Higgs and other searches at LHC

Igor Boyko


LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

The LHC

- Proton-proton collider at CERN (Geneva)
- Collision energy: 14 TeV (design), 8 TeV (reached)
- Luminosity: 10^{34} (design), 0.77×10^{34} (reached)
- 4 major experiments:
  - ALICE (heavy ions)
  - LHCb (b-physics)
  - ATLAS, CMS (general-purpose)

[Some of] ATLAS/CMS goals

- **Measurements**
  - Electroweak physics
  - QCD
  - top-quark physics
  - heavy-flavors (b-physics, D mesons)
- **Searches**
  - Higgs
  - SUSY
  - Exotics

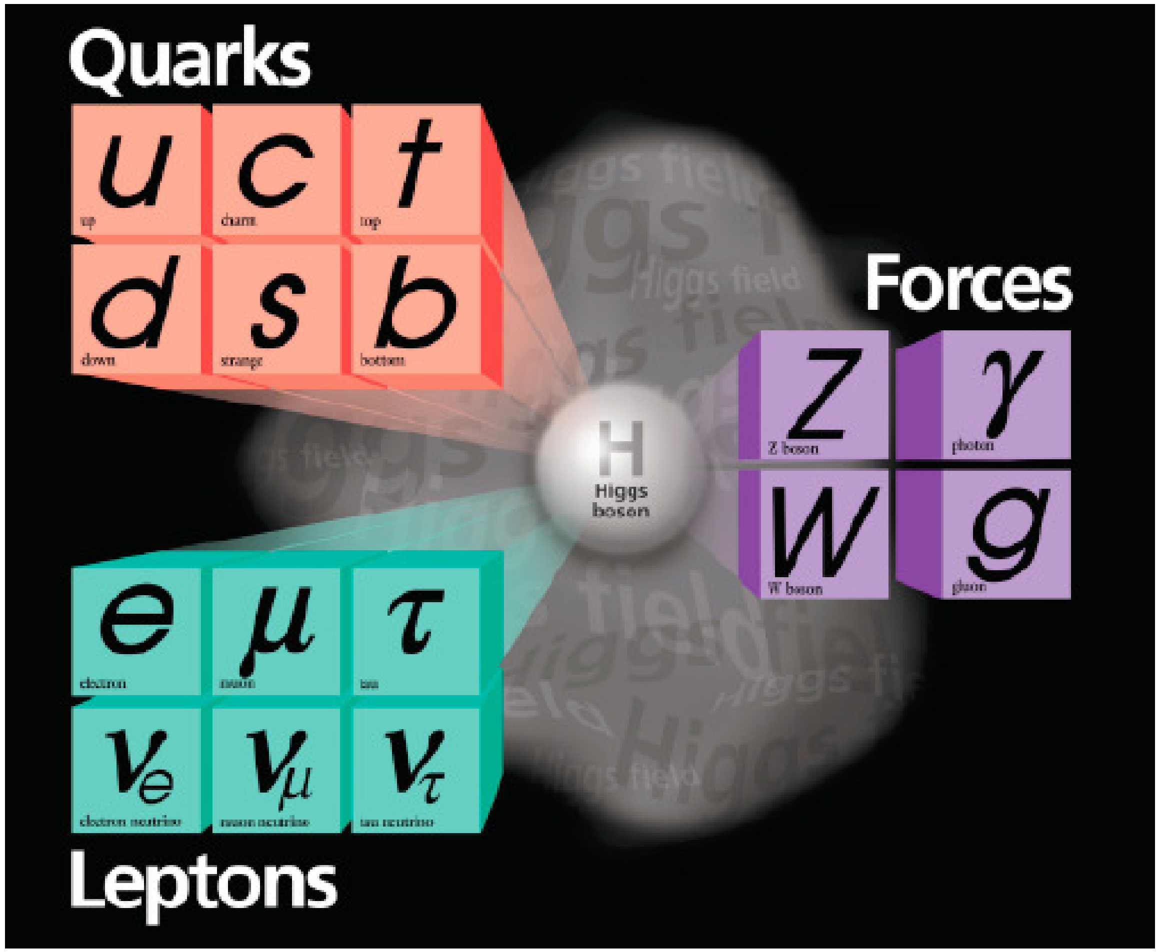
Higgs boson searches

1964: invention

- **Higgs.** **Phys.Lett. 12:132 (1964)**
- **Englert, Brout. PRL 13:321 (1964)**
- **Guralnik, Hagen, Kibble. PRL 13:585 (1964)**

2010

Particles, forces and …Higgs



Higgs boson solves two problems

1. In gauge theories interaction is mediated by a massless particle
   - But from the muon decay, $G_F \approx (1/300\ \text{GeV})^2$
   - Introduction of a Higgs scalar field generates non-zero mass of gauge bosons
2. Cross-sections of scattering WW→WW, WW → ZZ diverge like E^4, violating unitarity
   - Diagrams with Higgs cancel this divergence. Term E^4 is replaced by $(M_H)^4$

What we knew before LHC

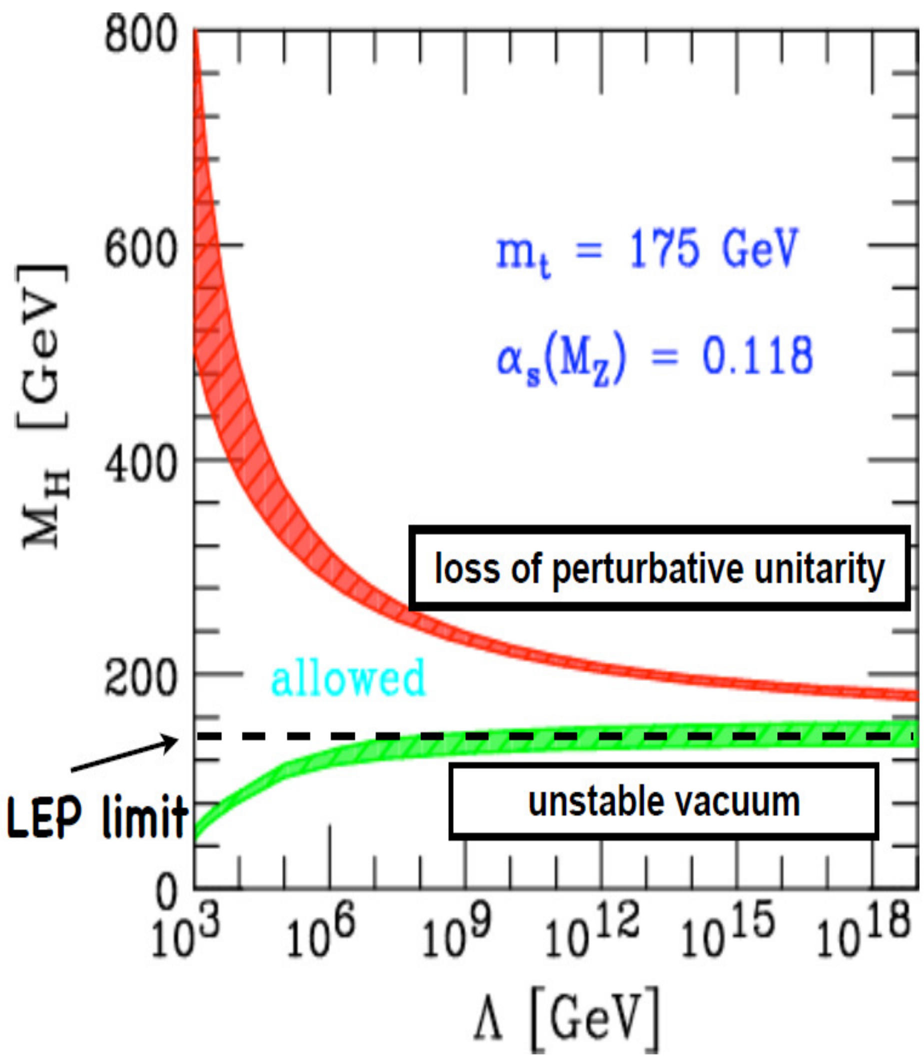
- Theoretical constrains
- Indirect experimental constrains (**LEP1+LEP2+Tevatron**)
- Direct searches of Higgs boson:
  - **LEP-2**
  - **Tevatron**

Note: in Standard Model all Higgs boson properties are predicted if M_H is known

M_H is (was!!) the last unknown

Theoretical constrains on M_H

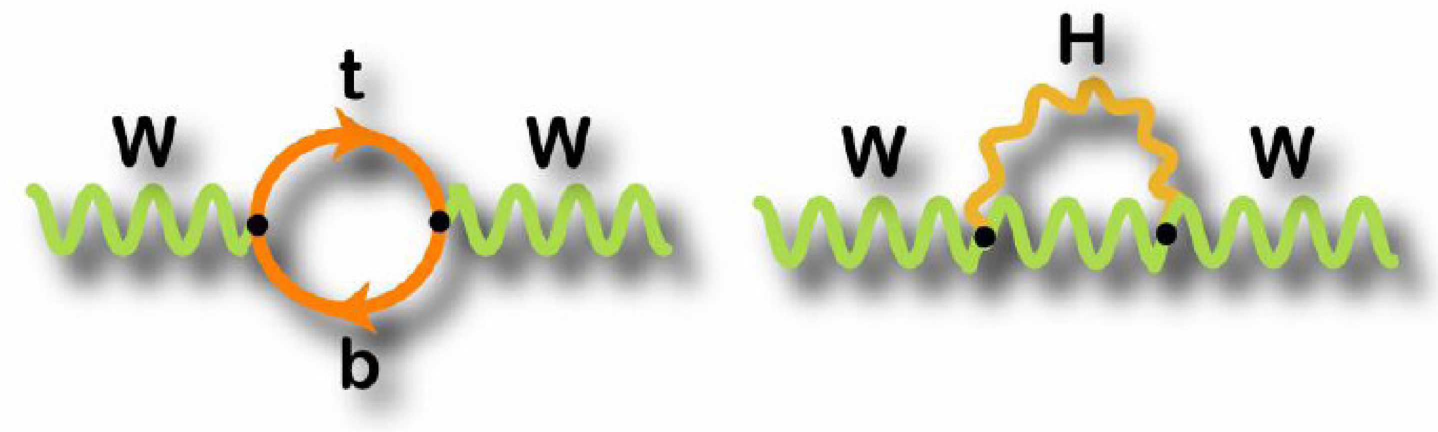
Renormalizability of the theory



- If SM is valid up to 10^{16} GeV, then $130<M_H<170$ ГэВ
- If valid up to 1 TeV, then $70<M_H<700$ GeV
- In addition, from the unitarity of WW→WW scattering: $M_H<710$ GeV

Indirect experimental constrains on M_H

Radiative corrections

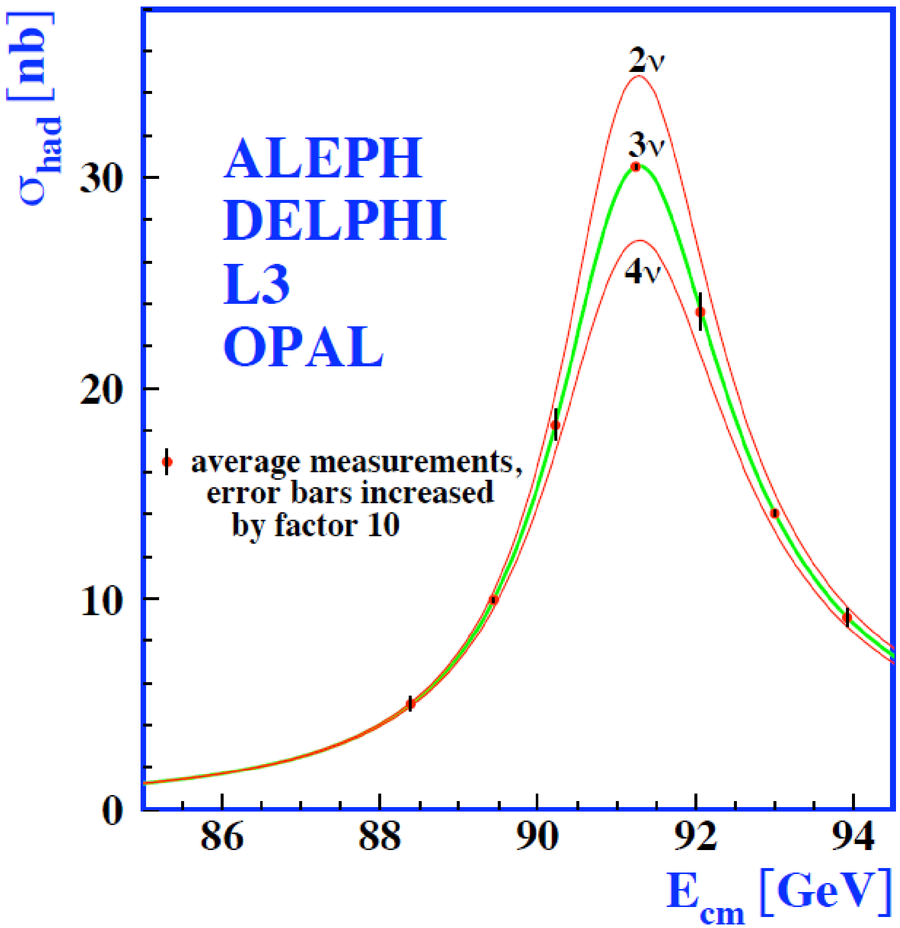


$$\rho = \frac{M_W^2/M_Z^2}{1-\sin^2\Theta_W} =$$

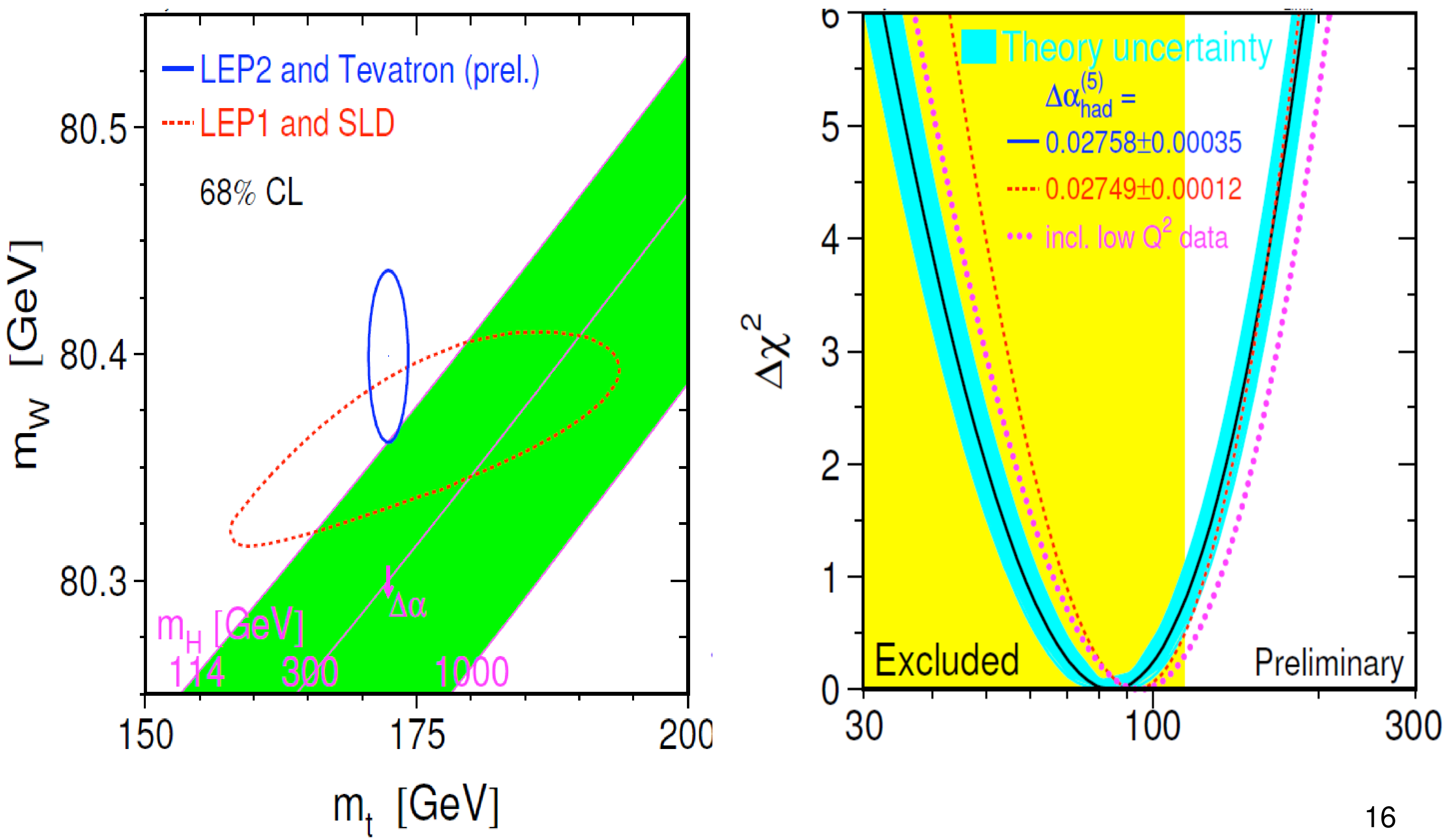
$$= 1 + \frac{3G_F}{8\pi^2\sqrt{2}} m_t^2 + \frac{\sqrt{2}G_F}{16\pi^2} m_t^2 \left[\frac{11}{3} \ln\left(\frac{M_H^2}{M_W^2}\right) + \ \ldots \right] + \ldots$$

