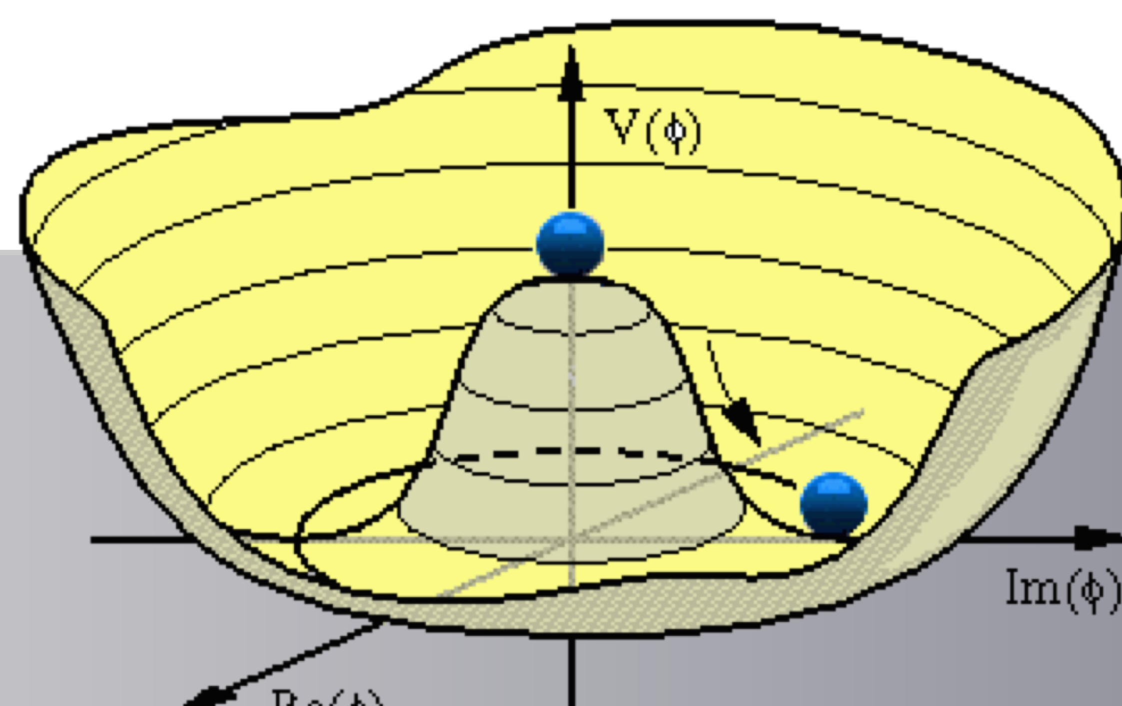
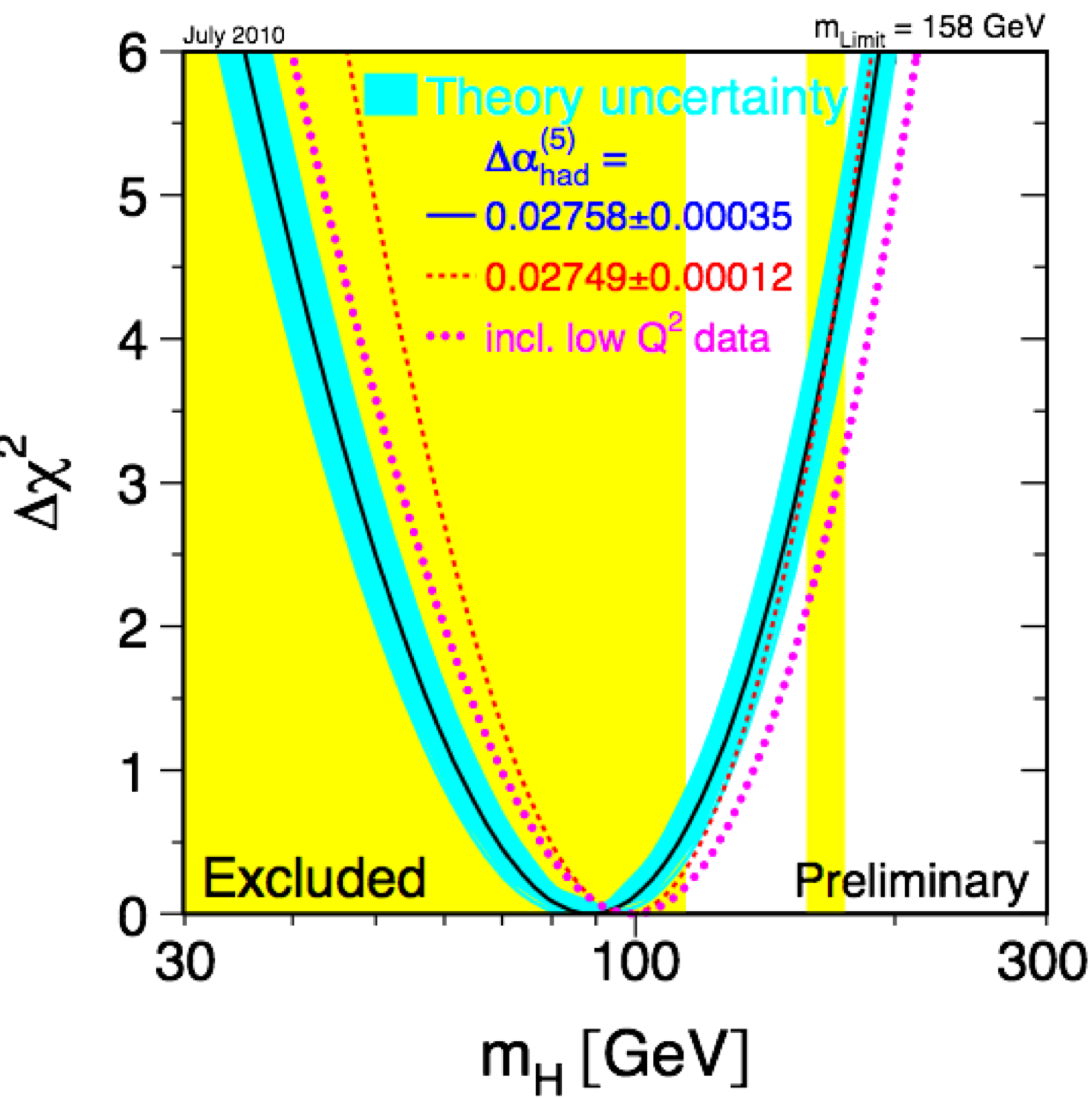
The Higgs

(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:

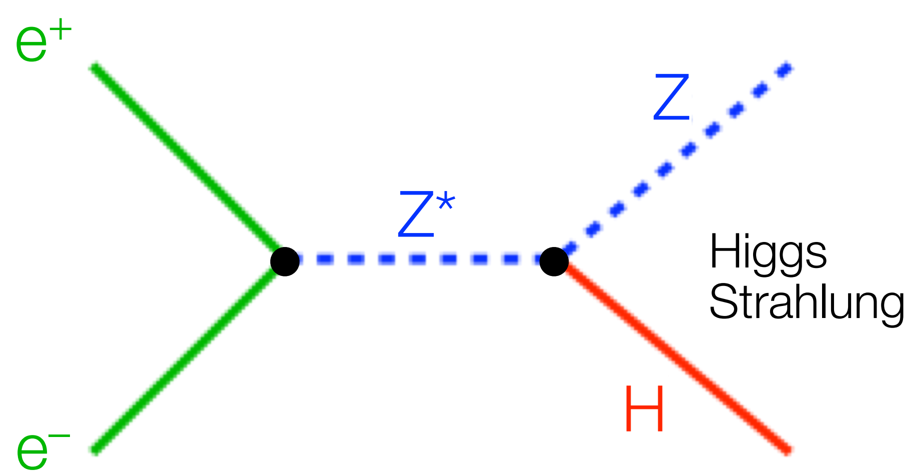
$158 < M_H < 175$ GeV @ 95% CL

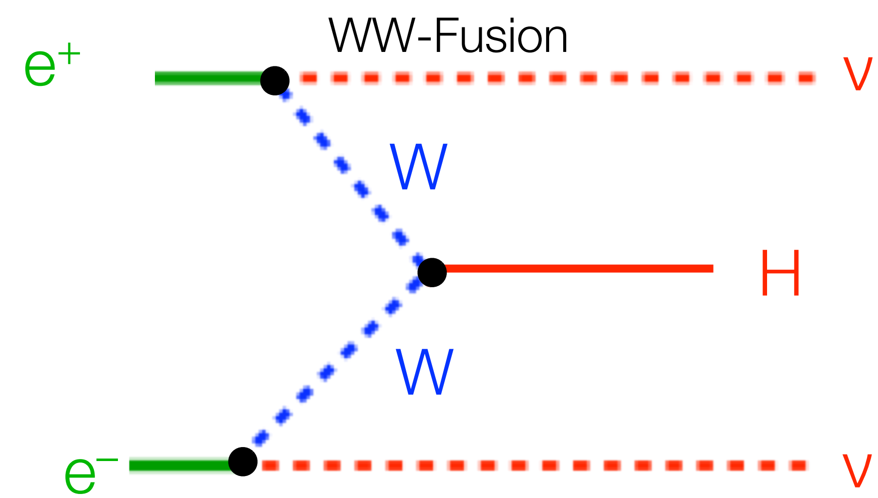
[Updated: Summer 2010]

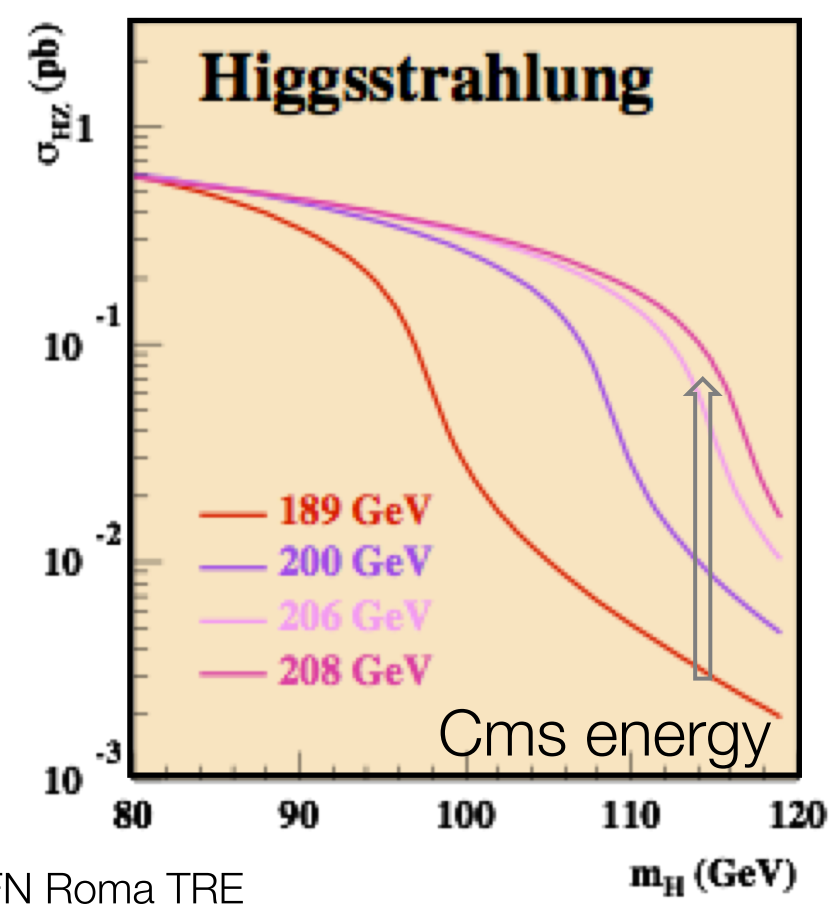
Higgs Search

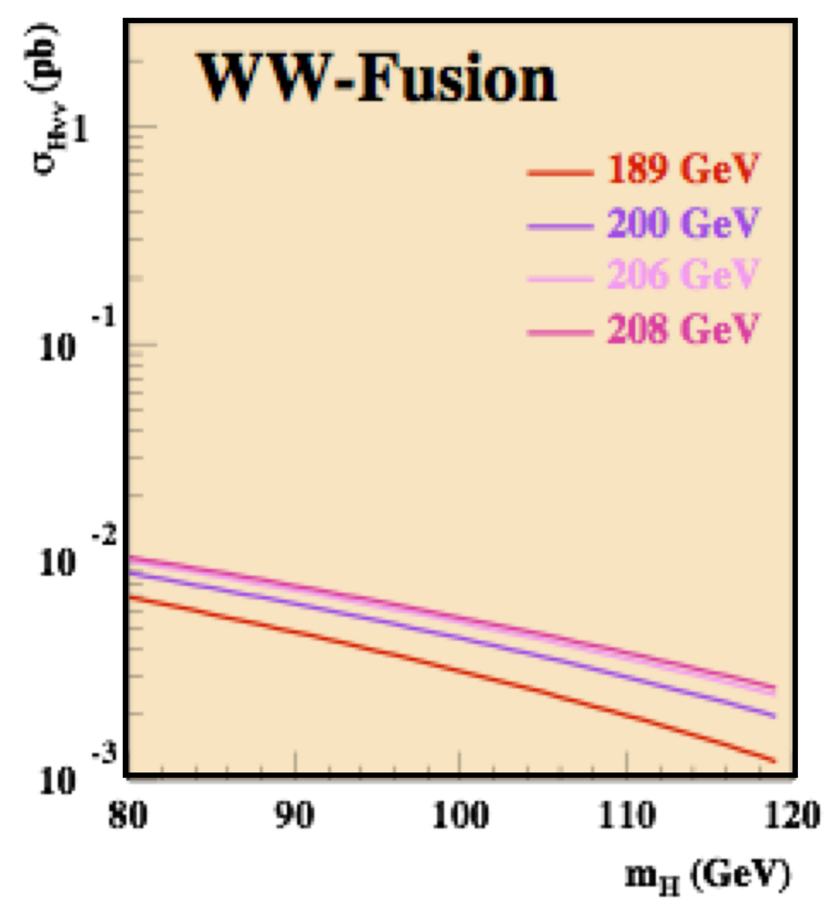
at LEP

SM Higgs Production at LEP

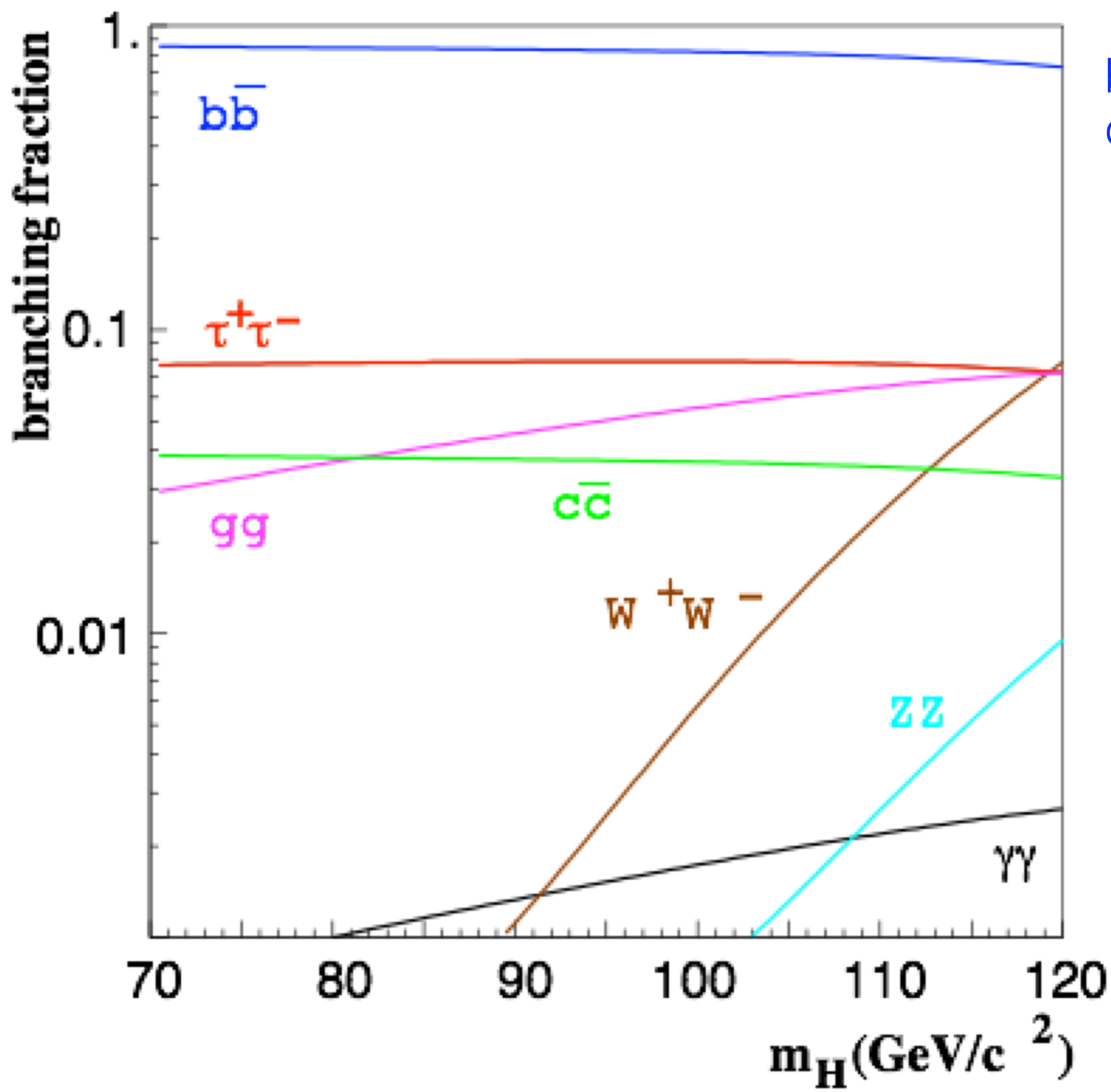








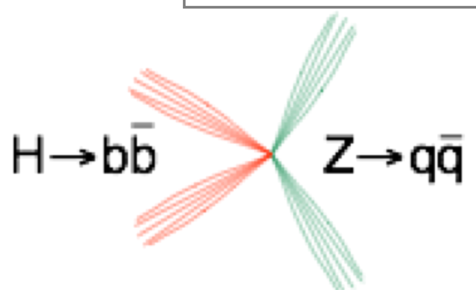
Higgs Decay at LEP Energies



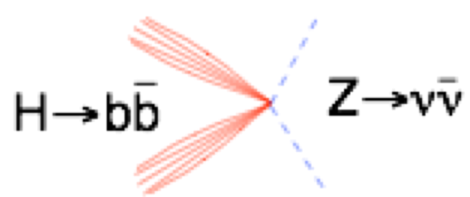
bb-decay dominant !!

LEP Higgs Signatures

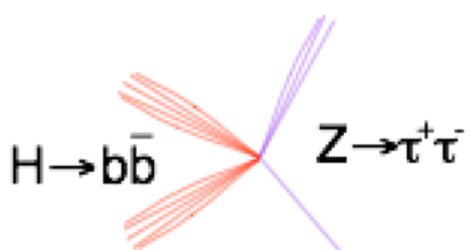
Clean events, no “pile-up”!!



