{-7} corresponds to a five-standard-deviation excess over the background-only prediction. ATLAS observed the largest excess with a local significance of 5.9σ at a mass m_H = 126.5GeV, to be compared with an expected significance of 4.6σ if a SM Higgs boson were present at such a mass. CMS observed an excess with a local significance of 4.9σ at a mass of 125.5GeV, to be compared with an expected significance of 5.9σ in this dataset.

Even as this discovery was being announced, ATLAS and CMS continued to accumulate pp collision data at $\sqrt{s}$ = 8TeV recording a total of about 20 fb^{-1} each at this energy. Figure below shows four snapshots of the evolution of the p-value and the signal significance near 125GeV with increasing datasets analysed by the two experiments.

Evolution of p_0

Year	$\sqrt{s}$ (TeV)	$\int$ L.dt (fb^{-1})	Run Period
2010	7	0.04	Run 1
2011	7	6.1	Run 1
2012	8	23.3	Run 1
2015	13	4.2	Run 2
2016	13	40.8	Run 2
2017	13	in progress (> 40)	Run 2



125

Evolution of the p-value and the signal significance observed by the ATLAS and CMS experiments with increasingly larger datasets: (a) Summer 2011 (≈ 1 fb^{-1}/expt) for ATLAS and CMS, (b) Spring 2012 (≈ 5 fb^{-1}/expt) for ATLAS and CMS, (c) Summer 2012 (≈ 10 fb^{-1}/expt) for ATLAS and CMS, and (d) December 2012 (≈ 25 fb^{-1}/expt) for ATLAS and CMS.

Decay & production channels of the Higgs

There are four main production modes of a SM Higgs boson at the LHC. In Run 1 SM Higgs bosons produced per experiment are approximately 0.5 million, 40,000, 20,000 and 3,000 in the gluon fusion, vector boson fusion, the associated VH and ttH production modes respectively. There are also five main decay channels: the $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$ and bb.

Analyses using exclusive categories according to production modes have been designed to maximize the sensitivity of the analyses to the presence of a signal using known features of these modes. These categories can also be used to further separate production modes for each decay channel. The typical number of events selected eventually in each decay channel ranges from a fraction of an event to O(100) events per experiment.

The analysis strategy used by the LHC and Tevatron experiments to perform the searches for the Higgs boson has been based on the Higgs decay modes. However, for each channel, exclusive subchannels have been defined according to the Higgs production processes and these subchannels have been combined.

The natural extension of this approach is to further measure the coupling properties of the Higgs boson. A combined measurement of a large variety of categories with different sensitivities to various production and decay modes permits a wide variety of measurements of the production, decay or in general coupling properties. These measurements require, in general, a limited but nevertheless restrictive number of assumptions.

Production Modes

ggf: At high-energy hadron colliders, the Higgs boson production mechanism with the largest cross section is the gluon-fusion process, $gg \rightarrow H+X$, mediated by the exchange of a virtual, heavy top quark. Contributions from lighter quarks propagating in the loop are suppressed by terms proportional to m^2_q .

VBF: The SM Higgs production mode with the second-largest cross section at the LHC is vector boson fusion (VBF). At the Tevatron collider, VBF also occurred, but for m_H = 125GeV had a smaller cross section than Higgs production in association with a W or Z boson. Higgs production via VBF, $qq \rightarrow qqH$, proceeds by the scattering of two quark (anti-) quarks, mediated by t- or u-channel exchange of a W or Z boson, with the Higgs boson radiated off the weak-boson propagator. The scattered quarks give rise to two hard jets in the forward and backward regions of the detector with a large dijet mass (≥ 400GeV) and separated by a large pseudorapidity ($\Delta\eta_{jj} \geq 3.5$).

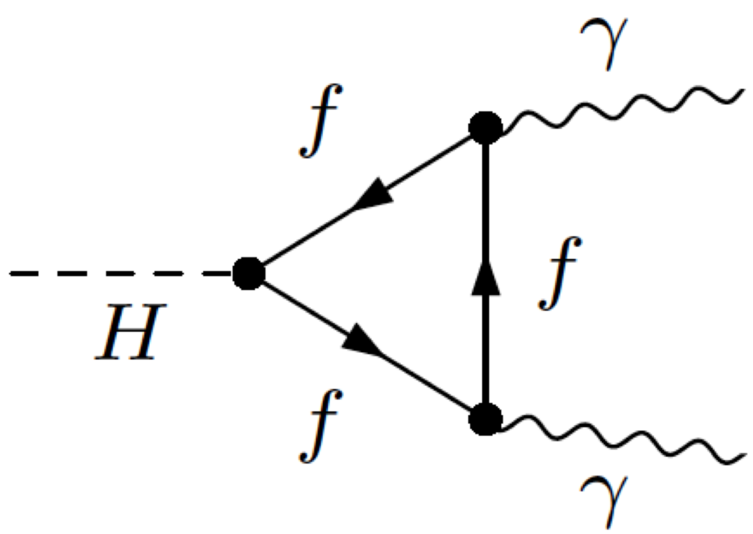
VH, V=Z or W: The next most relevant Higgs boson production mechanisms after gluon fusion and VBF at the LHC, and the most relevant ones after gluon fusion at the Tevatron collider, are associated production with W and Z gauge bosons. MET & high p_T leptons (W leptonic decay) and Z leptonic decays offer clean signatures.

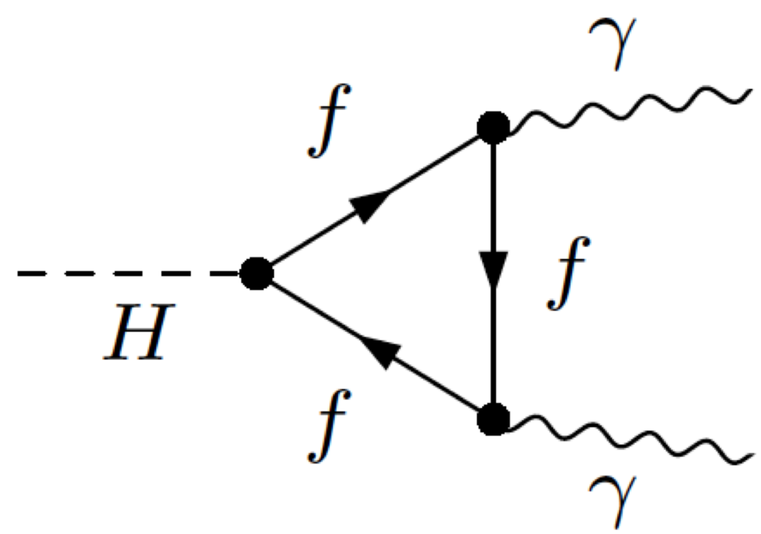
ttH: Higgs radiation off top quarks, $pp \rightarrow \bar{t}tH$, provides a direct probe of the top-Higgs Yukawa coupling. Distinctive features include high p_T leptons, MET. Complex topology when combined with several decay channels

Low mass Higgs: discovery channels

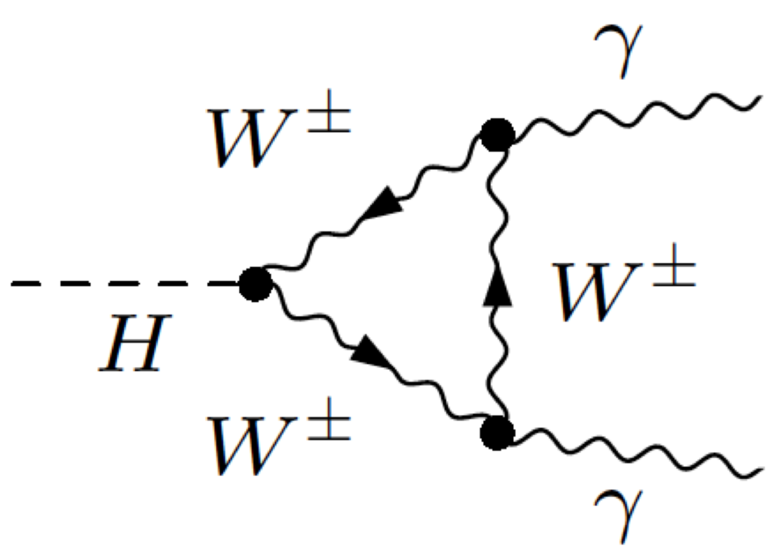
For a low-mass Higgs boson (110GeV< mH <150GeV), where the natural width is only a few MeV, **five decay channels** play an important role at the LHC. In the **$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$** channels, all final state particles can be very precisely measured and the reconstructed m_H resolution is excellent (typically 1-2%). While the **$H \rightarrow W^+W^- \rightarrow l^+\nu_l l'^- \bar{\nu}_l'$** channel has relatively large branching fraction, the mH resolution is poor (approximately 20%) due to the presence of neutrinos. The **$H \rightarrow b\bar{b}$ and the $H \rightarrow \tau^+\tau^-$** channels suffer from large backgrounds and a intermediate mass resolution of about 10% and 15% respectively. For mH > 150GeV, the sensitive search channels are $H \rightarrow WW$ and $H \rightarrow ZZ$ where the W or Z boson decays into a variety of leptonic and hadronic final states. These decay channels of the Higgs boson are searched for in the **five Higgs boson production processes (ggF, VBF, WH, ZH and ttH).** The candidate events in each Higgs boson decay channel are split into several mutually exclusive categories (or event tags) based on the specific topological, kinematic or other features present in the event. The categorization of events increases the sensitivity of the overall analysis and allows a separation of different Higgs boson production processes. Most categories are dominated by signal from one Higgs decay mode but contain an admixture of various Higgs production processes. For example, a typical **VBF** selection requires Higgs boson candidates to be accompanied by two energetic jets (≥ 30GeV) with a large dijet mass (≥ 400GeV) and separated by a large pseudorapidity ($\Delta\eta_{jj} \geq 3.5$). While such a category is enriched in Higgs bosons produced via VBF, the contamination from the gluon fusion production mechanism can be significant. Hence a measurement of the signal rate in the VBF category does not imply a measurement of VBF production cross-section. Simulations are used to determine the relative contributions of the various Higgs production modes in a particular category.

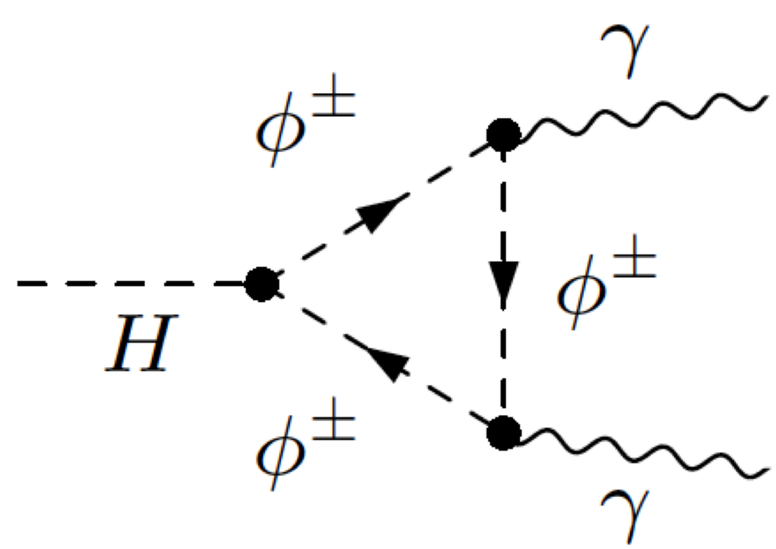
Higgs decay to 2 photons





Only top quarks contribute, contributions from light fermions negligible





W-bosons, Goldstone-bosons and ghosts occur in the loops

Higgs to $\gamma\gamma$

Method: look for a peak in the invariant mass of two high p_T photons over a smoothly falling background distribution.
Background: Irreducicle background: processes with the production of two prompt $\gamma\gamma$
Reducible background: γ+jets, di-jet events (where one jet fragments into a leading π^0)

Classification:
VH if the event contains a high p_T lepton + missing energy (decay of a W or a Z)
VH if the event contains a pair of jets compatible with the decay of a W or a Z
VBF if the event contains two high mass jets + pseudo-rapidity difference
Remaining events go into the ggf category

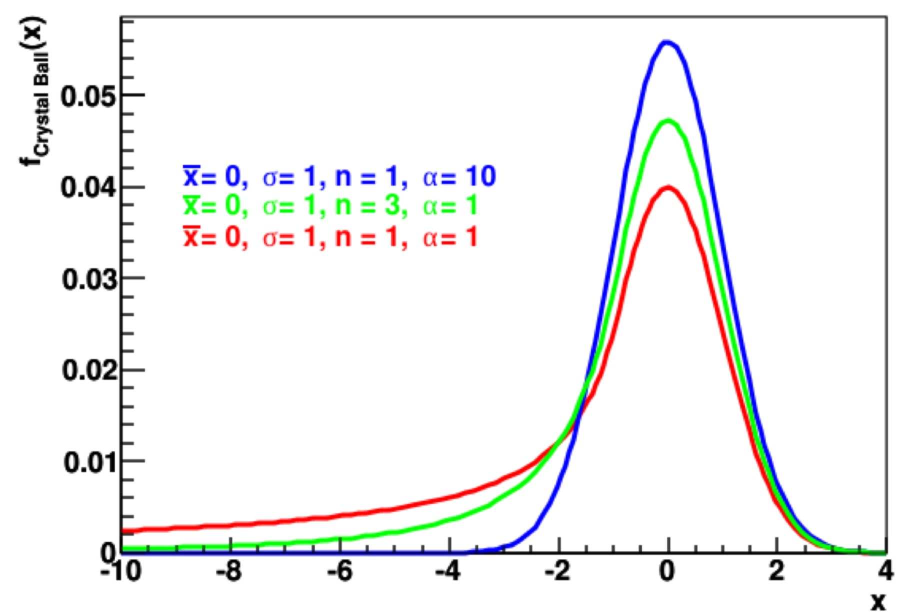
Practical aspects: two photons invariant mass reconstruction has been extensively studied using $Z \to e^+e^-$ and $Z \to e^+e^-\gamma$. These studies are used to determine the lineshape of the signal. Events are categorized to get larger sensitivity. In each category, parametric signal models are adjusted to these lineshape to provide a functional form for the signal. Simple monotonic functional forms of the backgrounds are determined by a fit to the $m_{\gamma\gamma}$ distribution in each category. All categories are fitted simultaneously to determine the signal yield at the measured combined Run 1 mass of 125.09 GeV.