Ingredients for M_H

- M_Z : LEP1
- $\sin\Theta_W$: LEP1
- M_W : LEP2, Tevatron
- m_t : Tevatron
- G_F : muon decay
- α_S : LEP1
- α_{EM} : Novosibirsk, BES, B-factories

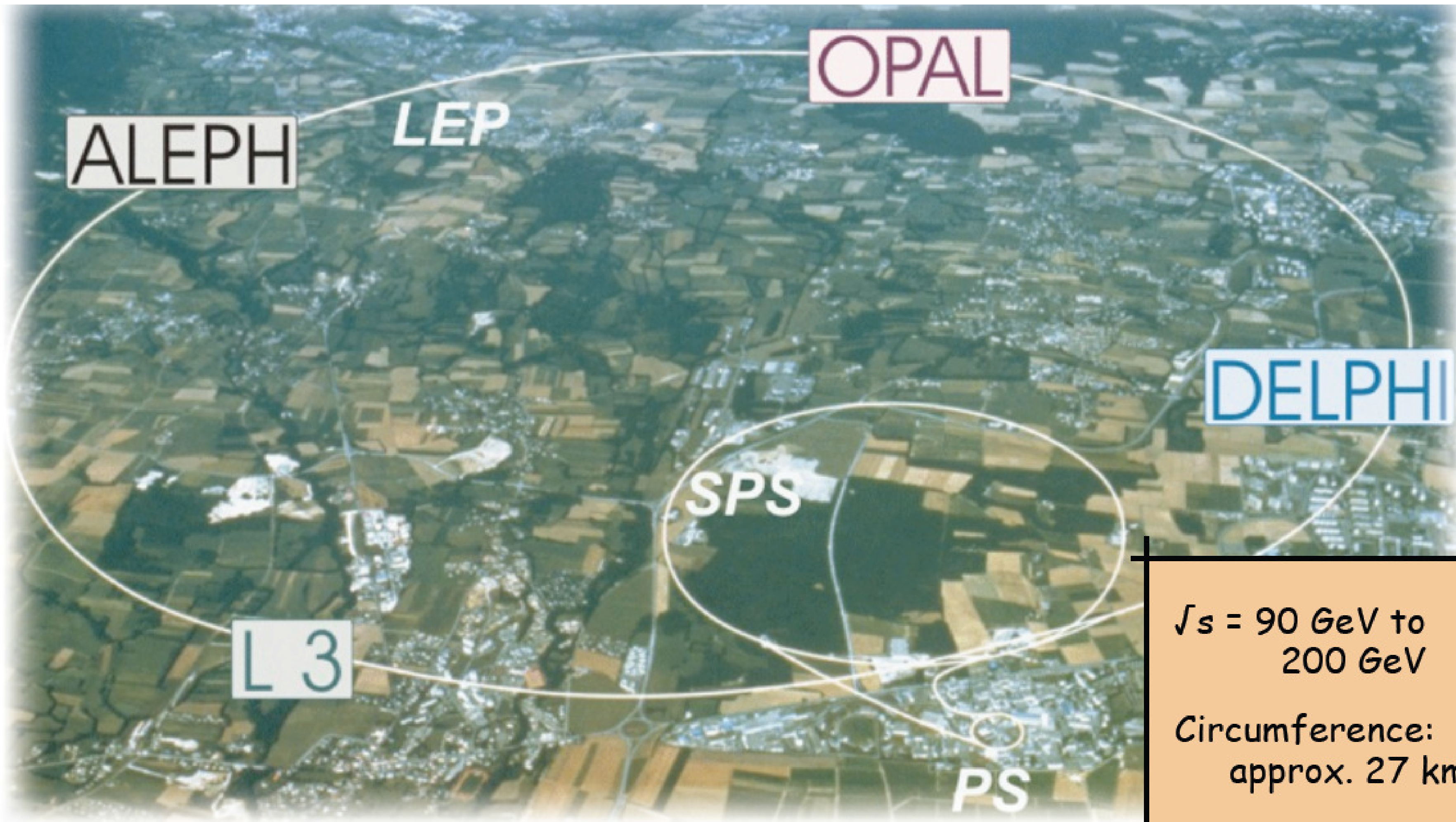


M_H=88±29GeV, M_H<161GeV (95%CL)



Direct Higgs search at LEP

LEP collider (1989-2000)

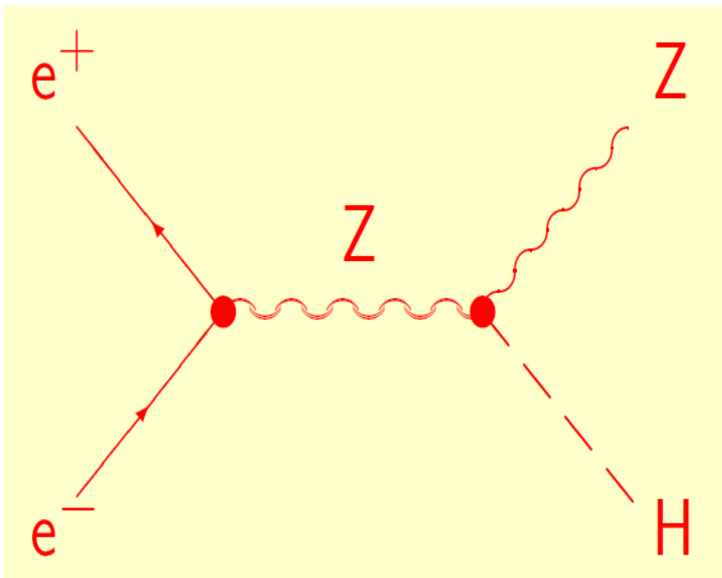


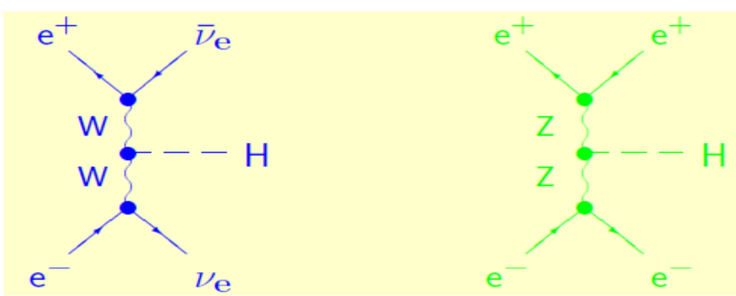
$\sqrt{s}$ = 90 GeV to 200 GeV

Circumference: approx. 27 km

4 Experiments

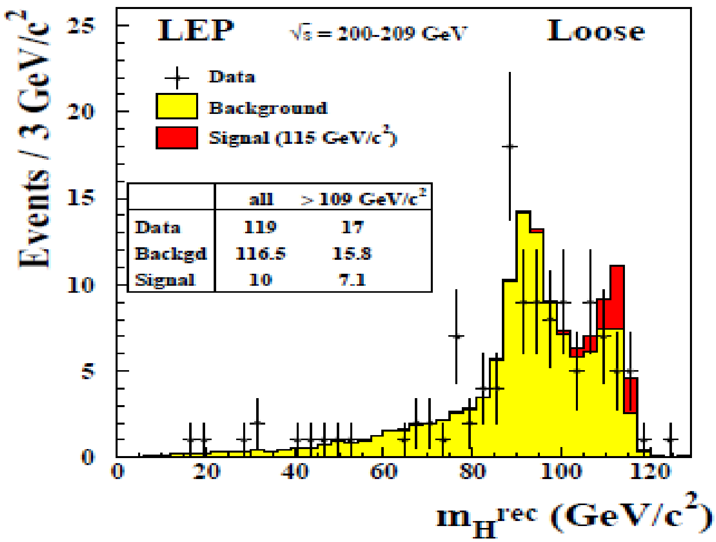
Associated ZH production

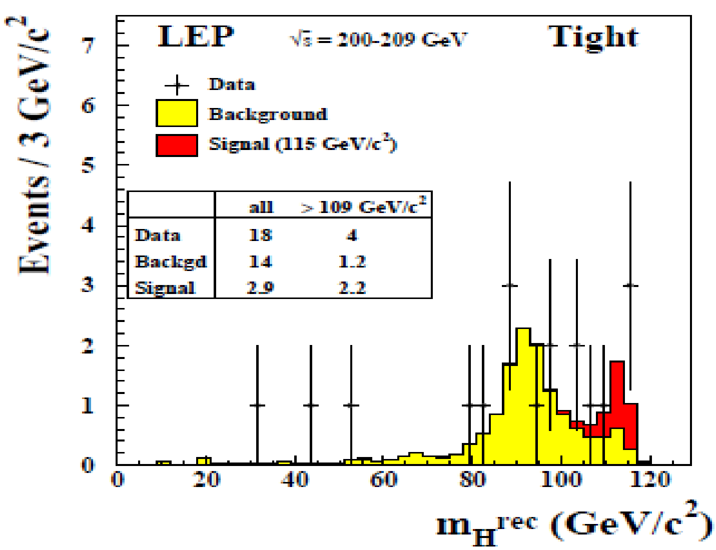




- **ee → ZH**
- H →bb/ττ (82%/9%)
- Z → qq/ee/μμ/νν
- Experimental reach $M_H \approx E_{CM} - M_Z$
- Maximum LEP-2 energy: 206.5 GeV
  - (+ very small statistics at 209 GeV)

M_H>114.4 GeV (95%CL)