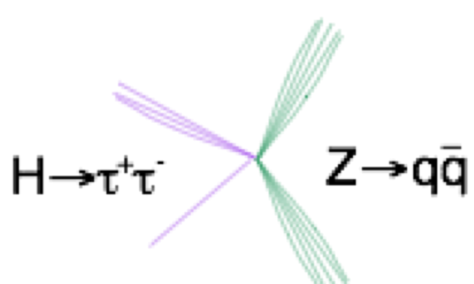
4-jets — 51%



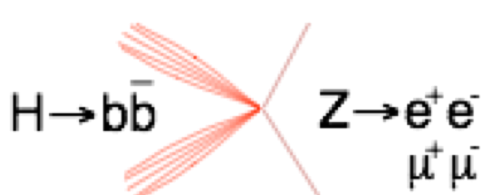
missing energy — 15%



τ-channel — 2.4%



τ-channel — 5.1%



lepton channel — 4.9%

Backgrounds

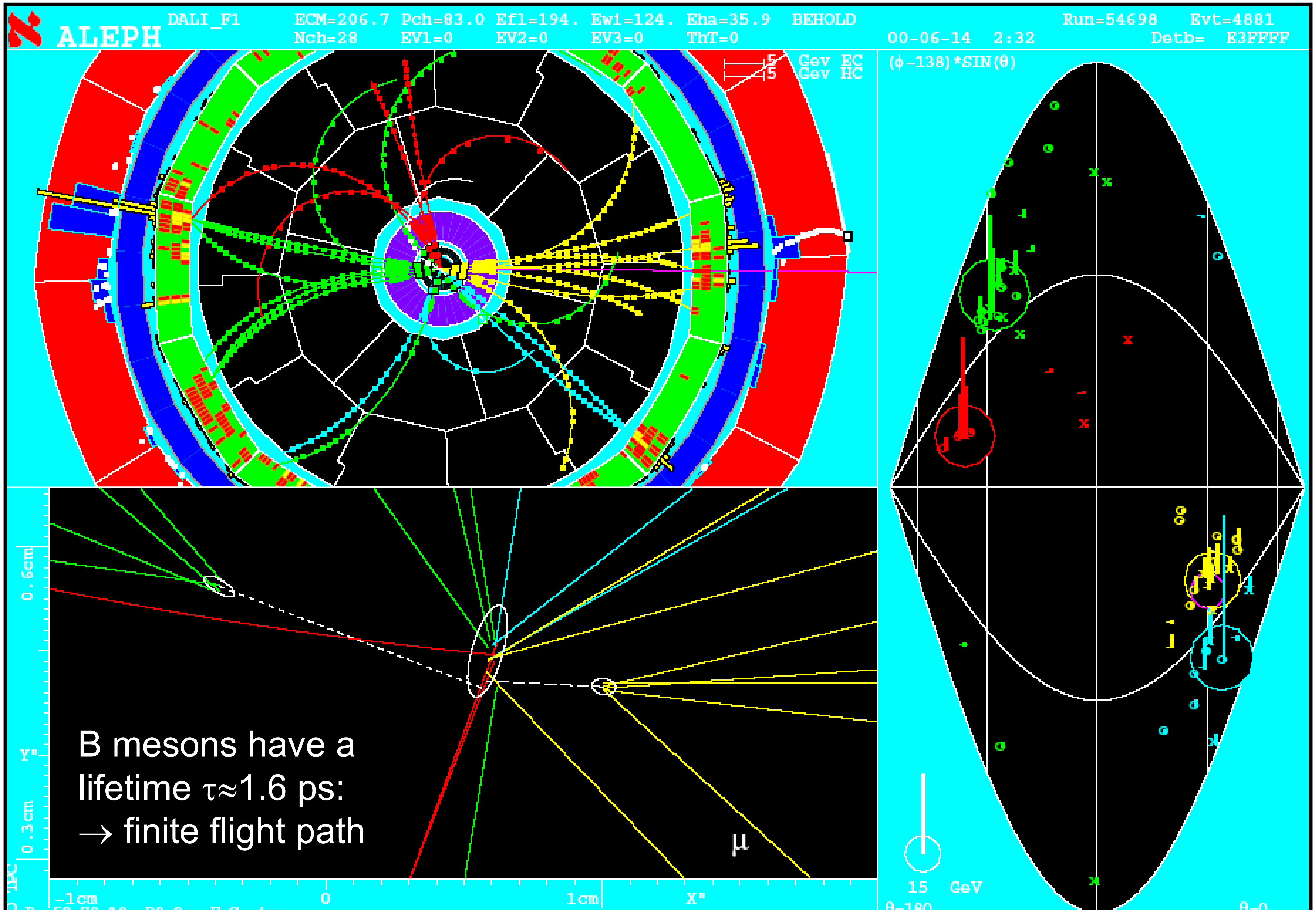
- WW ➛ qqqq
- ZZ ➛ qqqq
- QCD 4-jets

- WW ➛ qqlν
- ZZ ➛ bbνν

- WW ➛ qqτν
- 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

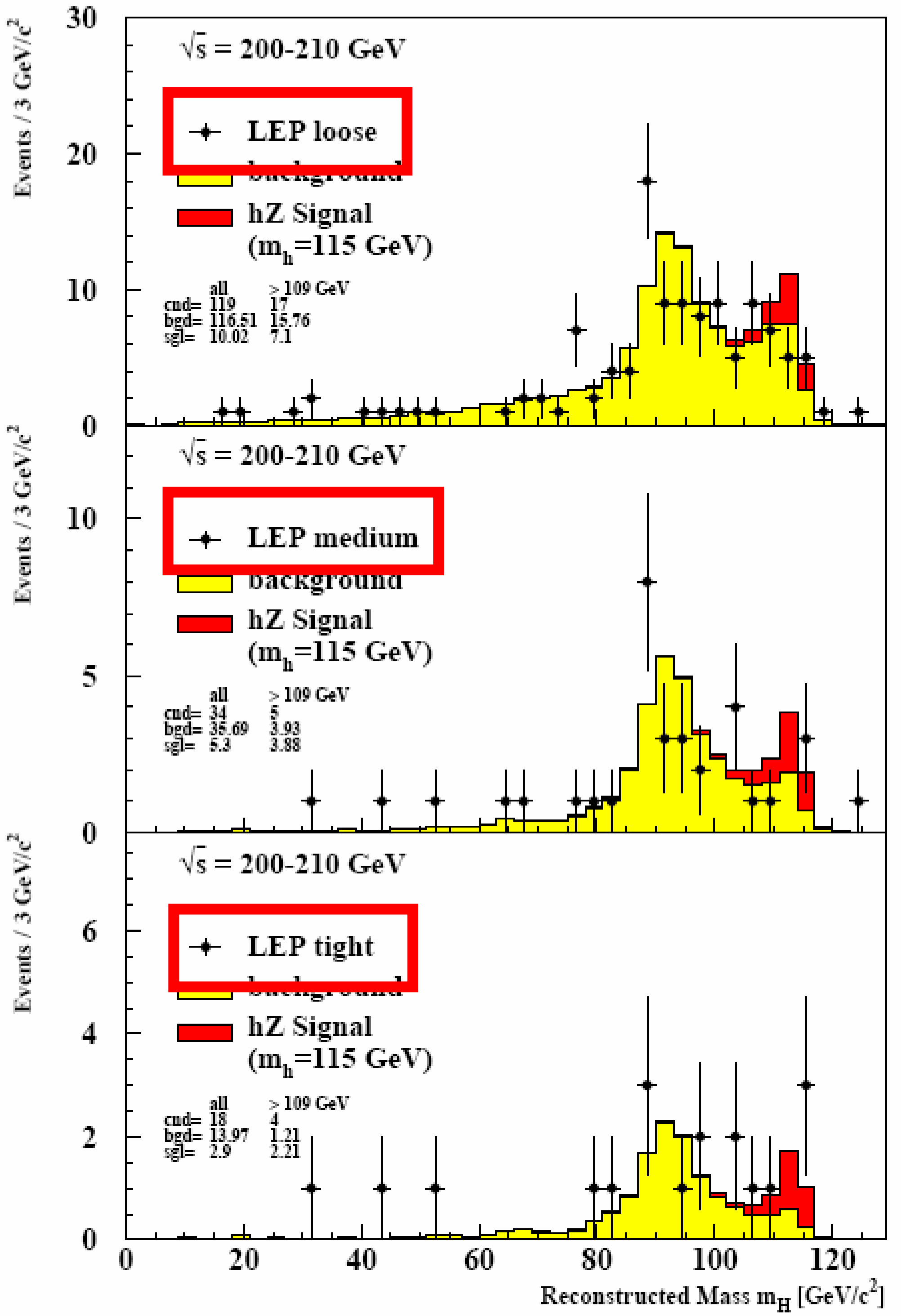
Expectation:
15.8 background events

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

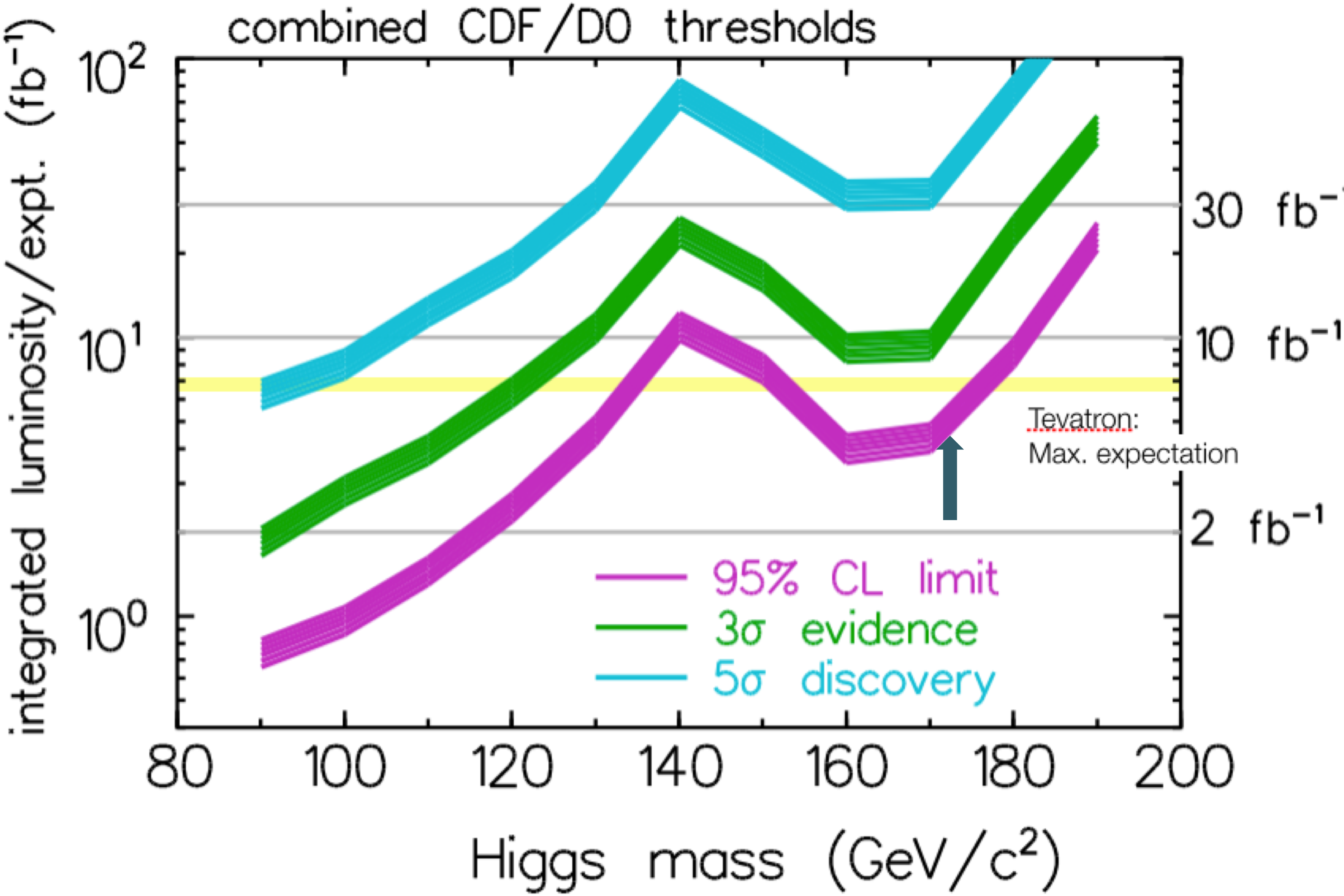
LEP Summary:

No signal above background

M_H > 114.4 GeV @ 95% CL

at Tevatron

Tevatron: Higgs Discovery Potential



Tevatron: Explored Channels

CDF

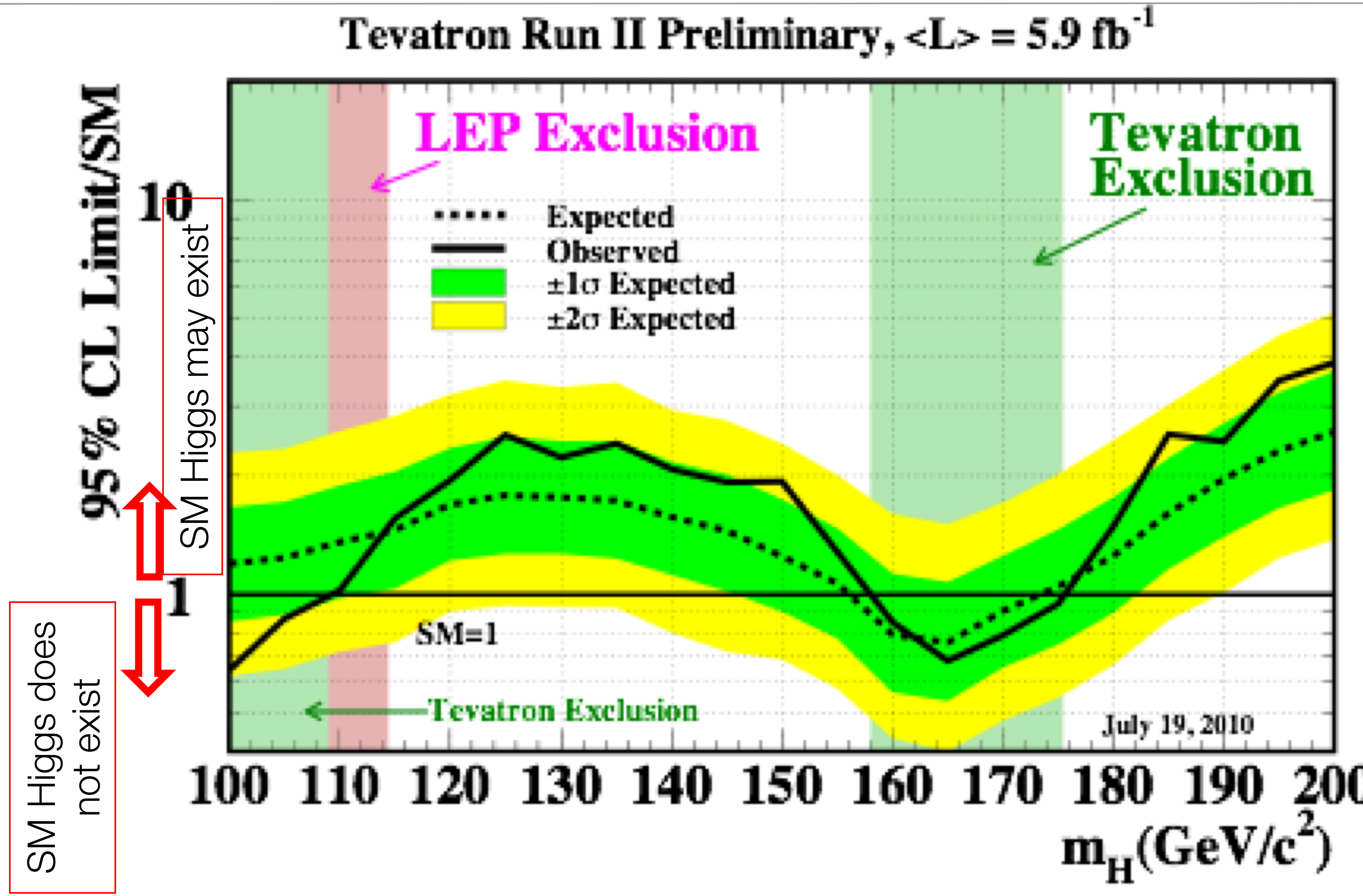
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ (ST,DT,2,3 jet)	5.3	100-150	[14]
$VH \to \tau^+\tau^- b\bar{b}/q\bar{q}\tau^+\tau^-$	4.9	105-145	[15, 16]
$ZH \to \nu\bar{\nu}b\bar{b}$ (ST,TLDT)	5.2-6.4	100-150	[17, 18]
$ZH \to \ell^+\ell^- b\bar{b}$ (ST,DT,ee,$\mu\mu$,ee_{ICR},$\mu\mu_{trk}$)	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)

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 ...

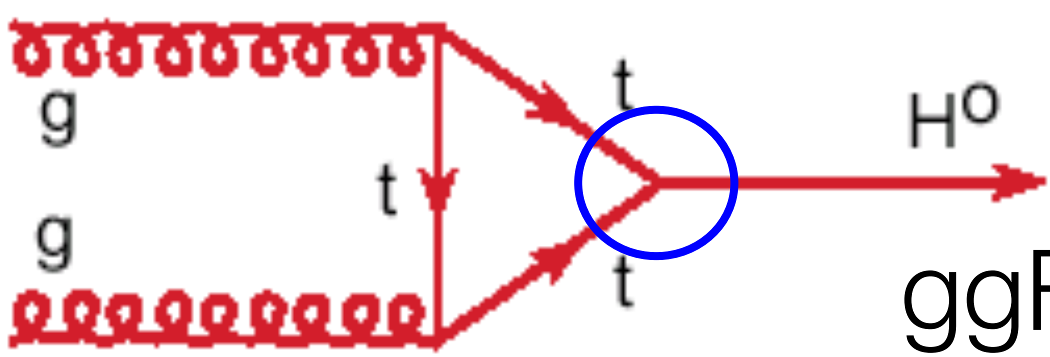
Higgs Search

at the LHC

Higgs Production Mechanisms

Gluon fusion

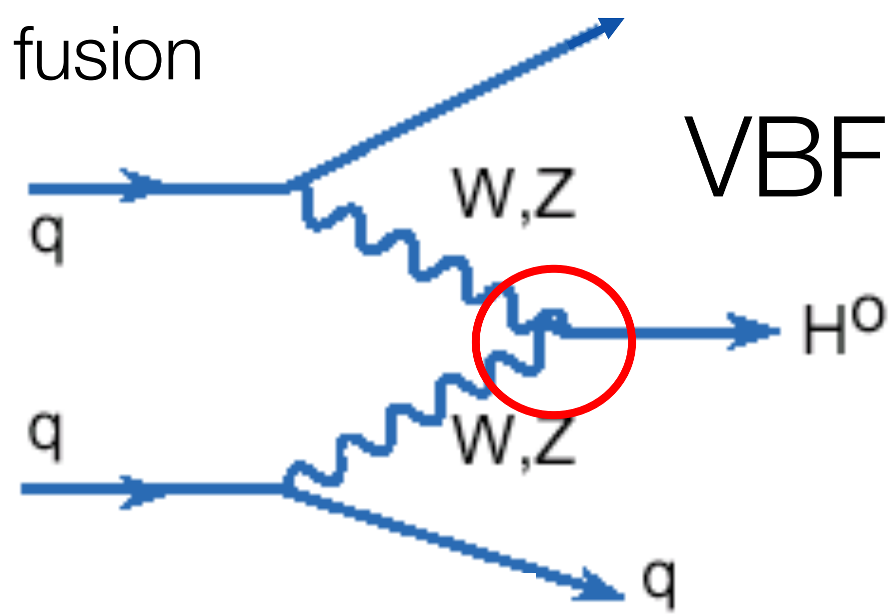
Other quarks contribution suppressed by m_q^2



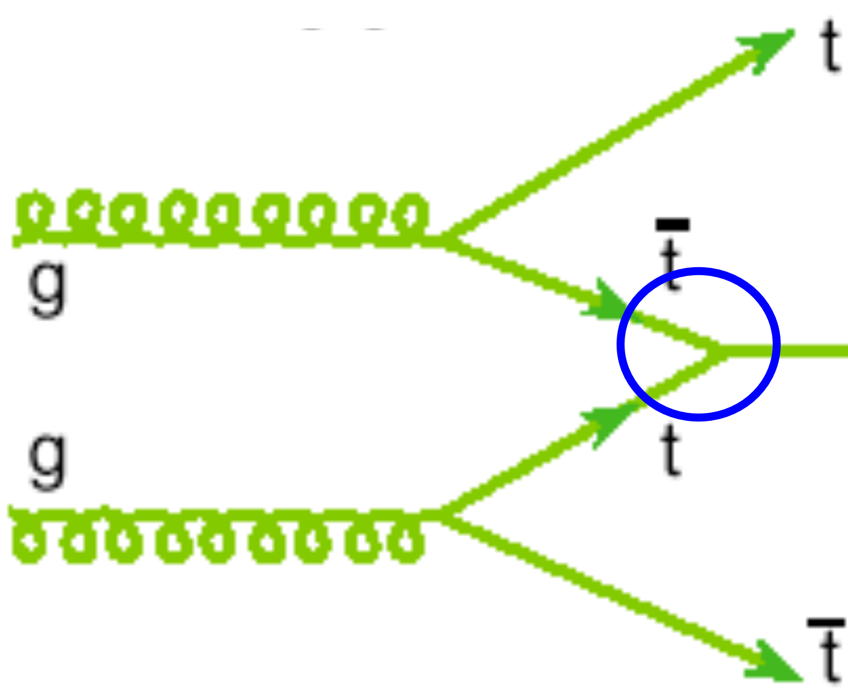
ggF

Vector boson fusion

VBF



ttH



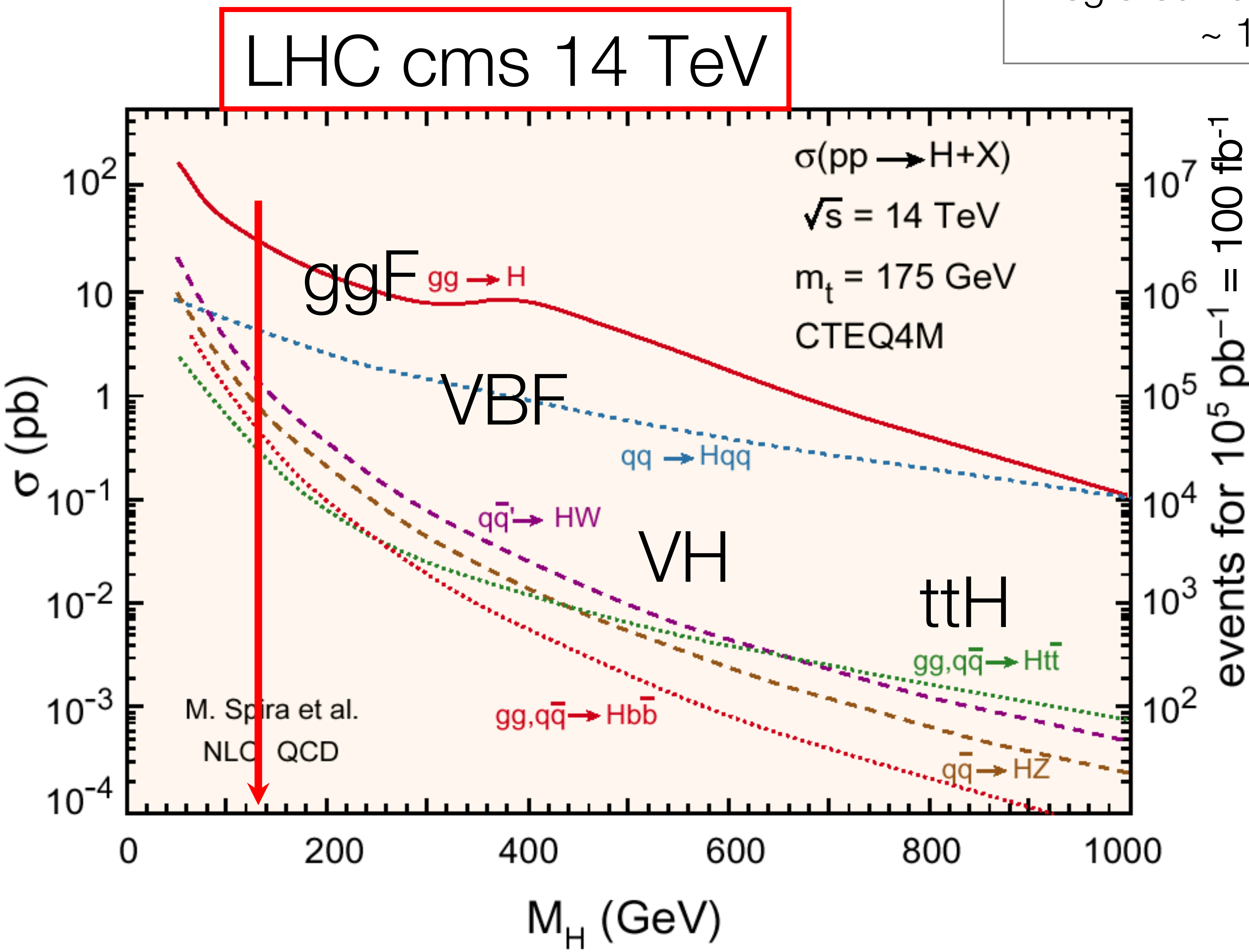
tt̄-fusion

VH

Associated production

Higgs Production Cross Sections

Integrated Luminosity in Run-2
~ 150 fb^{-1}

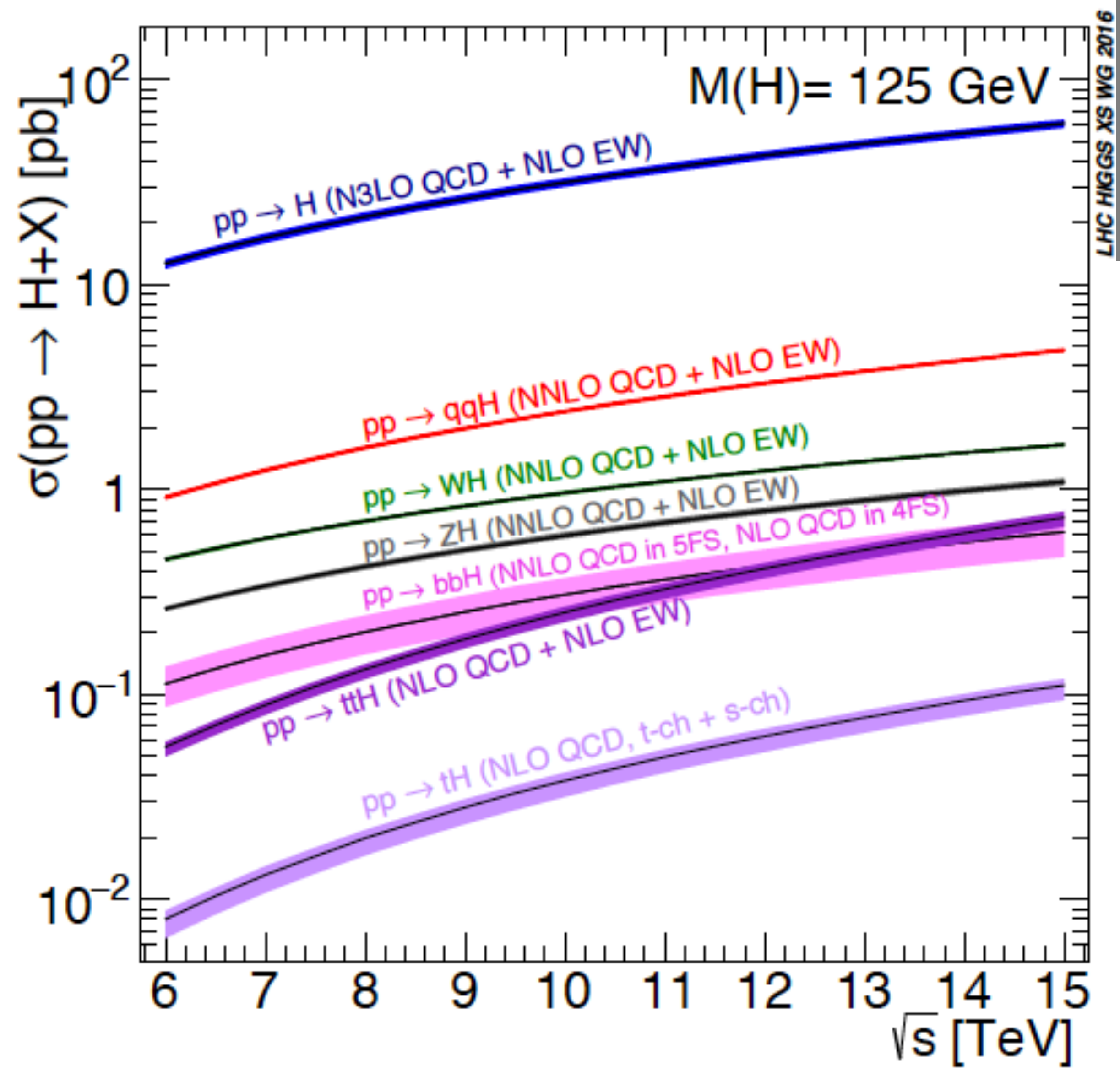


Multiples and sub-multiples[5][6]

Unit	Symbol	m^2	cm^2
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

Higgs Production

Higgs mass = 125 GeV

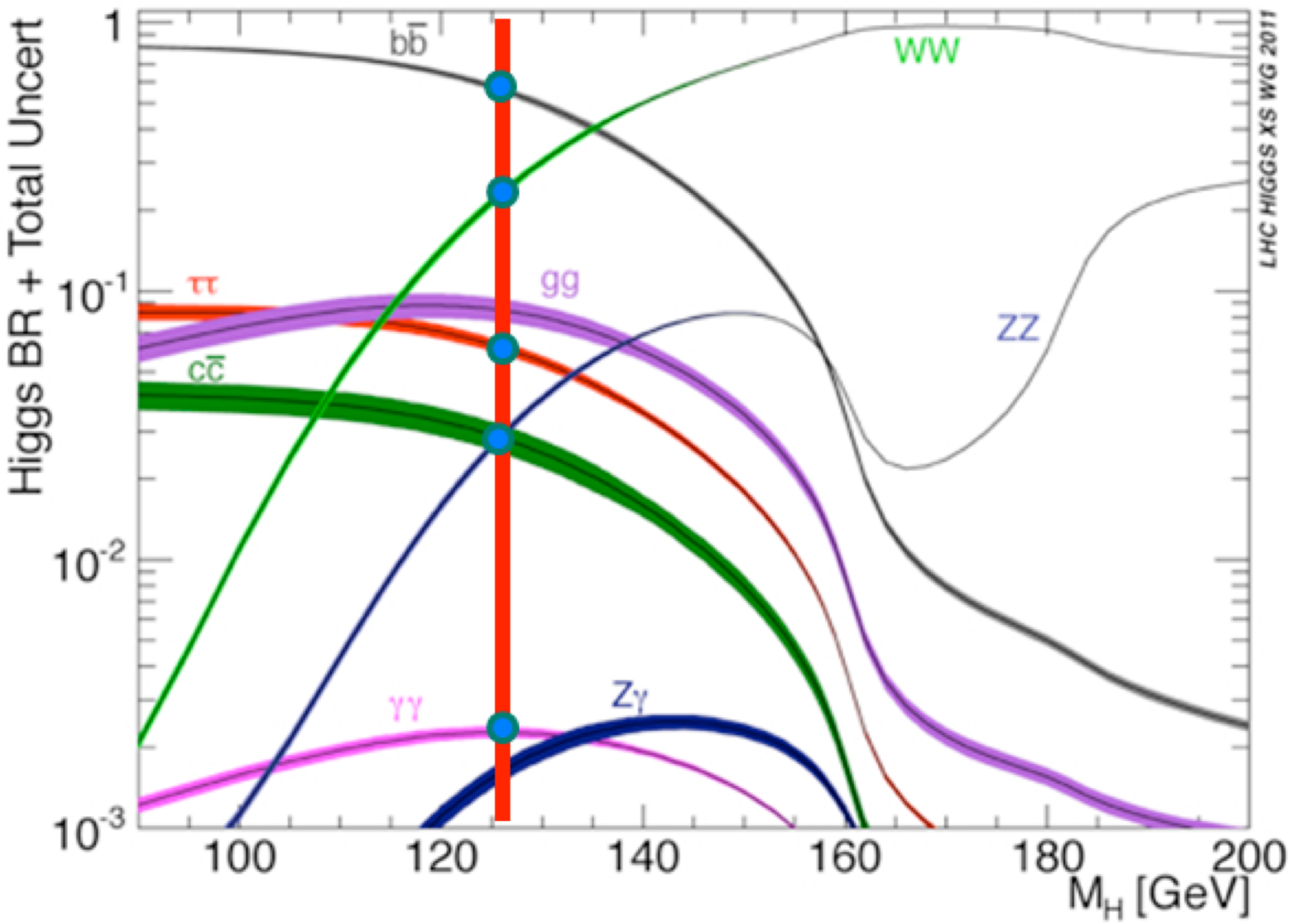


$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125$ GeV					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	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