Higgs to γγ, Signal Model

Signal & Background Model

The Higgs boson signal manifests itself as a narrow peak in the $m_{\gamma\gamma}$ spectrum. The signal distribution is empirically modeled as a double-sided Crystal Ball function, consisting of a Gaussian central part and power-law tails on both sides. The Gaussian core of the Crystal Ball function is parameterized by the peak position ($m_H + \Delta\mu_{CBi}$) and the width $\sigma_{CB,i}$.

The non-Gaussian contributions to the mass resolution arise mostly from converted photons $\gamma \to e^+e^-$ with at least one electron losing a significant fraction of its energy through γ bremsstrahlung in the inner detector material. The parametric form for a given reconstructed category or bin i of a fiducial cross section measurement, for a Higgs boson mass mH, can be written as:

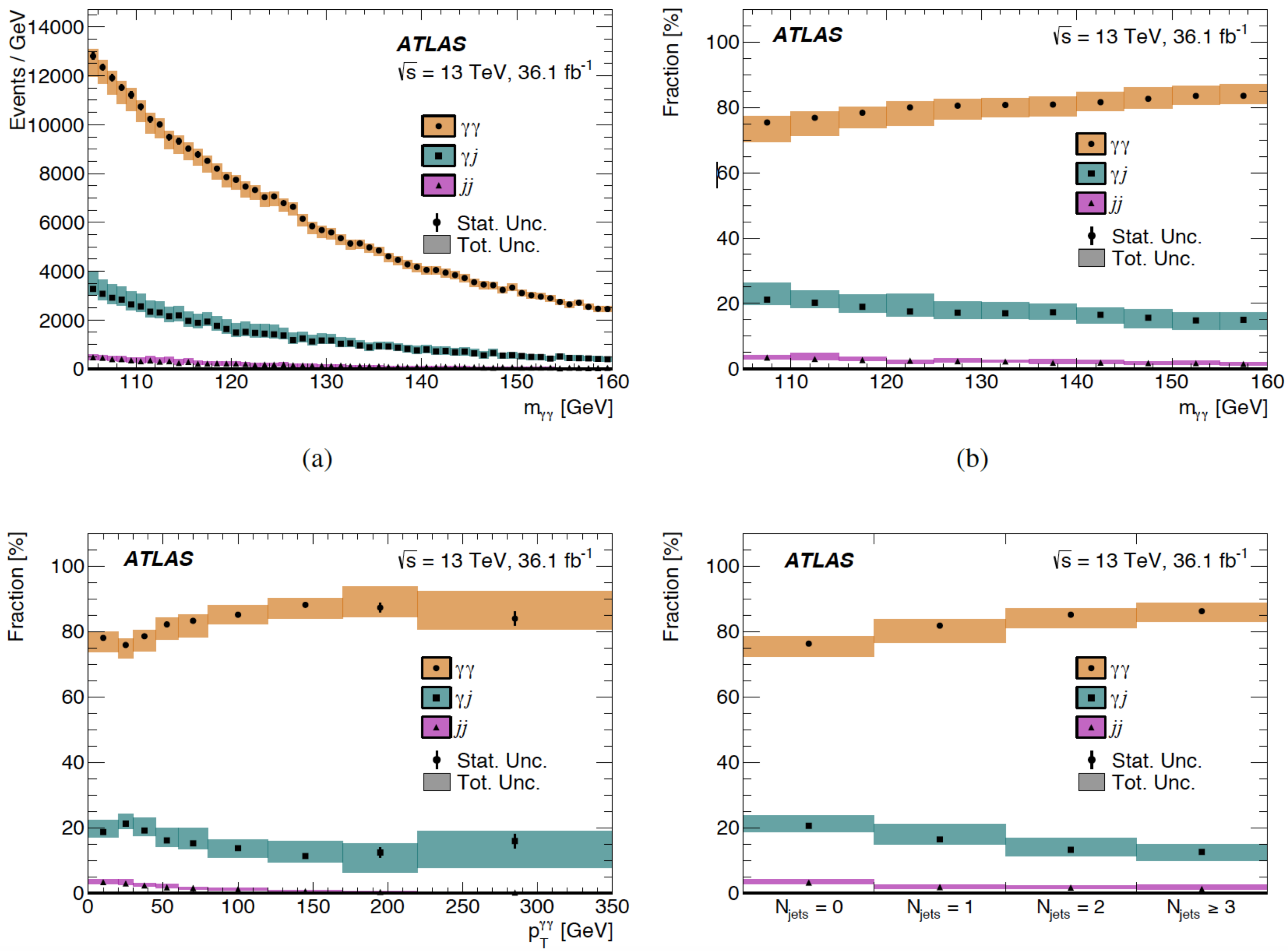


$$f_i^{\mathrm{sig}}(m_{\gamma\gamma};\Delta\mu_{\mathrm{CB},i},\sigma_{\mathrm{CB},i},\alpha^{\pm}_{\mathrm{CB},i},n^{\pm}_{\mathrm{CB},i}) = \mathcal{N}_c \begin{cases} e^{-t^2/2} & -\alpha^-_{\mathrm{CB},i} \le t \le \alpha^+_{\mathrm{CB},i} \\ \left(\frac{n^-_{\mathrm{CB},i}}{|\alpha^-_{\mathrm{CB},i}|}\right)^{n^-_{\mathrm{CB},i}} e^{-|\alpha^-_{\mathrm{CB},i}|^2/2} \left(\frac{n^-_{\mathrm{CB},i}}{\alpha^-_{\mathrm{CB},i}} - \alpha^-_{\mathrm{CB},i} - t\right)^{-n^-_{\mathrm{CB},i}} & t < -\alpha^-_{\mathrm{CB},i} \\ \left(\frac{n^+_{\mathrm{CB},i}}{|\alpha^+_{\mathrm{CB},i}|}\right)^{n^+_{\mathrm{CB},i}} e^{-|\alpha^+_{\mathrm{CB},i}|^2/2} \left(\frac{n^+_{\mathrm{CB},i}}{\alpha^+_{\mathrm{CB},i}} - \alpha^+_{\mathrm{CB},i} - t\right)^{-n^+_{\mathrm{CB},i}} & t > \alpha^+_{\mathrm{CB},i} \end{cases},$$

where $t = (m_{\gamma\gamma} - m_H - \Delta\mu_{\mathrm{CB},i})/\sigma_{\mathrm{CB},i}$, and $\mathcal{N}_c$ is a normalization factor. The non-Gaussian parts are parameterized by $\alpha^{\pm}_{\mathrm{CB},i}$ and $n^{\pm}_{\mathrm{CB},i}$ separately for the low- (−) and high-mass (+) tails.

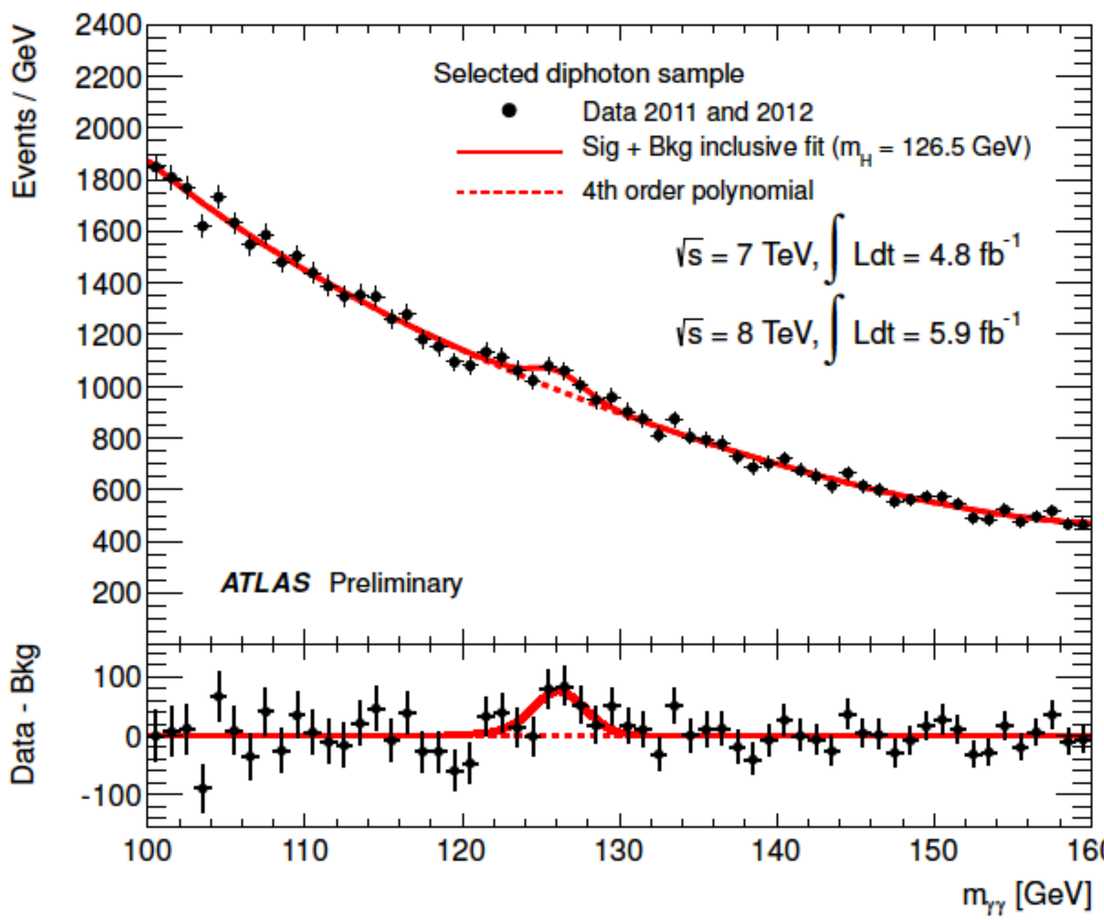
Higgs to γγ, Background model

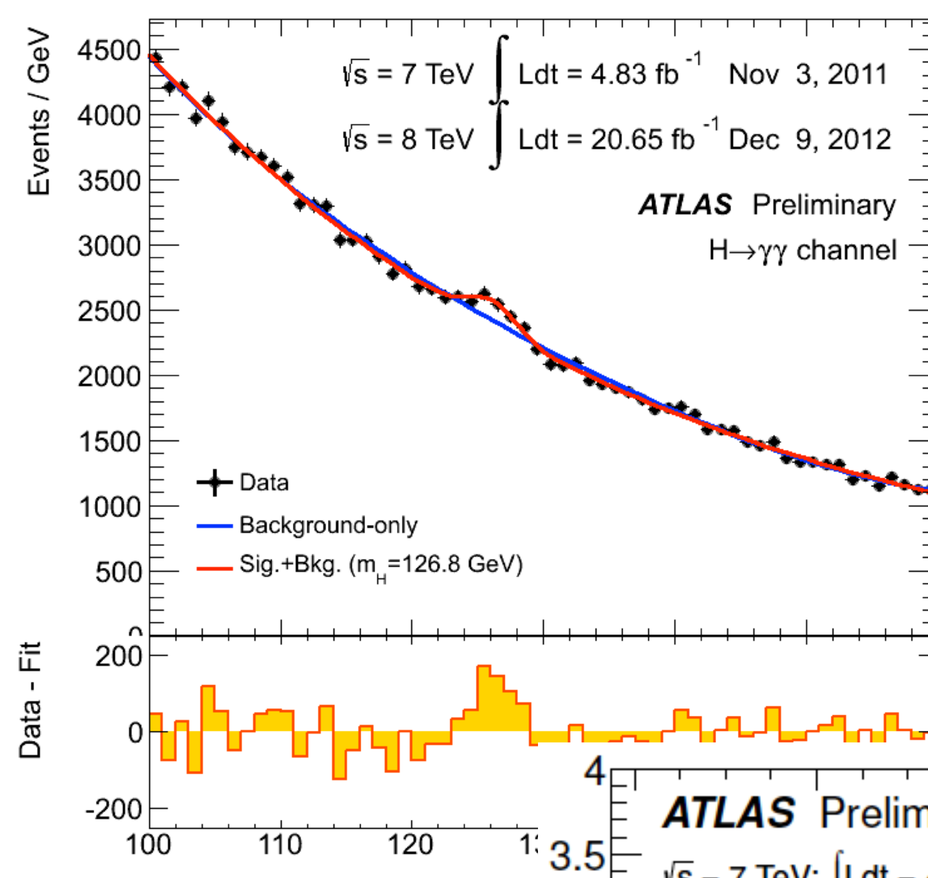
The diphoton invariant mass model for the background used to fit the data is determined from studies of the bias in the signal yield in signal+background fits to large control samples of data or simulated background events