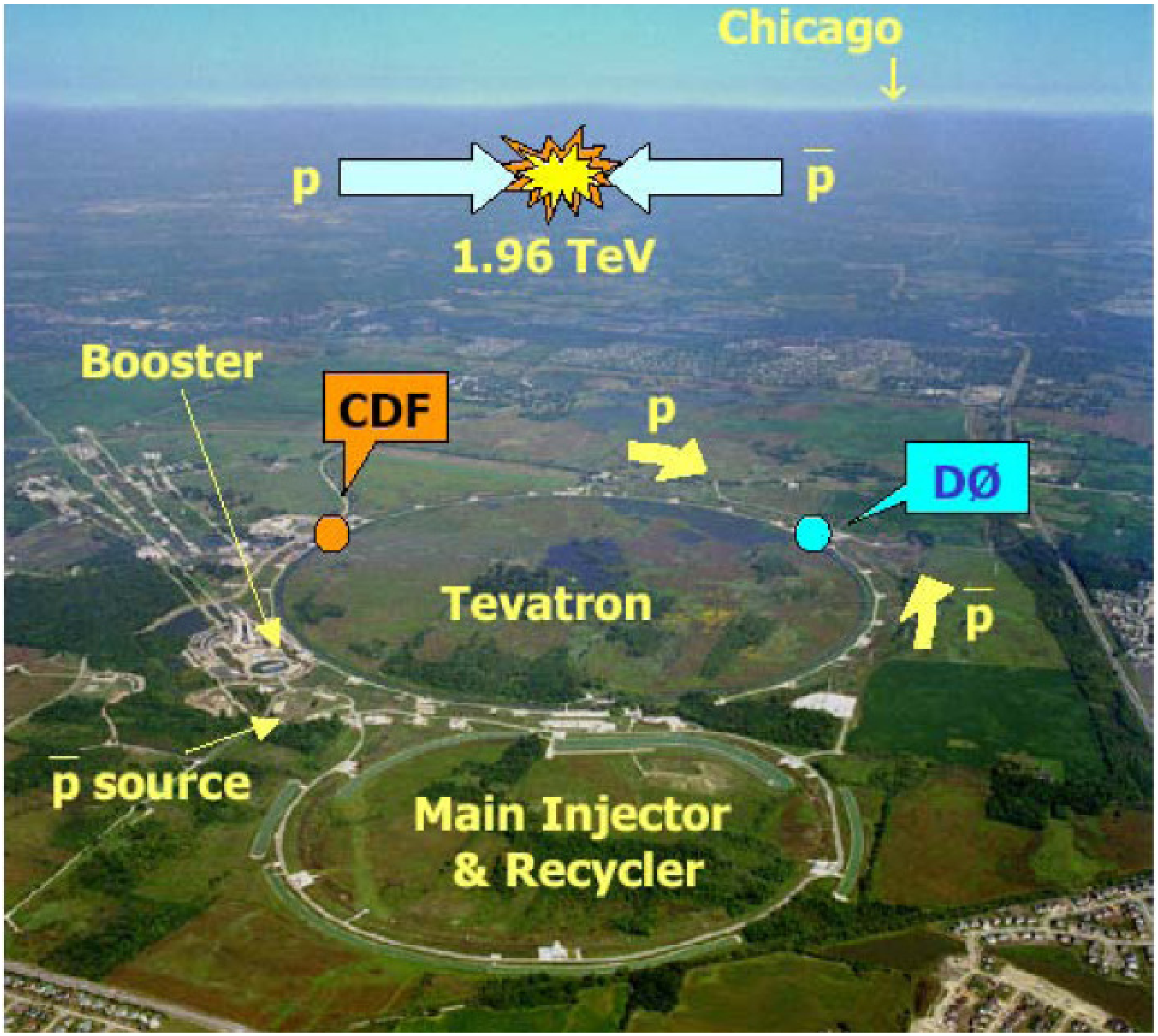




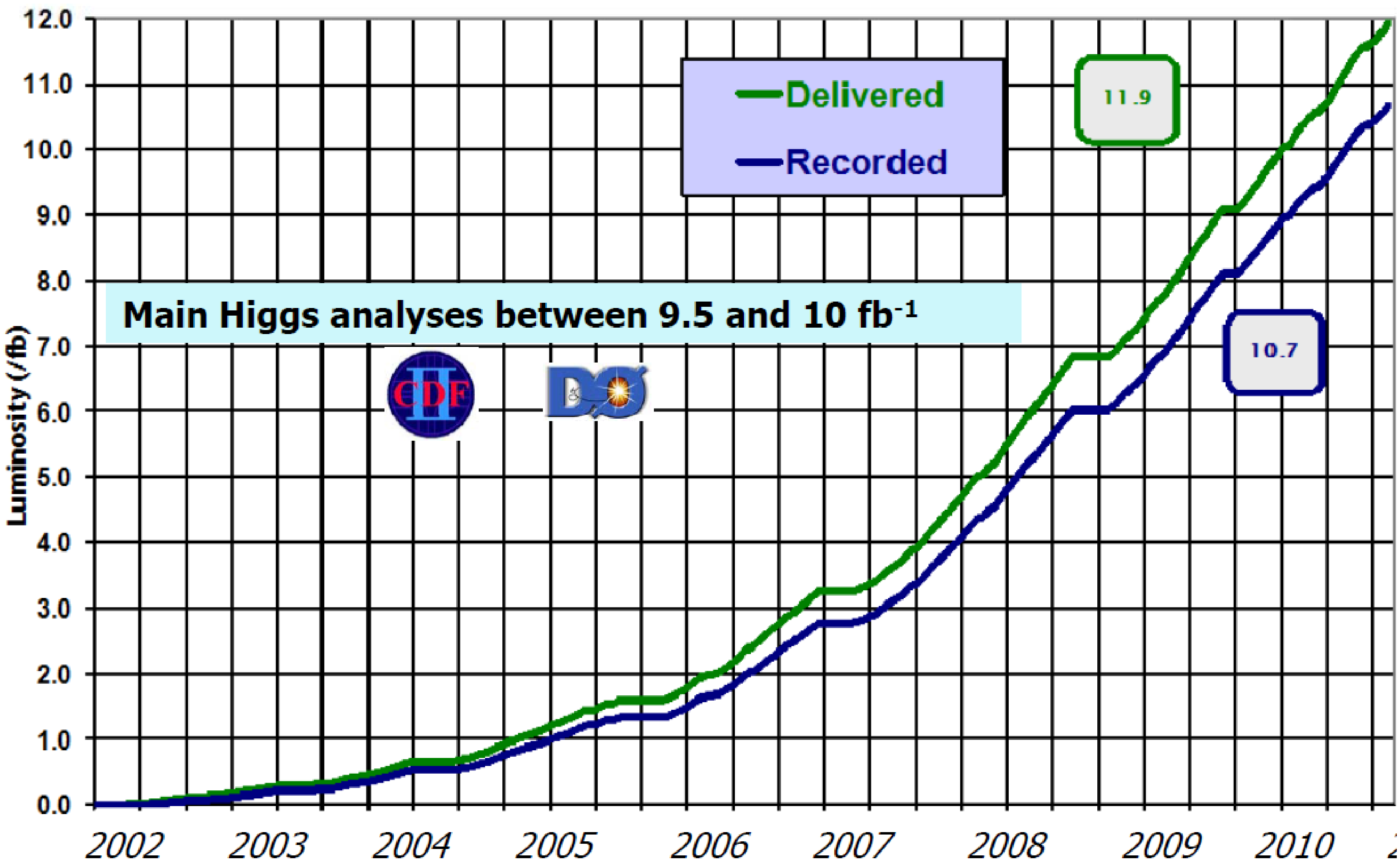
- LEP found 4 events around 115 GeV
- Expected background: 1.2 events
- Lower limit: M_H>114.4 GeV (expected limit 115.3)
- After hot debates LEP was closed to concentrate resources on LHC

Direct Higgs search at Tevatron

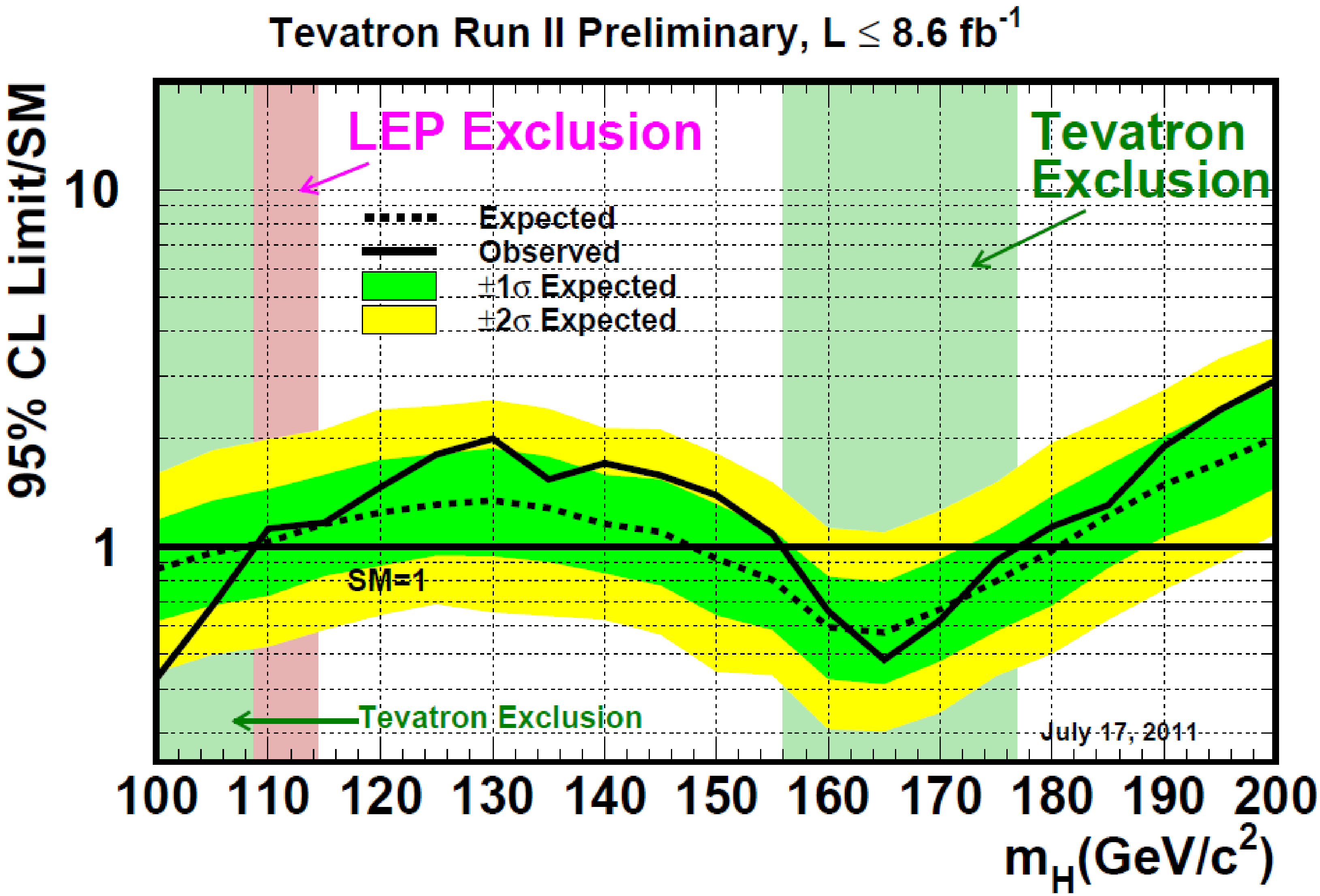
Tevatron accelerator complex



Integrated luminosity per experiment



Last result before LHC joined the game: excluded $156<M_H<177$ GeV



Direct Higgs search at LHC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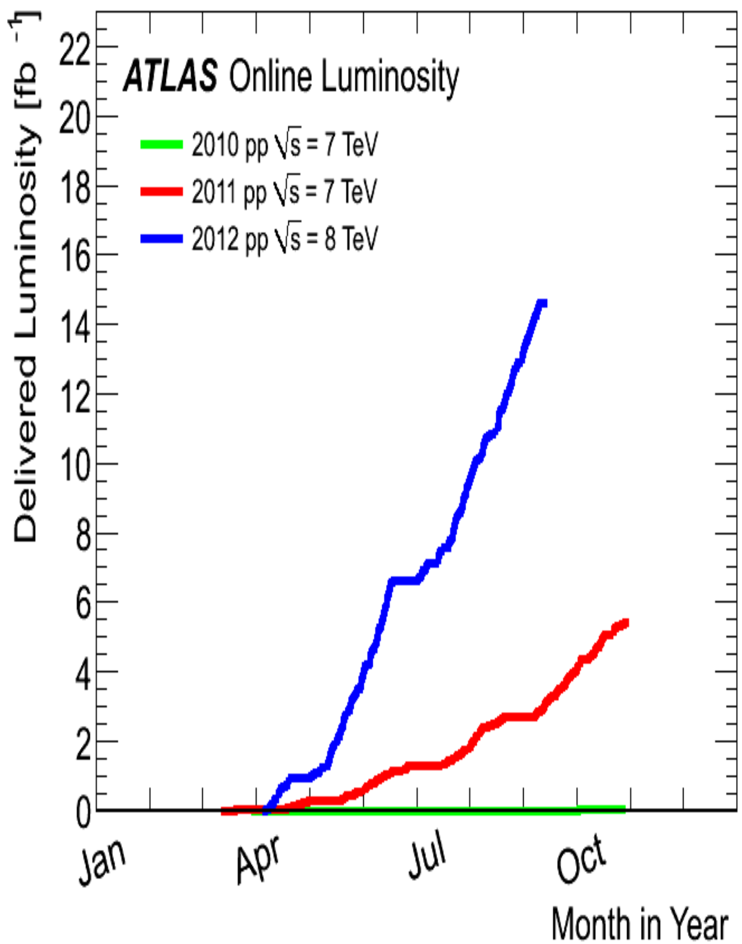
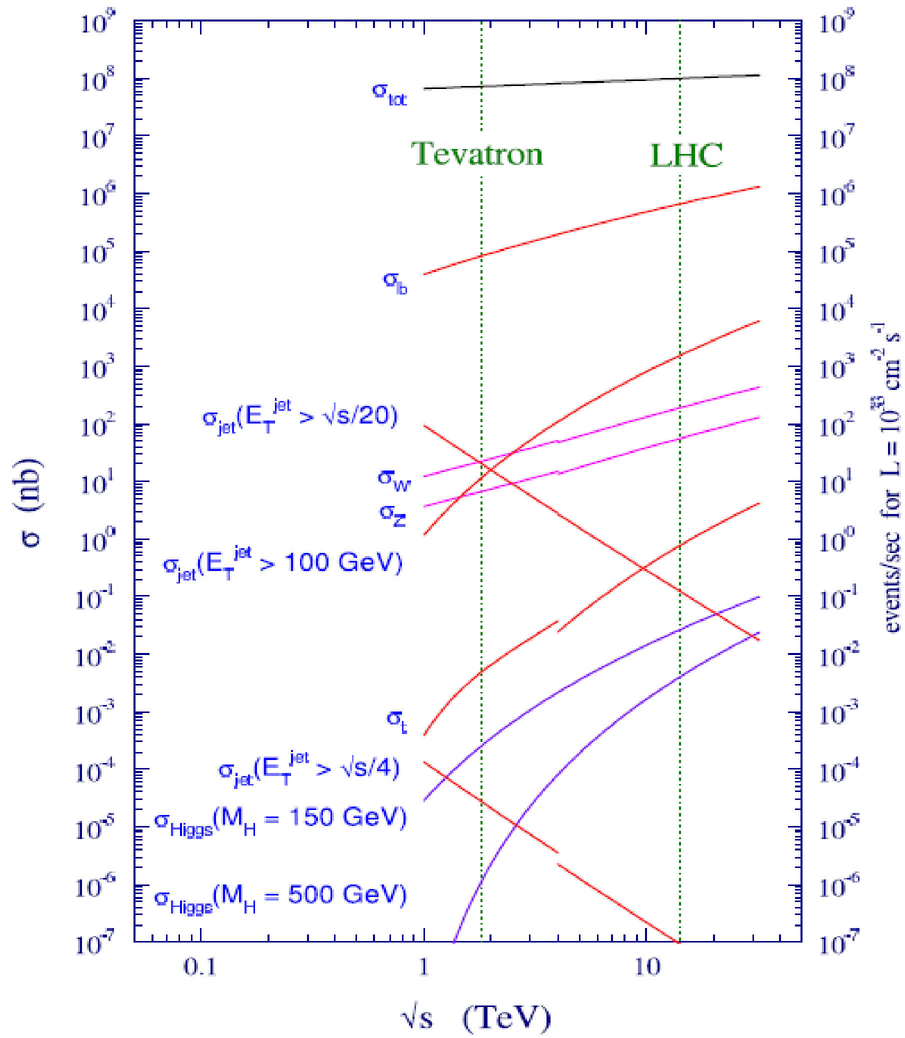
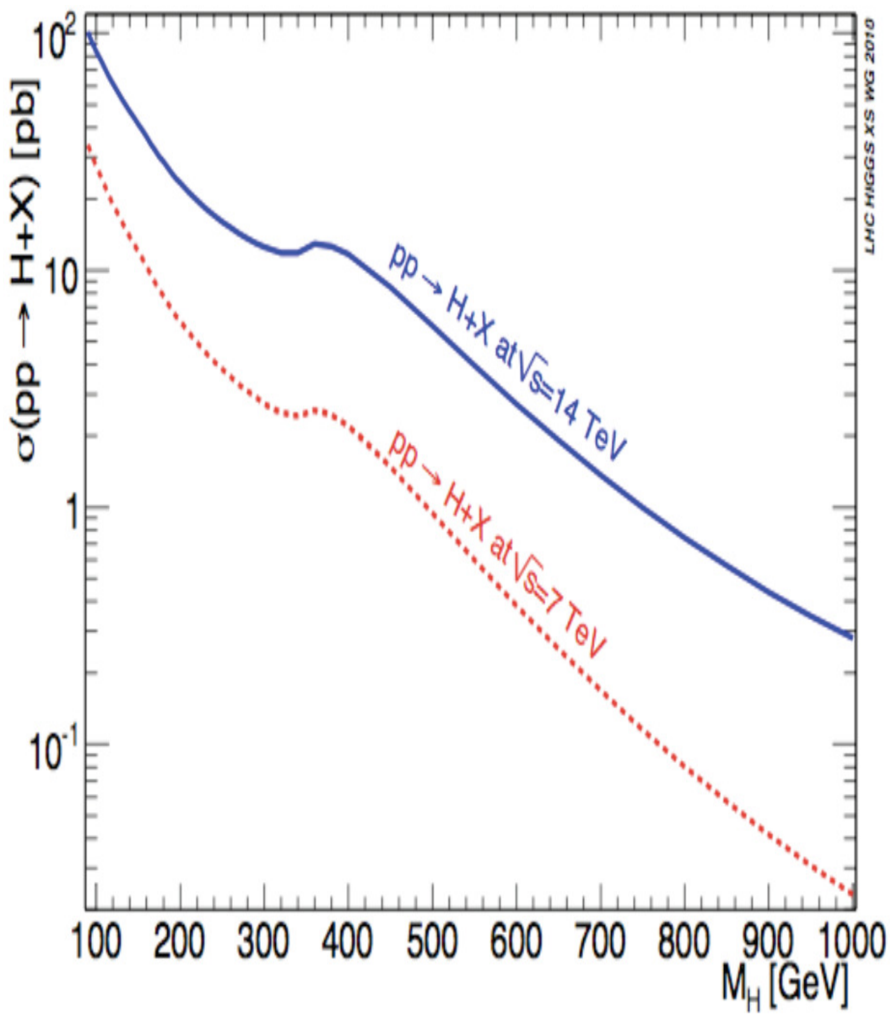
LHC operation



- 2010: warm-up
- 2011: 7 TeV
  - ➢ 5 pb^{-1}
- 2012: 8 TeV
  - ➢ 6 pb^{-1} by summer conferences
  - ➢ 15 pb^{-1} by now
  - ➢ 20-25 pb^{-1} by the end of year
- 2015: 13-14 TeV