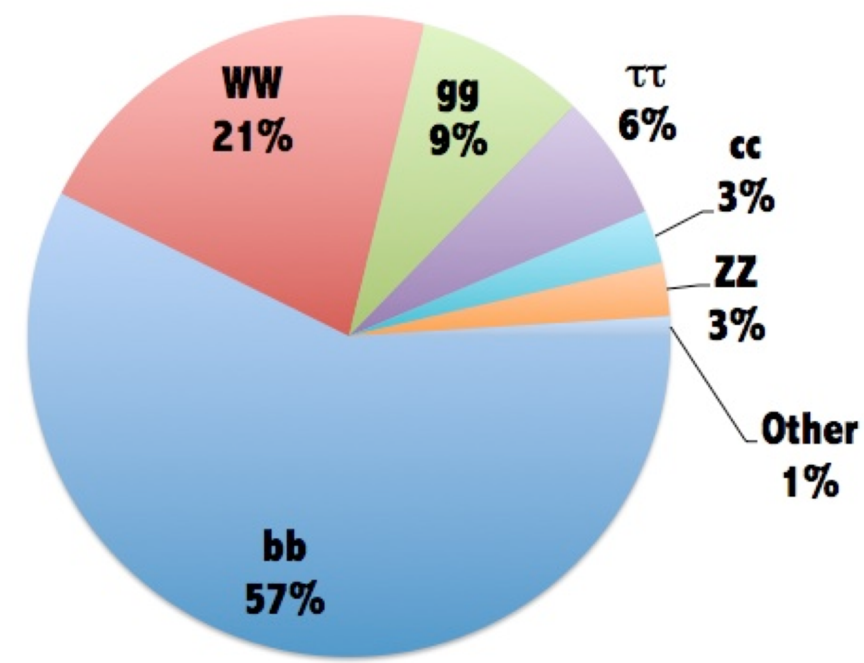
Run-1

Run-2

Higgs Boson Decays



Higgs decays at m_H=125GeV

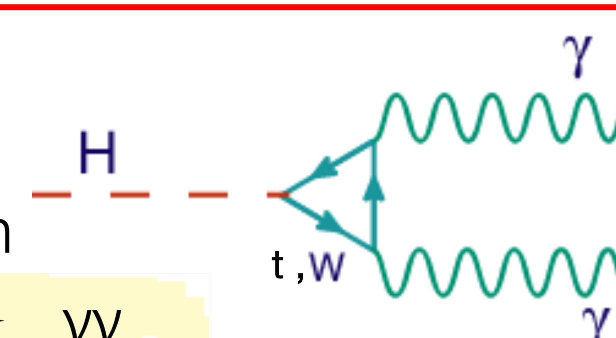


Discovery driven by significance of different channels

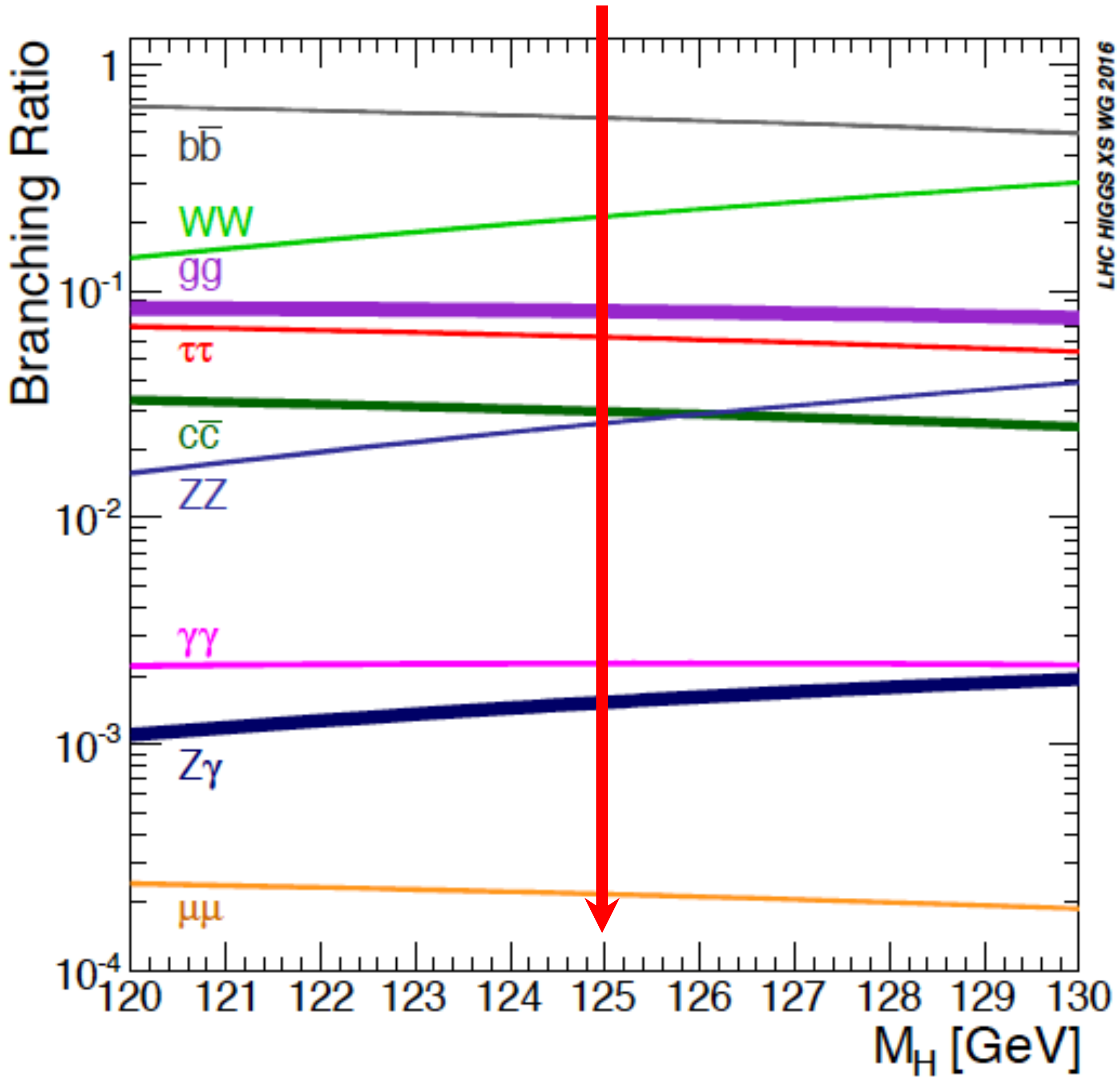
For M < 135 GeV: H ➝ bb, ττ dominant

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}	$^{+6.0\%}_{-5.9\%}$

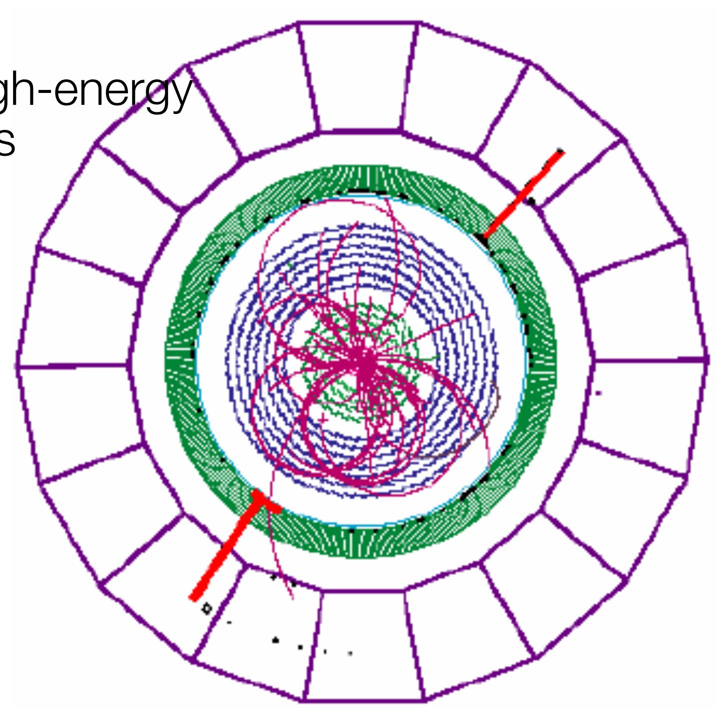
Direct Higgs Channels

Discovery potential driven by potential to distinguish signal from background

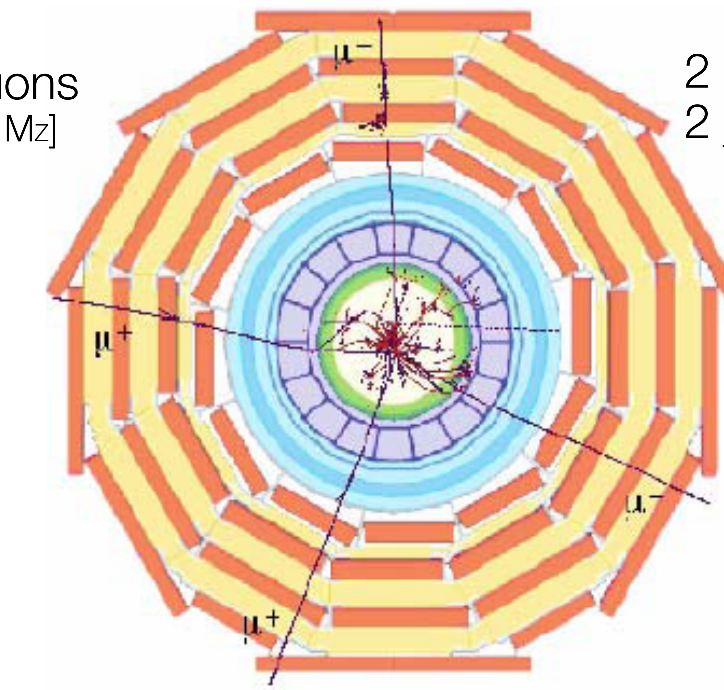
Channel	LHC Potential
$gg \to H \to bb$	Huge QCD background ($gg \to bb$); extremely difficult
$gg \to H \to \tau\tau$	Higgs with low p_T, hard to discriminate from background; problematic
$gg \to H \to \gamma\gamma$	Small rate, large combinatorial background, but excellent determination of m_H (CMS: 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

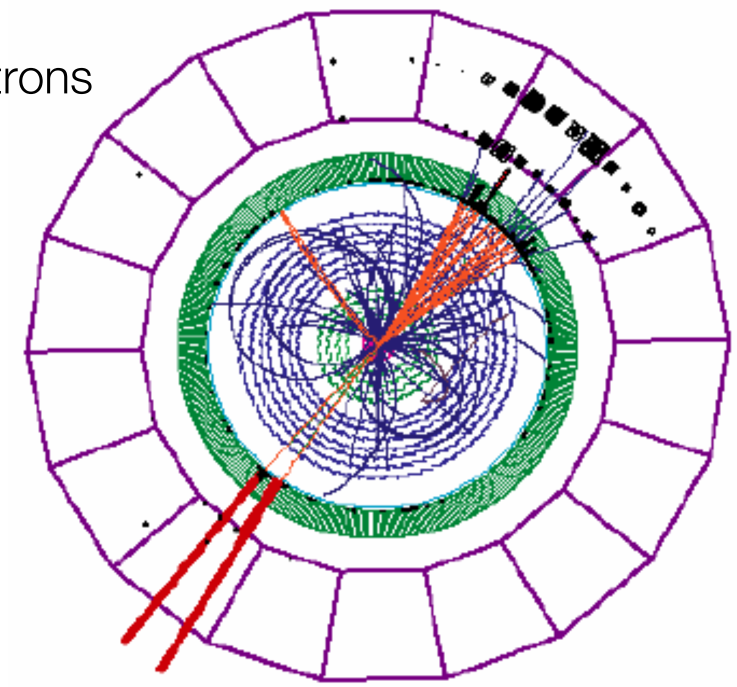
Two high-energy photons

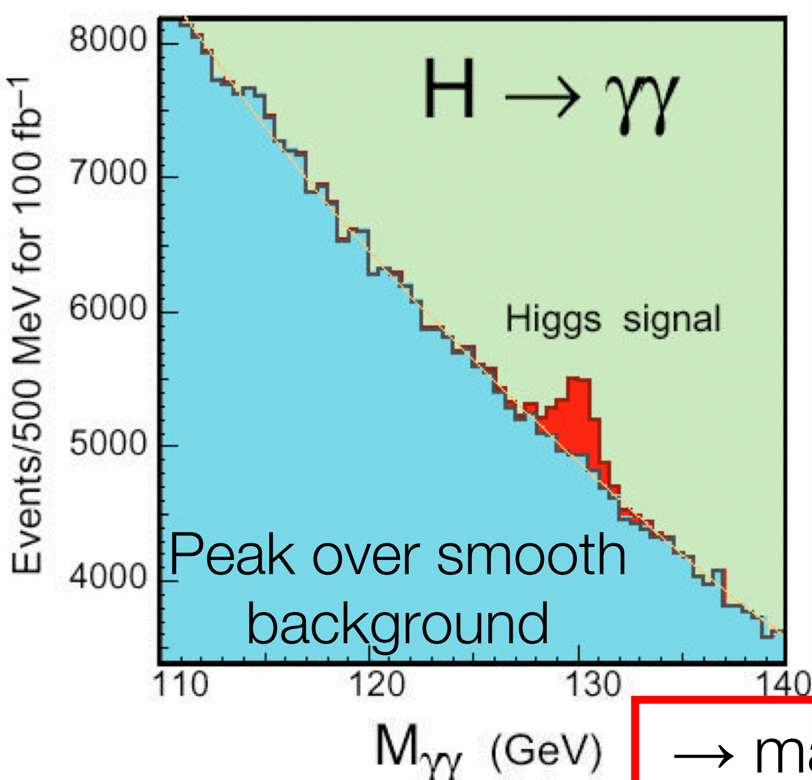


4 muons
[$M_{\mu\mu} = M_Z$]

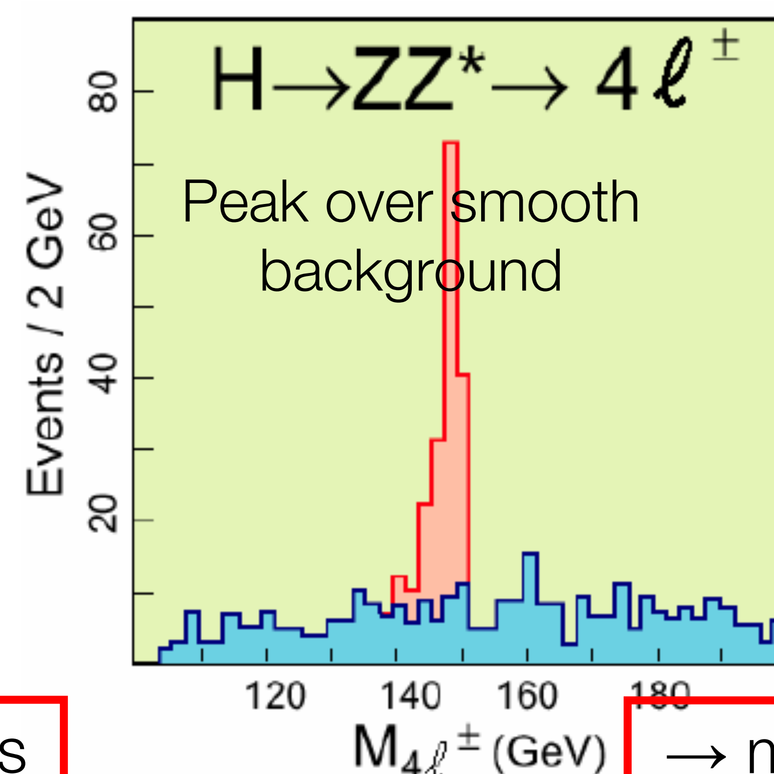


2 electrons
2 jets

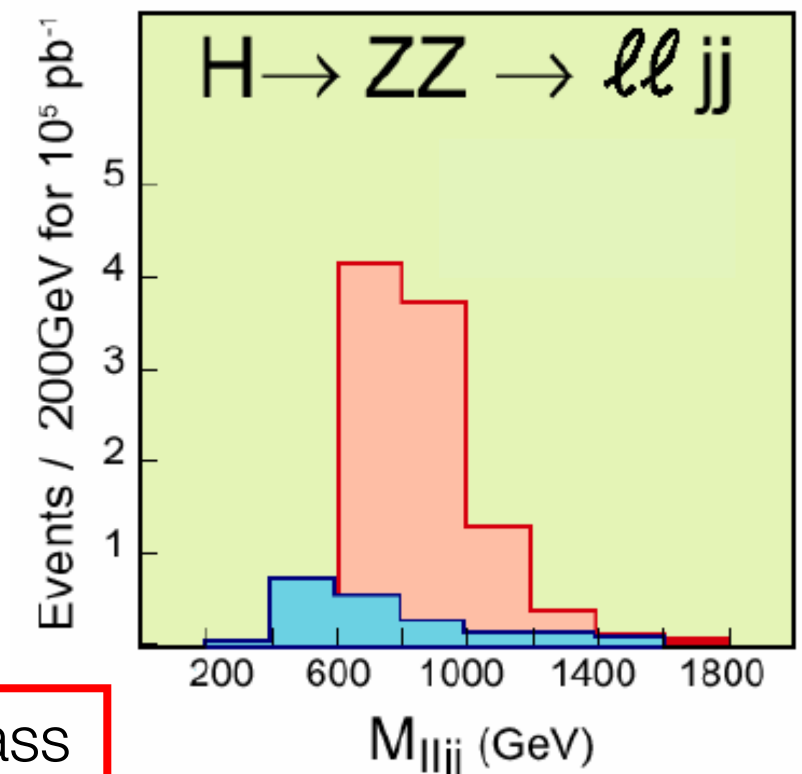




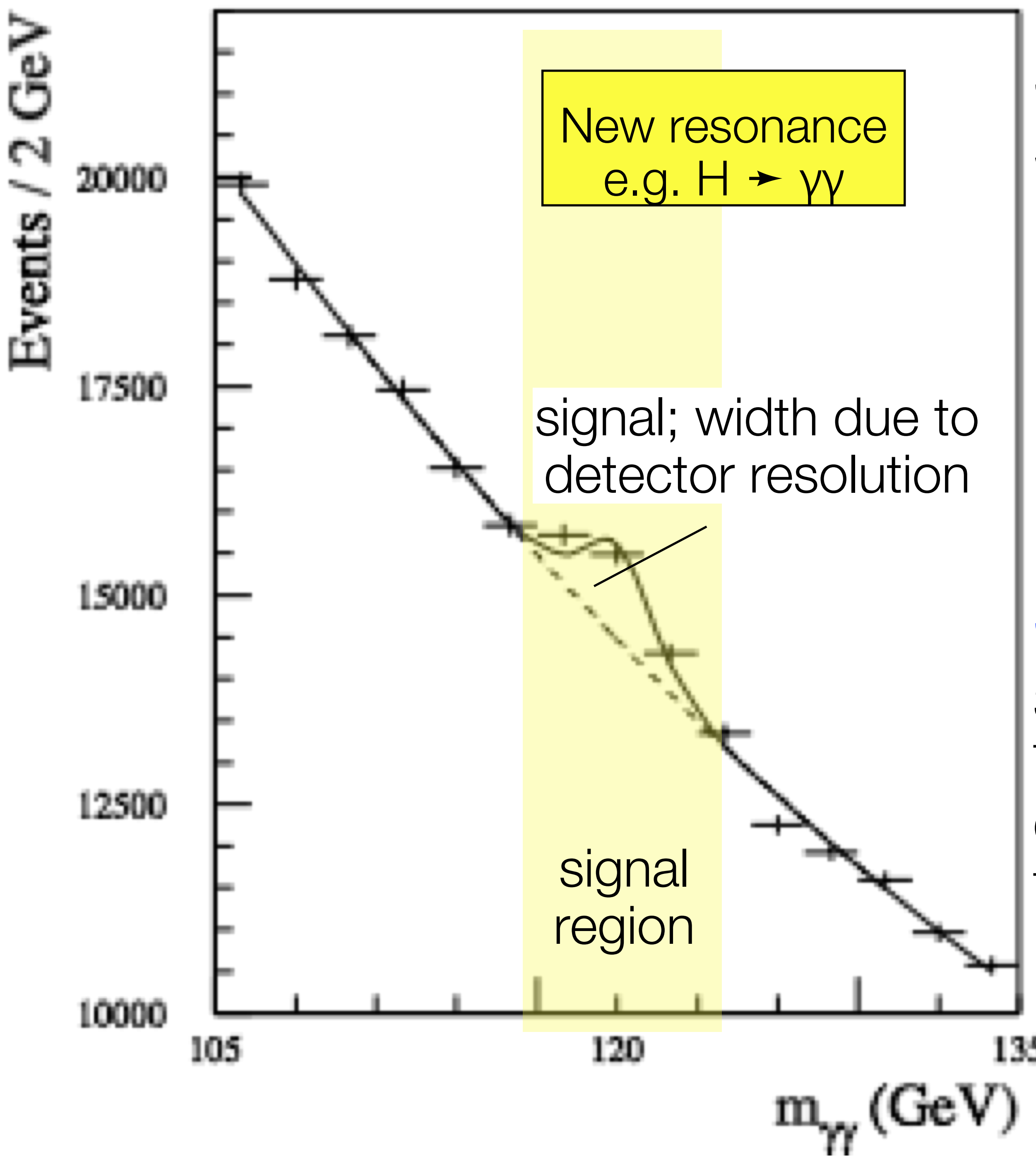
→ mass



→ mass



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 ➛ bb ... without associated production ...
possible: H ➛ γγ ... despite of small branching ratio ...
H ➛ ZZ ... with two (at least one) Z decaying leptonically ...
H ➛ WW ... Leptonic decays, MET & leptons; m_T...

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

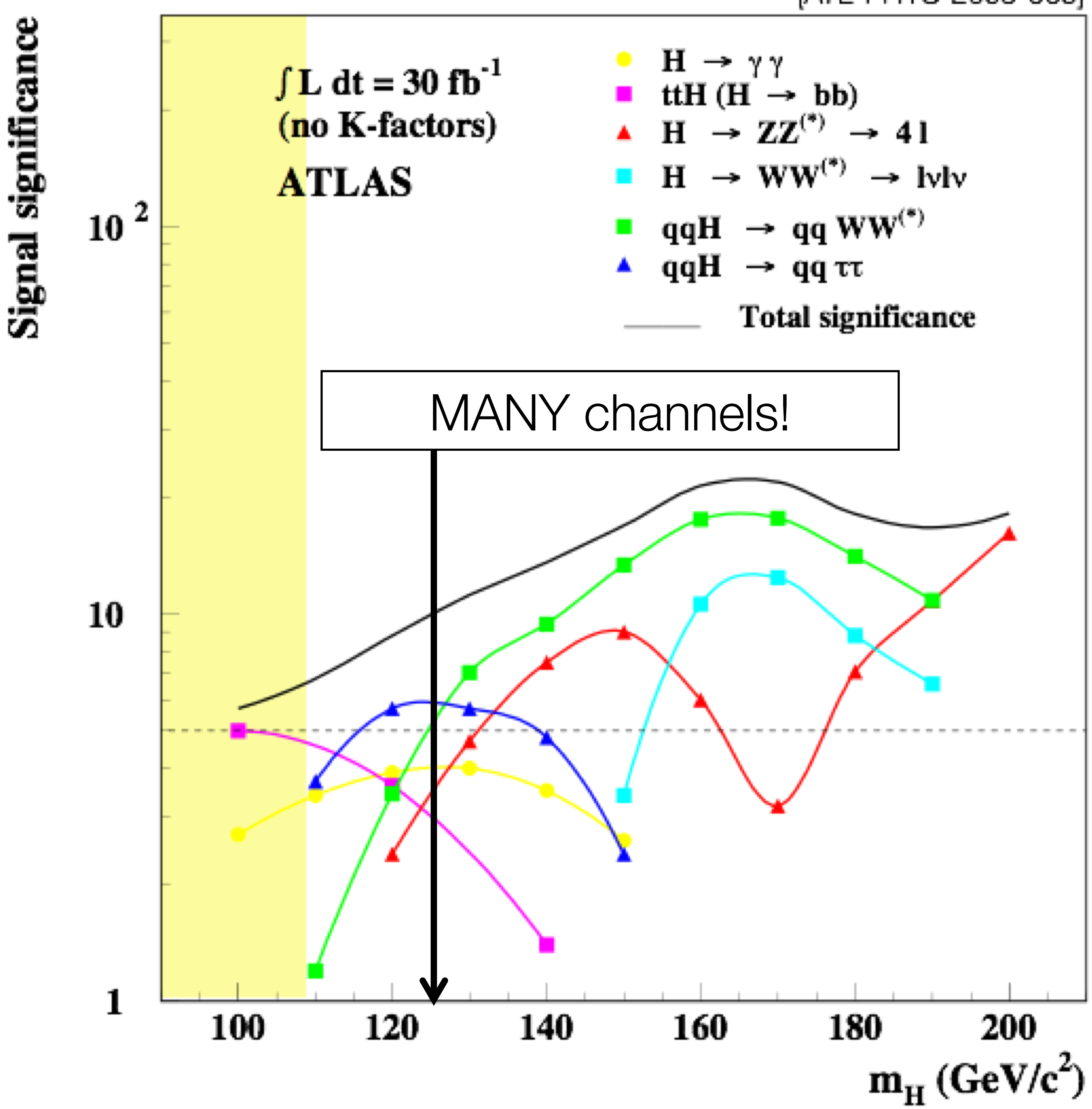
Signal: $N_S \sim L$
Background: $N_B \sim L$ } ➛ $S \sim \sqrt{L}$

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%

→ increase $\mathcal{L}$ decrease σ_m

LHC: Higgs Discovery Potential

[ATL-PHYS-2003-005]