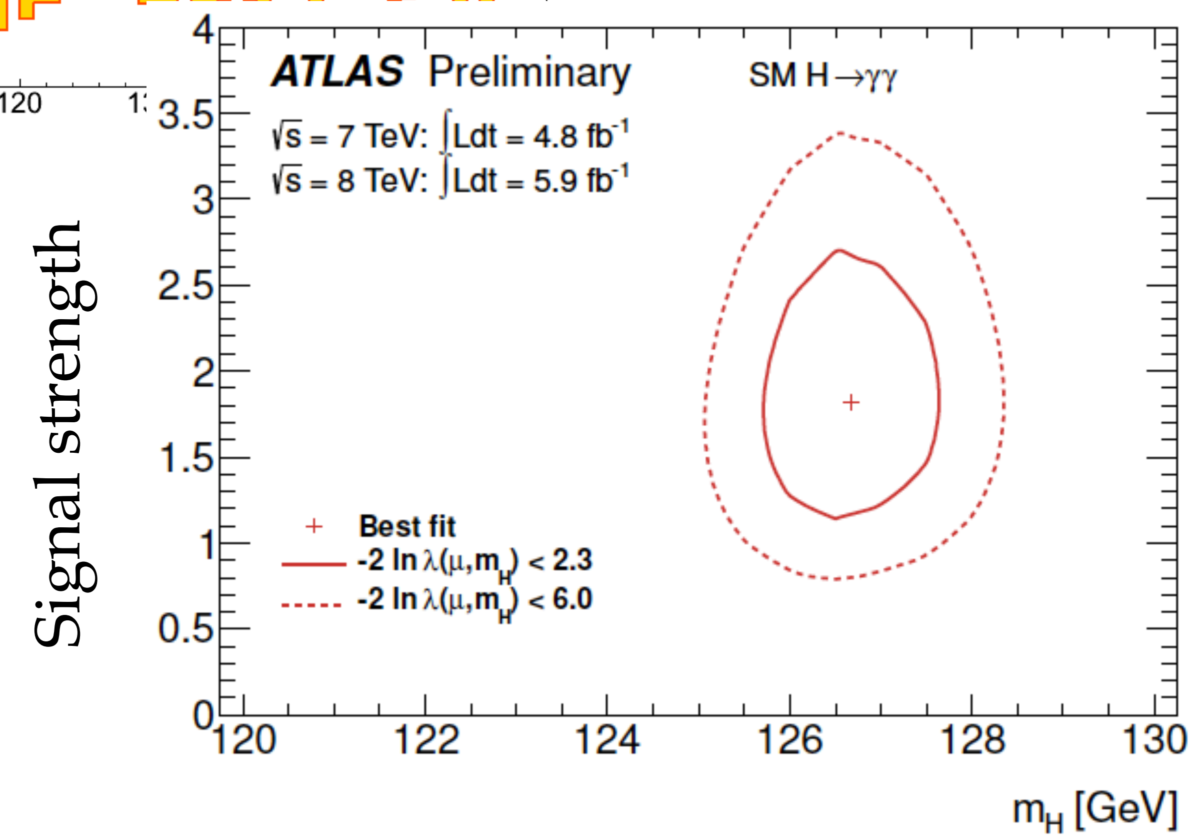


(a) (b)

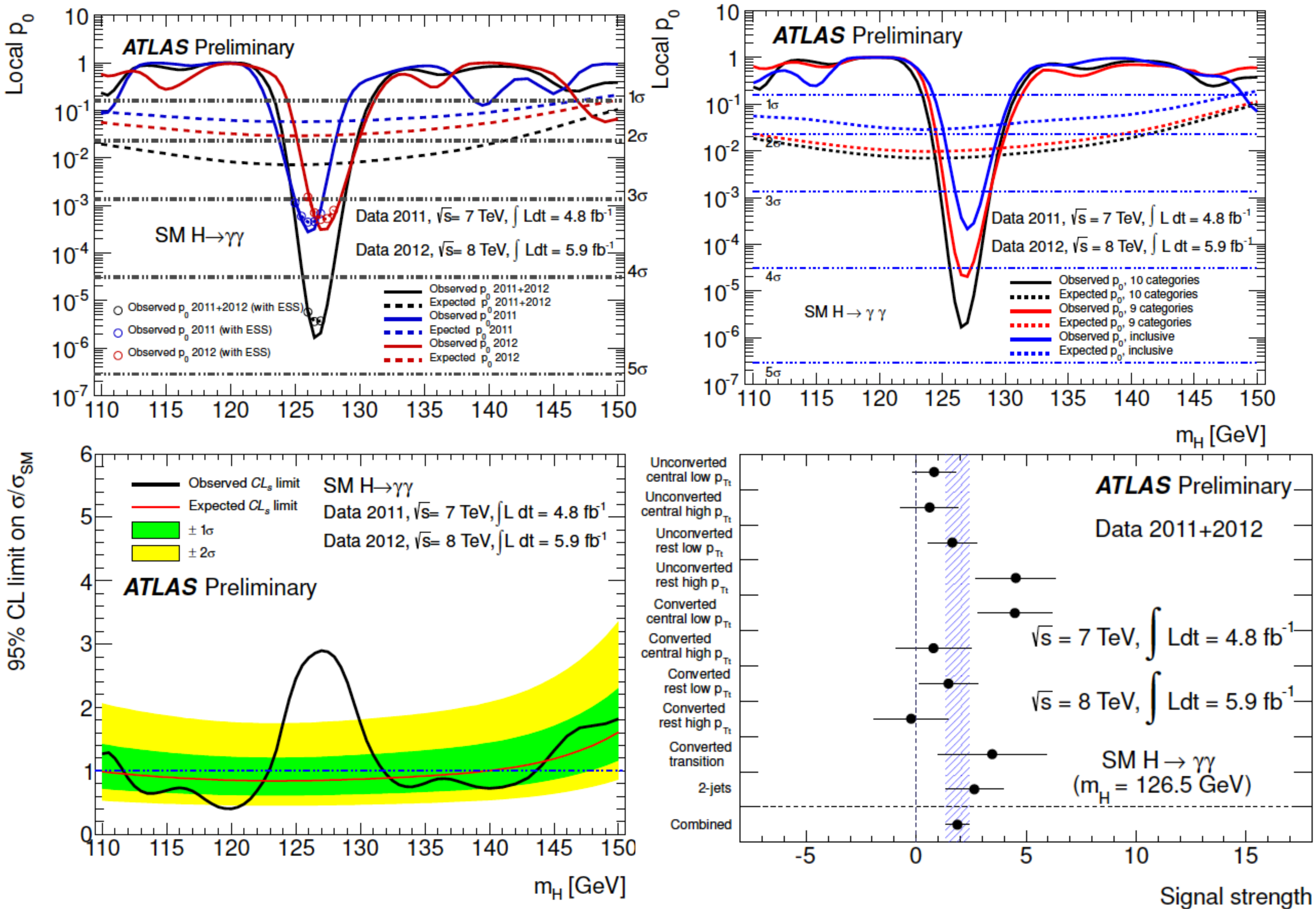
Observation of an excess of events in the search for the Standard Model Higgs boson in the $\gamma\gamma$ channel with the ATLAS detector



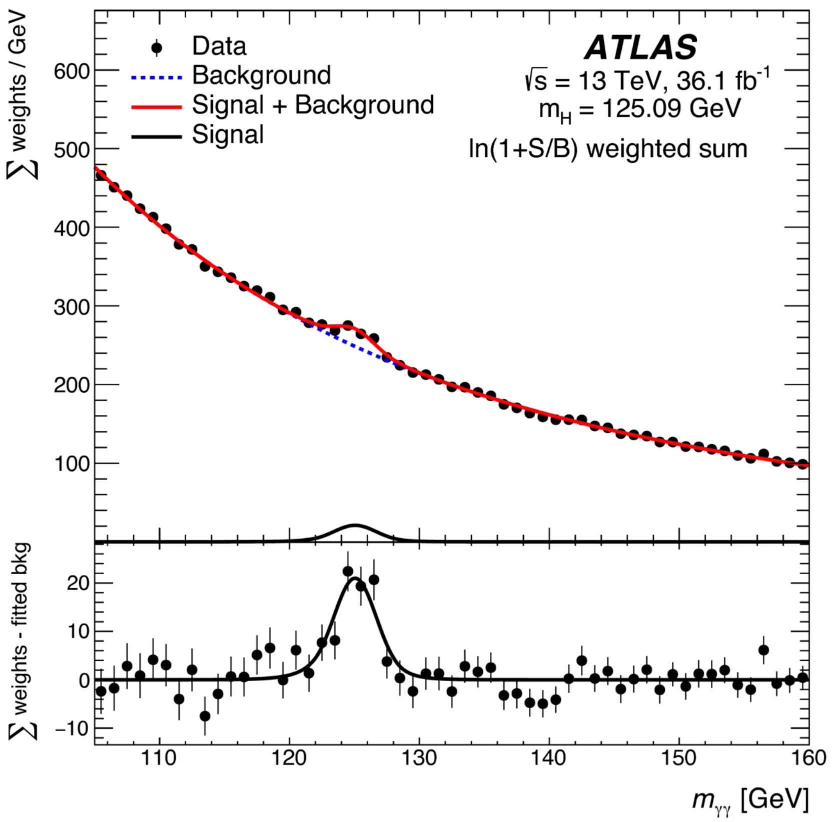


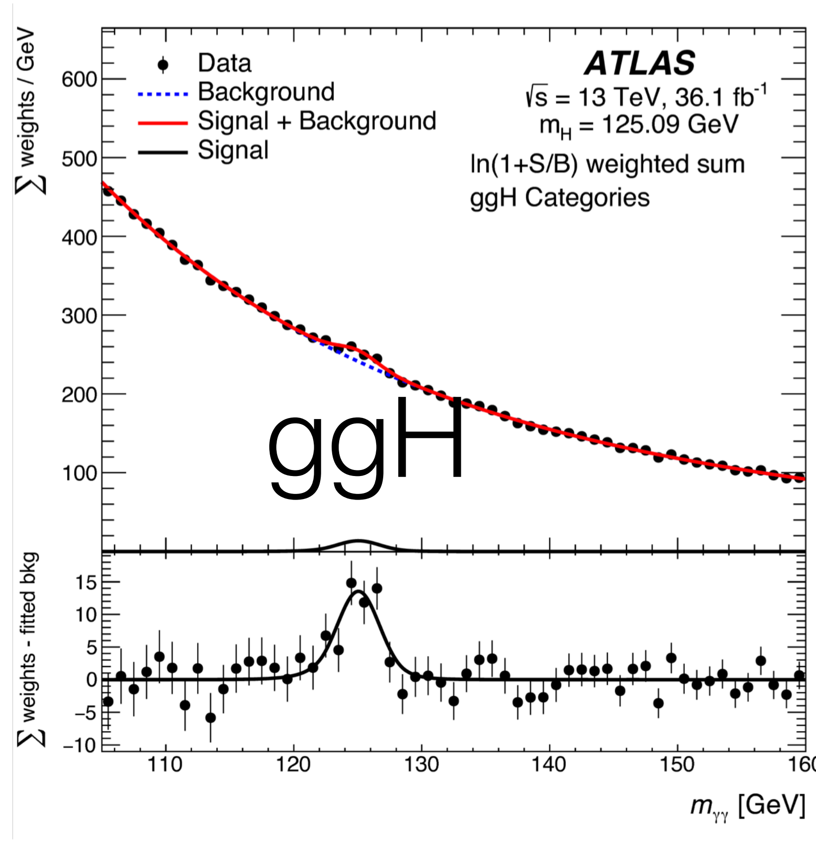


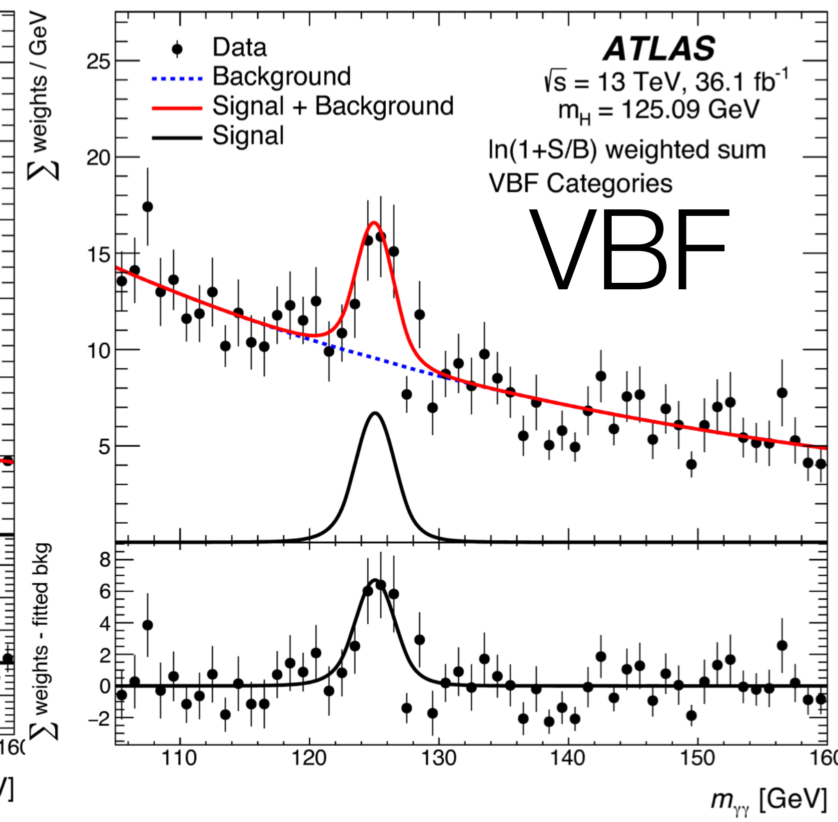
Observation of an excess of events in the search for the Standard Model Higgs boson in the $\gamma\gamma$ channel with the ATLAS detector