Cross-section vs energy vs M_H





Higgs decay modes

$$\Gamma(H \to f f) \sim M_H M_f^2$$

$$\Gamma(H \to WW) \sim M_H^3/2$$

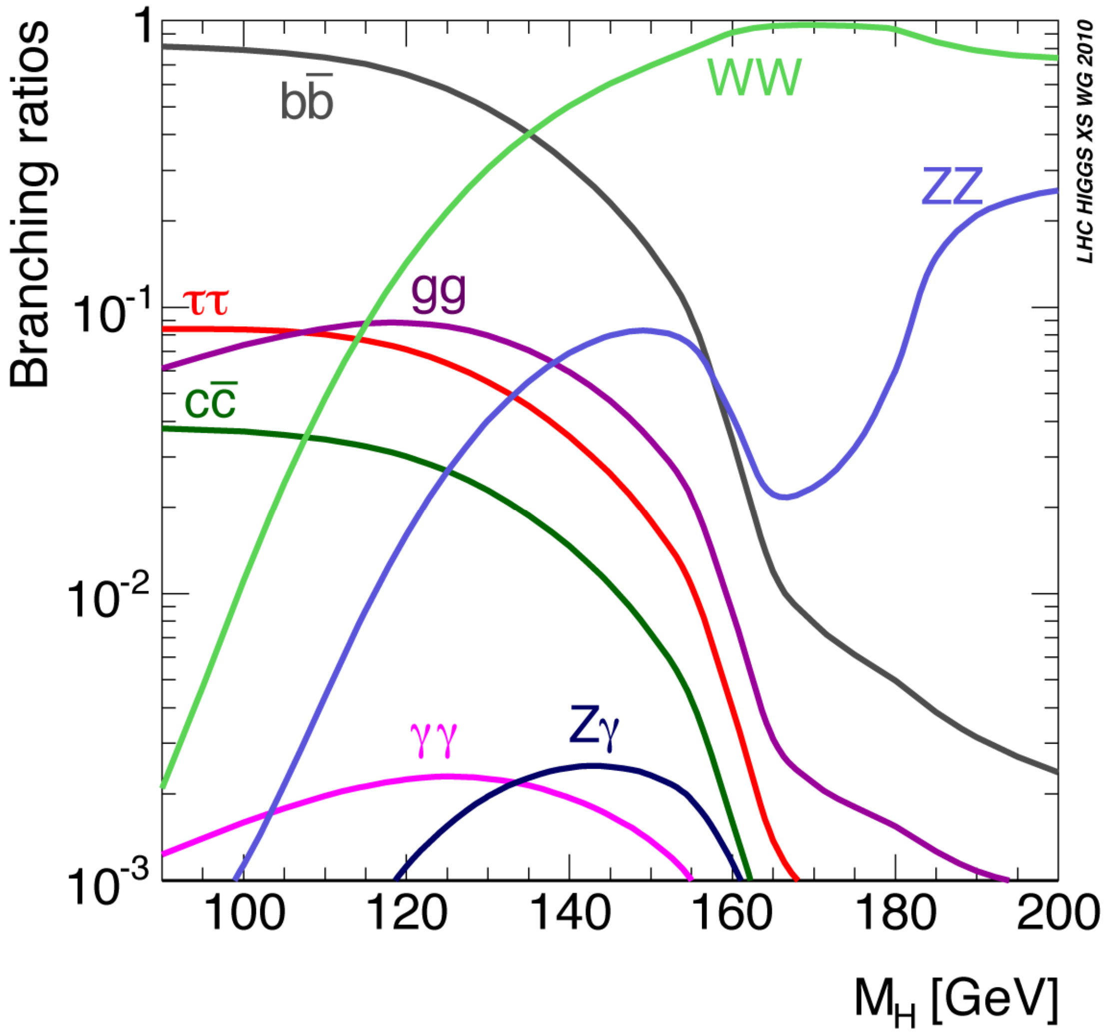
$$\Gamma(H \to ZZ) \sim M_H^3/4$$

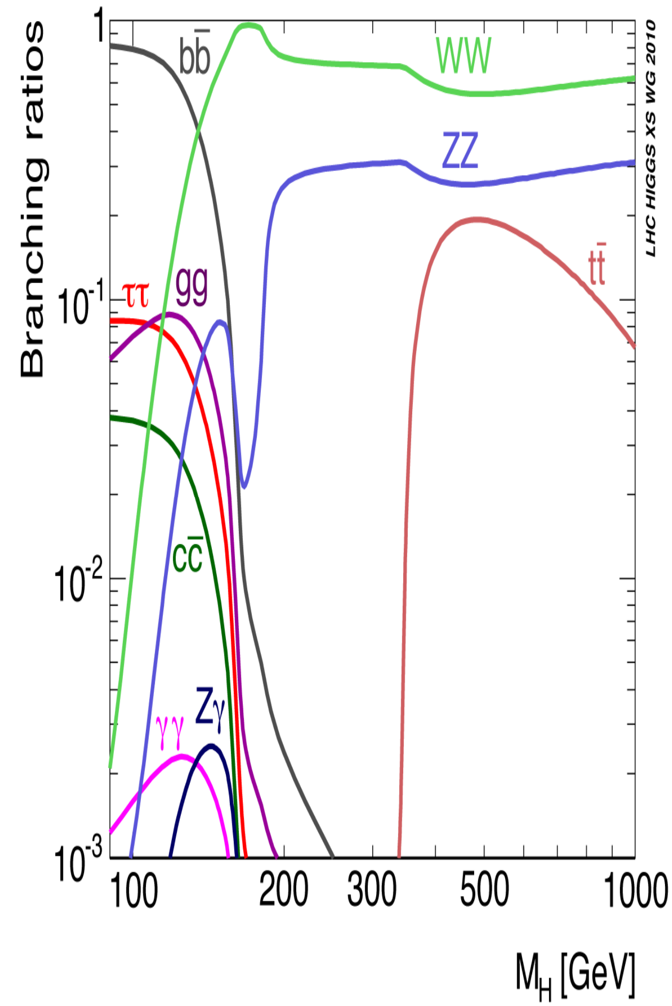
$$\Gamma(H \to gg) \sim M_H^3 \frac{\alpha_S^2}{9\pi}$$

$$\Gamma(H \to \gamma\gamma) \sim M_H^3 \frac{49\alpha_{EM}^2}{32\pi}$$

- Fermionic decay width proportional to the fermion mass squared
- Higgs decays to a pair of heaviest fermions (b-quarks)
- Decays to boson pairs WW and ZZ are dominant if **$M_H > 2M_{W(Z)}$**

Higgs decay modes

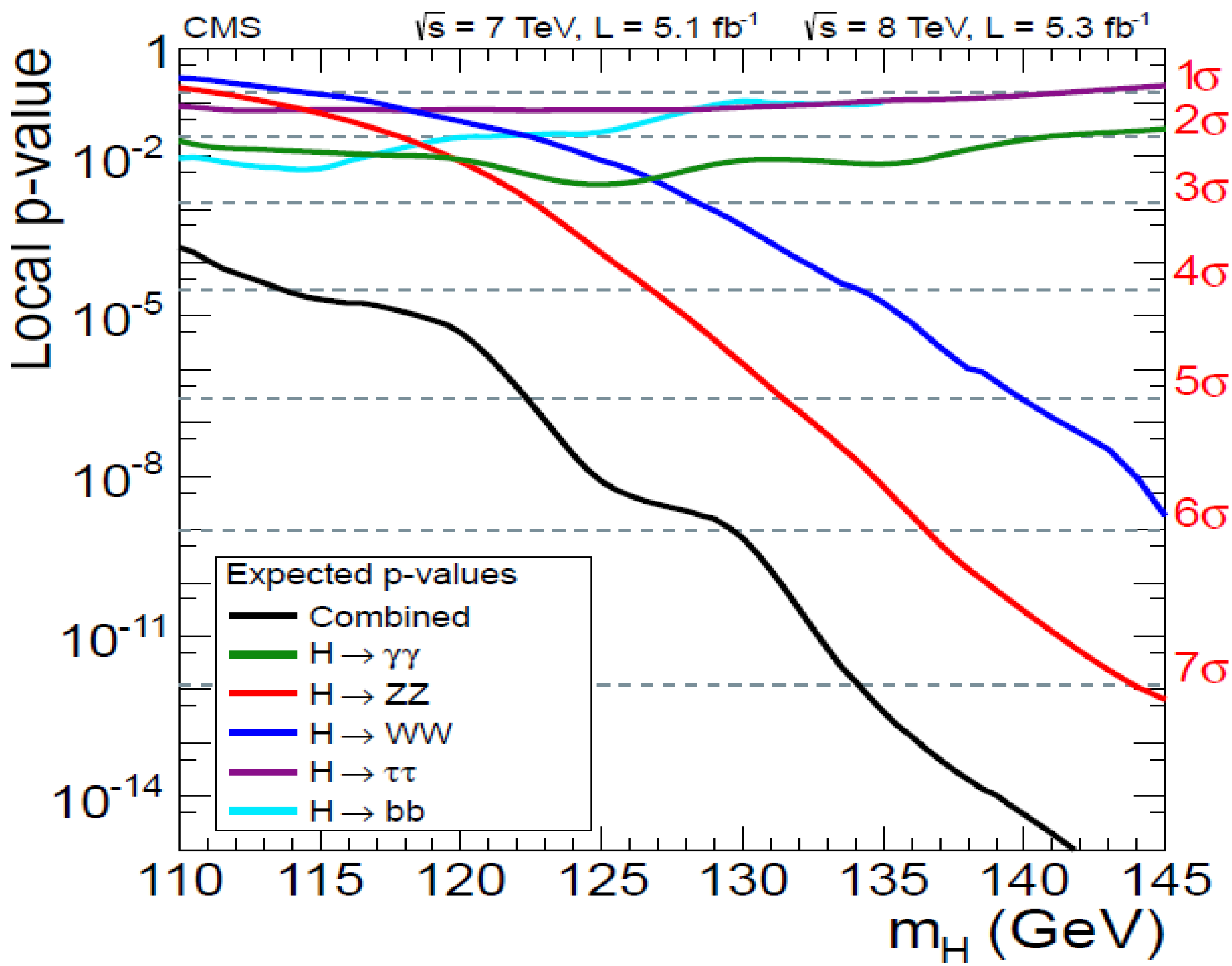




Analyzed decay modes (CMS)

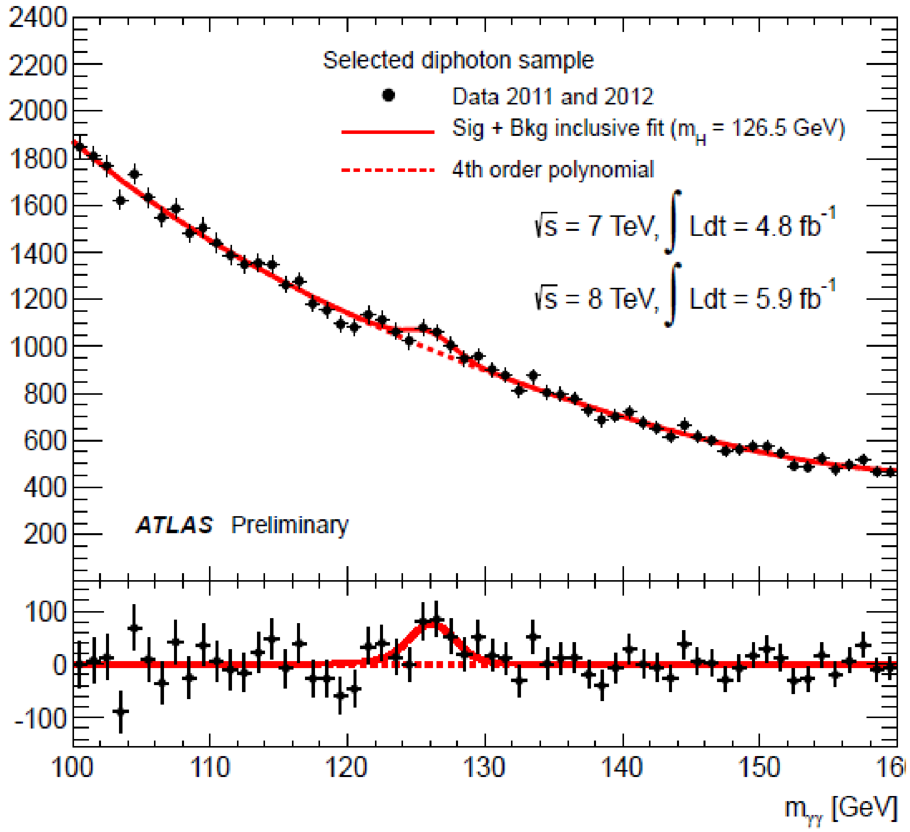
H decay	H prod	Analyses: Exclusive final states	No. of channels	m_H range (GeV)	m_H resolution
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	110–150	1-2%
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (low or high m_{jj} for 8 TeV)	1 or 2	110–150	1-2%
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets)$\otimes$ (low or high p_T^V)	10	110–135	10%
	ttH-tag	(ℓ with 4,5,$\geq$6 jets) $\otimes$ (3,$\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	9	110–140	
$H \to \tau\tau$	0/1-jets	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$)$\times$ (low or high $p_T^{\tau\tau}$) $\times$ (0 or 1 jets)	16	110–145	20%
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$) + $(jj)_{VBF}$	4	110–145	20%
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	110–160	
	WH-tag	$\tau_h ee$, $\tau_h\mu\mu$, $\tau_h e\mu$	3	110–140	
WW $\to \ell\nu qq$	untagged	($e\nu$, $\mu\nu$)$\otimes$($(jj)_W$ with 0 or 1 jets)	4	170–600	
WW $\to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\otimes$ (0 or 1 jets)	4	110–600	20%
WW $\to \ell\nu\ell\nu$	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 or 2	110–600	20%
WW $\to \ell\nu\ell\nu$	WH-tag	$3\ell 3\nu$	1	110–200	
WW $\to \ell\nu\ell\nu$	VH-tag	$\ell\nu\ell\nu + (jj)_V$ (DF or SF dileptons)	2	118–190	
ZZ $\to 4\ell$	inclusive	$4e$, 4μ, $2e2\mu$	3	110–600	1-2%
ZZ $\to 2\ell 2\tau$	inclusive	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	200–600	10-15%
ZZ $\to 2\ell 2q$	inclusive	(ee, $\mu\mu$)$\times$($(jj)_Z$ with 0, 1, 2 b-tags)	6	{130–164; 200–600}	3%
ZZ $\to 2\ell 2\nu$	untagged	((ee, $\mu\mu$) with MET) $\otimes$ (0 or 1 or 2 non-VBF jets)	6	200–600	7%
ZZ $\to 2\ell 2\nu$	VBF-tag	(ee, $\mu\mu$) with MET and $(jj)_{VBF}$	2	200–600	7%

Expected signal significance (CMS)