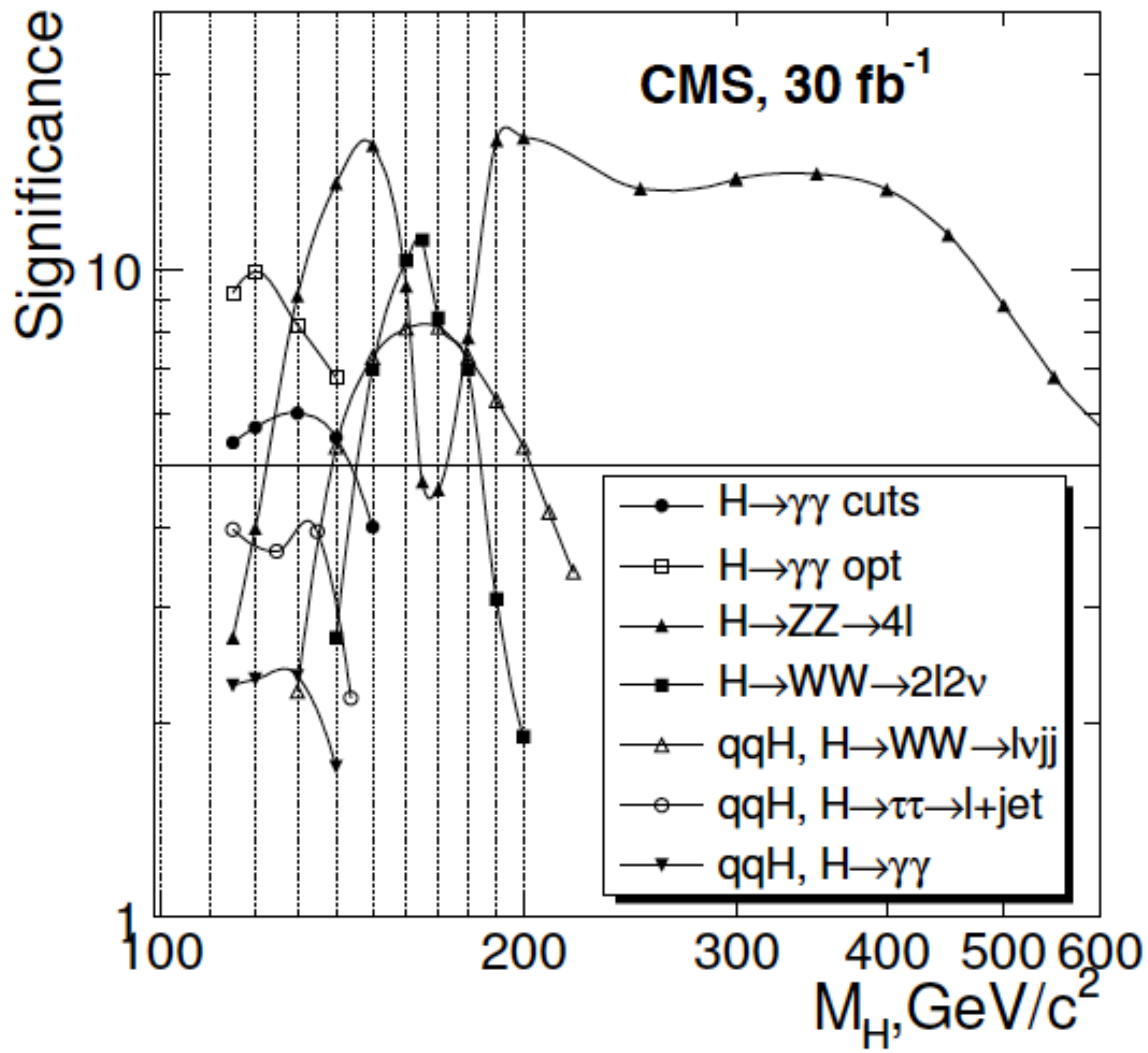
Full mass range can already be covered after a few years at low luminosity

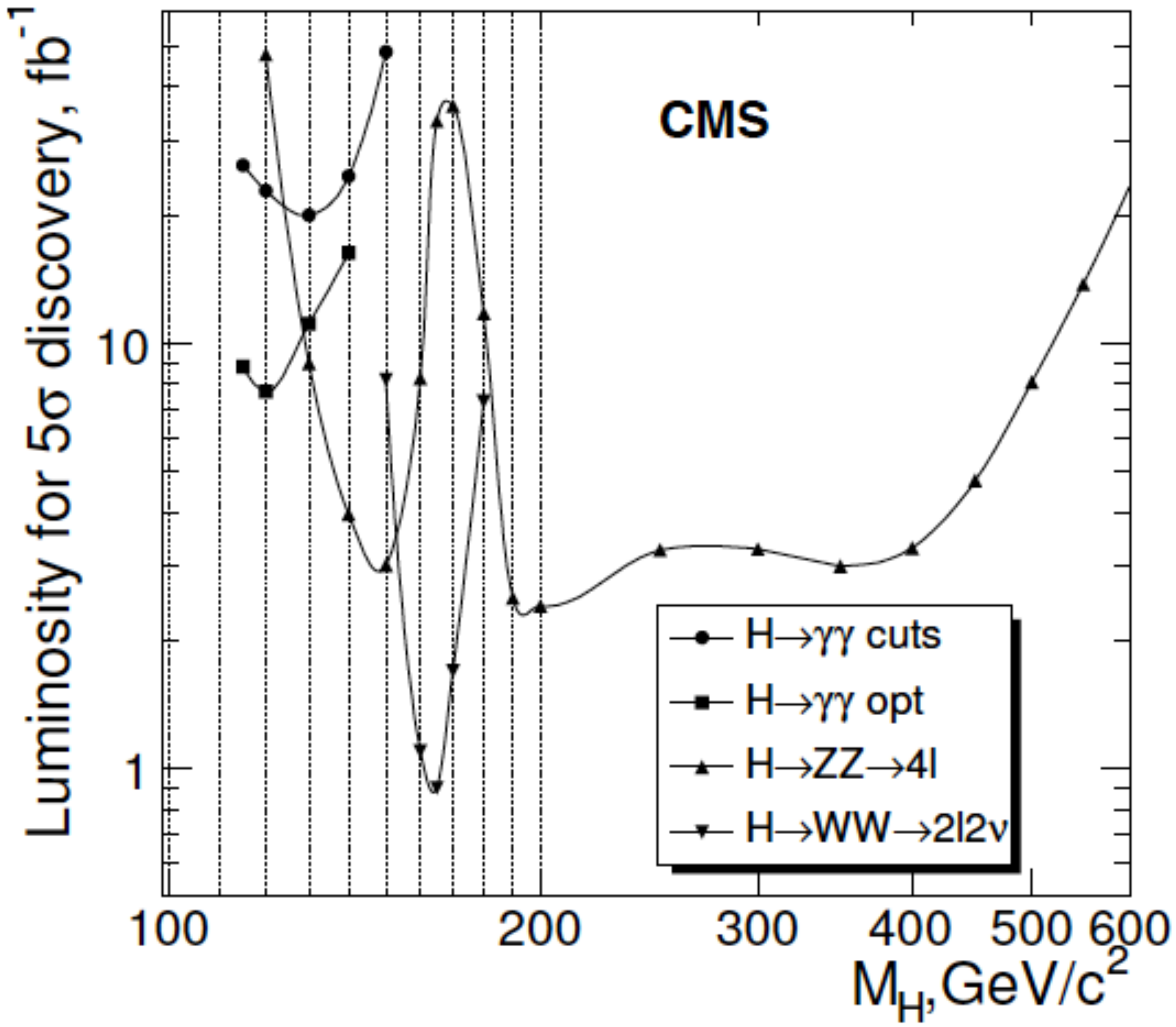
Several channels available over a large range of masses

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

Comparable situation for the CMS experiment

CMS
TDR 8.2 26 June 2006

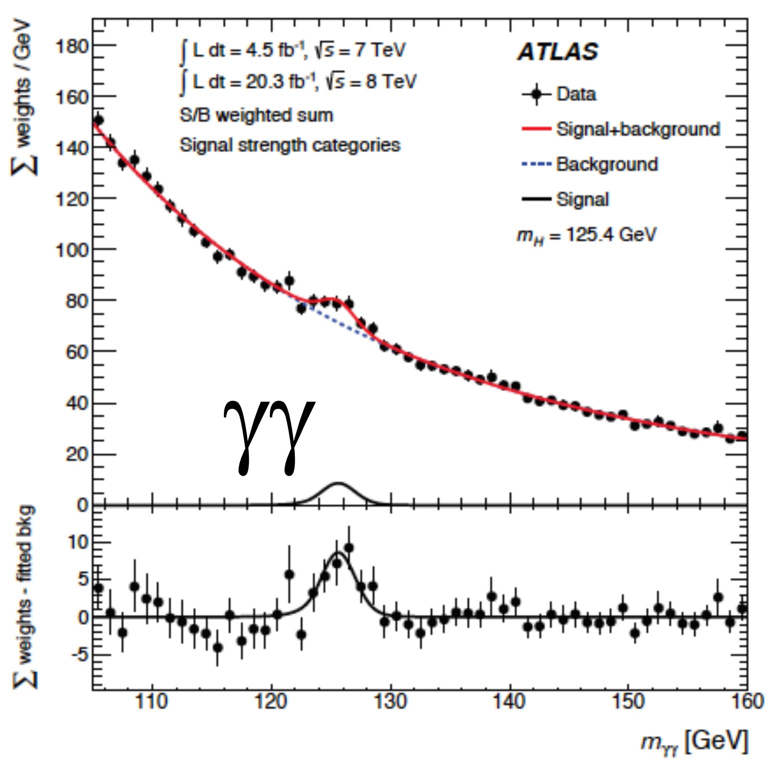


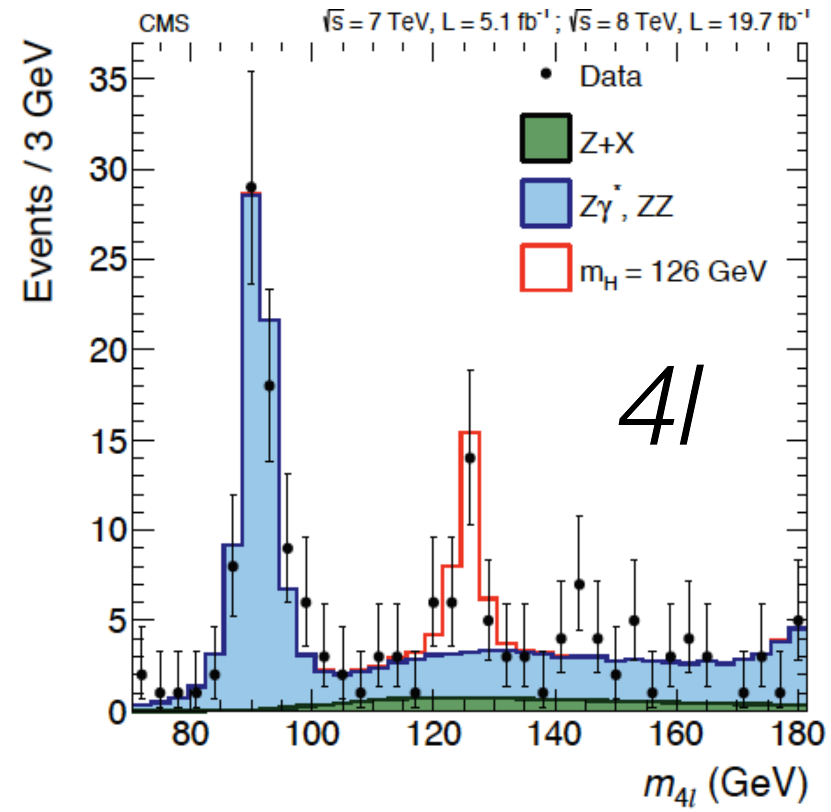


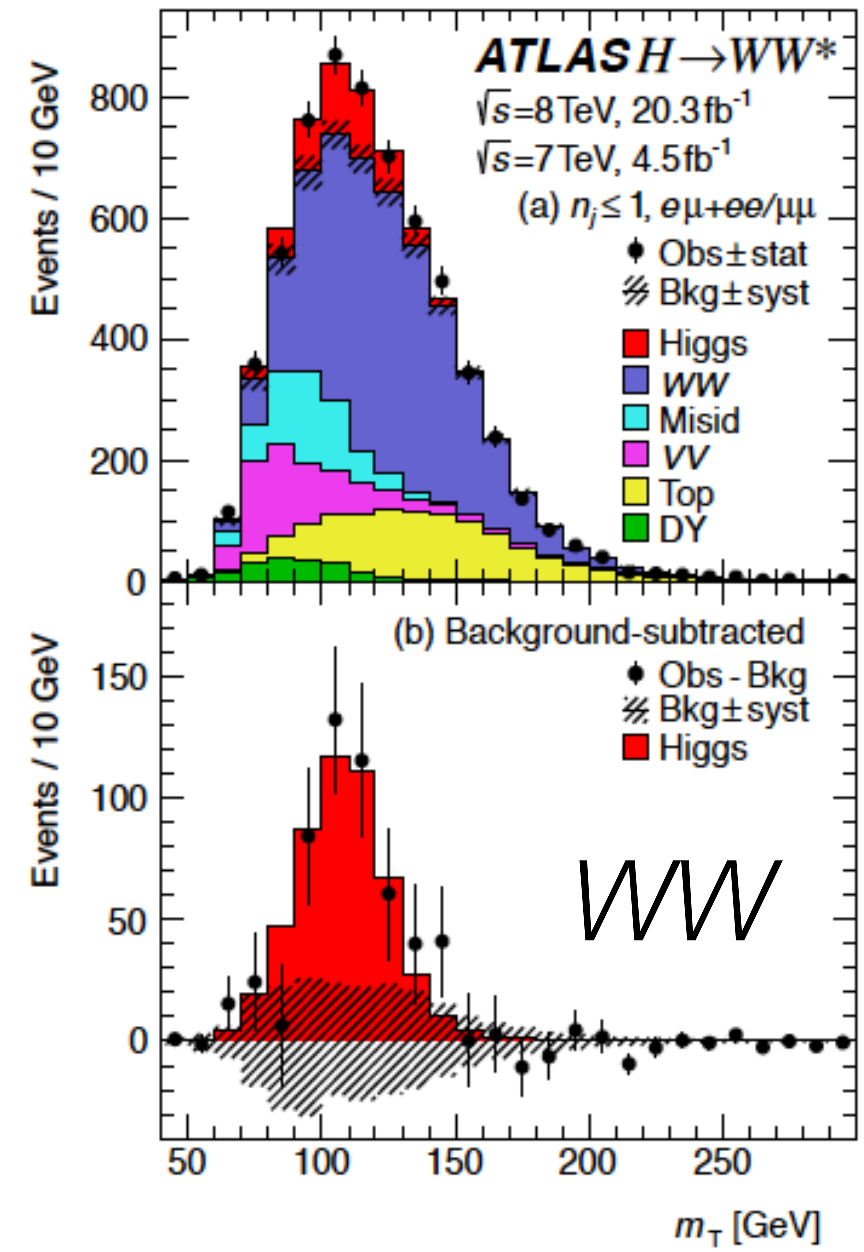
The signal significance as a function of the Higgs boson mass for 30 fb−1 of the integrated luminosity for the different Higgs boson production and decay channels

The integrated luminosity needed for the 5 discovery of the inclusive Higgs boson production pp ! H + X with the Higgs boson decay modes H ! , H ! ZZ ! 4`, and H ! WW ! 2`2.

A snapshot of ~ recent results







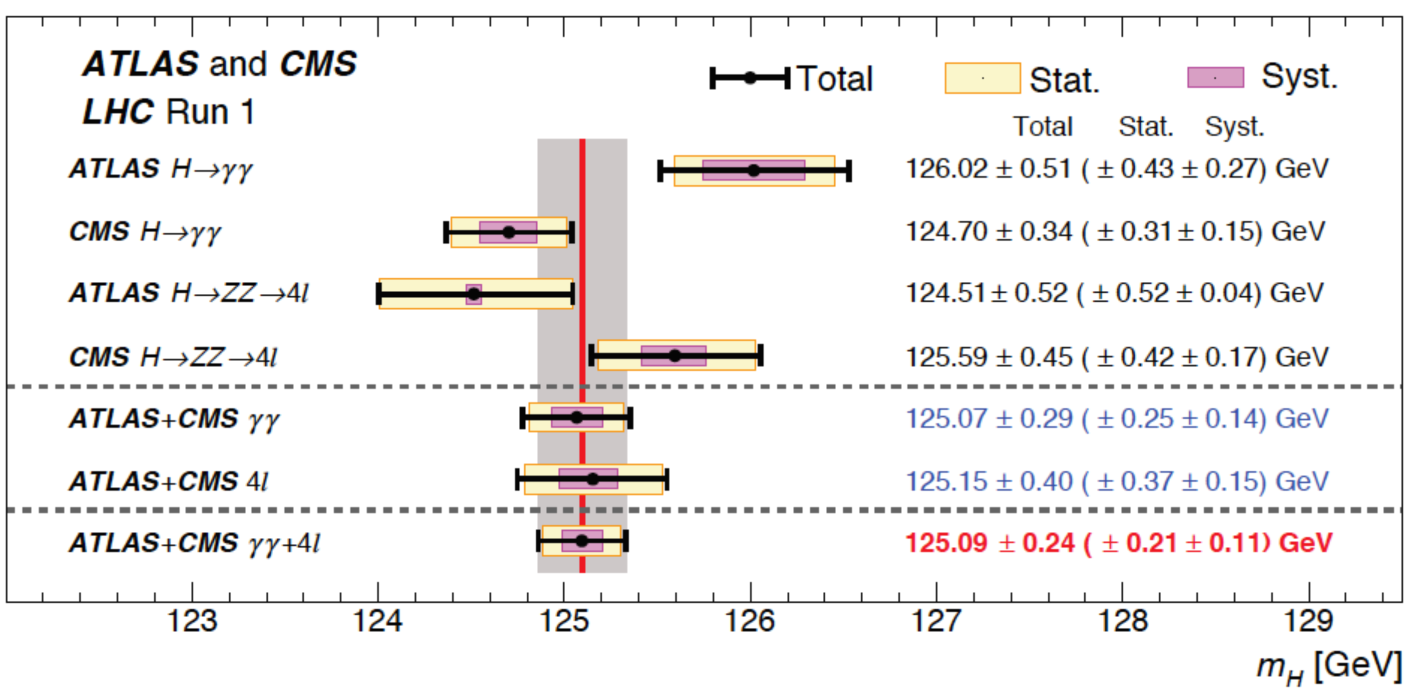


Figure 11.4: A compilation of the CMS and ATLAS mass measurements in the $\gamma\gamma$ and ZZ channels, the combined result from each experiment and their combination. From Ref. [134]

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

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

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

- the dominant mechanisms for Higgs boson production and decay: coupling of H to W, Z and/or the third generation quarks and leptons.
- The Higgs coupling to gluons, is induced at LO by a loop where H couples to a virtual tt pair.
- The Higgs coupling to photons is generated via loops, (in this case the loop with a virtual W+W– pair is the dominant contribution, and the one with tt pair is subdominant).

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

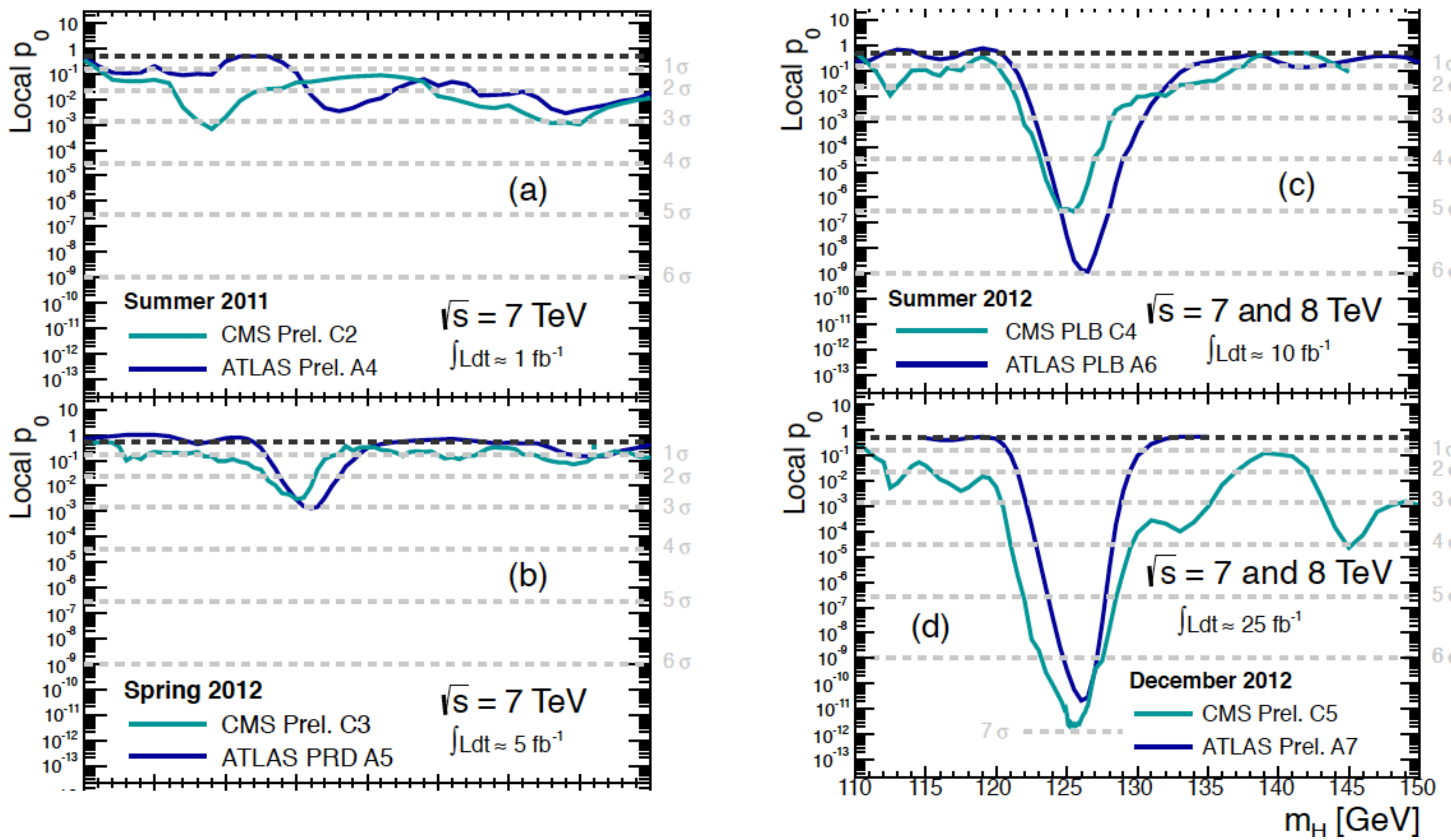
~Recent history

- July 4, 2012 observation at the LHC of a narrow resonance with a mass of about 125GeV
- integrated luminosities of 4.8 (5.1) fb^{-1} at $\sqrt{s}$ = 7TeV in 2011 and 5.9 (5.3) at $\sqrt{s}$ = 8TeV in 2012 by the ATLAS and CMS, respectively.
- The new particle decays to γγ and ZZ with rates consistent with the Standard Model (SM) Higgs boson (+indications of decays to W^+W^-). The observed decay channels indicated that the new particle is a boson.
- 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 an excess with a significance of 5.9σ at a mass m_H = 126.5GeV. CMS had a significance of 4.9σ at a mass of 125.5GeV.

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 **next slide** shows four snapshots of the evolution of the p-value and the signal significance near 125GeV with increasing datasets analysed by the two experiments.

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

Evolution of p_0



125

p-value and signal significance by the ATLAS and CMS with increasingly larger datasets:

(a) Summer 2011 (≈ 1 fb^{-1}/expt) (b) Spring 2012 (≈ 5 fb^{-1}/expt),
(c) Summer 2012 (≈ 10 fb^{-1}/expt) (d) December 2012 (≈ 25 fb^{-1}/expt).

Decay & production channels of the Higgs

4 main production modes (events in Run1, ~30 fb^{-1}):

gluon fusion	vector boson fusion	associated VH	ttH
500000	40000	20000	3000

5 main decay channels: $\gamma\gamma$, ZZ, WW, $\tau+\tau-$ and bb.

Known features → exclusive categories designed according to decay channels (first) and production modes (then) → selections to maximize the sensitivity to the presence of a signal.

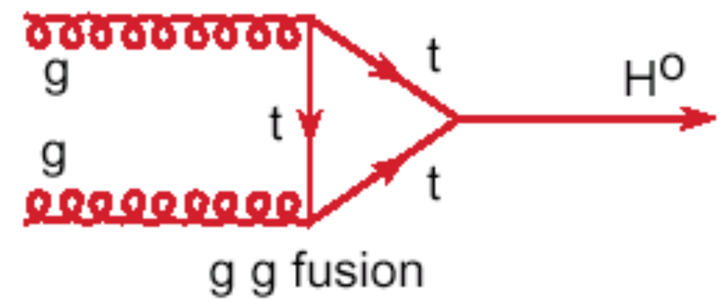
The typical number of events selected eventually in each decay channel ranges from a fraction of an event to O(100) events per experiment.

The discovery Higgs boson has been based on the Higgs decay modes, integrating over production channels.

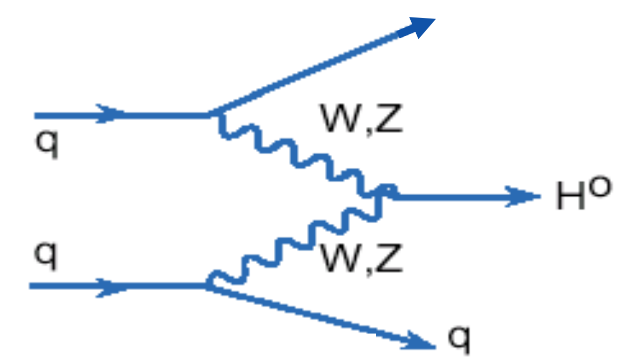
The natural extension is the measurement of the coupling properties of the Higgs boson. These measurements require, in general, a limited but nevertheless restrictive number of assumptions.

Features of Production Modes

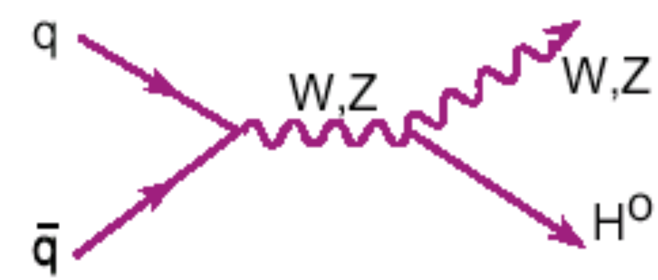
- **ggf:** the gluon-fusion process , gg → H+X, has the largest cross section; it is mediated by the exchange of a virtual, heavy top quark. Contributions from lighter quarks propagating in the loop are suppressed by terms proportional to m^2_q .