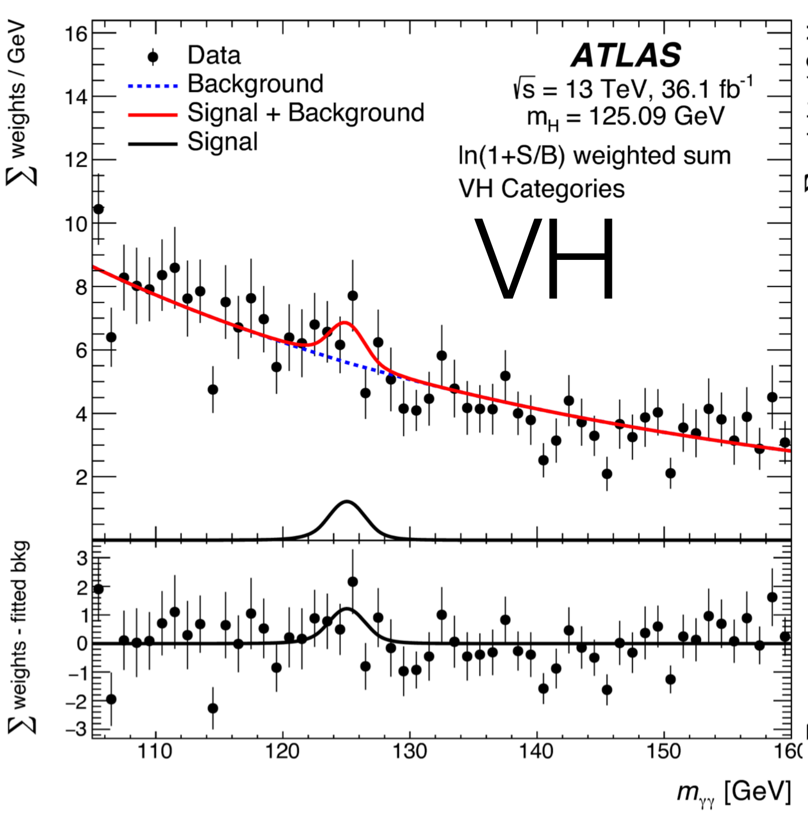


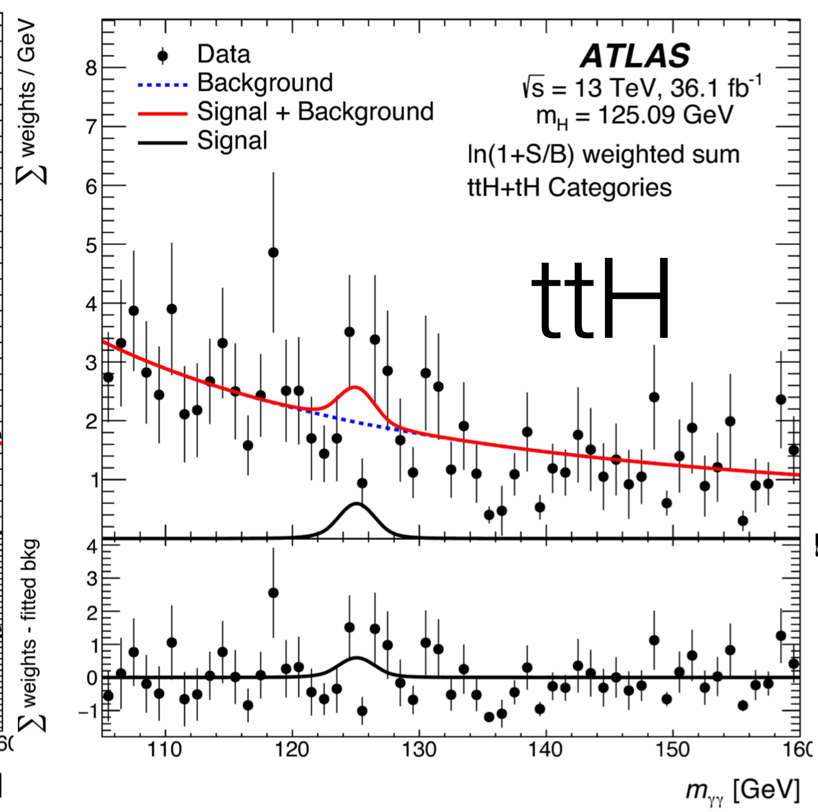
Results H to two photons in ATLAS

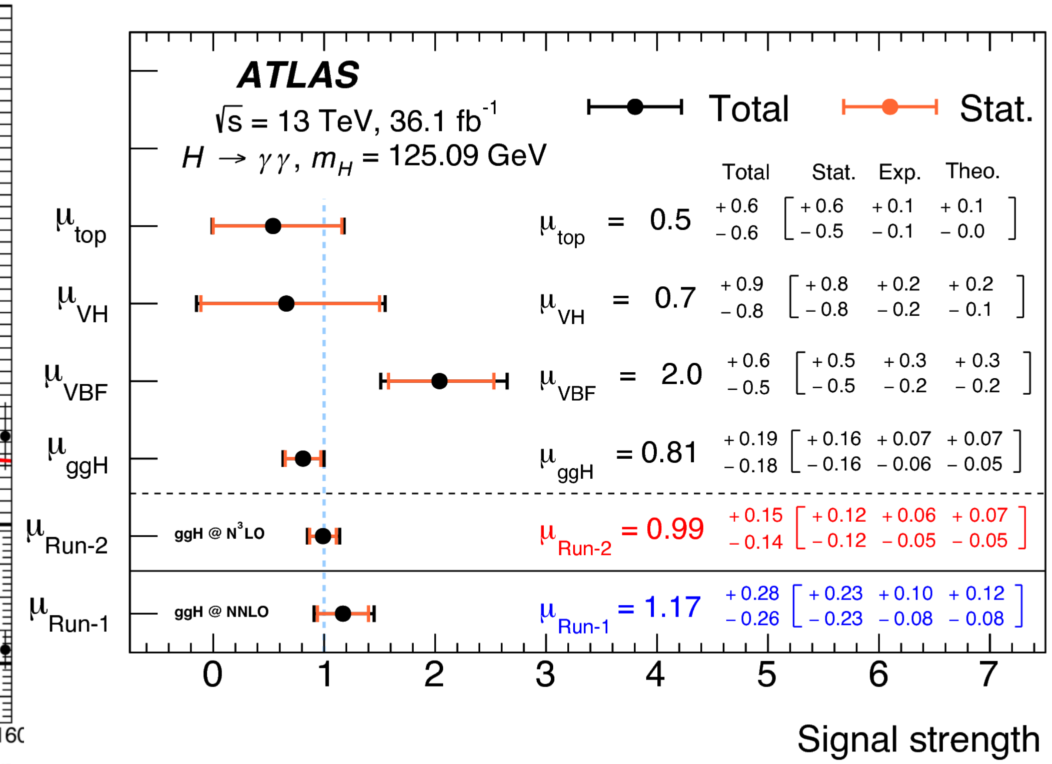










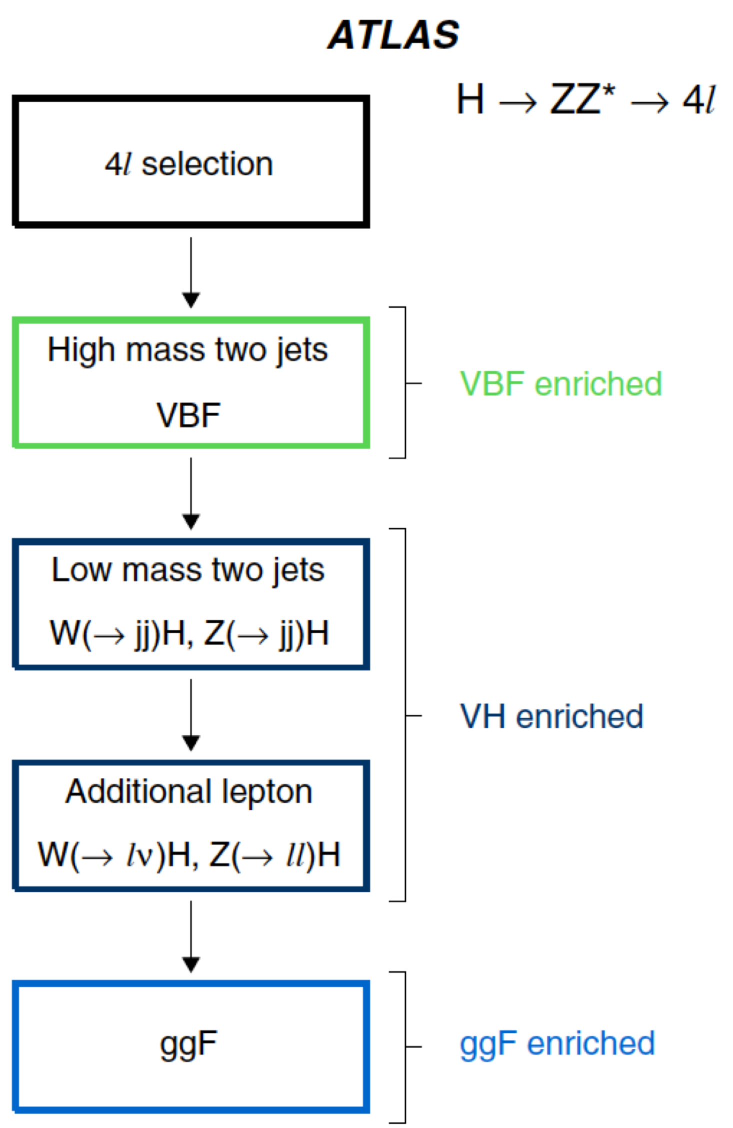


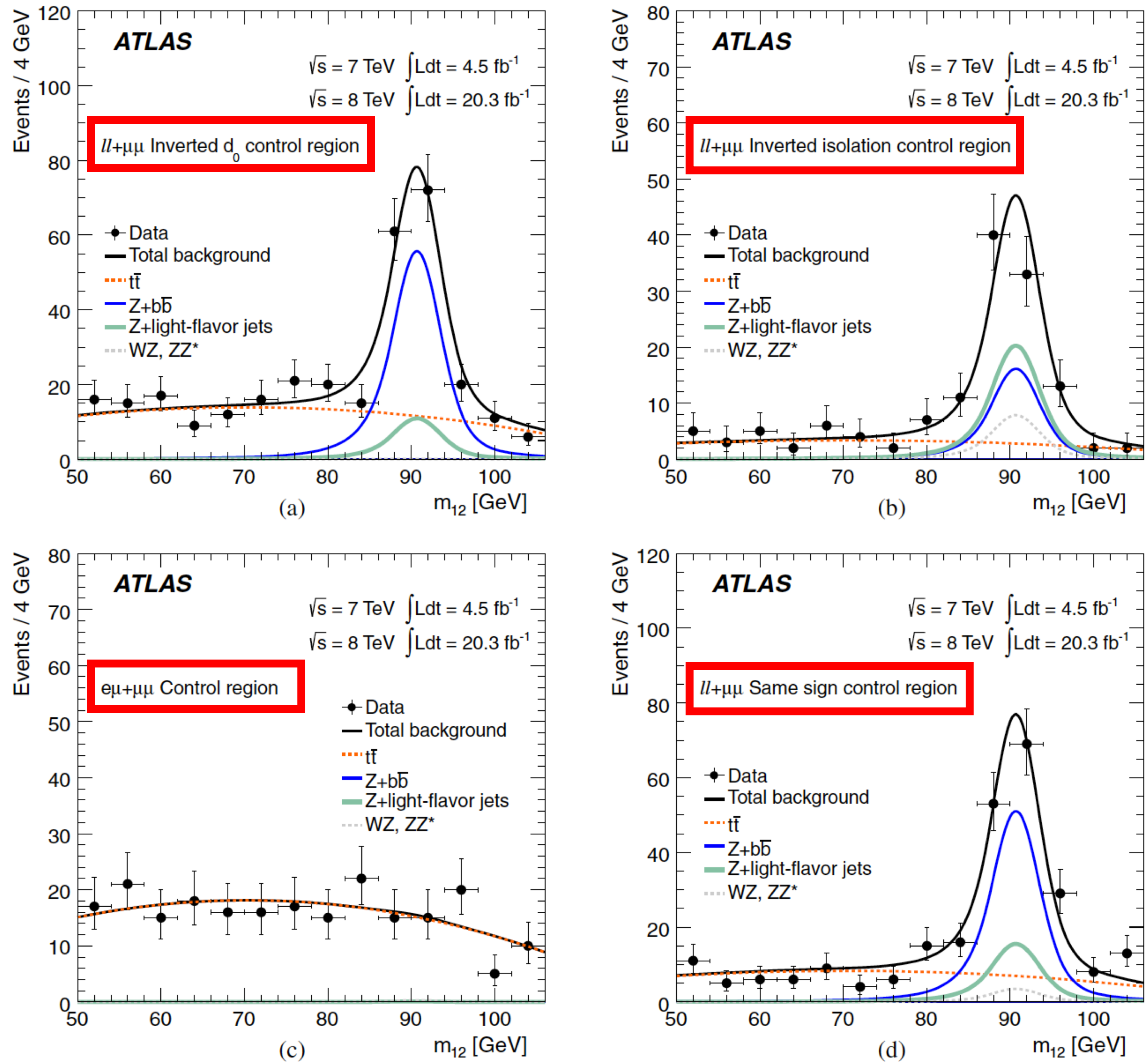
Higgs to ZZ to 4 leptons

In the $H \to ZZ* \to l^+l^-l'^+l'^-$ channel a search is performed for a narrow mass peak over a small continuous background dominated by non-resonant ZZ^* production from qq annihilation and gg fusion processes. The contribution and the shape of this irreducible background is taken from simulation. The subdominant and reducible backgrounds stem from $Z + \bar{b}b$, tt and Z + jets events. Their contribution is suppressed by requirements on lepton isolation and lepton impact parameter and their yield is estimated from control samples in data.

To help distinguish the Higgs signal from the dominant non-resonant ZZ∗ background, both ATLAS and CMS use a matrix element likelihood approach to construct a kinematic discriminant built for each 4l event based on the ratio of complete leading-order matrix elements $|Msig^2/Mbkg^2|$ for the signal ($gg \to H \to 4l$) and background($qq \to ZZ \to 4l$) hypotheses. The signal matrix element Msig is computed assuming $mH = m_{4l}$. To further enhance the sensitivity to a signal, various techniques are used by the experiments based on the matrix element or a multivariate analyses. To enhance the sensitivity to VBF and V H production processes, the ATLAS and CMS experiments divide 4l events into mutually exclusive categories. Events containing dijets with a large mass and pseudorapidity difference populate the VBF category. ATLAS requires the presence of an additional lepton in the V H category. In events with less than two jets, CMS uses the p^{4l}_T to distinguish between production via the gluon fusion and the VH/VBF processes.

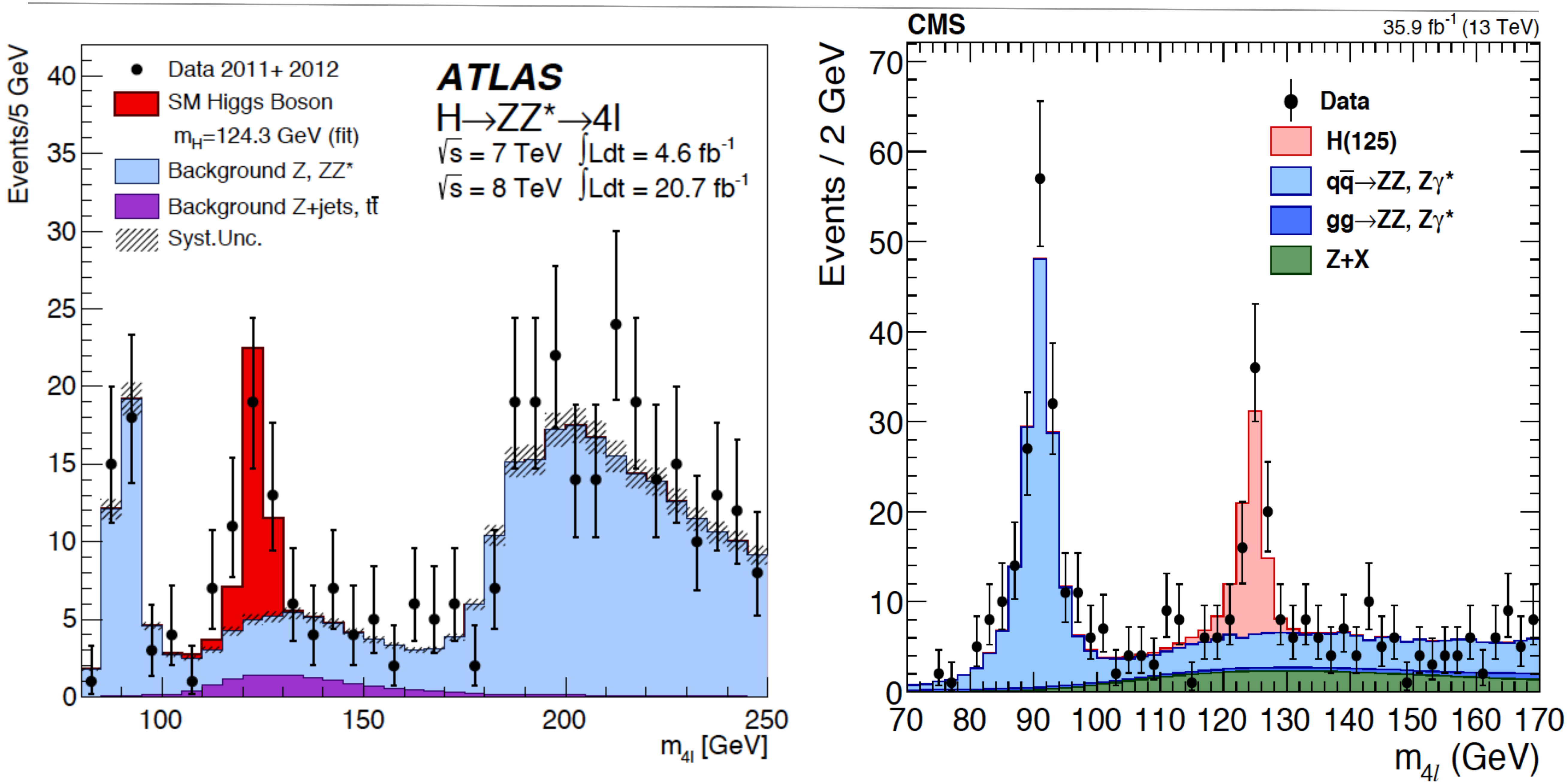
ATLAS analysis