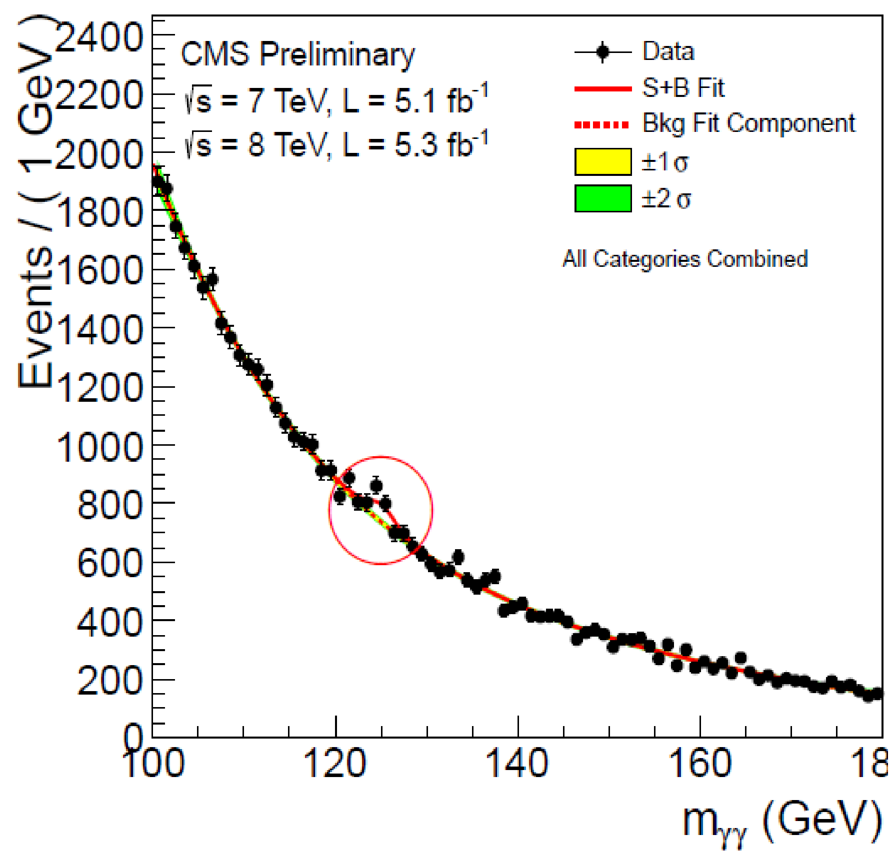


H→γγ mass spectrum

ATLAS

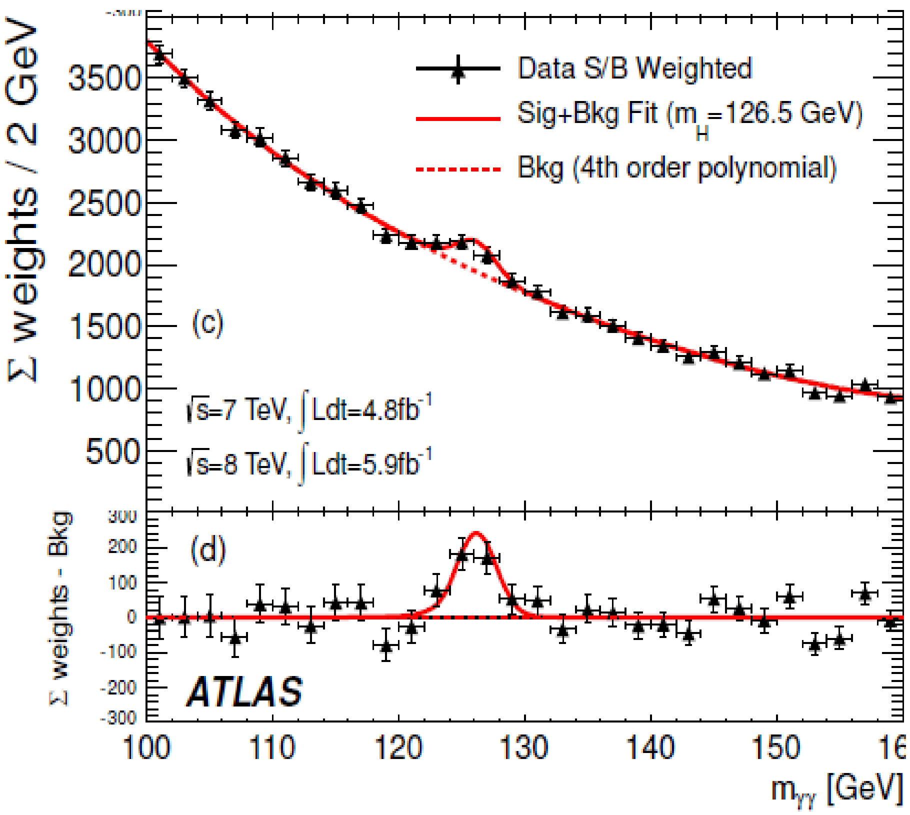


CMS

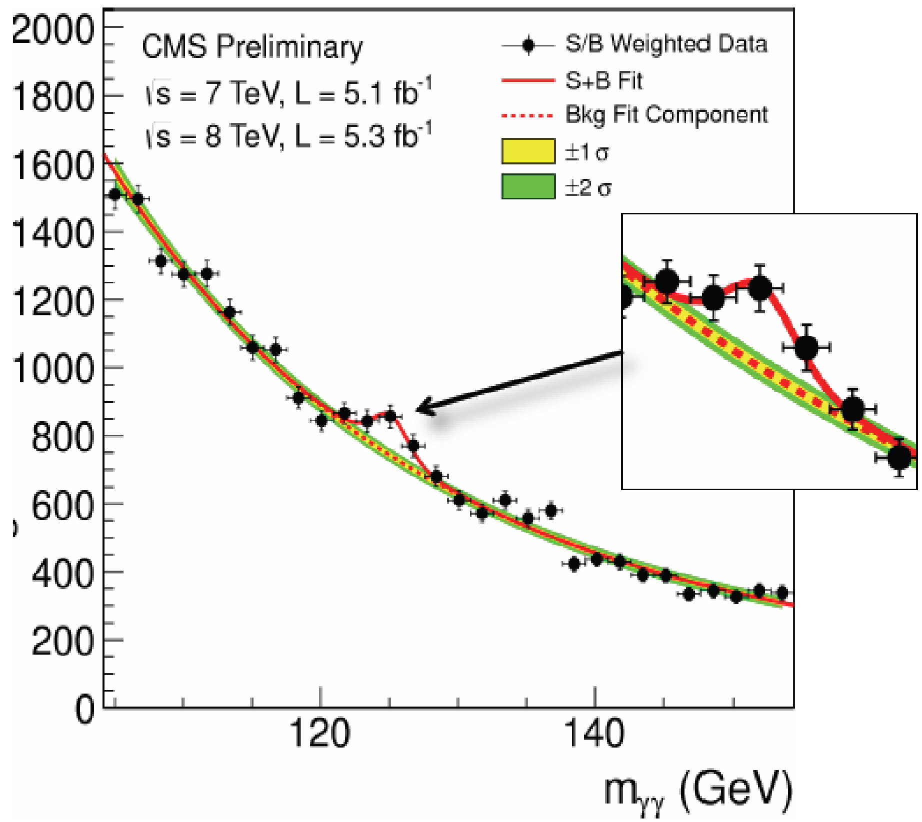


H→γγ mass spectrum (weighted)

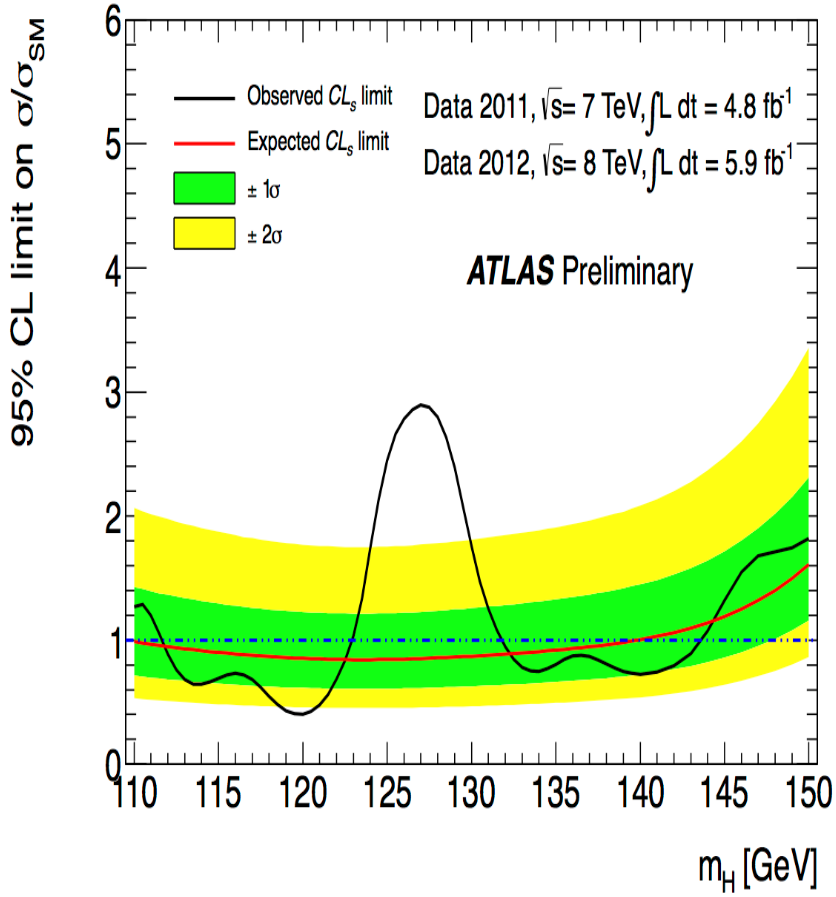
ATLAS

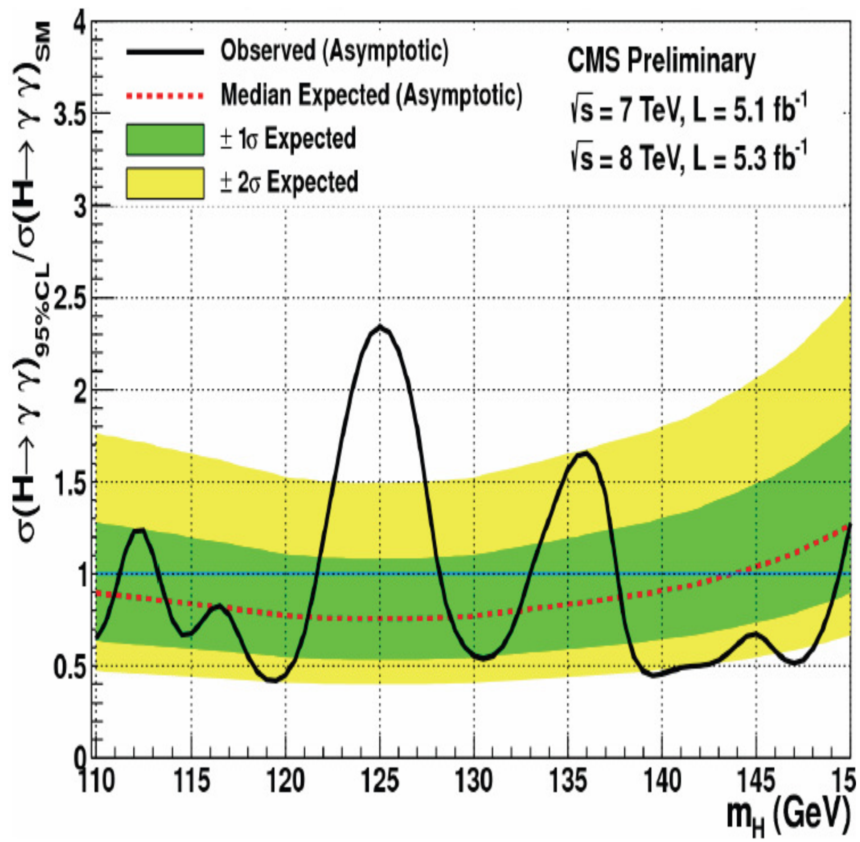


CMS

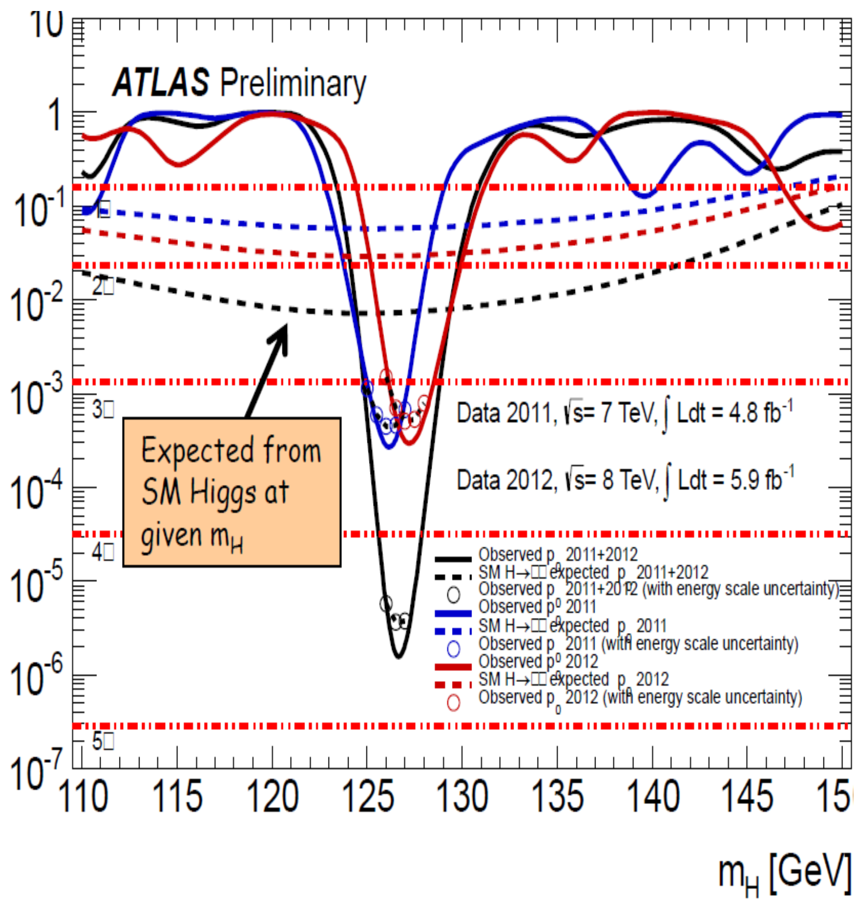


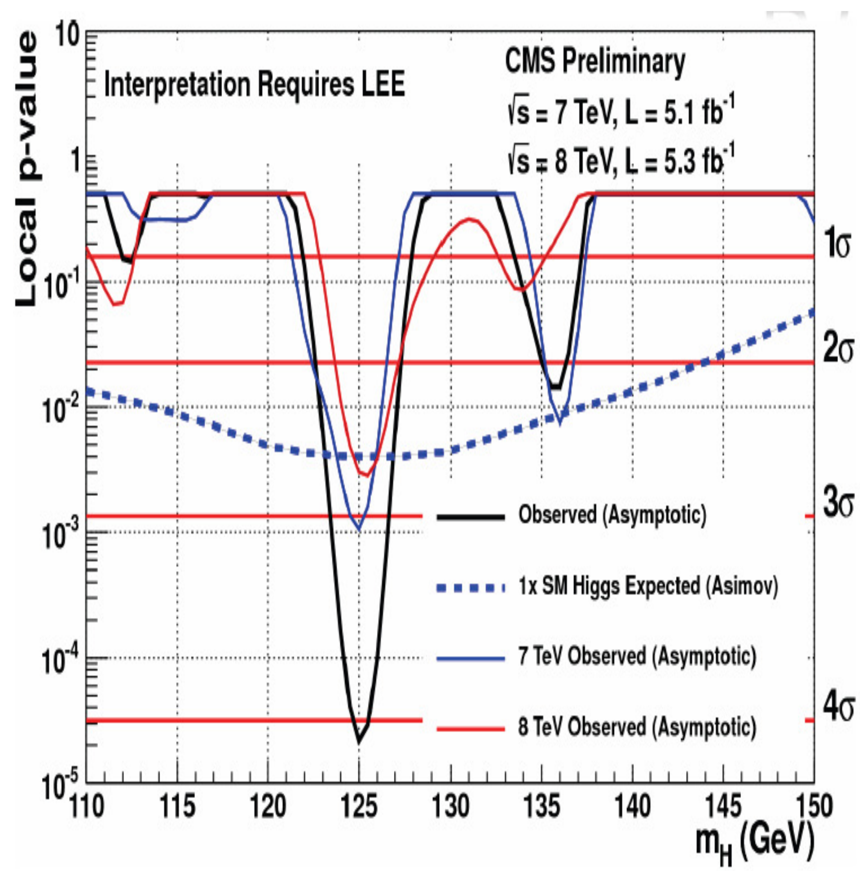
$H \rightarrow \gamma\gamma$ production upper limit