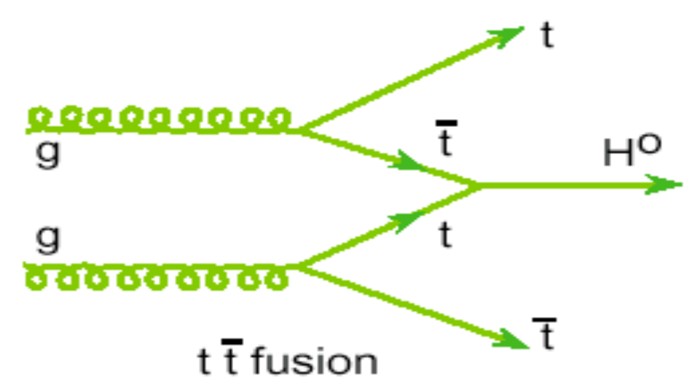
- **VBF:** The SM Higgs production mode with the second-largest cross section at the LHC is vector boson fusion (VBF). Higgs production via VBF, qq → qqH, proceeds by the scattering of two quark anti-quarks, mediated by channel exchange of a W or Z boson, with the Higgs boson radiated off the weak-boson propagator. Two hard jets in the forward and backward regions of the detector with a large dijet mass (≥ 400GeV) and separated by a large pseudorapidity ($\Delta\eta_{jj} \geq 3.5$)(or large $\Delta\eta$).



- **VH, V=Z or W:** 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 → $t\bar{t}H$, provides a direct probe of the top-Higgs Yukawa coupling. high p_T leptons, MET. Complex topology when combined with several decay channels



~Low mass Higgs: strategies

For a low-mass Higgs boson, m_H <150GeV **five decay channels** play an important role at the LHC. Integrate over all production modes!

- 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%).
- $H \rightarrow W^+W^- \rightarrow l^+\nu_l l'^- \bar{\nu}_l'$ channel has relatively large branching fraction, the m_H resolution is poor (approximately 20%) due to the presence of neutrinos. Large samples!
- $H \rightarrow b\bar{b}$ and the $H \rightarrow \tau^+\tau^-$ channels suffer from large backgrounds and a intermediate mass resolution of about 10% and 15% respectively. Difficult!

Decay

Five Higgs boson production processes (ggF, VBF, WH, ZH and ttH).

- The candidate events in each Higgs decay channel are split into several mutually exclusive categories based on the specific topological, kinematic or other event features.
- The categorization of events increases the sensitivity of the overall analysis and allows a separation of different Higgs boson production processes.

Production

Low mass Higgs categorisation

Most categories are

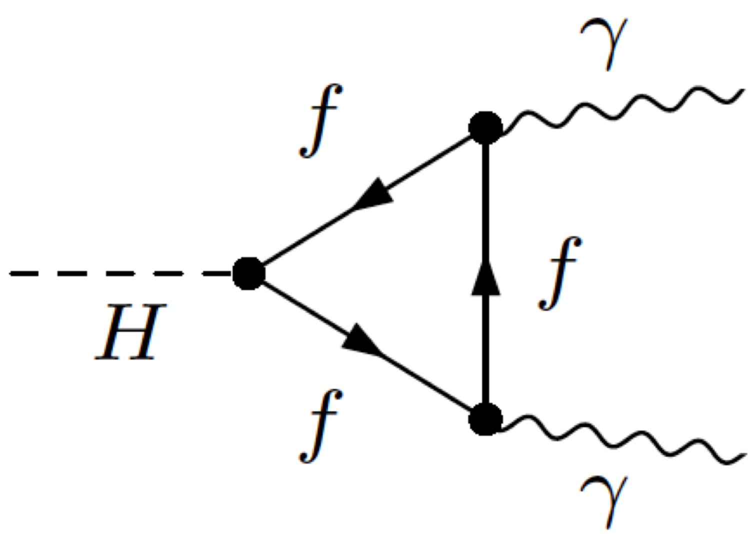
- dominated by signal from one Higgs decay mode but
- contain an admixture of various Higgs production processes.

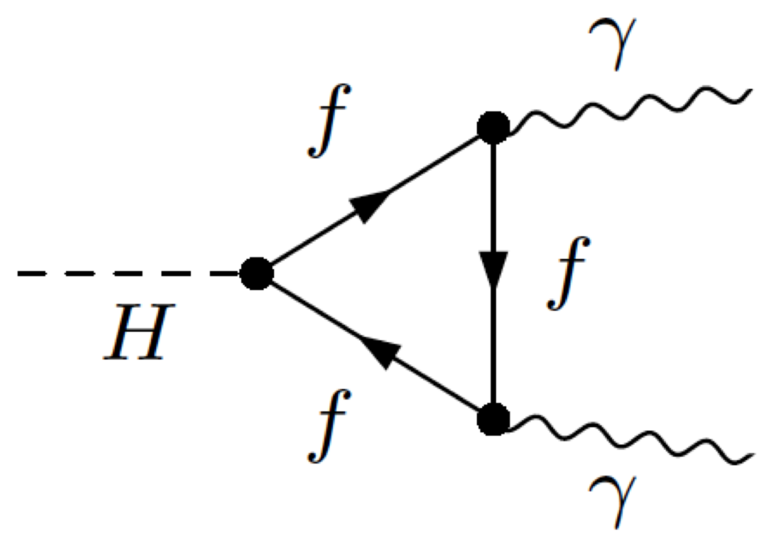
For example, a typical **VBF** selection requires Higgs boson candidates to be accompanied by two energetic jets (≥ 30GeV) with a large dijet mass (≥ 400GeV) and separated by a large pseudorapidity ($D\eta_{jj} \geq 3.5$).

While such a category is enriched in Higgs bosons produced via VBF, the contamination from the gluon fusion production mechanism can be significant. → a measurement of the signal rate in the VBF category does not imply a measurement of VBF production cross-section.

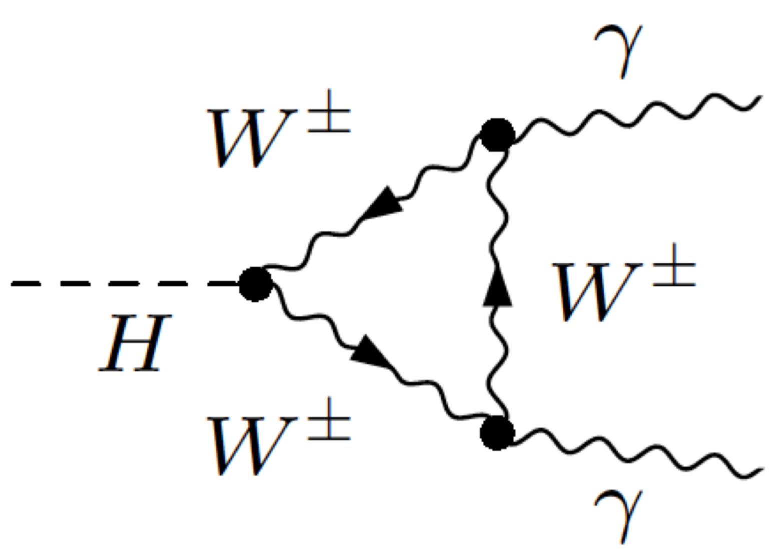
Simulations are used to determine the relative contributions of the various Higgs production modes in a particular category.

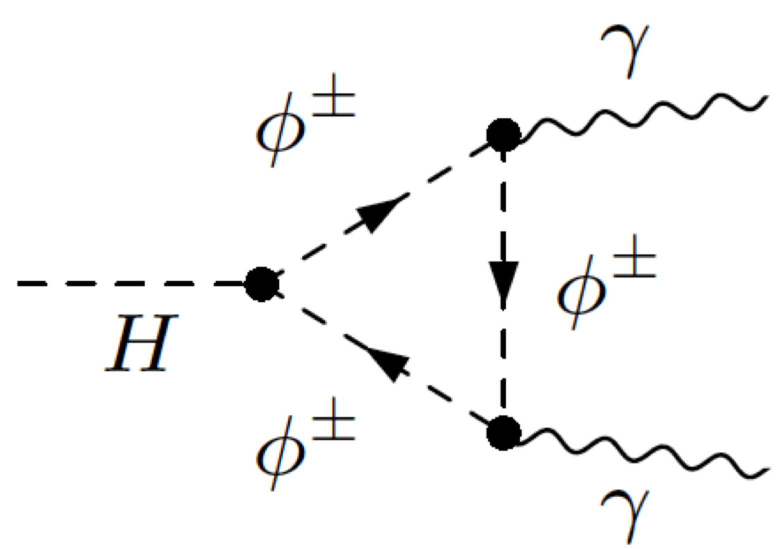
Higgs decay to 2 photons





Only top quarks contribute, contributions from light fermions negligible



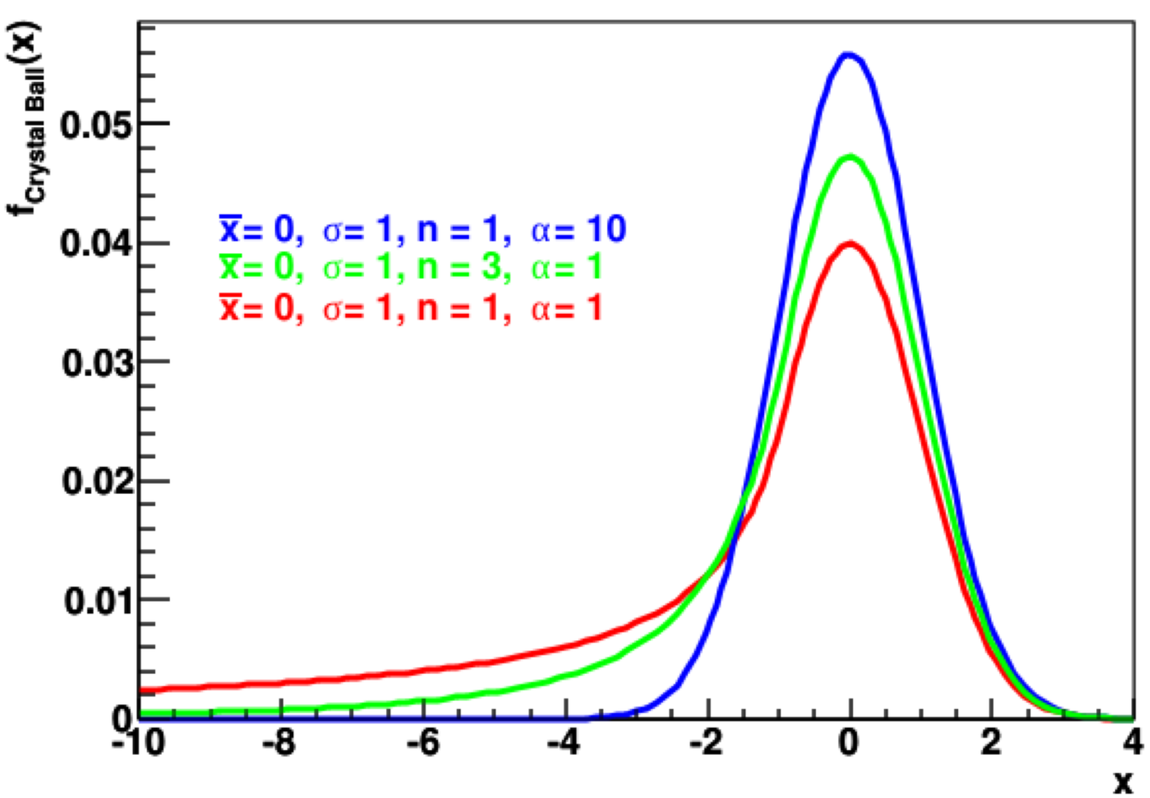


W-bosons, Goldstone-bosons and ghosts occur in the loops

Higgs to $\gamma\gamma$

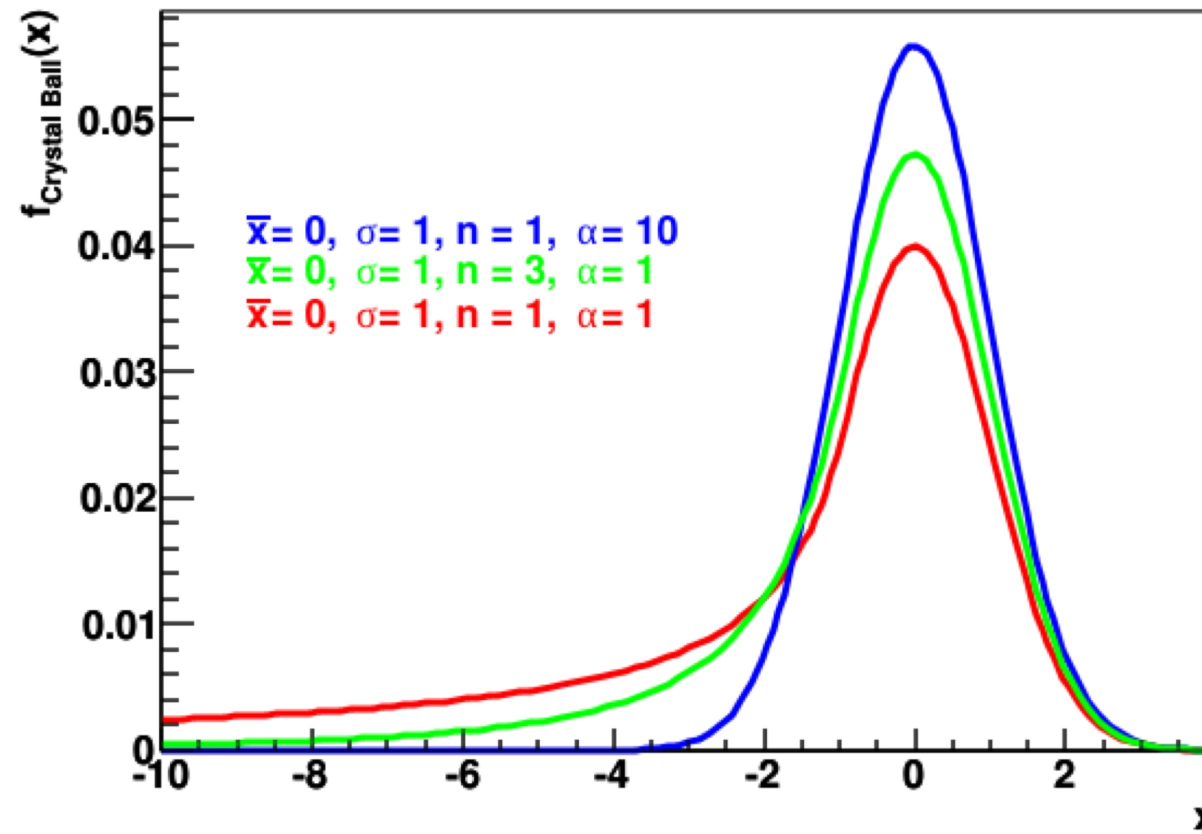
Method: look for a peak in the invariant mass of two high p_T photons over a smoothly falling background distribution.
Irreducible Background: : processes with the production of two prompt $\gamma\gamma$
Reducible background: γ+jets, di-jet events (where one jet fragments into a leading π^0)
Classification:
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: $m_{\gamma\gamma}$ reconstruction has been studied using $Z \to e^+e^-$ and $Z \to e^+e^-\gamma$ to determine the shape of the signal. Simple functional forms of the backgrounds are determined by a fit to the $m_{\gamma\gamma}$ distribution. 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 ($m_H + \Delta m_{CBi}$) and the width $\sigma_{CB,i}$.



Higgs to $\gamma\gamma$, Signal Model (details)

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:

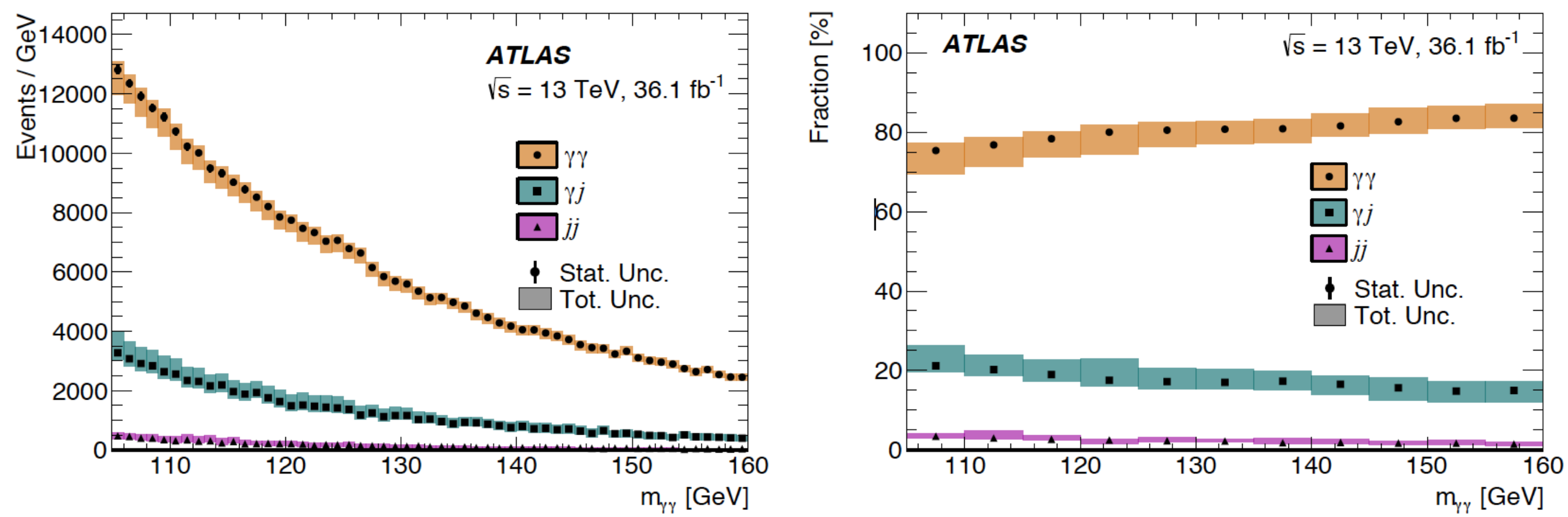


$$f_i^{\text{sig}}(m_{\gamma\gamma}; \Delta\mu_{\text{CB},i}, \sigma_{\text{CB},i}, \alpha^{\pm}_{\text{CB},i}, n^{\pm}_{\text{CB},i}) = \mathcal{N}_c \begin{cases} e^{-t^2/2} & -\alpha^{-}_{\text{CB},i} \leq t \leq \alpha^{+}_{\text{CB},i} \\ \left(\frac{n^{-}_{\text{CB},i}}{|\alpha^{-}_{\text{CB},i}|}\right)^{n^{-}_{\text{CB},i}}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

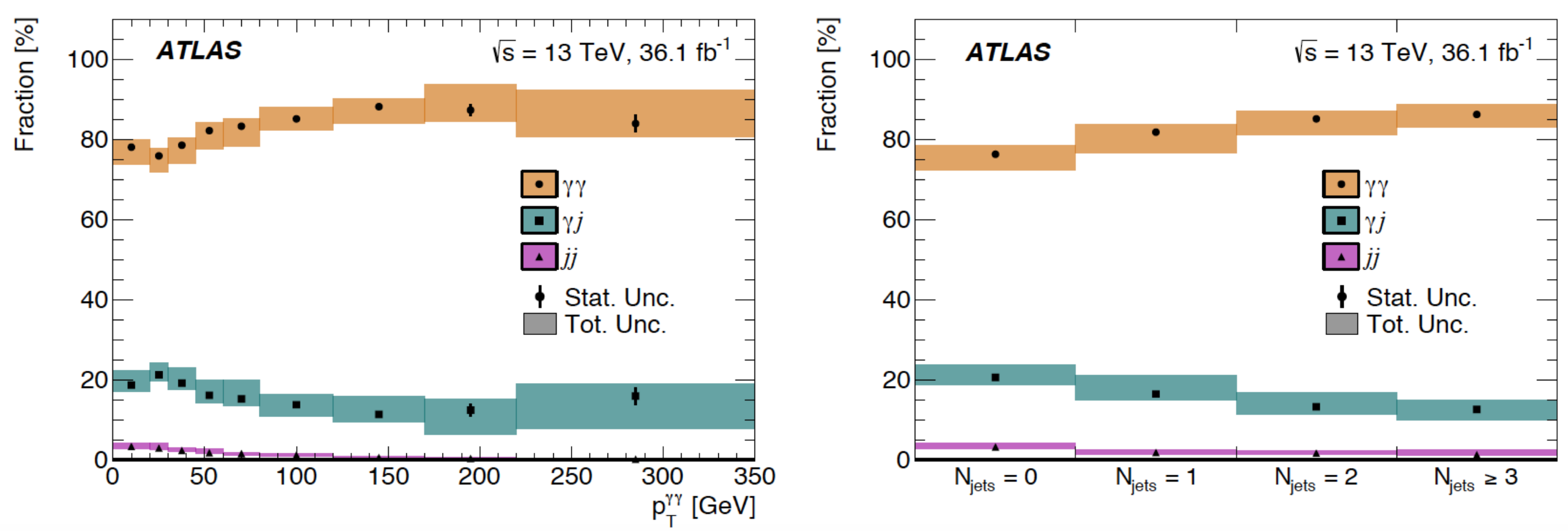
where $t = (m_{\gamma\gamma} - m_H - \Delta\mu_{\text{CB},i})/\sigma_{\text{CB},i}$, and $\mathcal{N}_c$ is a normalization factor. The non-Gaussian parts are parameterized by $\alpha^{\pm}_{\text{CB},i}$ and $n^{\pm}_{\text{CB},i}$ separately for the low- (−) and high-mass (+) tails.

Higgs to $\gamma\gamma$, Background model

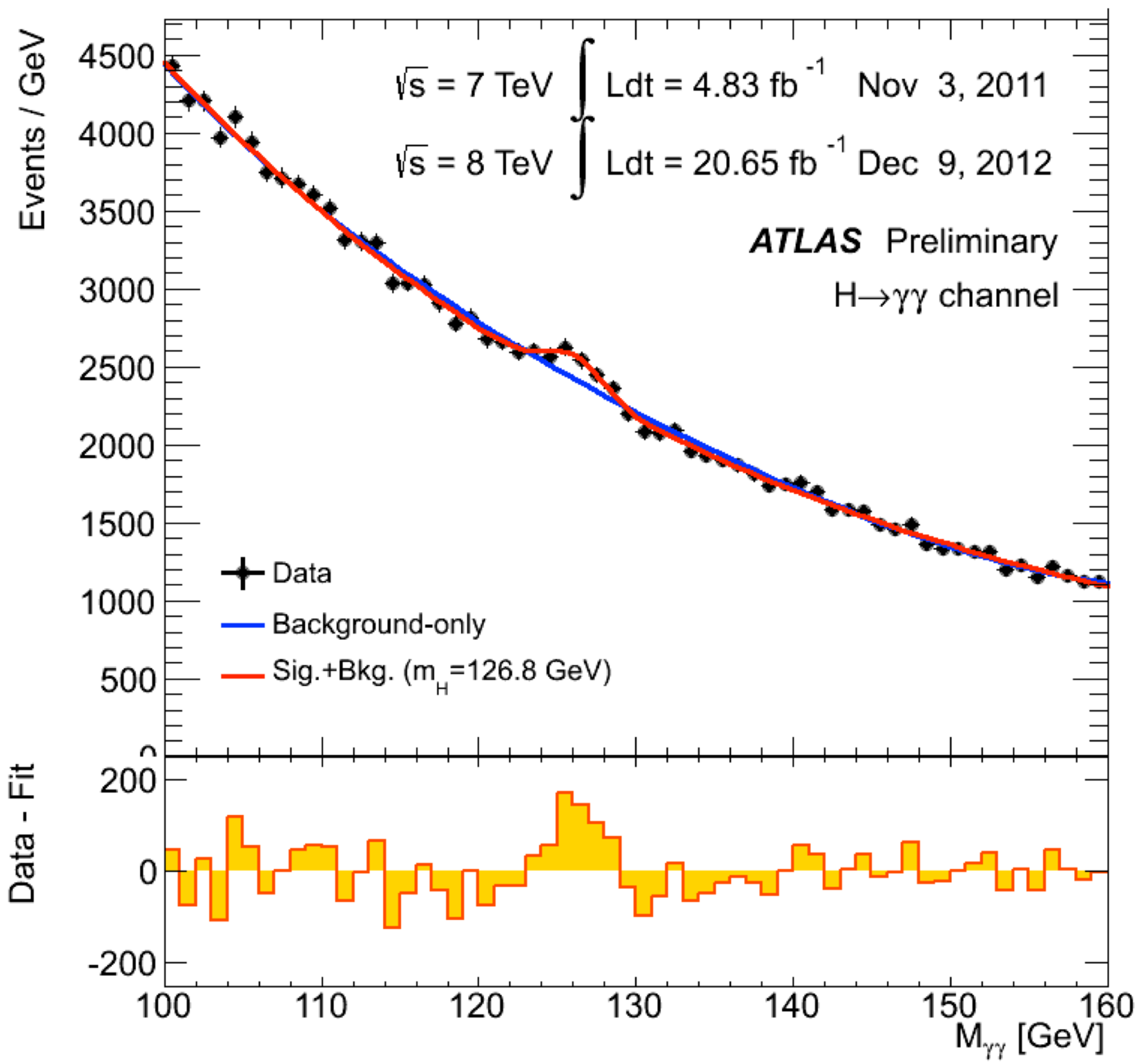
The diphoton invariant mass model for the background used to fit the data is determined from studies of the bias in the signal yield in signal+background fits to large control samples of data or simulated background events