Schematic view of the event categorization. Events are required to pass the four-lepton selection, and then they are assigned to one of four categories which are tested sequentially: VBF enriched, VH-hadronic enriched, VH-leptonic enriched, or ggF enriched.

Higgs to 4 leptons



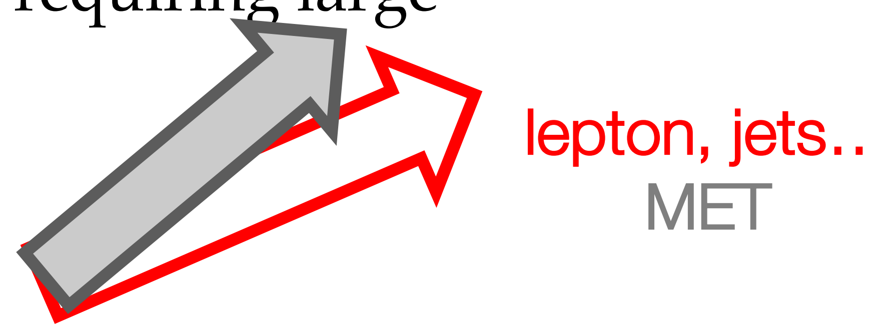
The signal strengths μ for the inclusive $H \to 4\ell$ production measured by the ATLAS and CMS experiments are $1.44^{+0.40}_{-0.33}$ at $m_H = 125.36\,\text{GeV}$ [129] and $0.93^{+0.29}_{-0.25}$ at $m_H = 125.6\,\text{GeV}$ [131] respectively, in Run 1. The signal strengths measured by the ATLAS and CMS experiments in Run 2 are $1.28^{+0.21}_{-0.19}$ [132] and $1.05^{+0.19}_{-0.25}$ [125] respectively, both measurements are made at the combined Run 1 Higgs mass of $m_H = 125.09\,\text{GeV}$.

Observation of an Excess of Events in the Search for the Standard Model Higgs Boson in the $H \to WW^{(*)} \to \ell\nu\ell\nu$ Channel with the ATLAS Detector

Selection of events

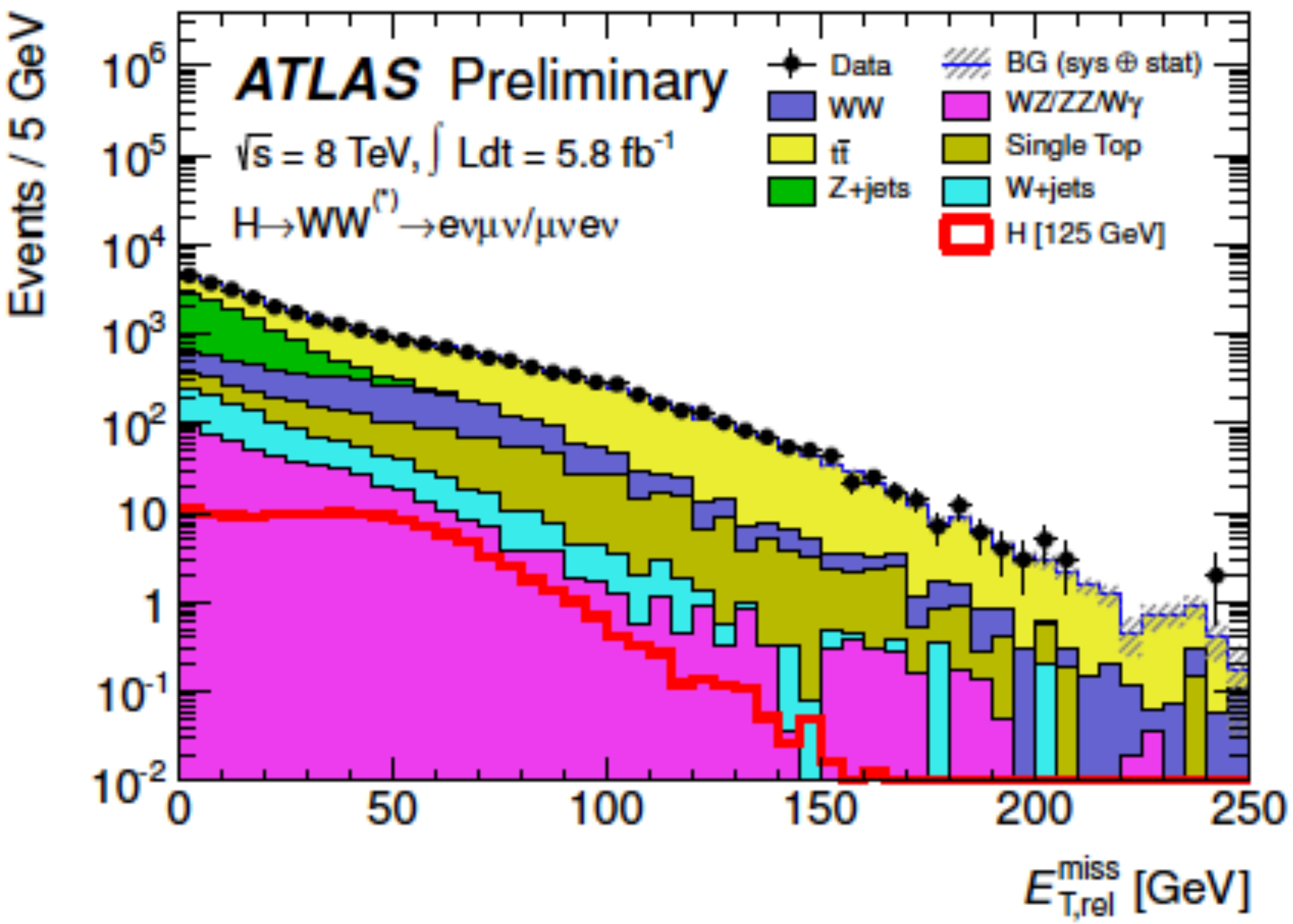
- Association with single muon & single electron triggers.
- The p_T of the lepton has to exceed 24 GeV and the lepton has to be isolated: the scalar sum of the p_T of charged particles within $R = \sqrt{\varphi 2 + \eta 2} = 0.2$ of the lepton direction is required to be less than 0.12 and 0.10 times the lepton p_T for the muon and electron, respectively.
- Because of the detector geometry, the acceptance of the muon trigger is limited to $|\eta| < 2.4$.
- vertex quality & lepton quality
- $H \to WW(*) \to \ell\nu\ell\nu$ candidates (with ℓ = e, μ) are pre-selected by requiring exactly two oppositely charged leptons **of different flavours**, with p_T thresholds of 25 GeV and 15 GeV for the leading and sub-leading lepton, respectively. Events are classified into two exclusive lepton channels depending on the flavour of the leading lepton.
- Drell-Yan and QCD multijet events are suppressed by requiring large