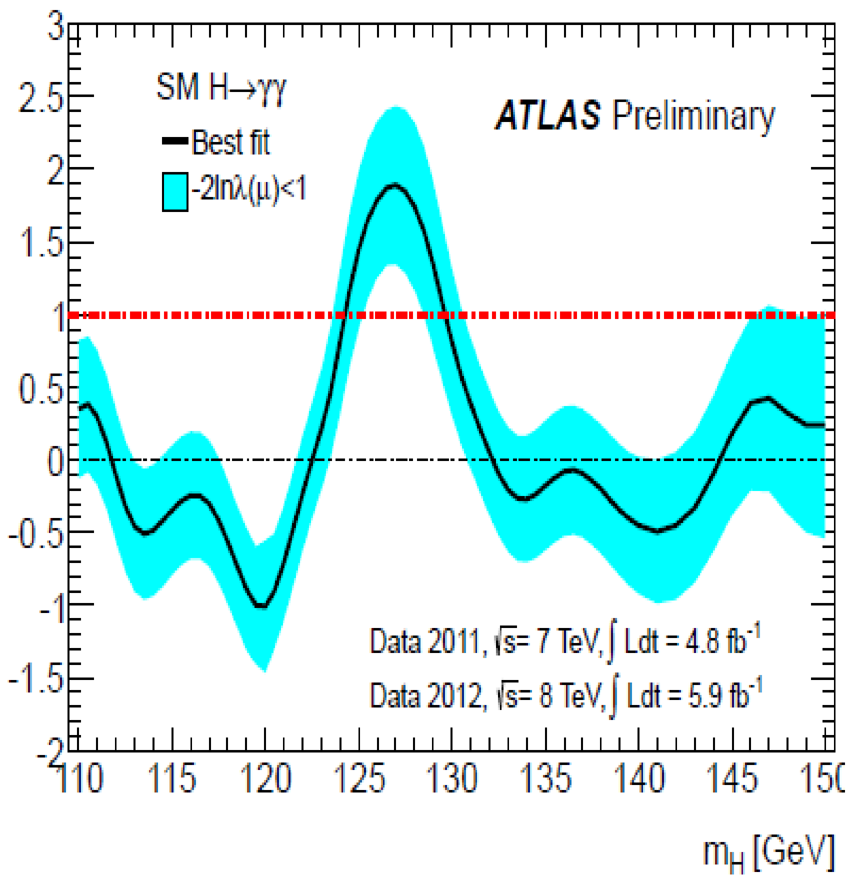
$H\rightarrow\gamma\gamma$ fluctuation probability