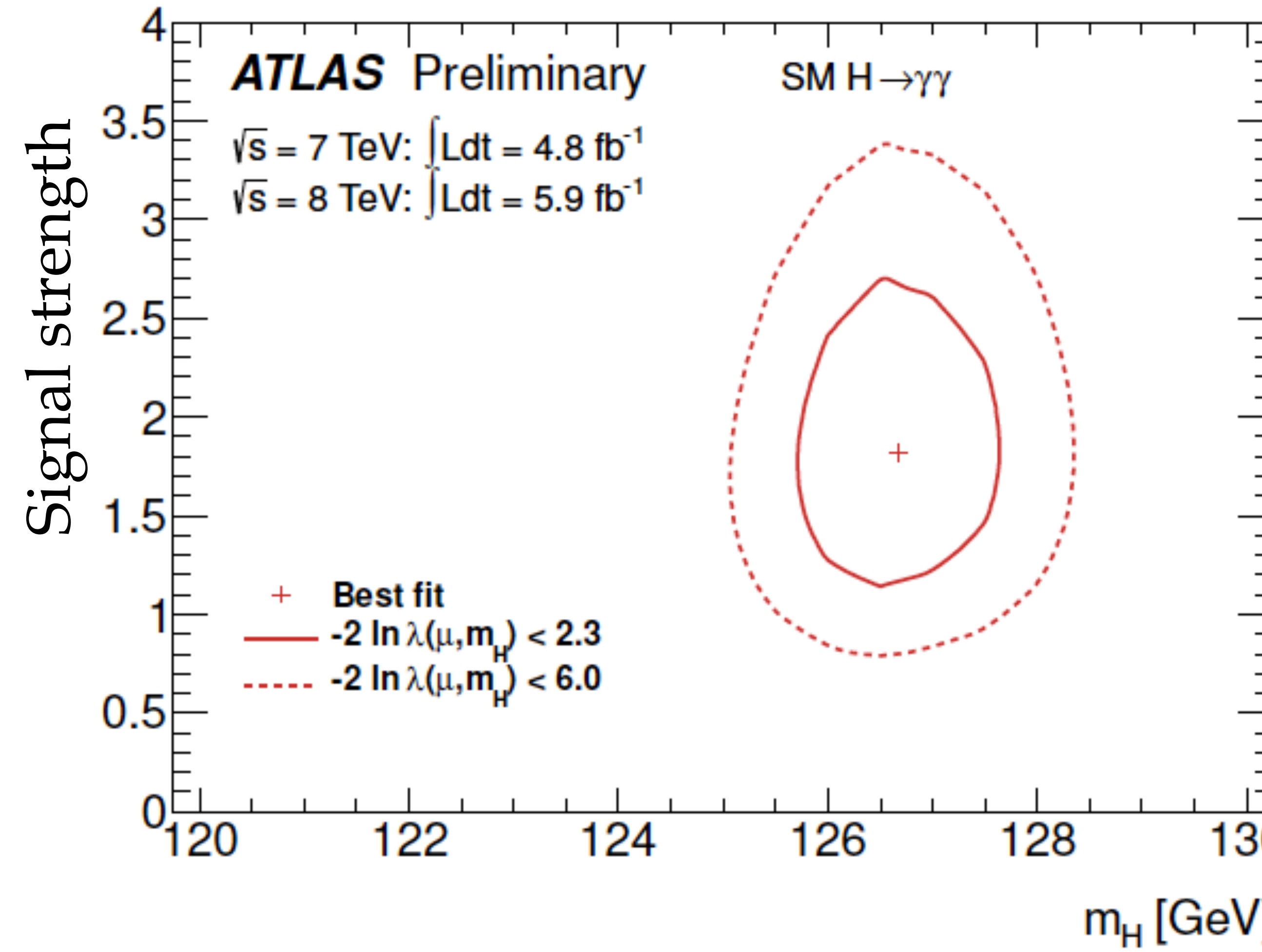


(a) (b)

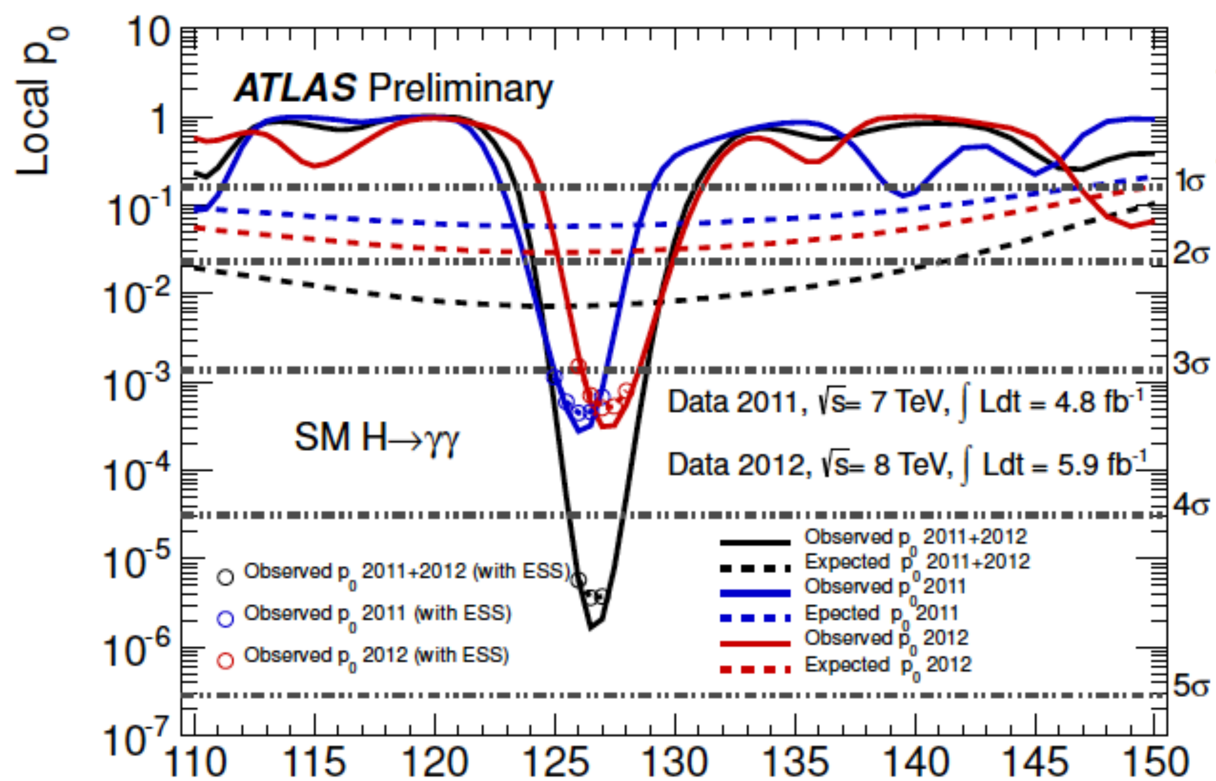


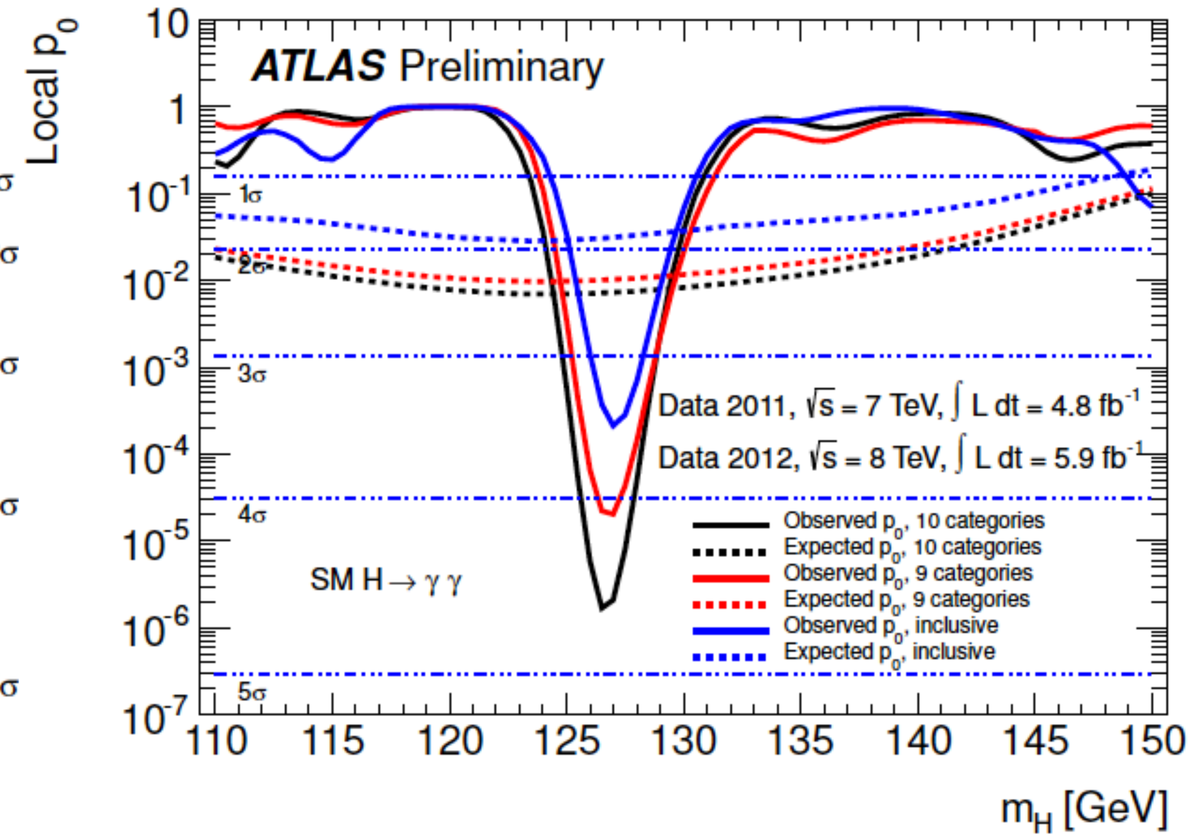
The fit to data

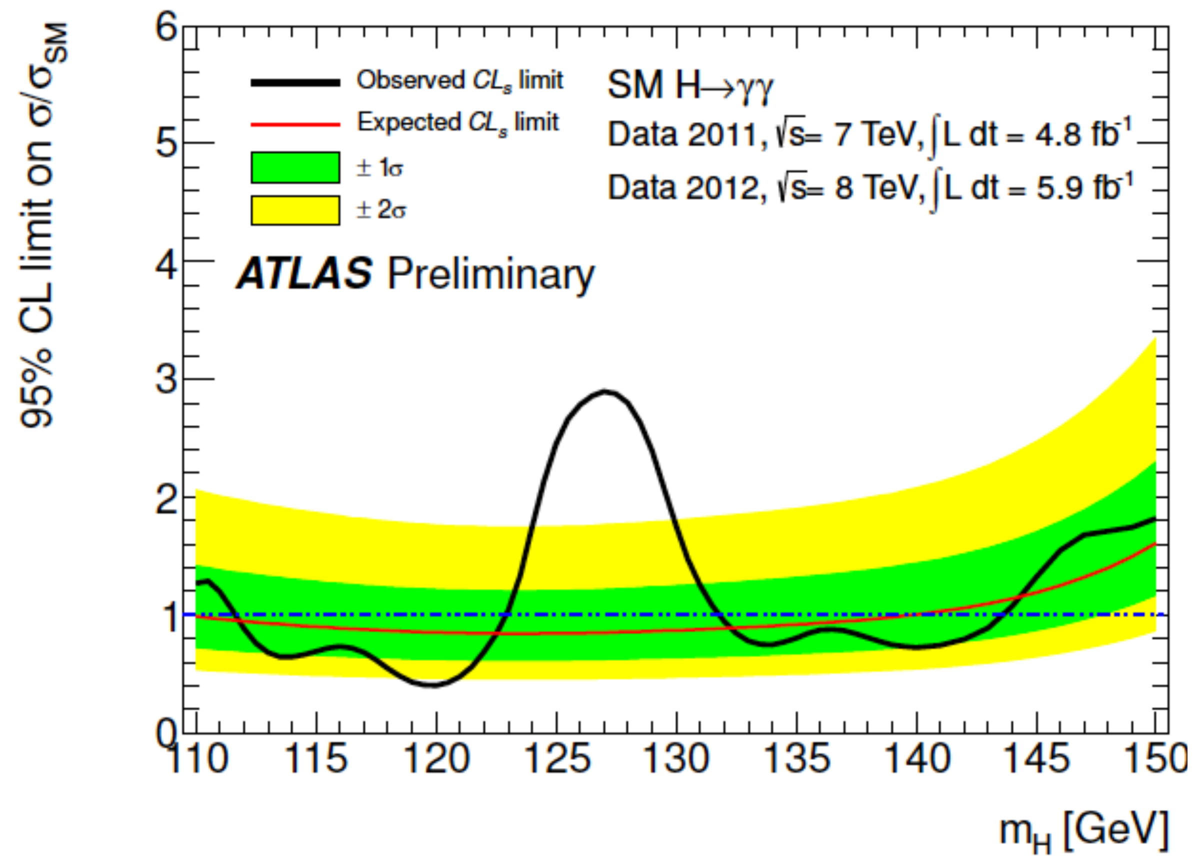


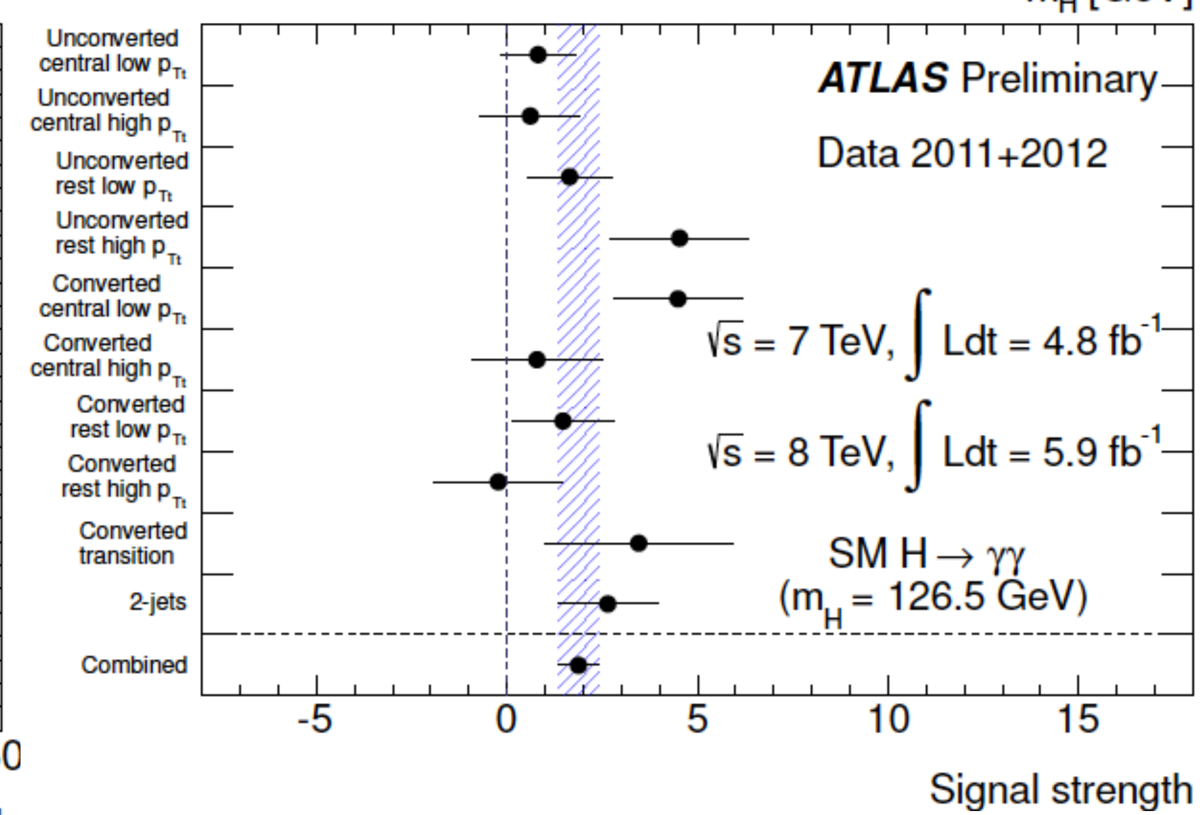


Observation of an excess of events in the search for the Standard Model Higgs boson in the $\gamma\gamma$ channel with the ATLAS detector