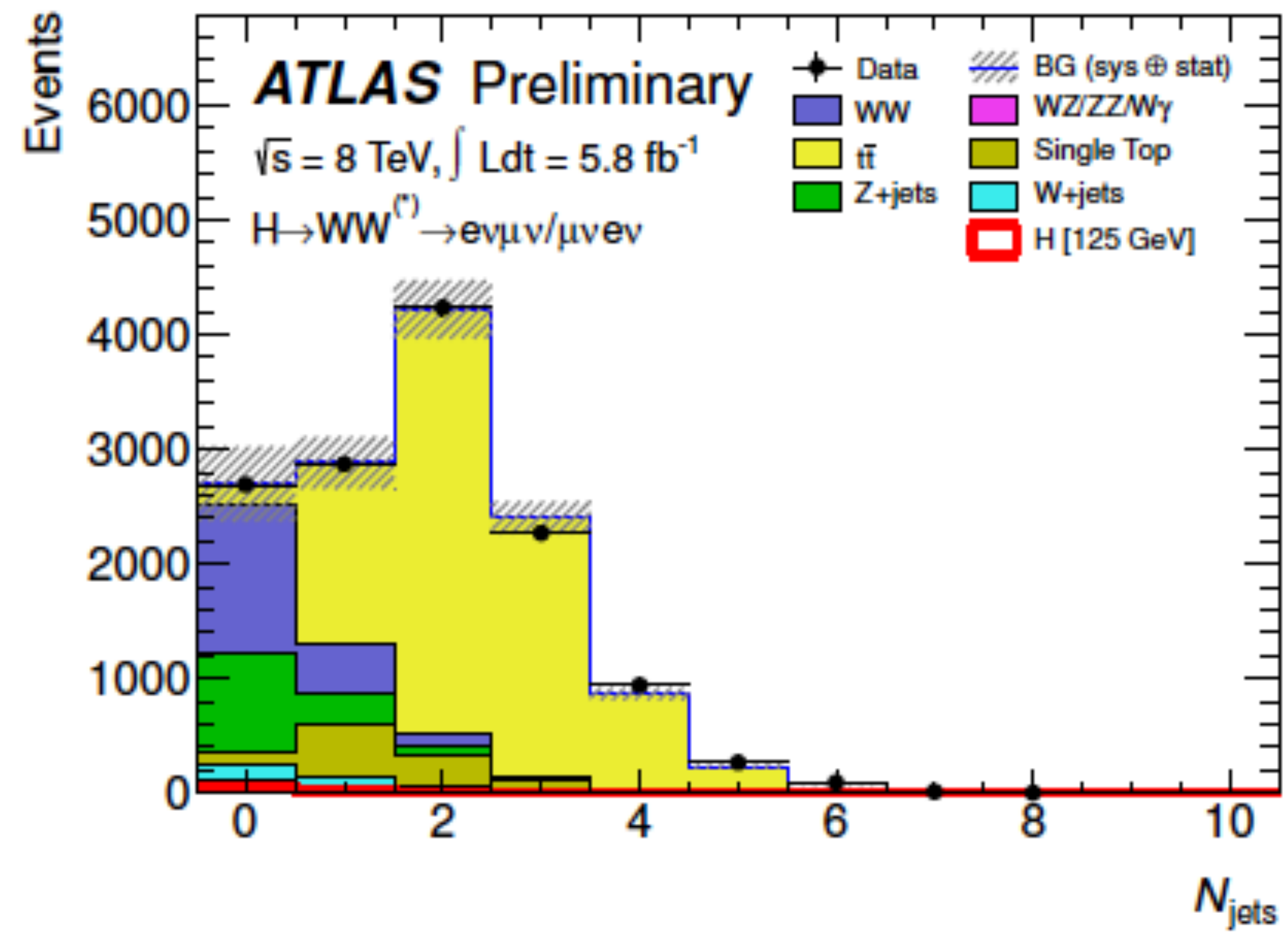
$E^{miss}_{T,rel} = E^{miss}_T \sin\Delta\varphi_{min} > 25$ GeV,
with $\Delta\varphi_{min} \equiv \min(\varphi, \pi/2)$.



Here, φ is the minimum azimuthal angle between E^{miss}_T and the leading lepton, the sub-leading lepton or any jet with $p_T > 25$ GeV. The use of this variable increases the rejection of events with significant mismeasurement of a jet or a lepton, since in such events the direction in φ of the E^{miss}_T is correlated with the direction of the mismeasured object.

Background





The background rate and composition depend significantly on the jet multiplicity, as does the signal topology. Without accompanying jets, the signal originates almost entirely from the ggF process and the background is dominated by WW and Drell-Yan events. In contrast, when produced in association with two or more jets, the signal contains a much larger contribution from the VBF process and the background is dominated by the tt production. To maximise the sensitivity, further selection criteria that depend on the jet multiplicity are applied to the pre-selected sample. The difference between the leptons, $\Delta\varphi_{\ell\ell}$, be less than 1.8 radians, and that the dilepton invariant mass, $m_{\ell\ell}$, be less than 50 GeV.

Transverse Mass (Wikipedia) in

$$H \to W^+W^- \to l^+\upsilon l^-\overline{\upsilon}$$

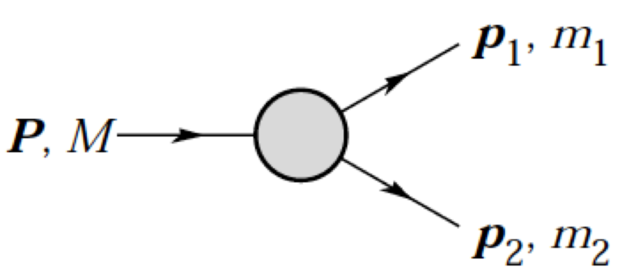
This is often used when one particle cannot be detected directly but is only indicated by missing transverse energy. In that case, the total energy is unknown and the above definition cannot be used.

$$M_T^2 = (E_{T,1} + E_{T,2})^2 - (\overrightarrow{p}_{T,1} + \overrightarrow{p}_{T,2})^2$$

where E_T is the transverse energy of each daughter, a positive quantity defined using its true invariant mass m as:

$$E_T^2 = m^2 + (\overrightarrow{p}_T)^2$$

So equivalently,



$$M_T^2 = m_1^2 + m_2^2 + 2\left(E_{T,1}E_{T,2} - \overrightarrow{p}_{T,1} \cdot \overrightarrow{p}_{T,2}\right)$$

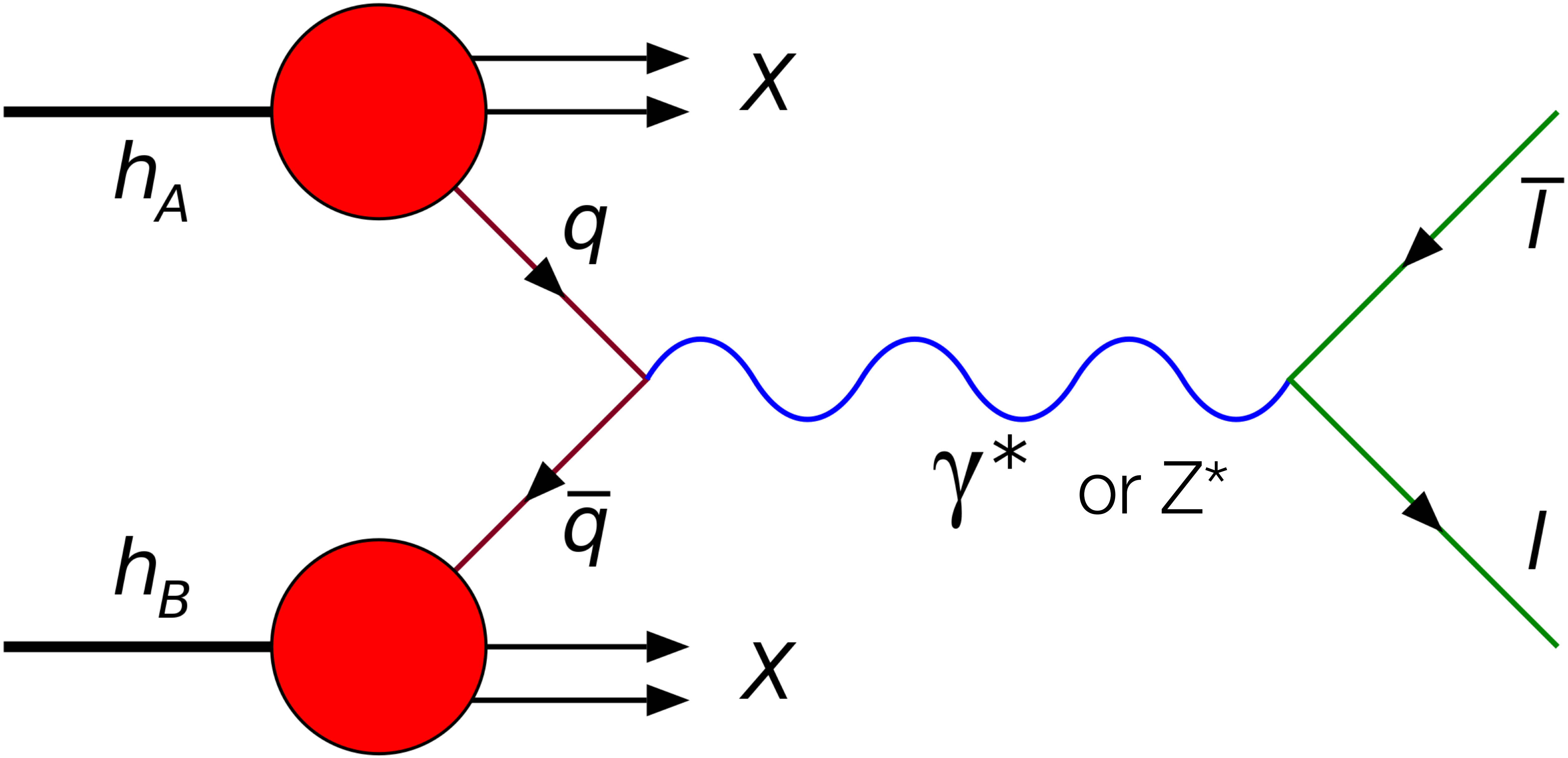
For massless daughters, where $m_1 = m_2 = 0$, the transverse energy simplifies to $E_T = |\overrightarrow{p}_T|$, and the transverse mass becomes

$$M_T^2 \to 2E_{T,1}E_{T,2}\,(1 - \cos\phi)$$

where ϕ is the angle between the daughters in the transverse plane:

A distribution of M_T has an end-point at the true mother mass: $M_T \leq M$. This has been used to determine the W mass at the Tevatron.