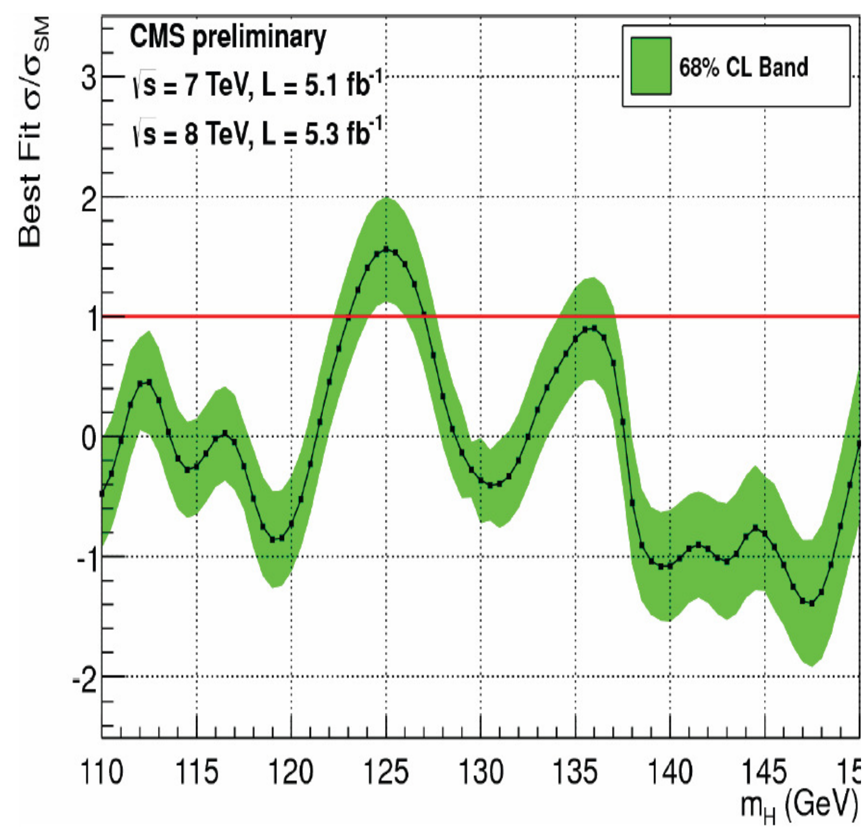




ATLAS: 4.5σ ($2\cdot10^{-6}$) **CMS: 4.1σ ($2\cdot10^{-5}$)**

H→γγ signal strength

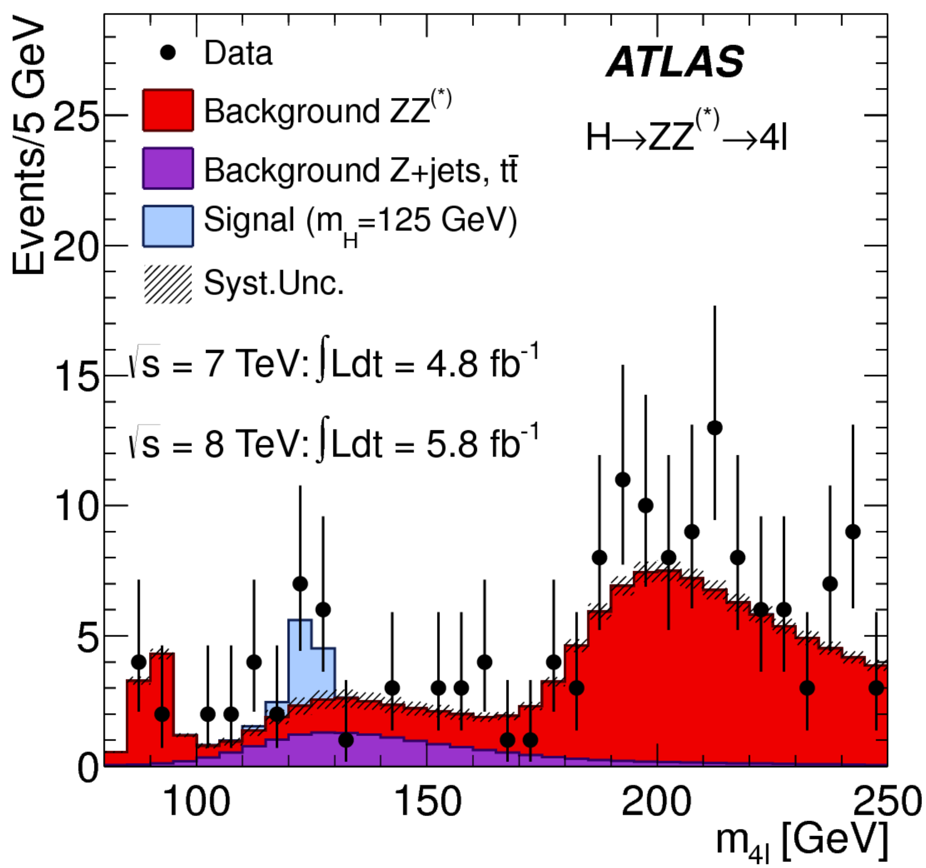


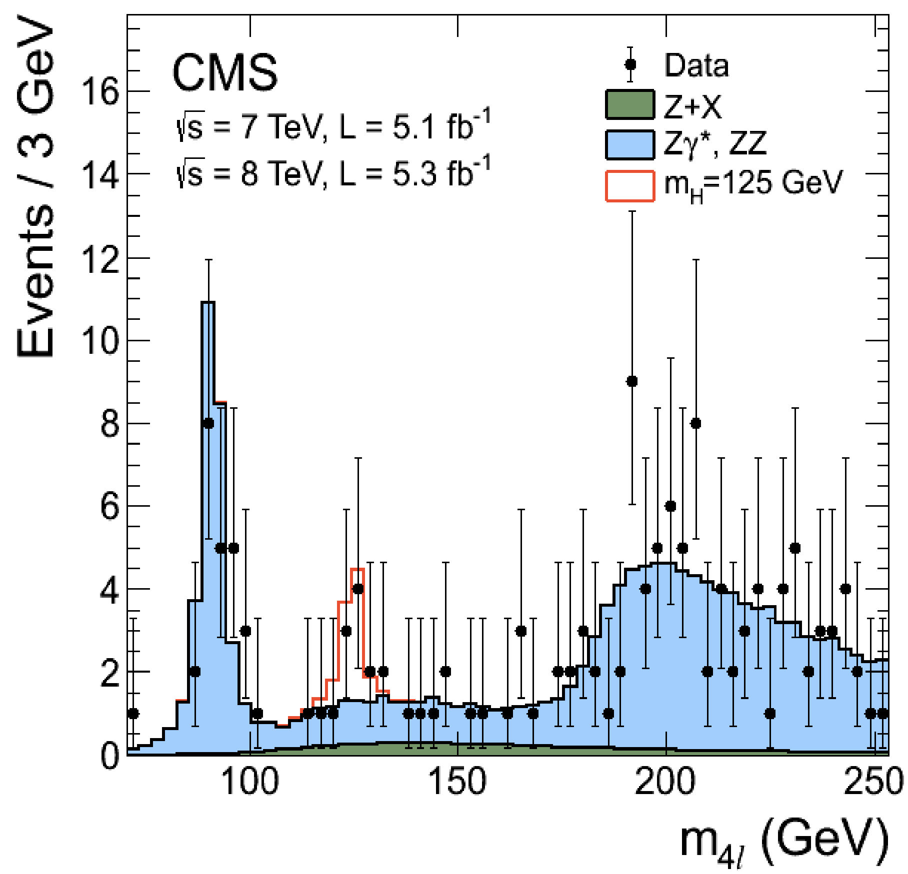


ATLAS: μ=1.9 ± 0.5

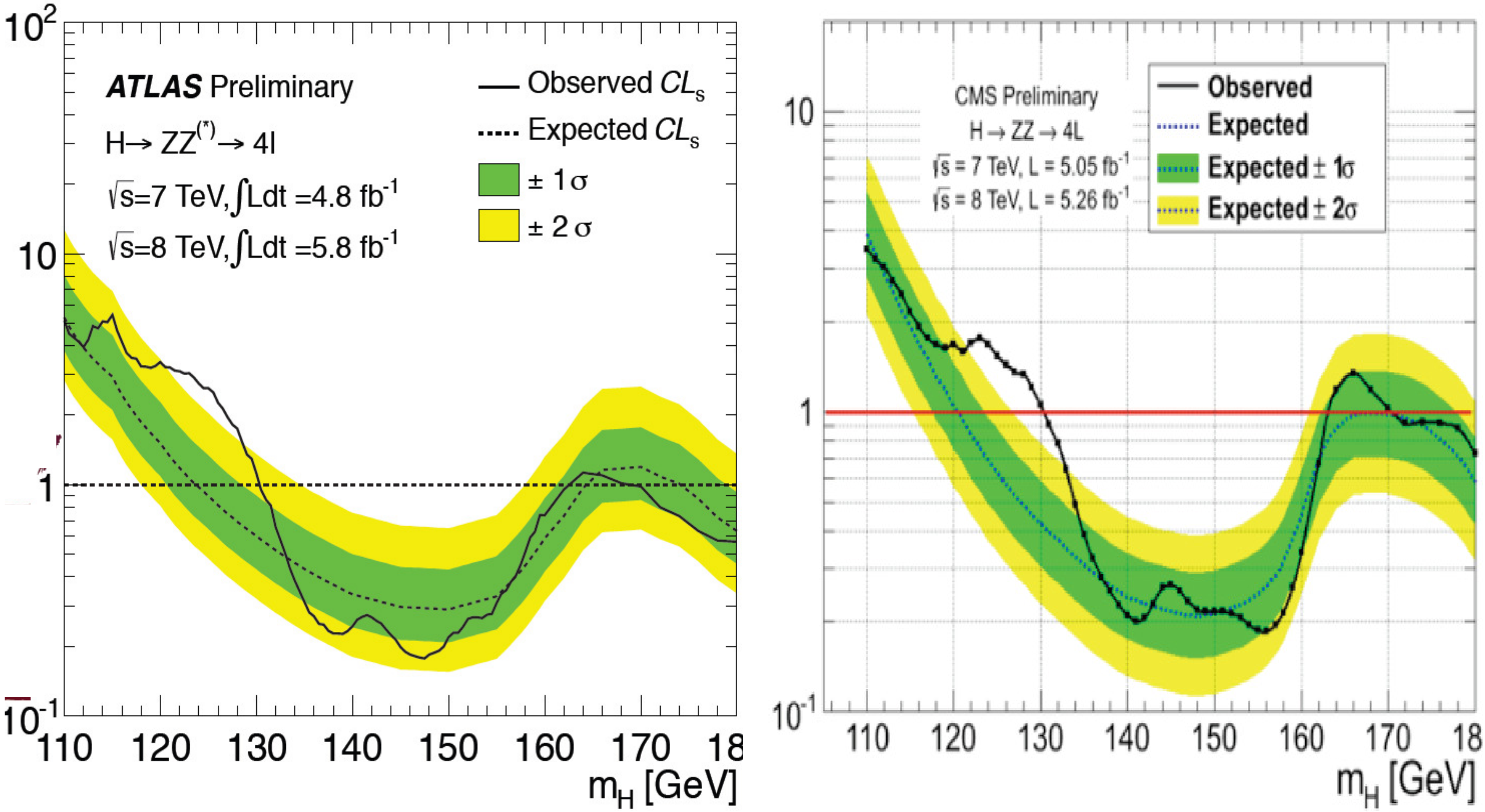
CMS: μ=1.46 ± 0.43

$H \to ZZ \to 4\ell$ mass spectrum

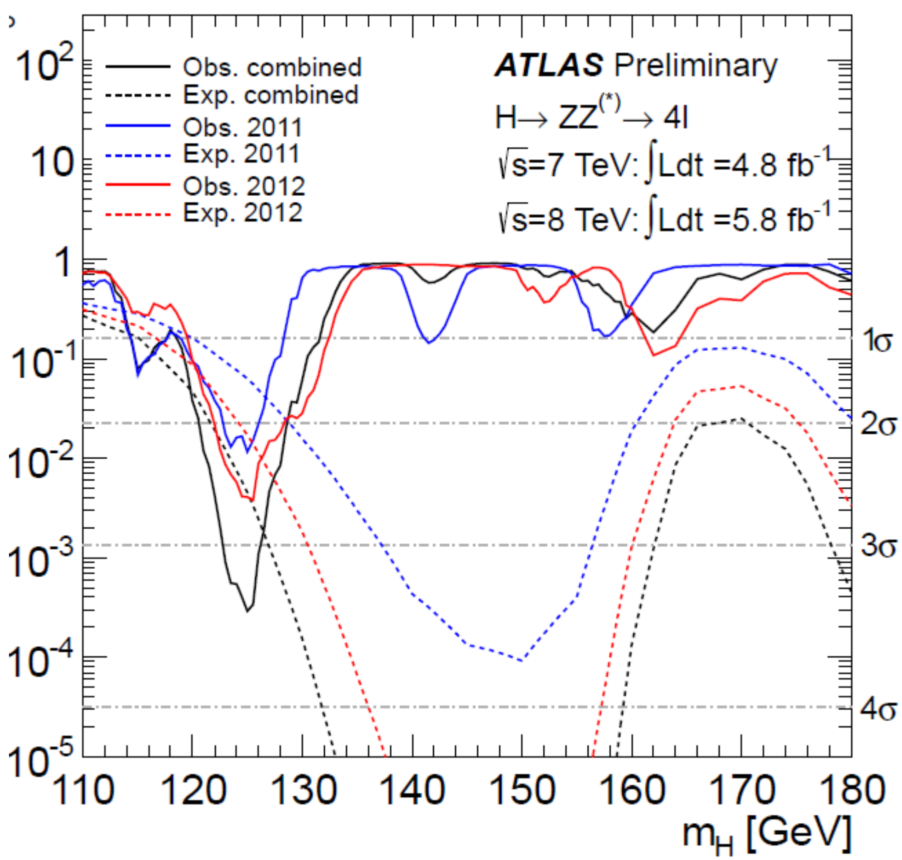


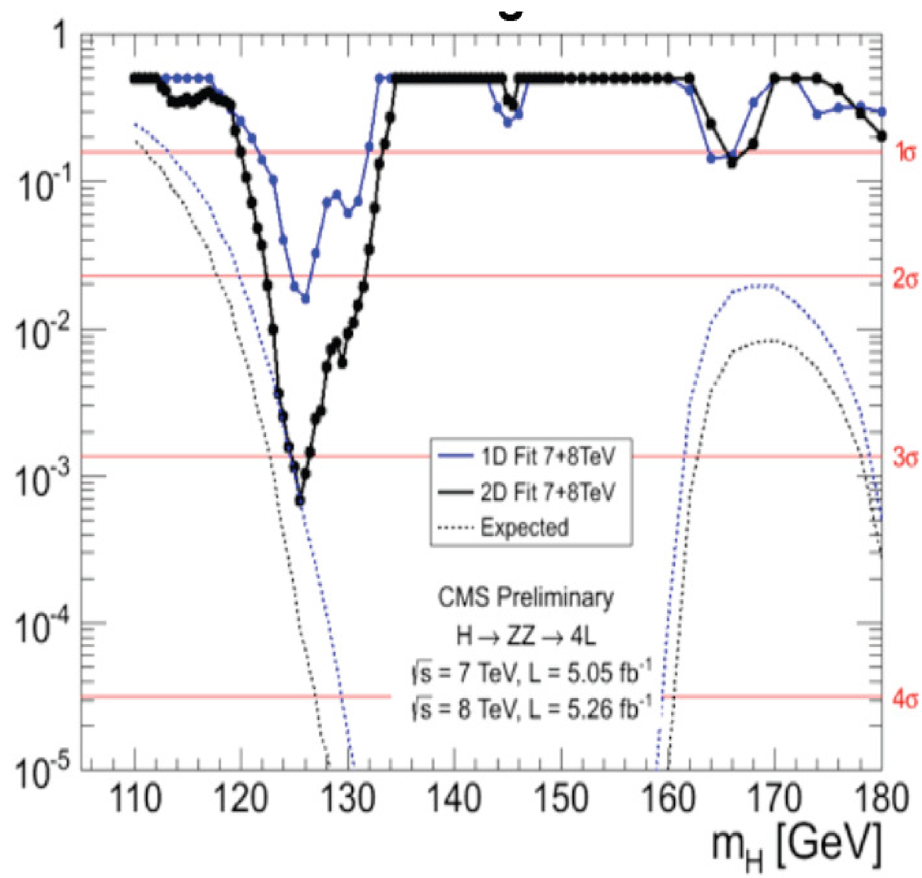


$H \rightarrow ZZ \rightarrow 4\ell$ upper limit



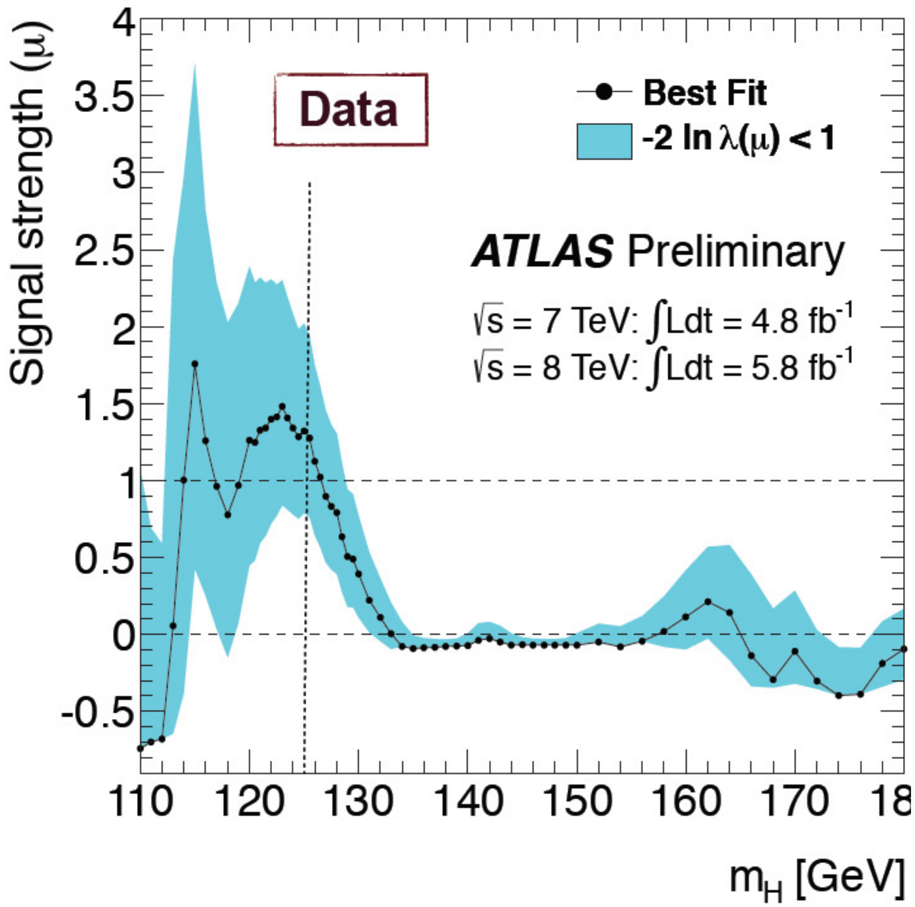
H→ZZ →4ℓ fluctuation probability

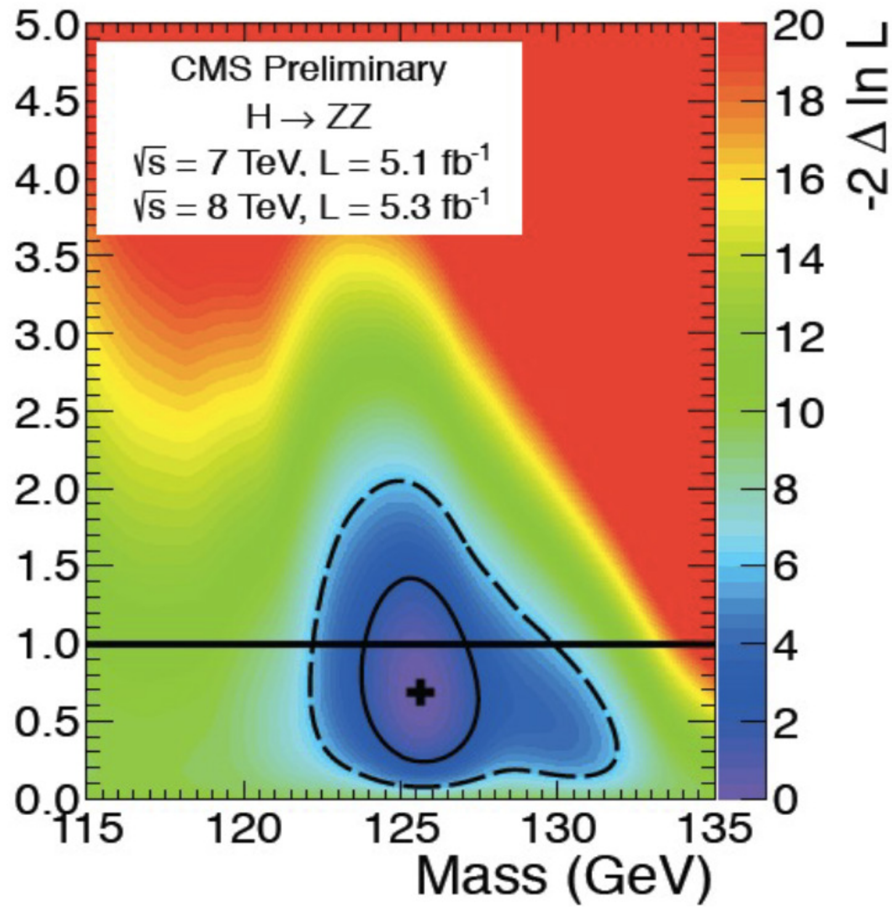




ATLAS: 3.4σ (3·10^{-4}) **CMS: 3.2σ (7·10^{-4})**

$H \to ZZ \to 4\ell$ signal strength

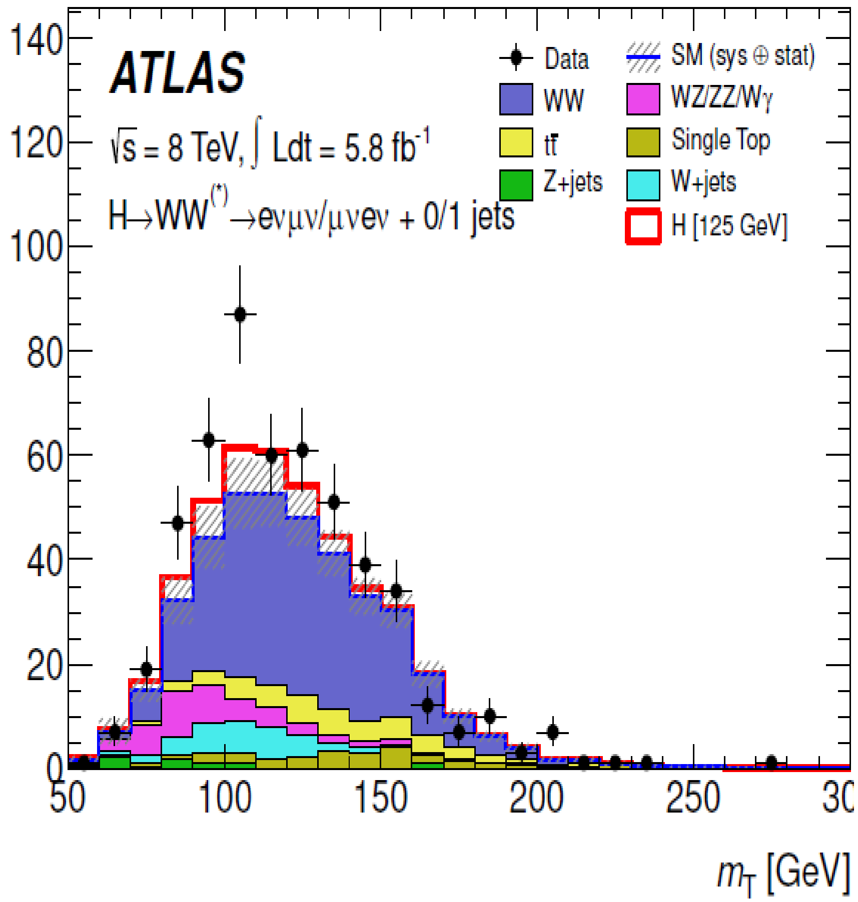


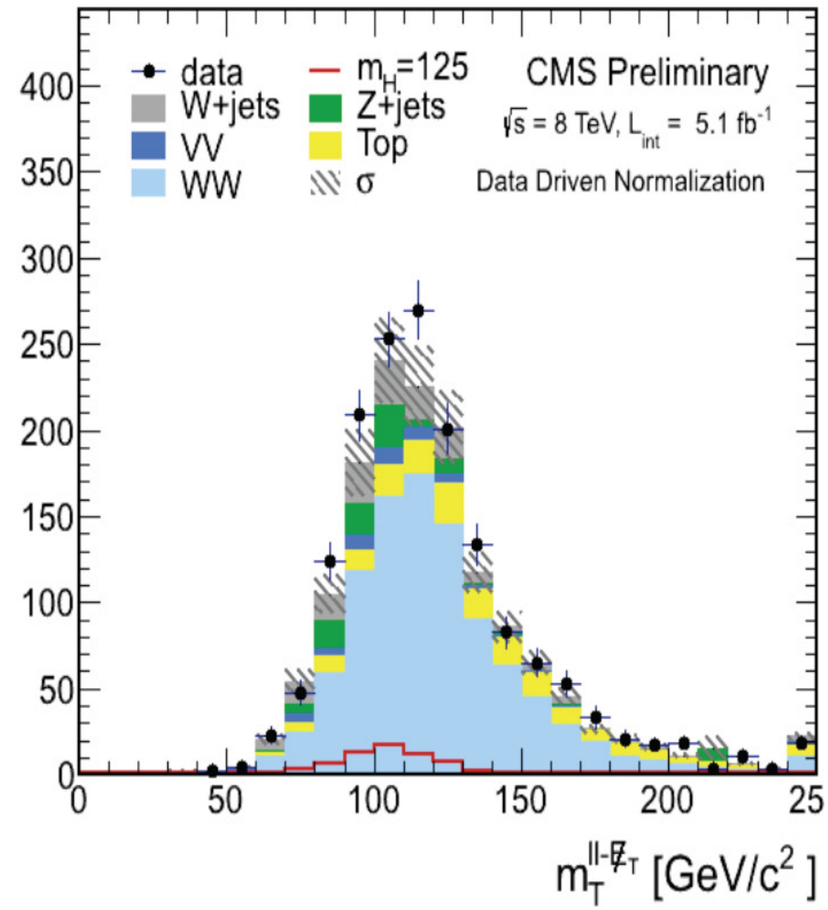


ATLAS: μ=1.3 ± 0.6

CMS: μ=0.7 ± 0.4

H→WW→ℓνℓν m_T spectrum