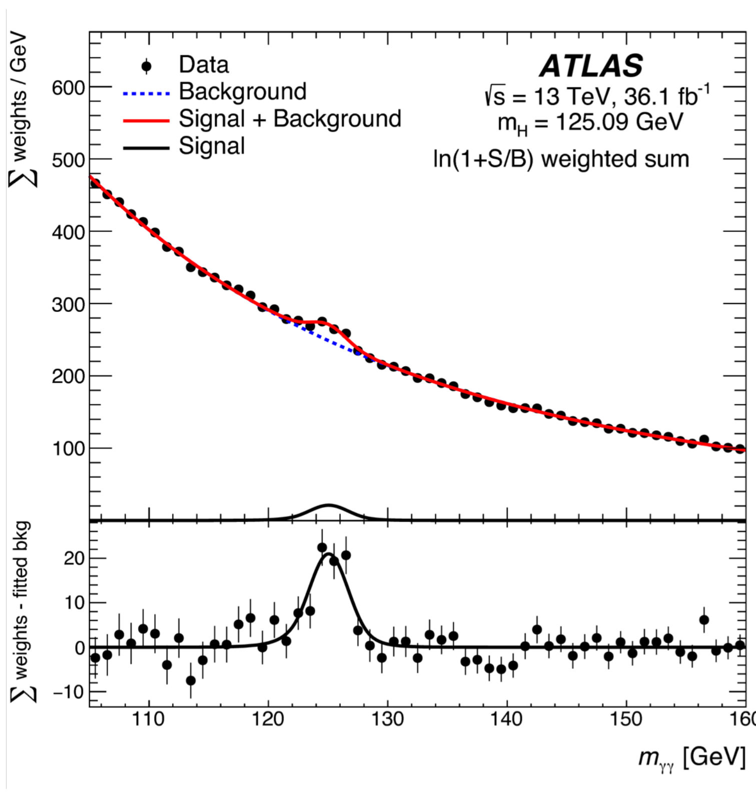


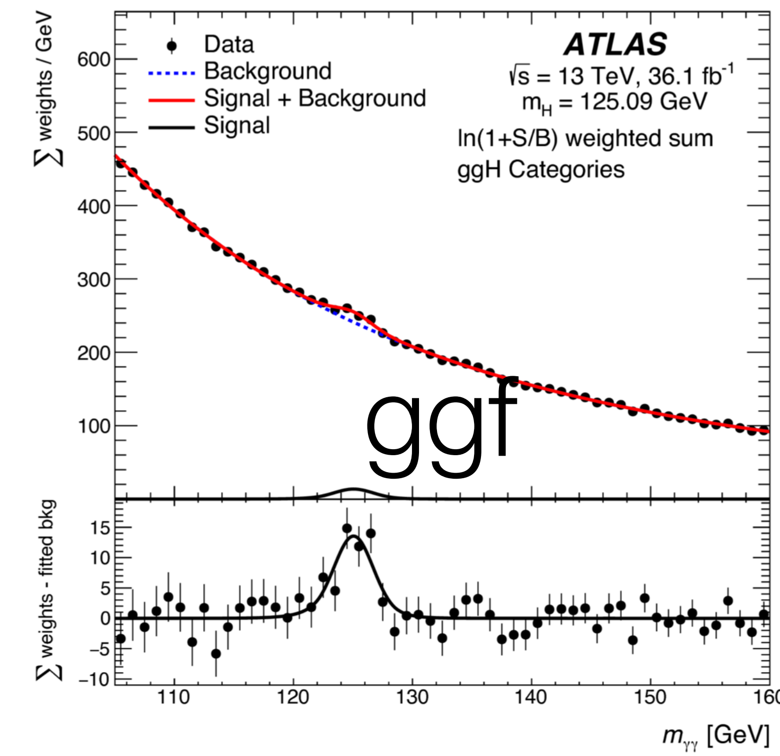


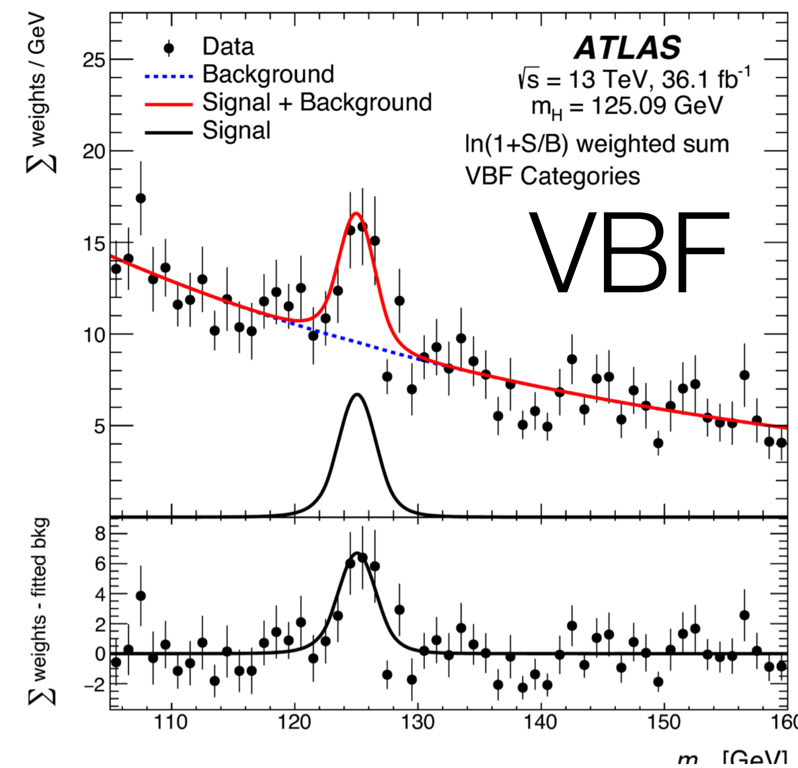


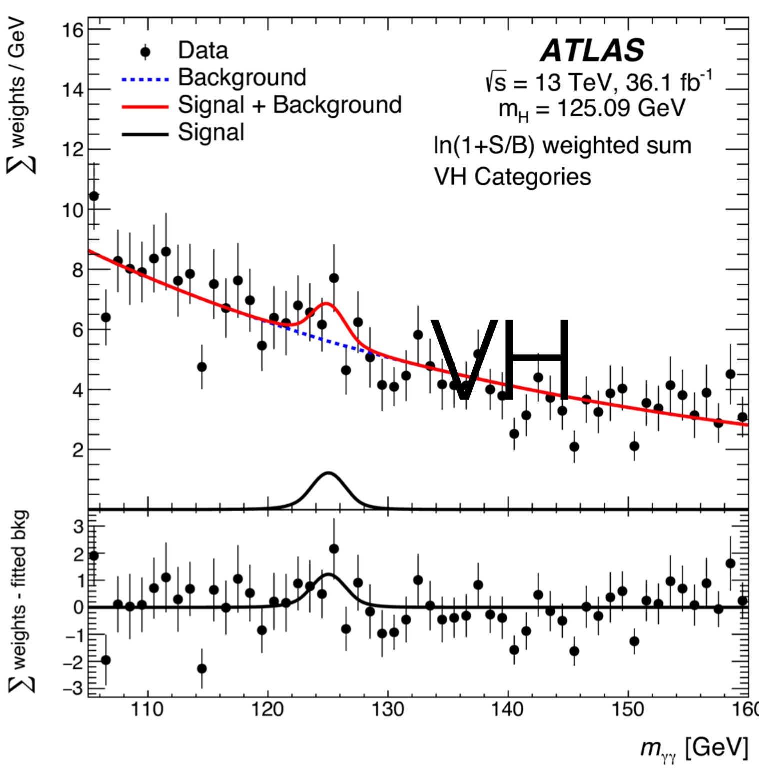


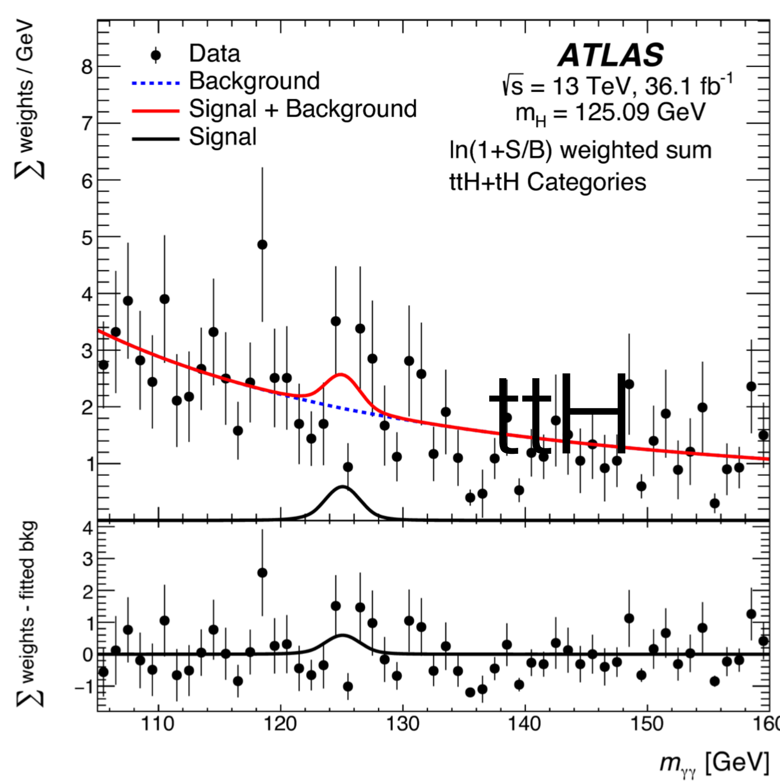
Results H to two photons in ATLAS

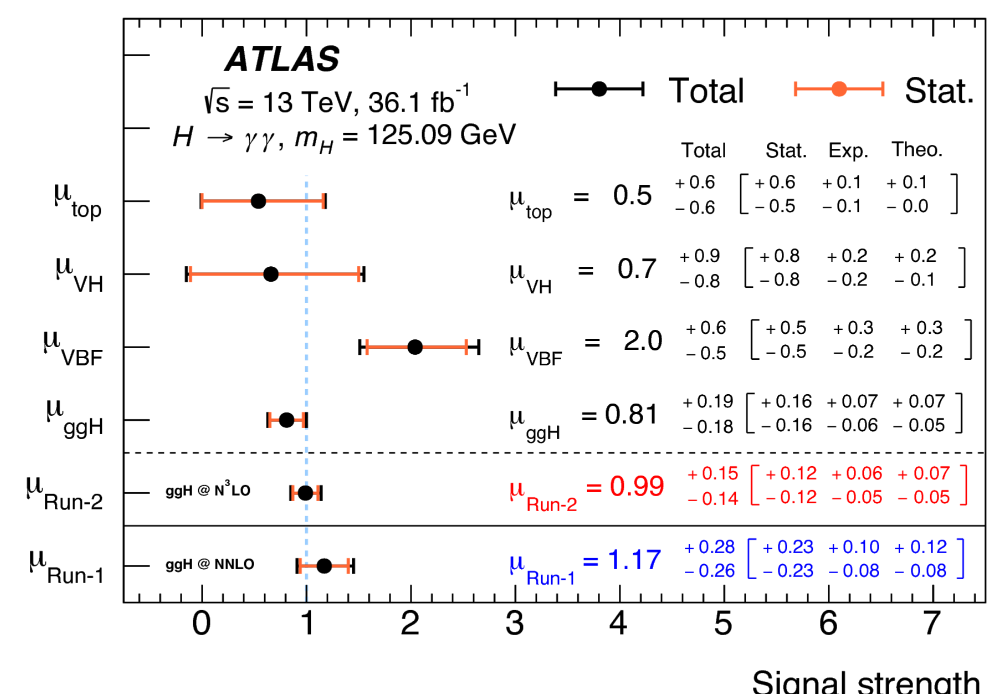












Higgs to ZZ to 4 leptons

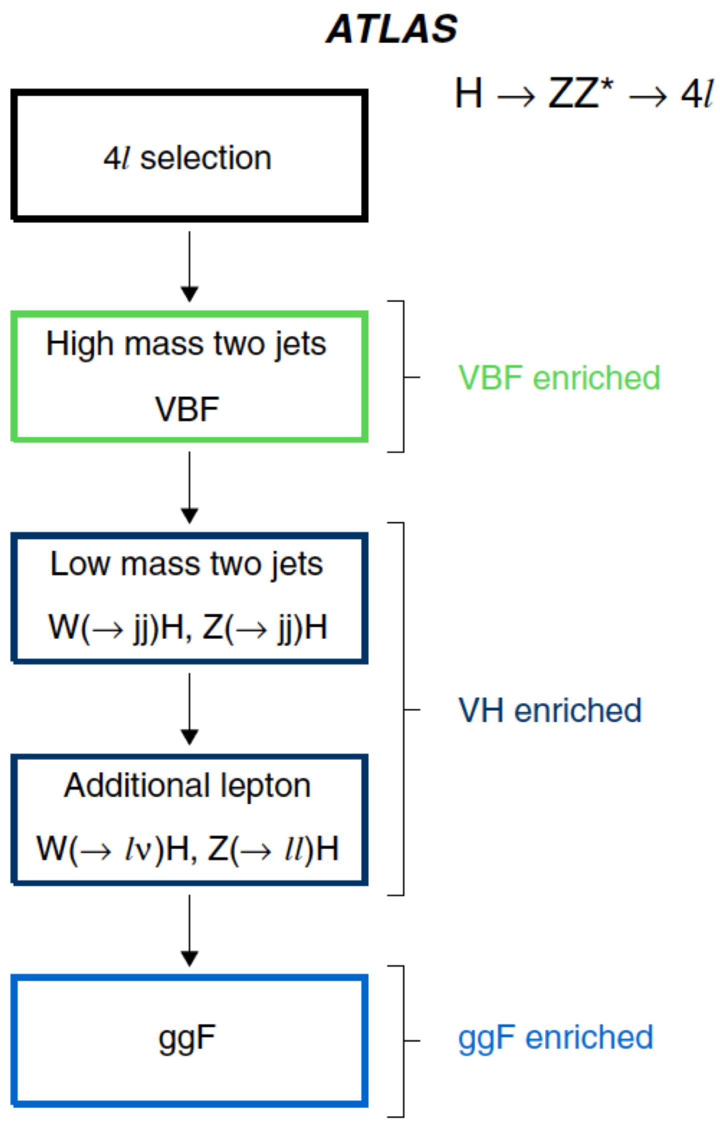
Method: search for a narrow mass peak over a small continuous background

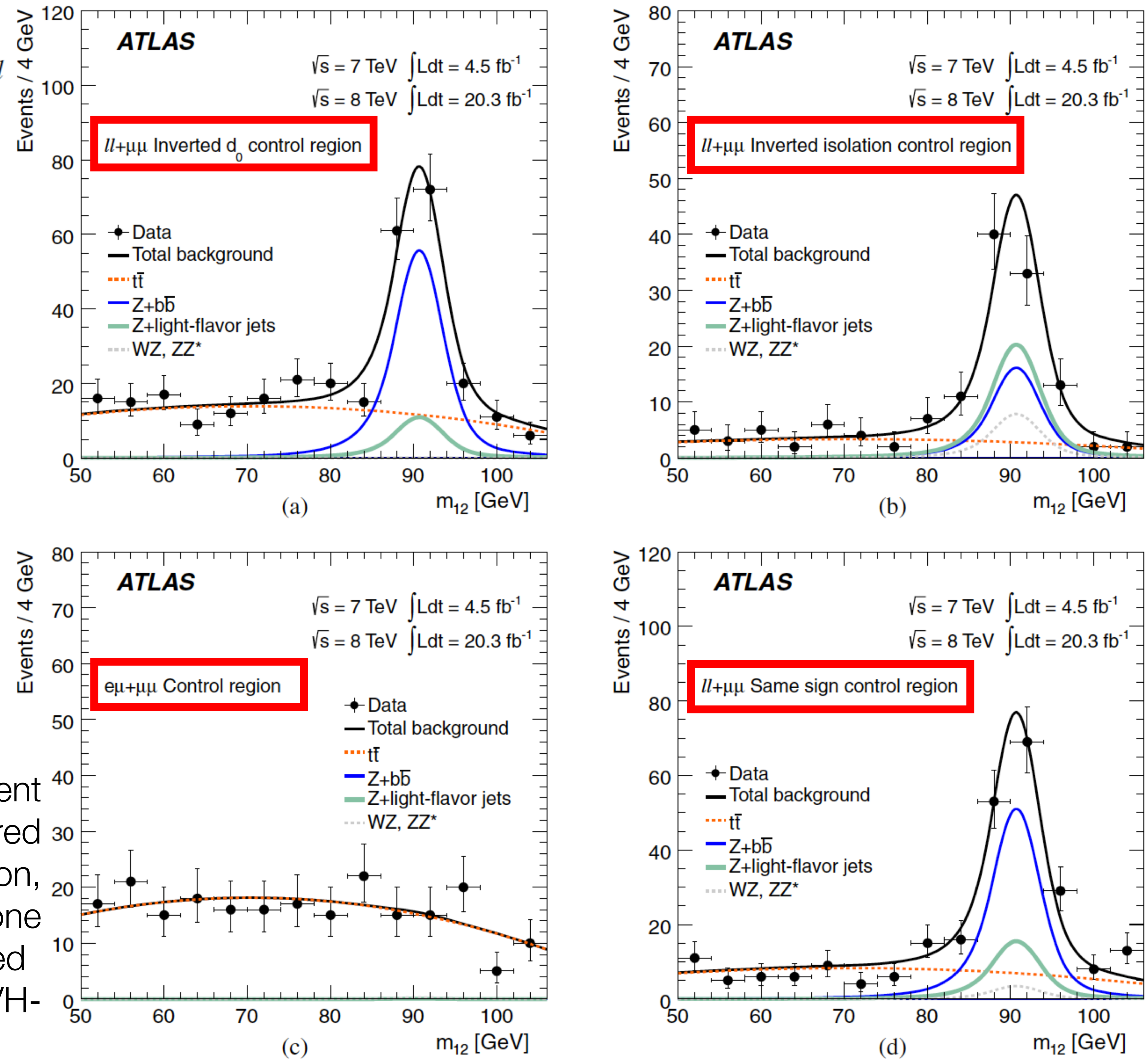
Background: dominated by non-resonant ZZ^* production from qq annihilation and gg fusion processes. The contribution and the shape of this irreducible background is taken from simulation. Their contribution is suppressed by requirements on lepton isolation and lepton impact parameter and their yield 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 ($gg \rightarrow H \rightarrow 4l$) and background($qq \rightarrow ZZ \rightarrow 4l$) 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.

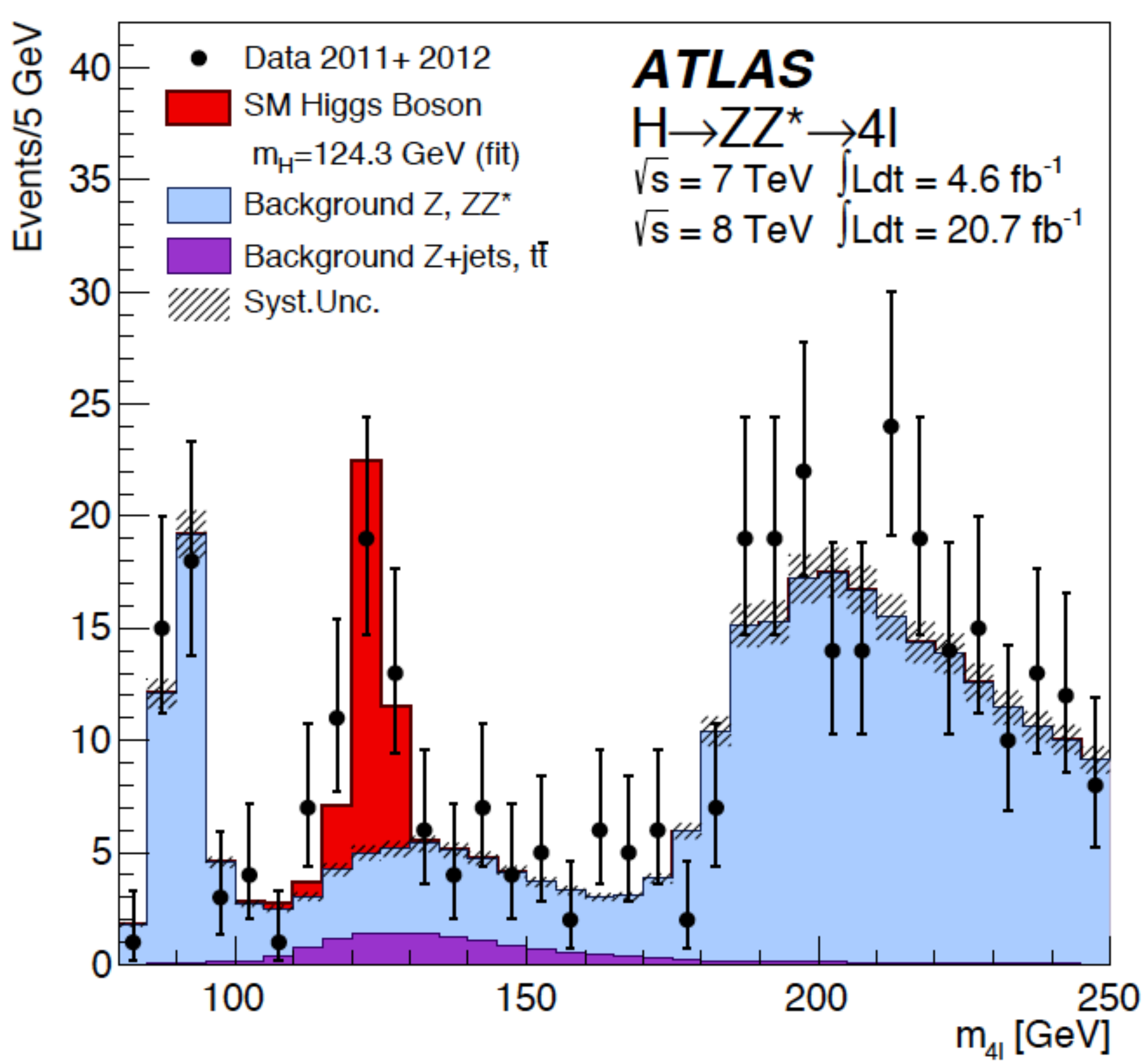
ATLAS analysis

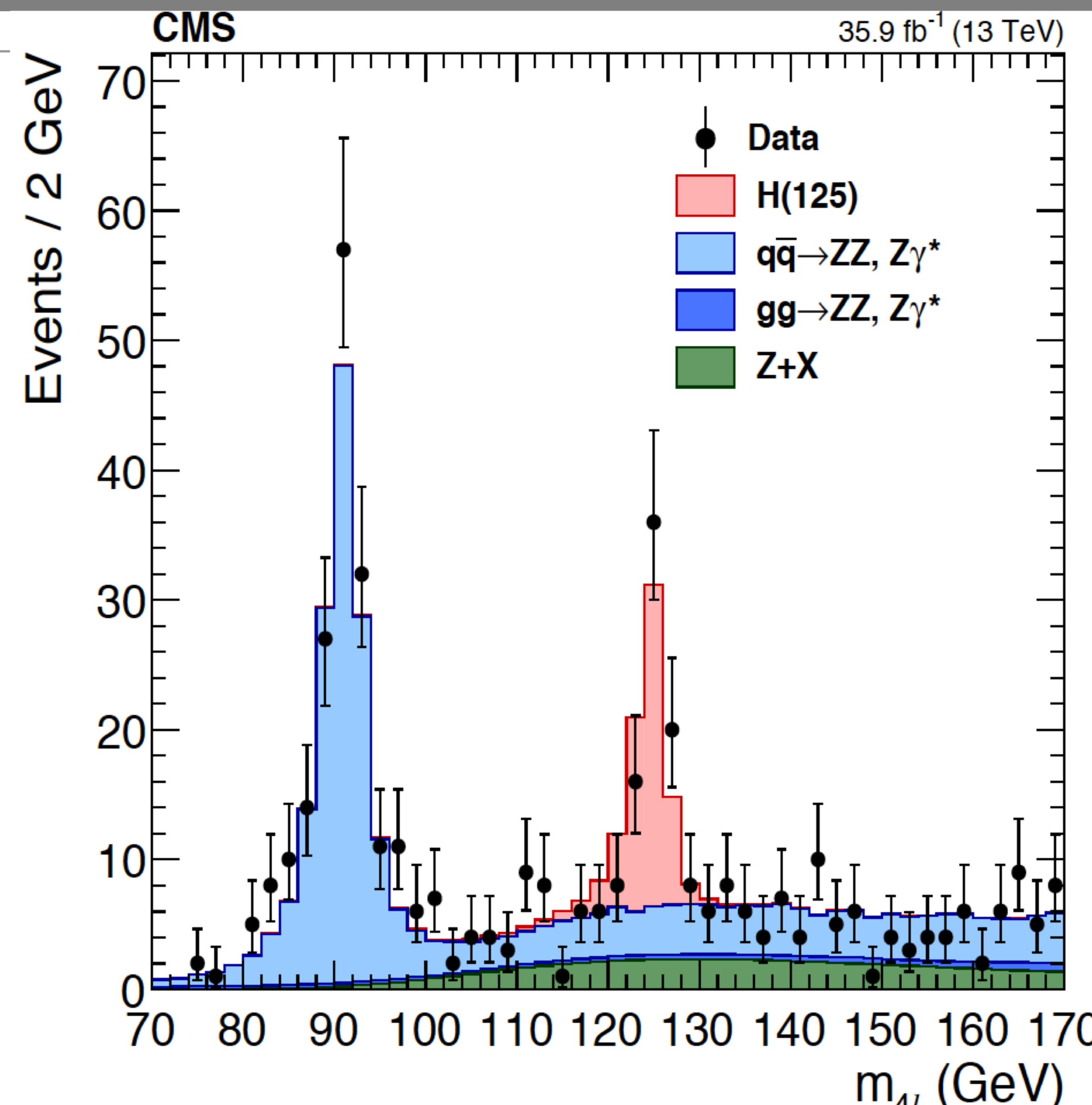




Schematic view of the event categorization. Events are required to pass the four-lepton selection, and then they are assigned to one of four categories which are tested sequentially: VBF enriched, VH-hadronic enriched, VH-leptonic enriched, or ggF enriched.

Higgs to 4 leptons





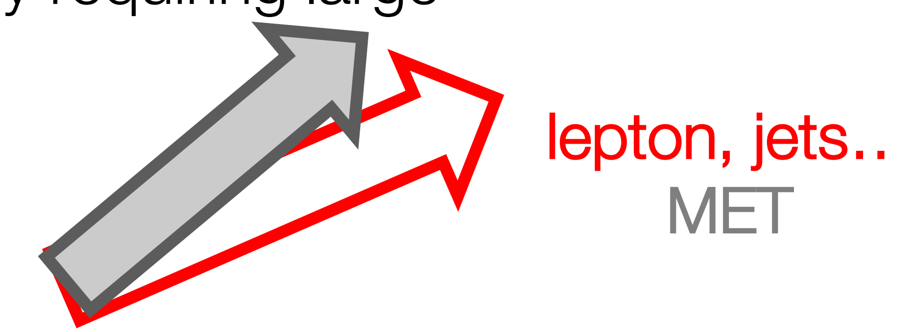
The signal strengths μ for the inclusive $H \to 4\ell$ production measured by the ATLAS and CMS experiments are $1.44^{+0.40}_{-0.33}$ at $m_H = 125.36\,\text{GeV}$ [129] and $0.93^{+0.29}_{-0.25}$ at $m_H = 125.6\,\text{GeV}$ [131] respectively, in Run 1. The signal strengths measured by the ATLAS and 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 > 24 GeV and the lepton has to be isolated: the scalar sum of the p_T of charged particles within $R = \sqrt{\phi^2 + \eta^2} = 0.2$ 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.
- Due to the detector geometry, the acceptance of the trigger is limited to $|\eta| < 2.4$.
- vertex quality & lepton quality
- $H \to WW(*) \to \ell\nu\ell\nu$ candidates (with $\ell = e, \mu$) 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

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



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.

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

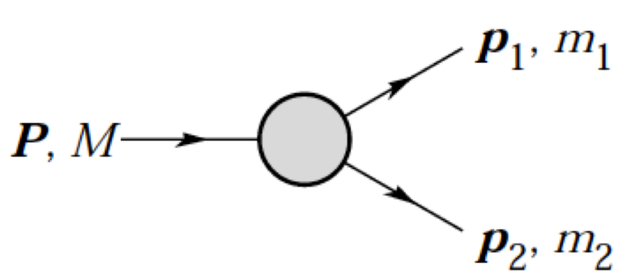
This is often used when one particle cannot be detected directly but is only indicated by missing transverse energy. In that case, the total energy is unknown and the above definition cannot be used.

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

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

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

So equivalently,



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

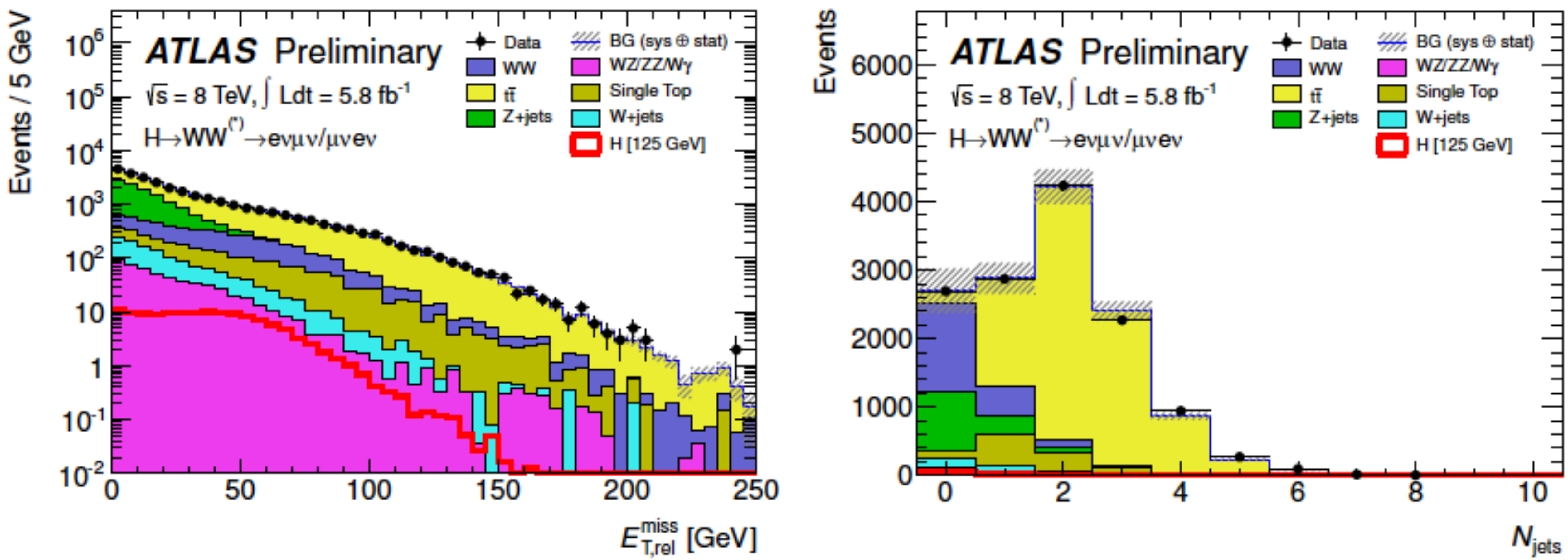
For massless daughters, where $m_1 = m_2 = 0$, the transverse energy simplifies to $E_T = |\vec{p}_T|$, and the transverse mass becomes

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

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.

Background in H→WW*



The background rate and composition depend on the jet multiplicity:

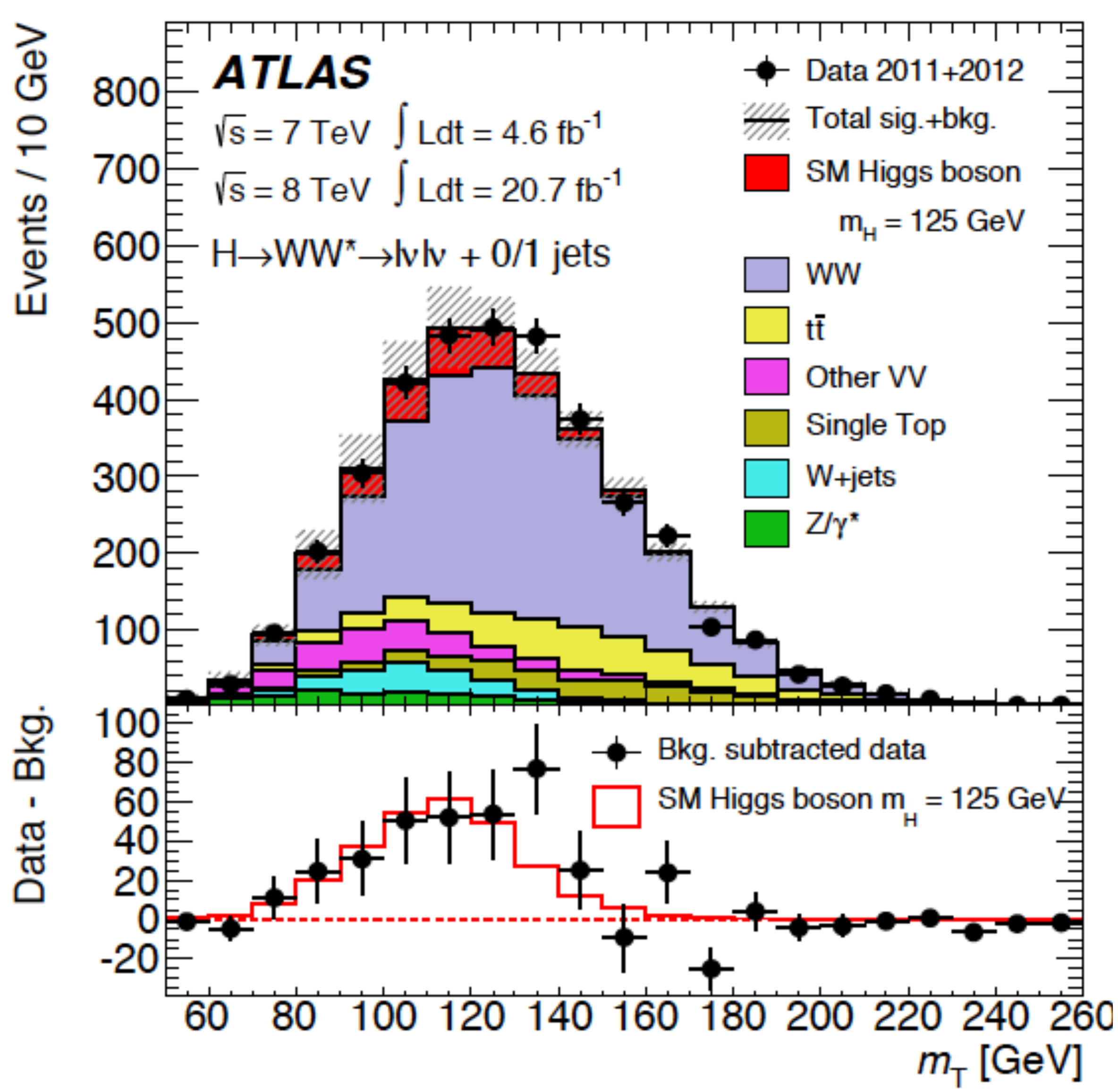
- Without jets, the signal originates from the ggF process and the background is dominated by WW and Drell-Yan events.
- with two or more jets, the signal contains a much larger contribution from the VBF process and the background is dominated by the tt production.