Drell-Yan

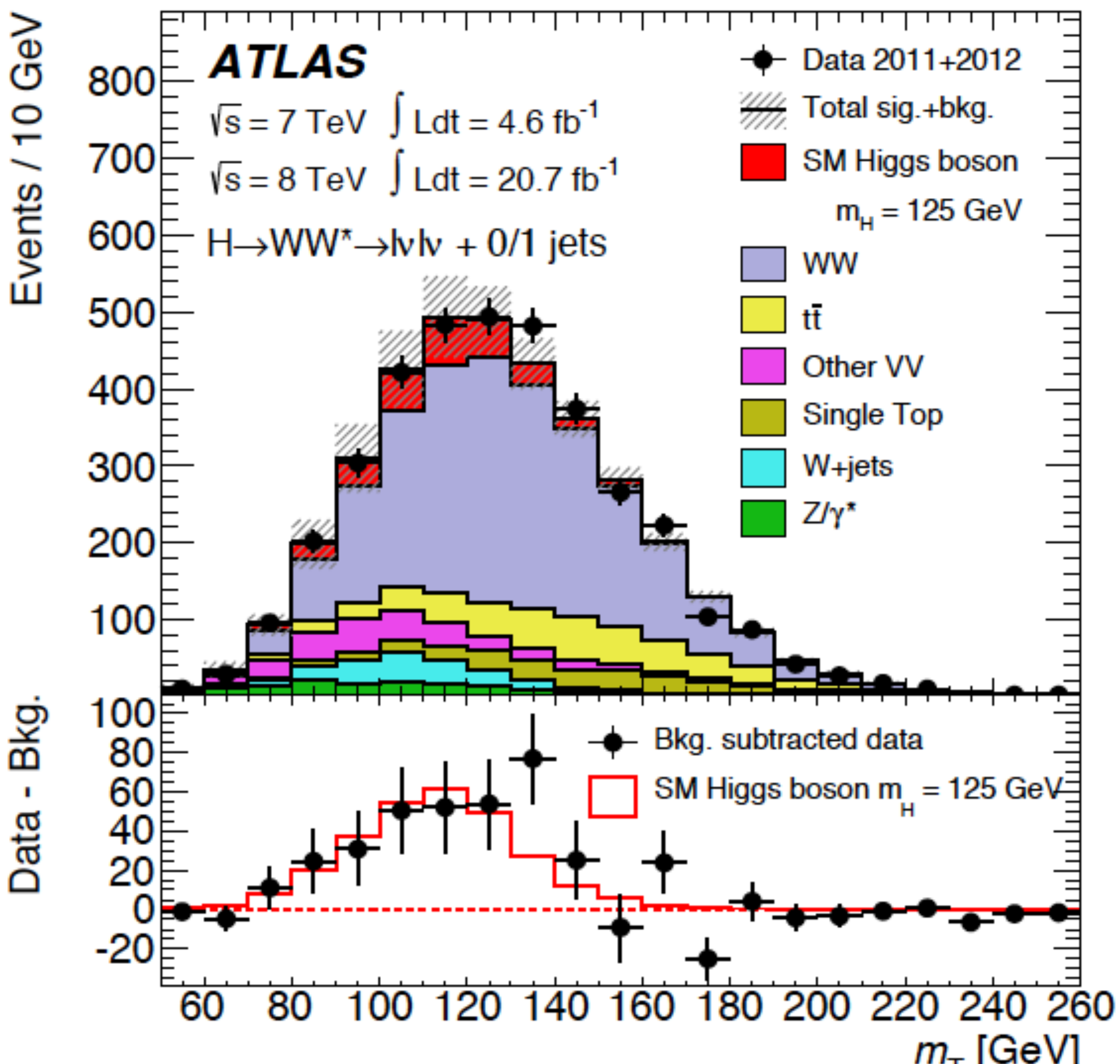


ATLAS:

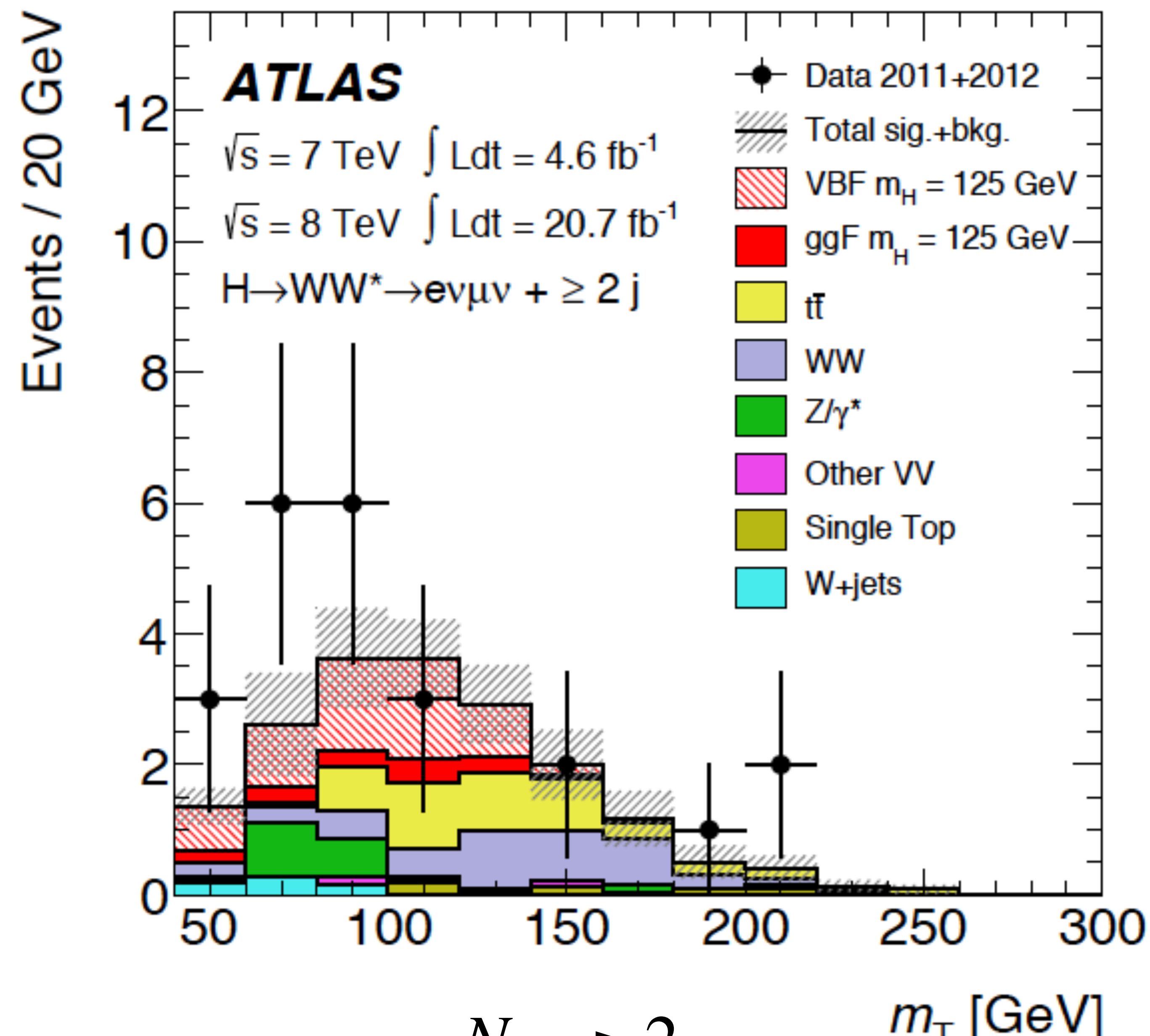
$$H \to W^+W^- \to l^+\upsilon l^-\overline{\upsilon}$$

$$m_T = \sqrt{2 p_T^{\ell\ell} E_T^{\mathrm{miss}} (1 - \cos \Delta\phi_{E_T^{\mathrm{miss}}\ell\ell})}$$

Undetected υ's ➡ M_T



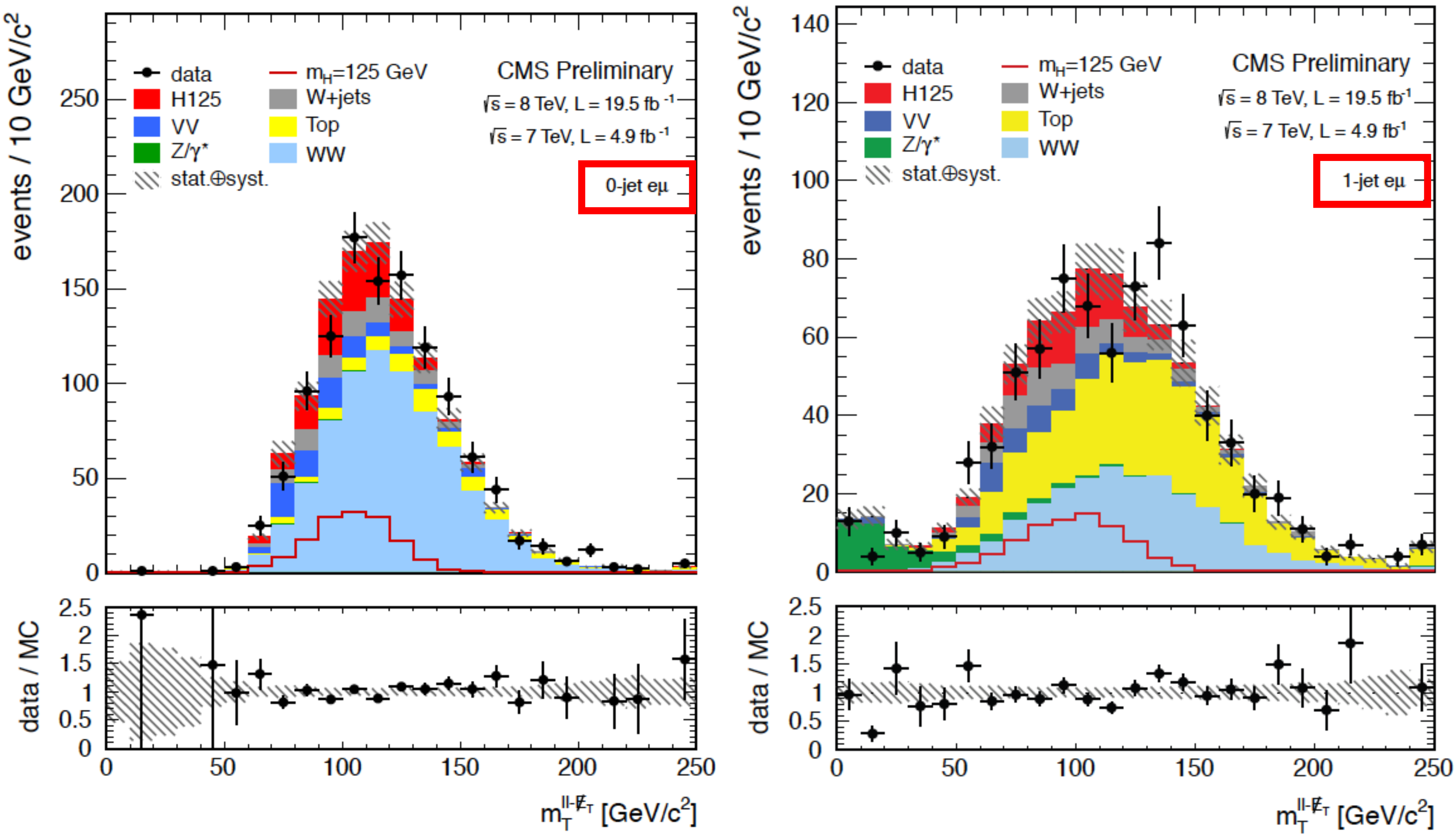
$N_{jets} \leq 1$



$N_{jets} \geq 2$

CMS :

$$H \rightarrow W^+W^- \rightarrow l^+\upsilon l^-\overline{\upsilon}$$



ATLAS & CMS combination of Run 1 data

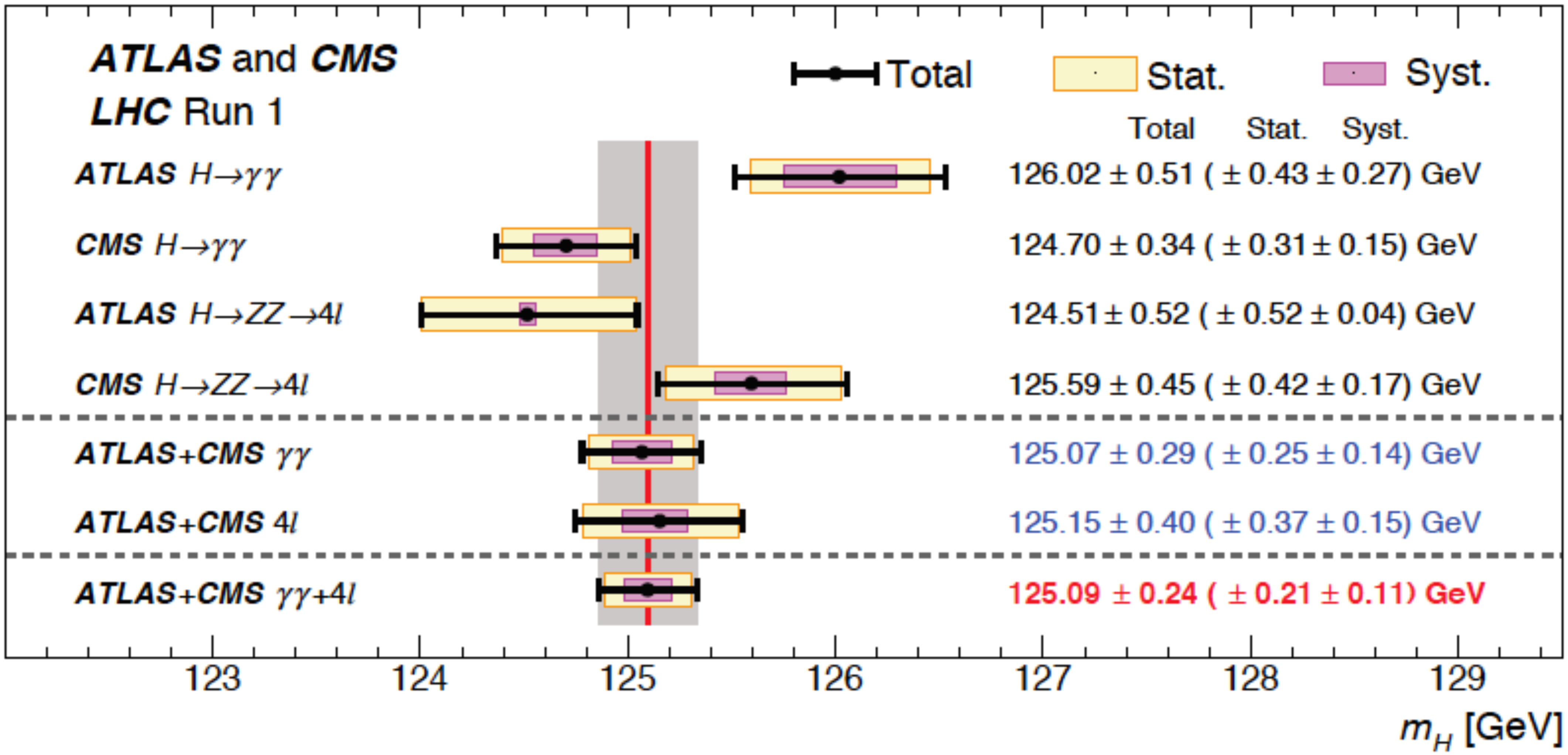
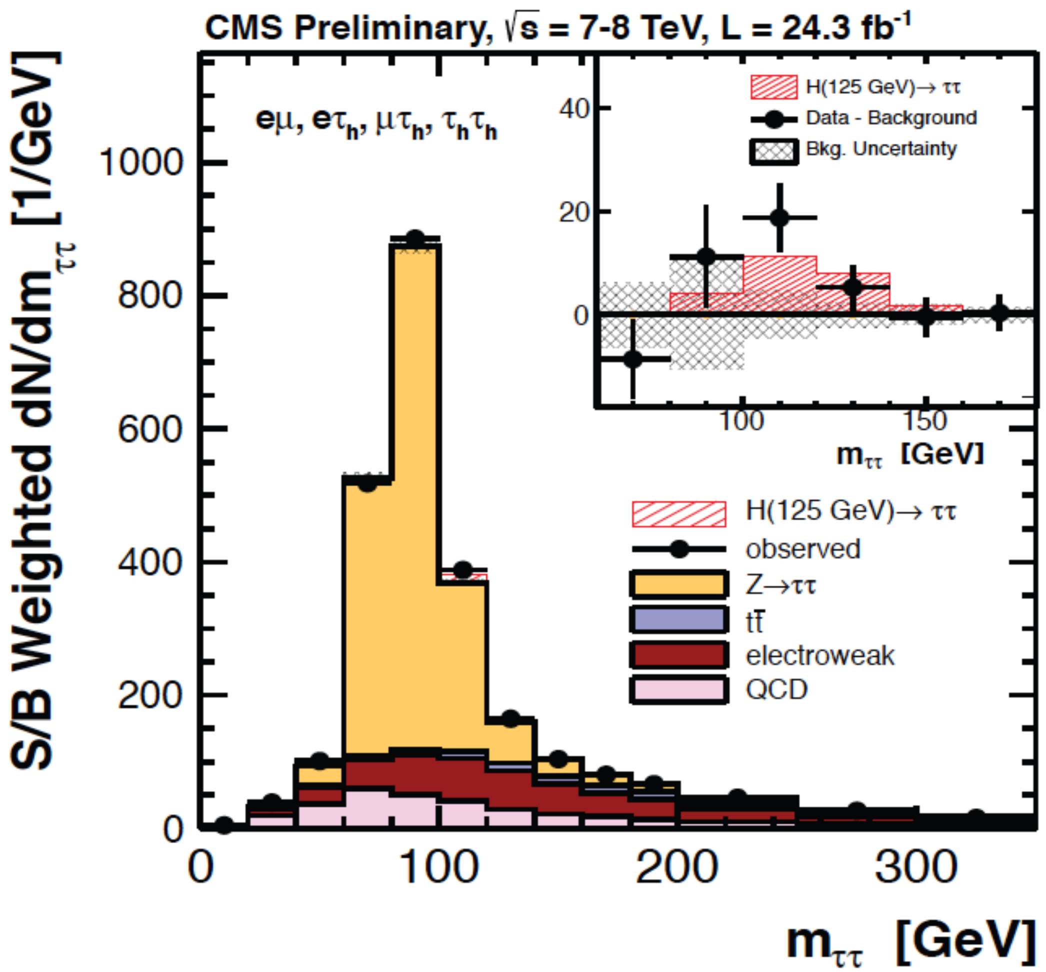


Figure 11.4: A compilation of the CMS and ATLAS mass measurements in the $\gamma\gamma$ and ZZ channels, the combined result from each experiment and their combination. From Ref. [134]

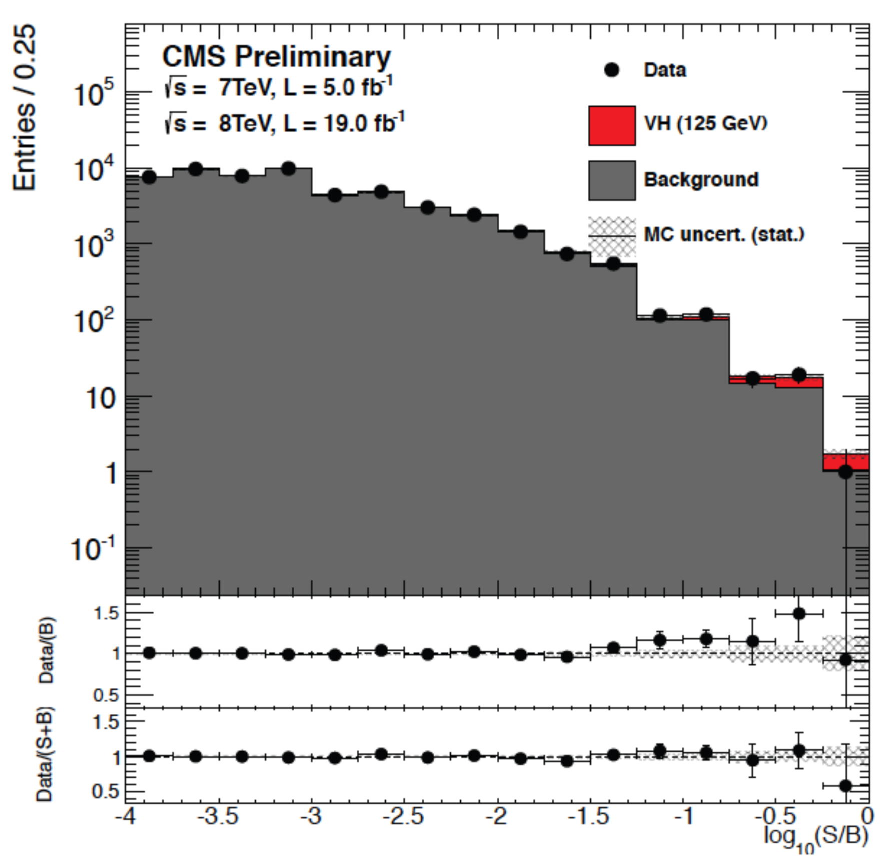
Higgs decays to fermions: ττ

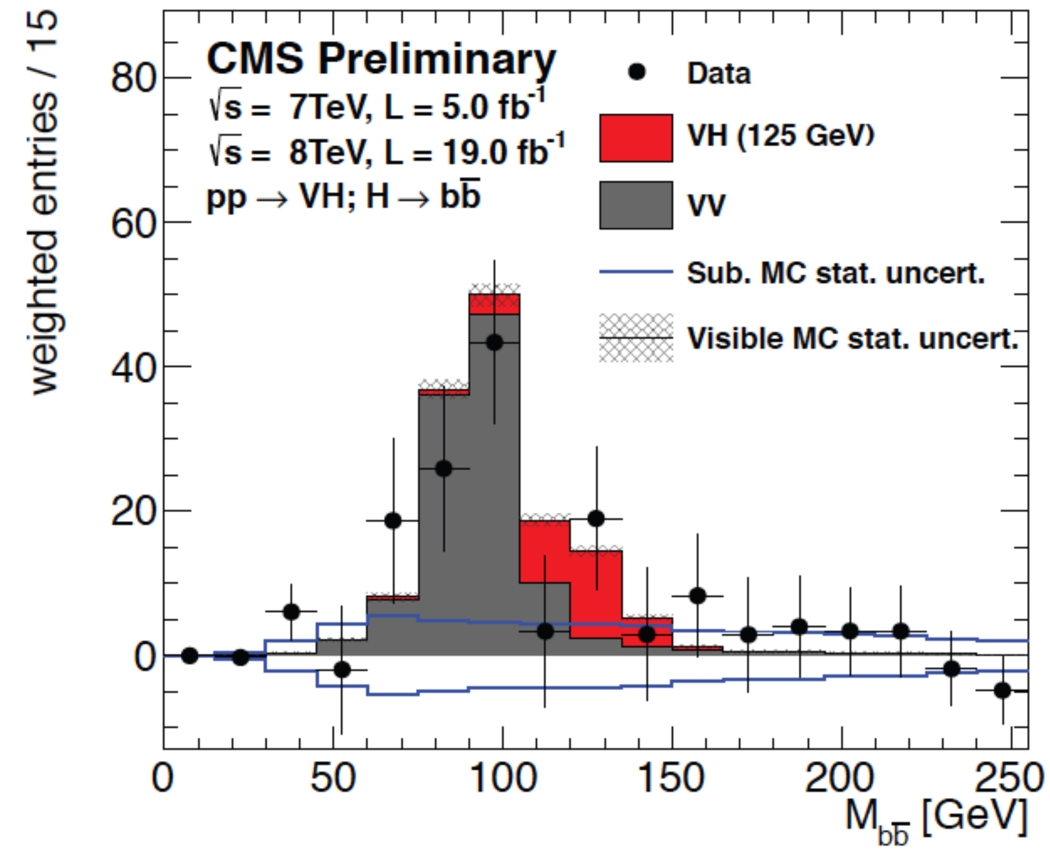


In the H → τ τ search, τ leptons decaying to electrons (τ_e), muons (τ_μ) and hadrons (τ_{had}) are considered. The $\tau^+\tau^-$ invariant mass ($m_{\tau\tau}$) is reconstructed from a kinematic fit of the visible products from the two τ leptons and the missing energy observed in the event. Due to the presence of missing neutrinos, the $m_{\tau+\tau-}$ resolution is poor (≈ 15%). As a result, a broad excess over the expected background in the $m_{\tau\tau}$ distribution is searched for. The major sources of background stem from Drell–Yan Z → τ+τ− and Z → e+e−, W+jets, tt and multijet production.

For the CMS, the significance of the observed excess at mH = 125GeV in Run 1 is 3.2 standard deviations, and corresponds to a signal strength of μ = 0.86±0.29. The observed deviation from the background-only hypothesis in ATLAS corresponds to a local significance of standard deviations and the best fit value of the signal strength is μ = 1.43+0.43−0.37. When the ATLAS and CMS H → τ τ Run 1 measurements are combined , the significance of the observed excess corresponding to mH = 125.09 GeV is 5.5 standard deviations and the combined signal strength is μ = 1.11+0.24 −0.22, consistent with the Standard Model expectation.

Higgs decays to fermions : bb





In the search for the decay of the Higgs boson to a pair of b-quarks the most sensitive production modes are the associated WH and ZH processes allowing use of the leptonic W and Z decays for triggering, and to purify the signal and reject QCD backgrounds. The W bosons are reconstructed via their leptonic decay $W \to \ell\bar{\nu}_\ell$ where $\ell = e, \mu$ or τ. The Z bosons are reconstructed via their decay into $e^+e^-, \mu^+\mu^-$ or $\nu\bar{\nu}$. The Higgs boson candidate mass is reconstructed from two b-tagged jets in the event. Backgrounds arise from production of W and Z bosons in association with gluon, light and heavy-flavored jets (V+jets), $t\bar{t}$, diboson (ZZ and WZ with $Z \to b\bar{b}$) and QCD multijet processes. Due to the limited $m_{b\bar{b}}$ mass resolution, a SM Higgs boson signal is expected to appear as a broad enhancement in the reconstructed dijet mass distribution. The crucial elements in this search are b-jet tagging with high efficiency and low fake rate, accurate estimate of b-jet momentum and estimate of backgrounds from various signal depleted control samples constructed from data.

Higgs to bb: results

$H \to b\bar{b}$	Tevatron	ATLAS Run 1	CMS Run 1	ATLAS Run 2	CMS Run 2
VH	1.6 ± 0.7	$0.52 \pm 0.32 \pm 0.24$	1.0 ± 0.5	$1.20 \pm 0.24 \pm 0.28$	1.2 ± 0.4
VBF	—	-0.8 ± 2.3	$2.8 \pm 1.4 \pm 0.8$	-3.9 ± 2.8	-3.7 ± 2.7
ttH	—	$1.4 \pm 0.6 \pm 0.8$	0.7 ± 1.9	$2.1 \pm 0.5 \pm 0.9$	$1.19 \pm 0.5 \pm 0.7$
Inclusive	—	—	—	—	2.3 ± 1.7
PDG Comb.	1.6 ± 0.7	0.6 ± 0.4	1.1 ± 0.5	1.2 ± 0.3	1.2 ± 0.4

Table 11.5: Summary of the results of searches for a Higgs boson decaying to a pair of b-quarks by the ATLAS and CMS collaborations. The results are given in terms of measured signal strength. Where available the uncertainty the total uncertainty is reported as the statistical and systematic contributions separately and in this order.