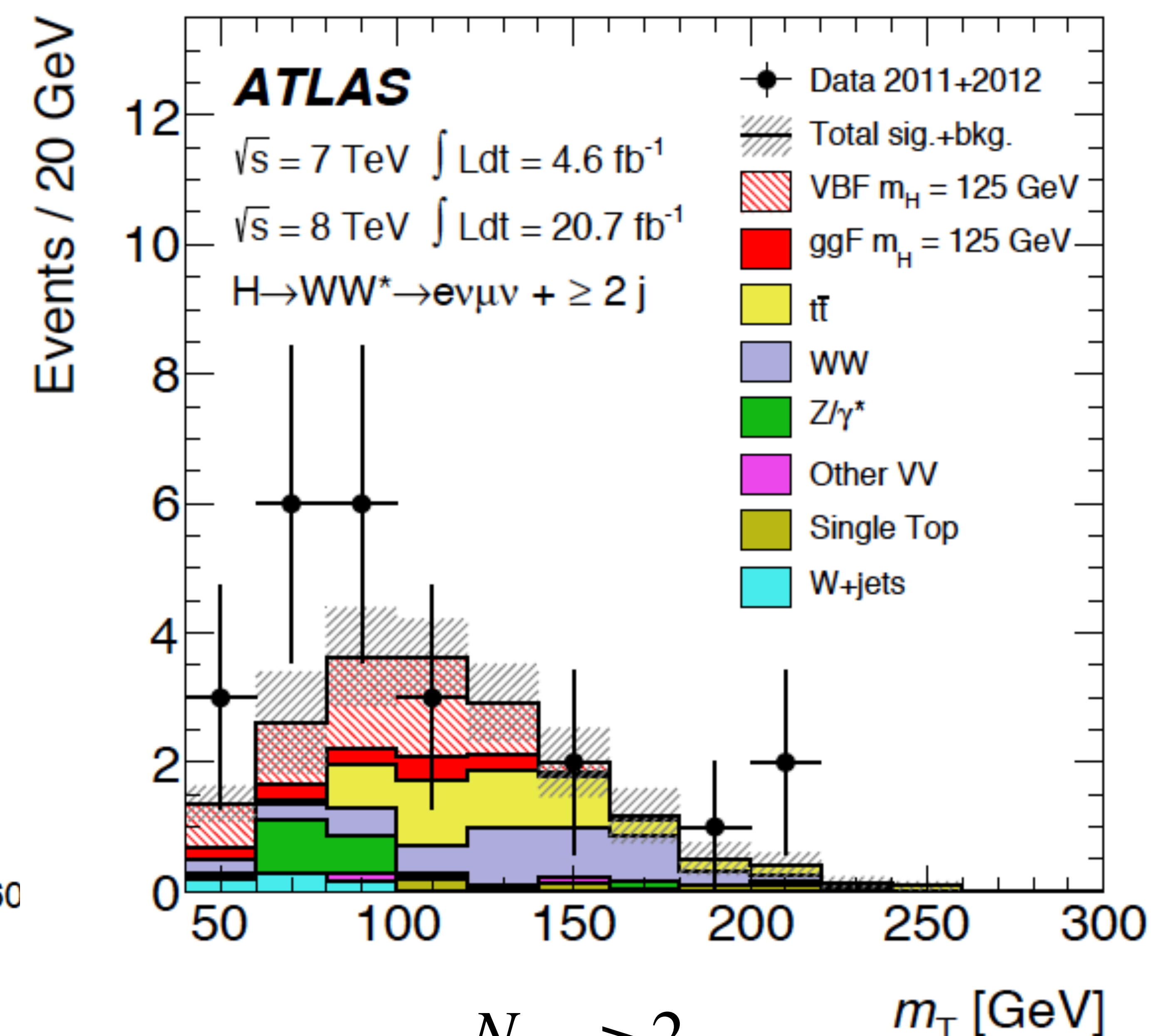
ATLAS:

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

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

Undetected υ's ➡ M_T



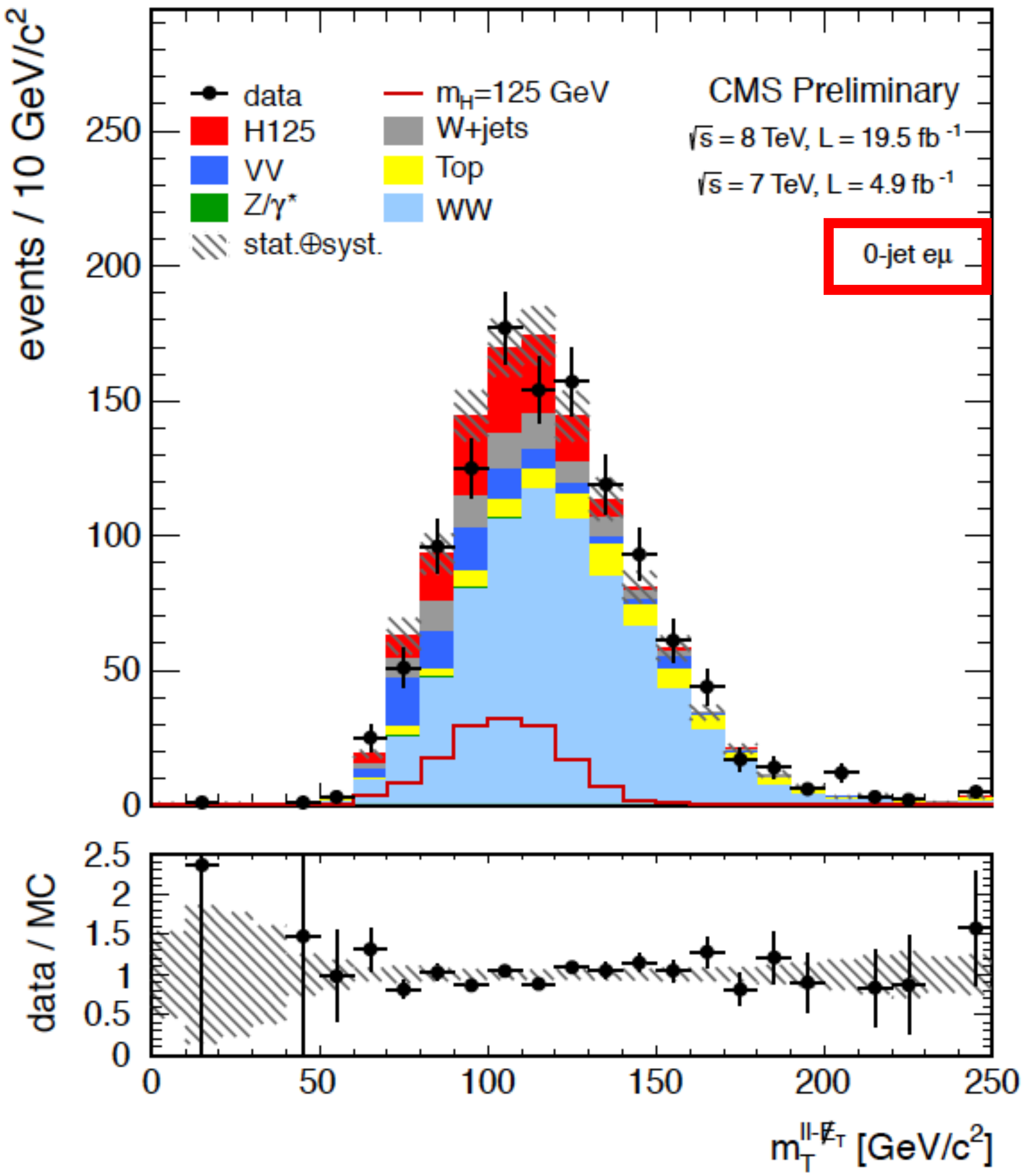


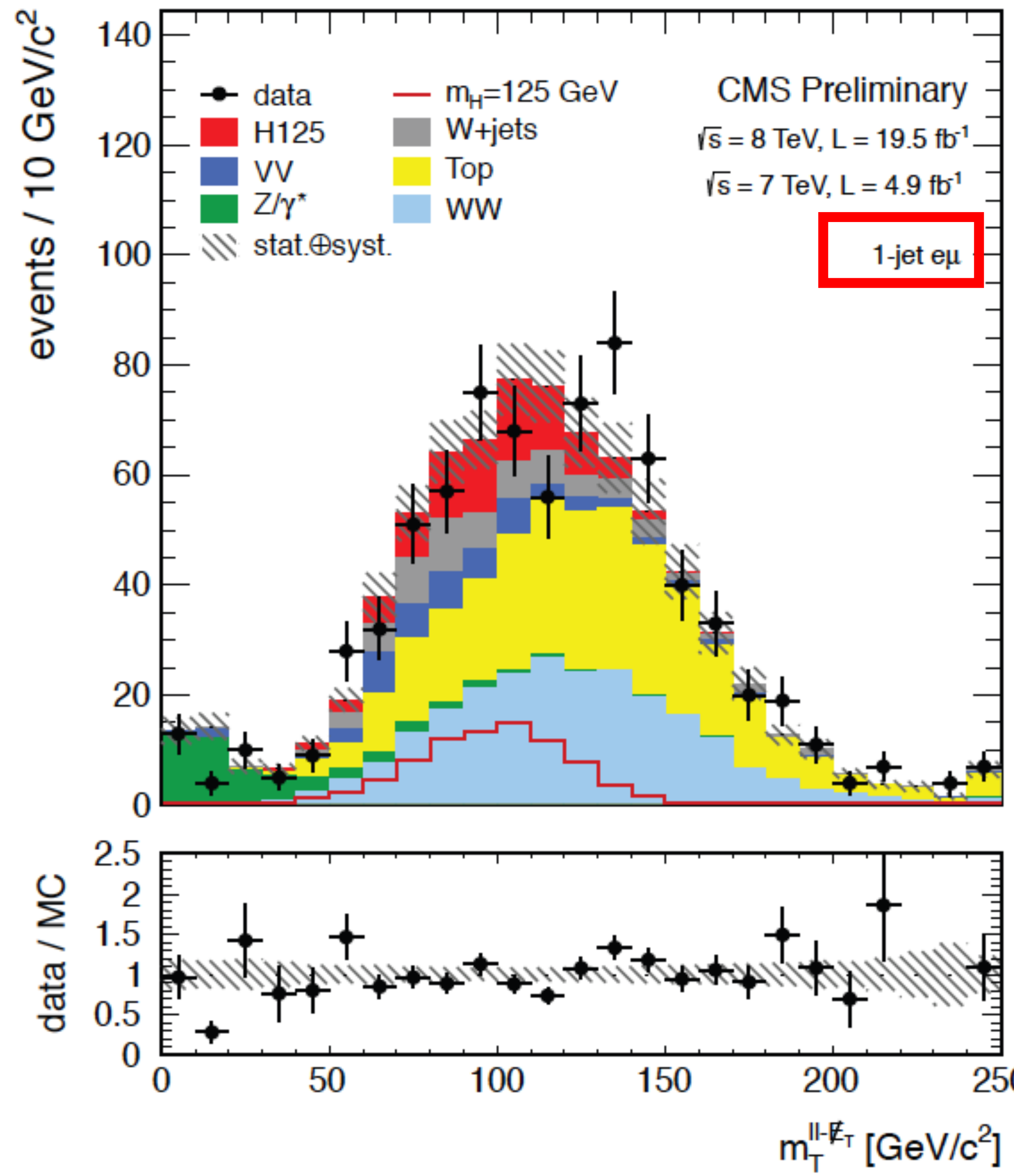
$N_{jets} \leq 1$

$N_{jets} \geq 2$

CMS :

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





ATLAS & CMS combination of Run 1 data

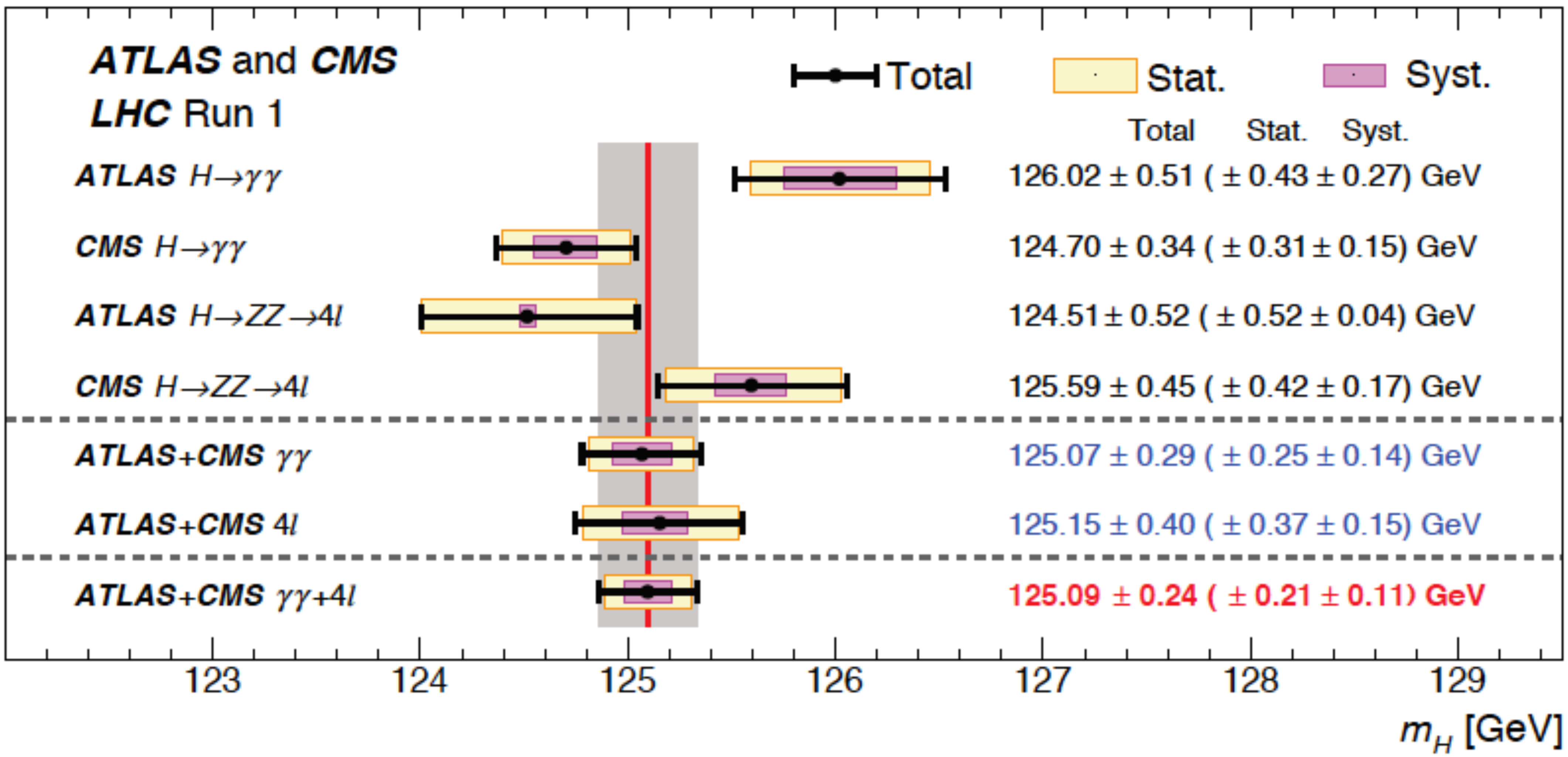
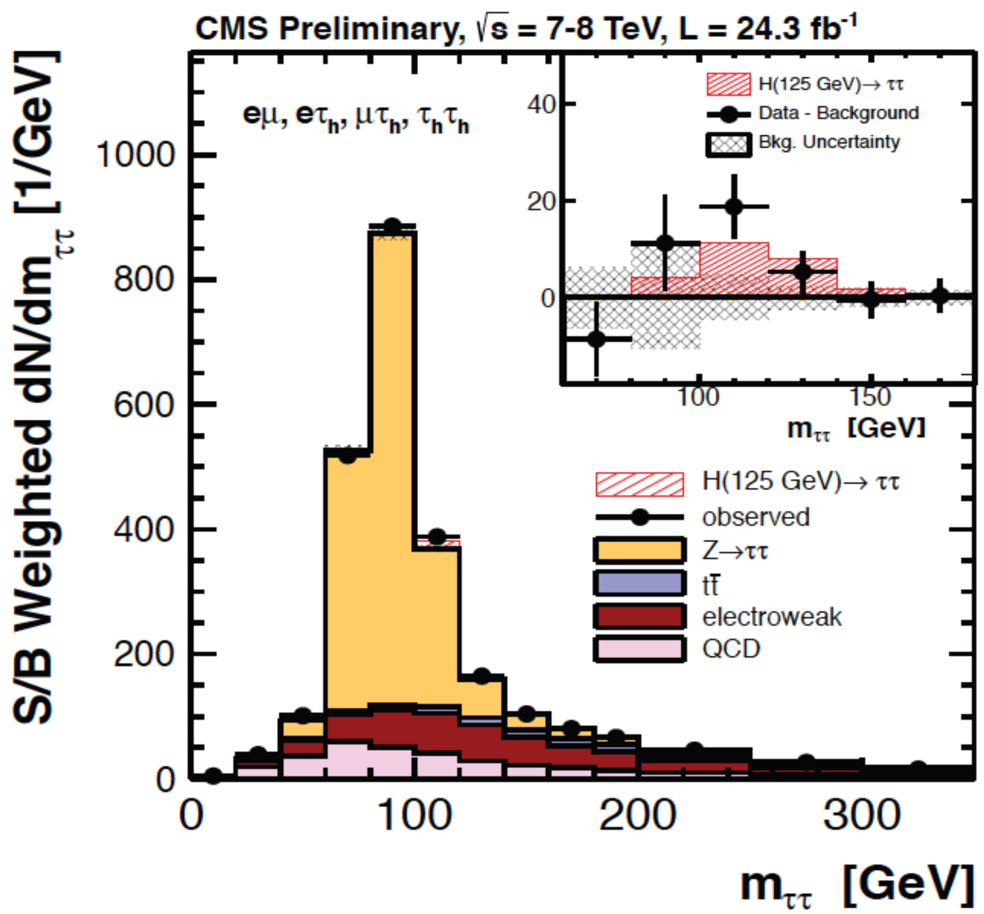


Figure 11.4: A compilation of the CMS and ATLAS mass measurements in the $\gamma\gamma$ and ZZ channels, the combined result from each experiment and their combination. From Ref. [134]

Higgs decays to fermions: $\tau\tau$



Leptons decaying to

- electrons (τ_e),
- muons (τ_μ) and
- Hadrons (τ_{had})

($m_{\tau\tau}$) is reconstructed from a kinematic fit of charged tracks from the two τ leptons and MET. Due to missing neutrinos the $m_{\tau+\tau-}$ resolution is poor (≈ 15%) → a broad excess is searched for.

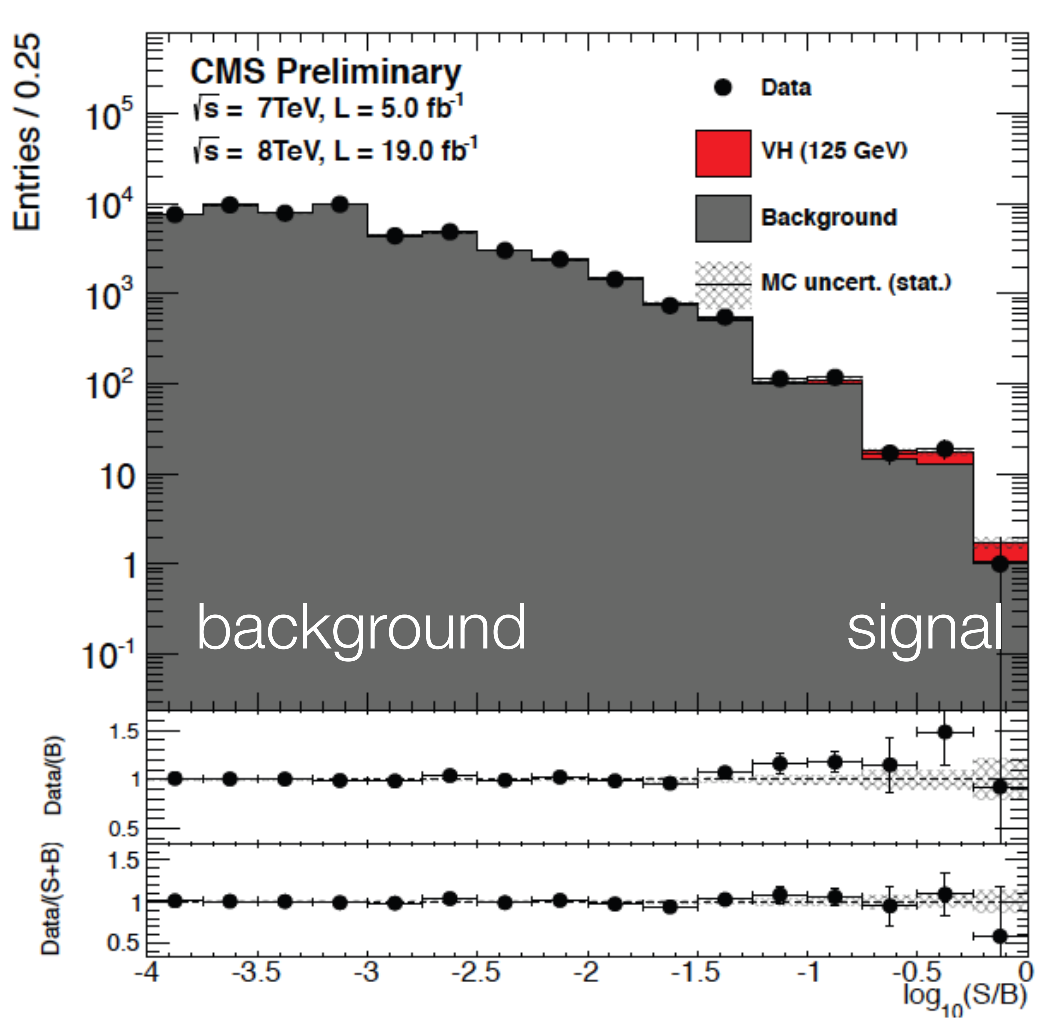
The major background is $Z \rightarrow \tau^+\tau^-$ and $Z \rightarrow e^+e^-$, W+jets, tt and multijet production.

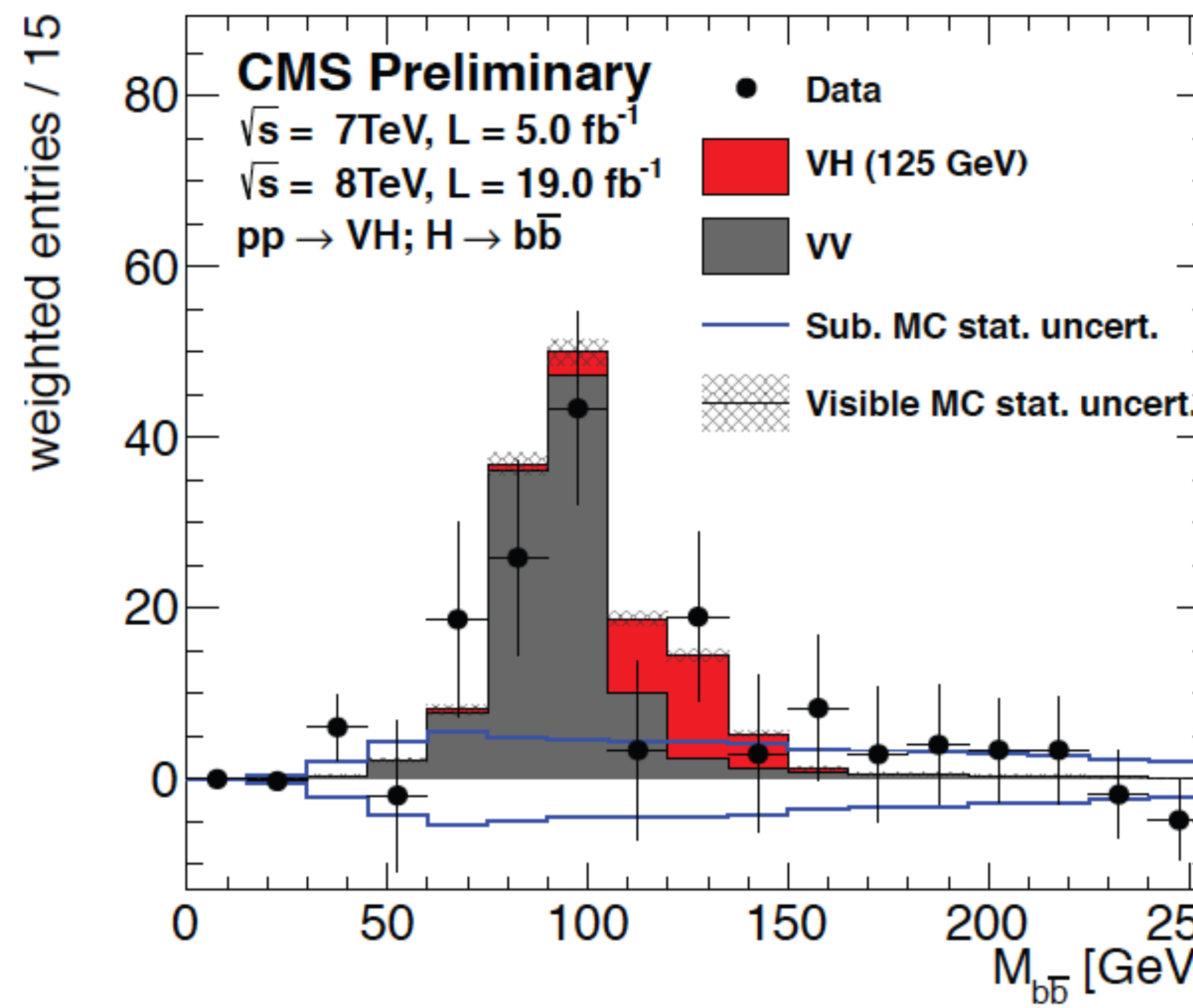
- CMS: the significance of the observed excess at m_H = 125 GeV in Run 1 is 3.2 standard deviations, and corresponds to a signal strength of μ = 0.86±0.29.
- ATLAS: the best fit value of the signal strength is μ = 1.43+0.43–0.37.
- ATLAS and CMS H → τ τ Run 1 measurements are combined , the significance of the observed excess is 5.5 standard deviations and the combined signal strength is

$$\mu = 1.11^{+0.24}_{-0.22},$$

consistent with the Standard Model expectation.

Higgs decays to fermions : bb





In the search for the Higgs decay to bb most sensitive production is VH, V=Z,W

- Multivariate analysis
- The presence of “clean” leptonic decays allows triggering & reject QCD background
- Higgs is reconstructed from two b-tagged jets in the event
- Background: mostly di-bosons ZZ and WZ with $Z \to b\bar{b}$
- Poor resolution in $m_{b\bar{b}}$ → broad excess in the $m_{b\bar{b}}$ distribution

Higgs to bb: results Run1+Run2

$H \to b\bar{b}$	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

Signal strength: μ is the ratio between the observed cross section and the one predicted by the SM