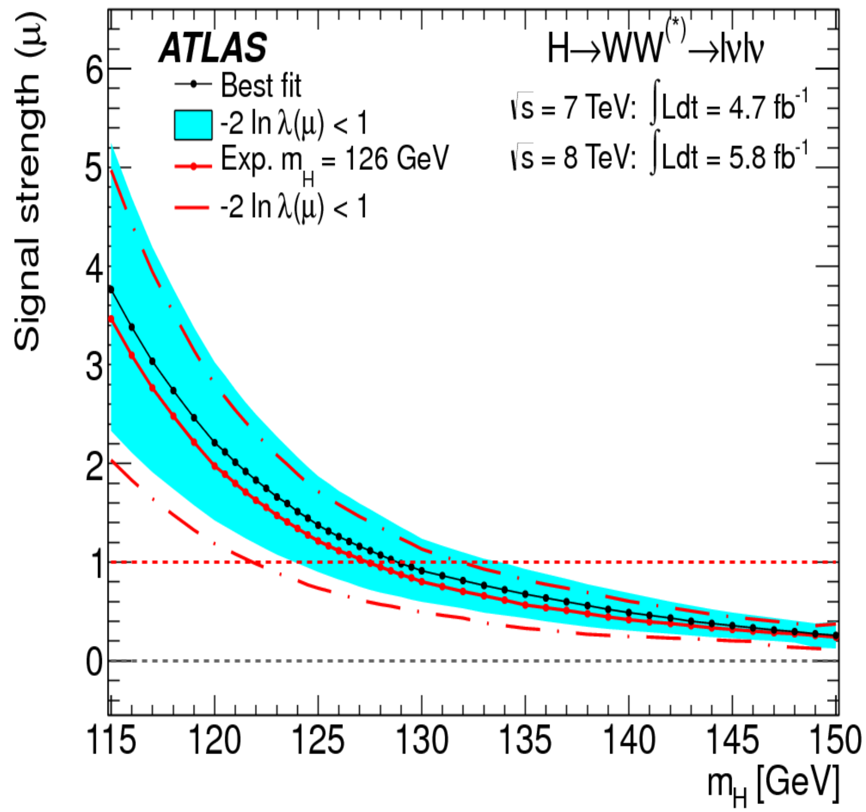


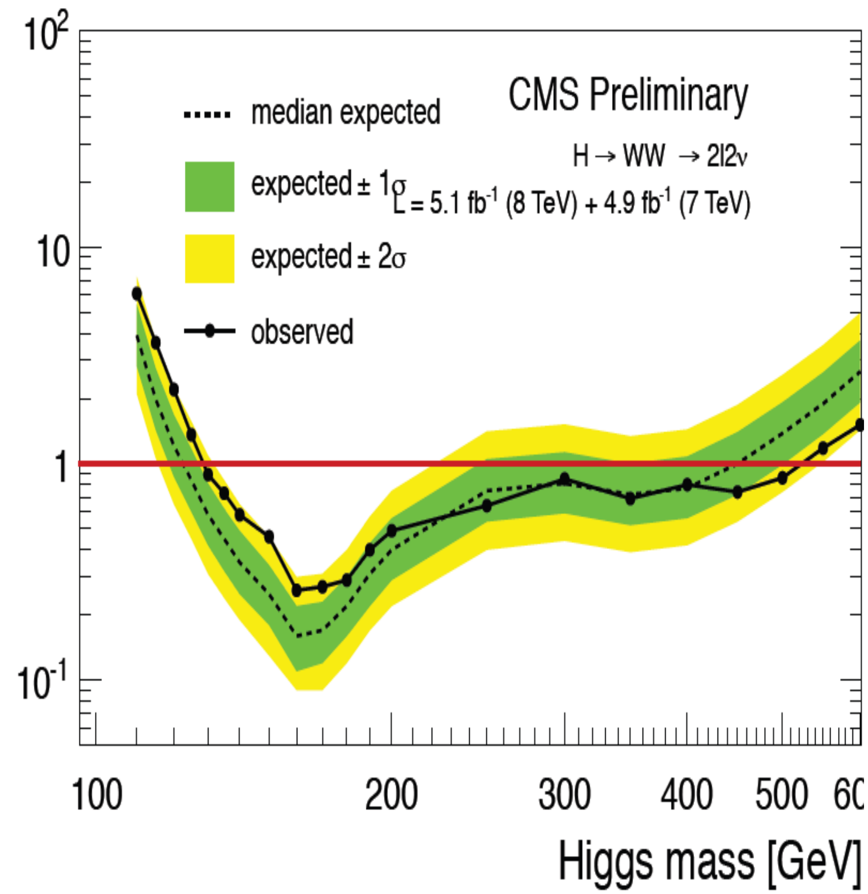


ATLAS: ≈ 3σ excess

CMS: ≈ 1.5σ excess

H→WW→ℓνℓν signal strength/exclusion



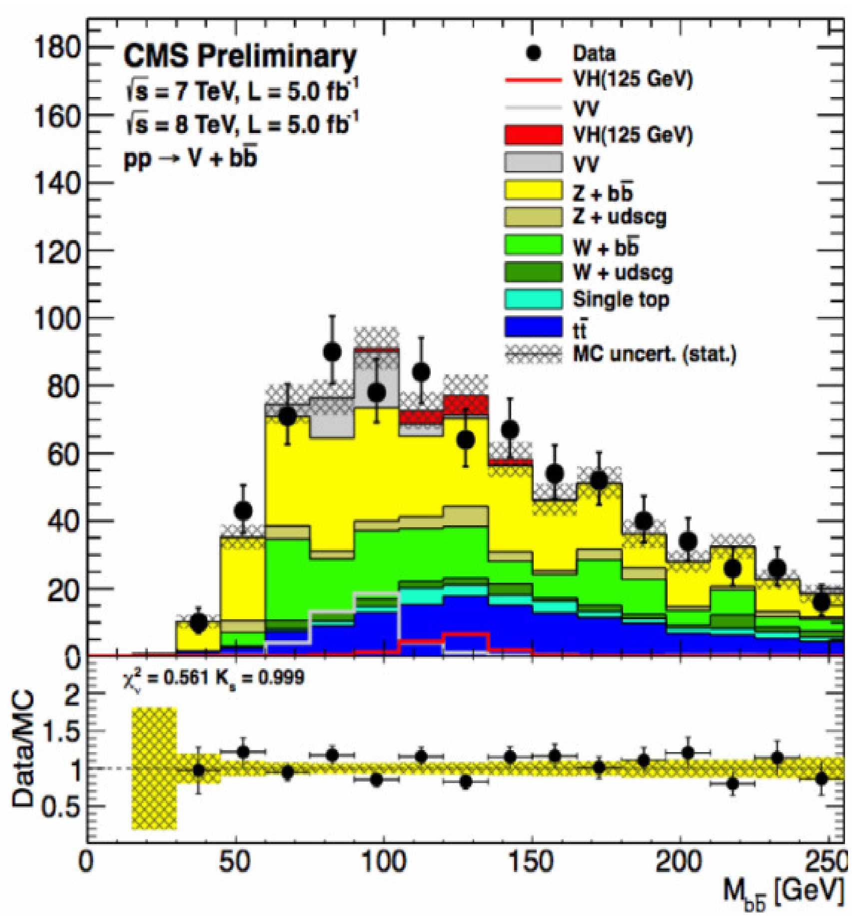


ATLAS: μ = 1.4 ± 0.5

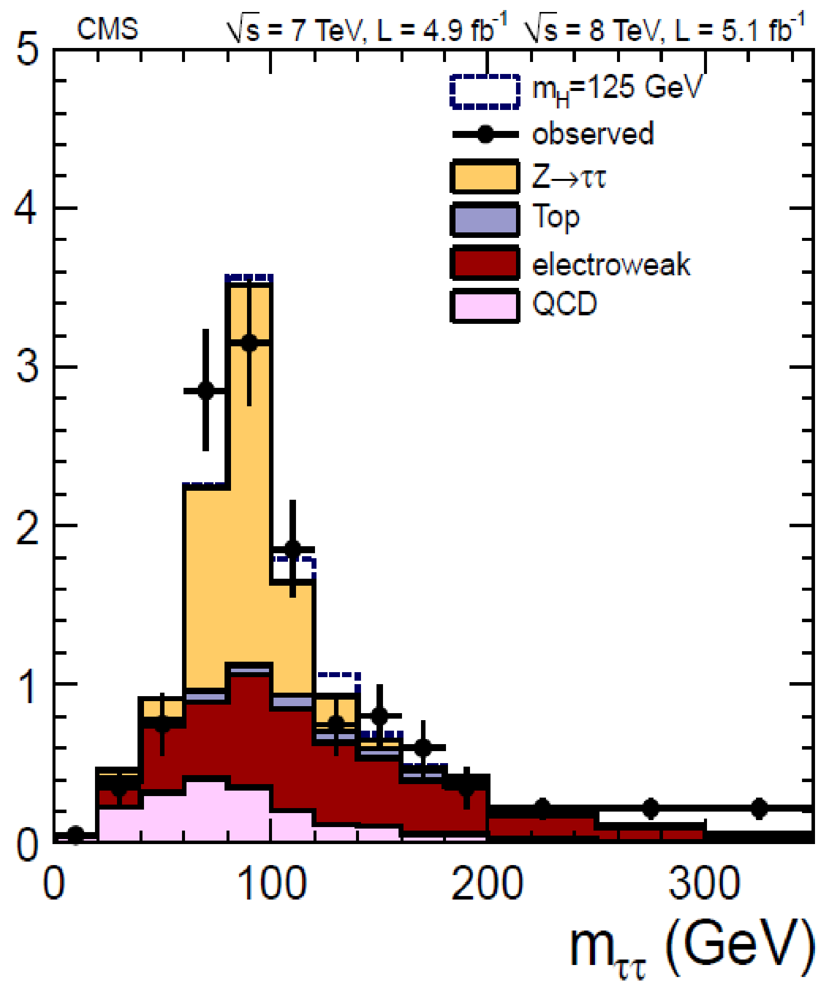
CMS: μ = 0.6 ± 0.4

(assuming M_H=125 GeV)

H→bb and H→ττ



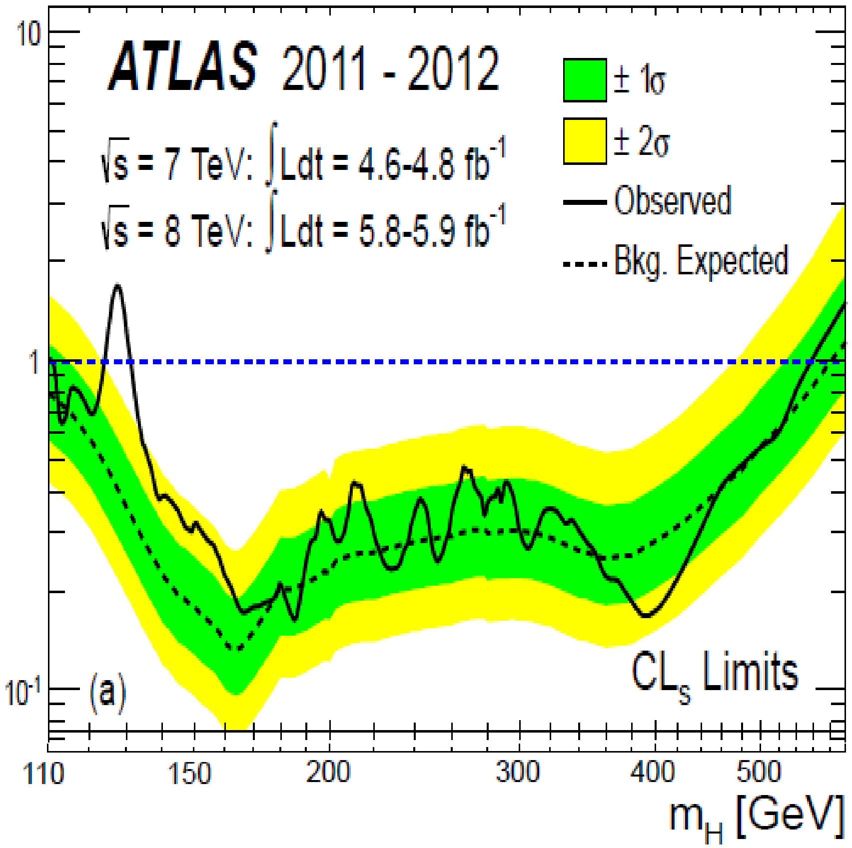
CMS Preliminary
√s = 7 TeV, L = 5.0 fb⁻¹
√s = 8 TeV, L = 5.0 fb⁻¹
pp → V + bb̄
Data
VH(125 GeV)
VV
VH(125 GeV)
VV
Z + bb̄
Z + udscg
W + bb̄
W + udscg
Single top
tt̄
MC uncert. (stat.)
χ²ᵥ = 0.561 Kₛ = 0.999
Data/MC
M_bb̄ [GeV]

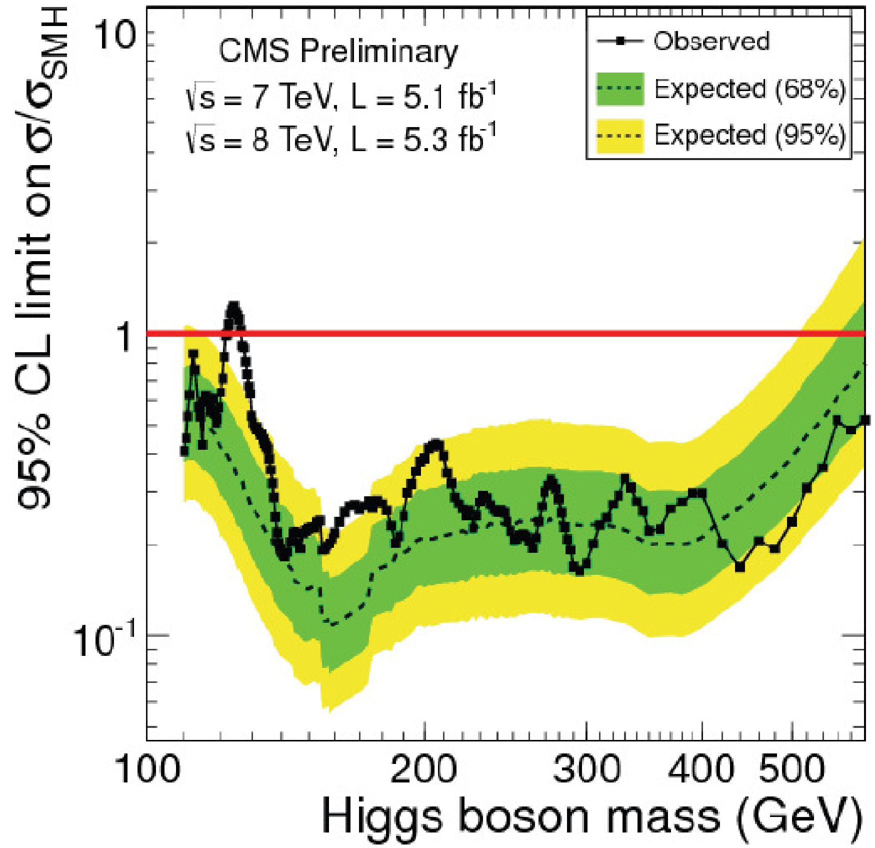


CMS
√s = 7 TeV, L = 4.9 fb⁻¹ √s = 8 TeV, L = 5.1 fb⁻¹
m_H=125 GeV
observed
Z→ττ
Top
electroweak
QCD
m_ττ (GeV)

Combination of all channels

Cross-section upper limit

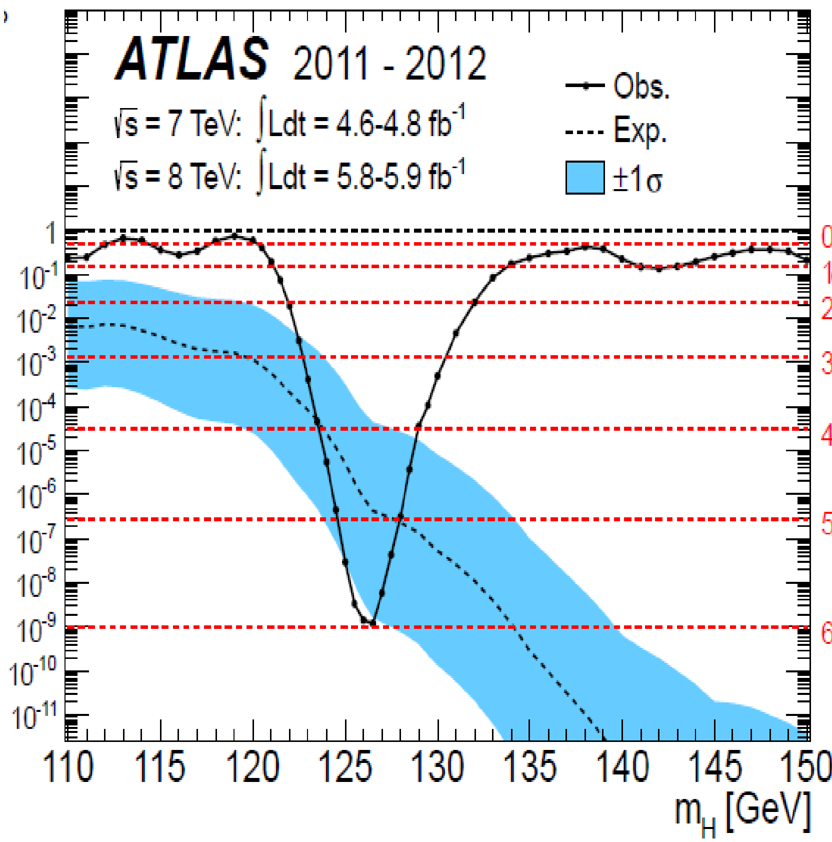


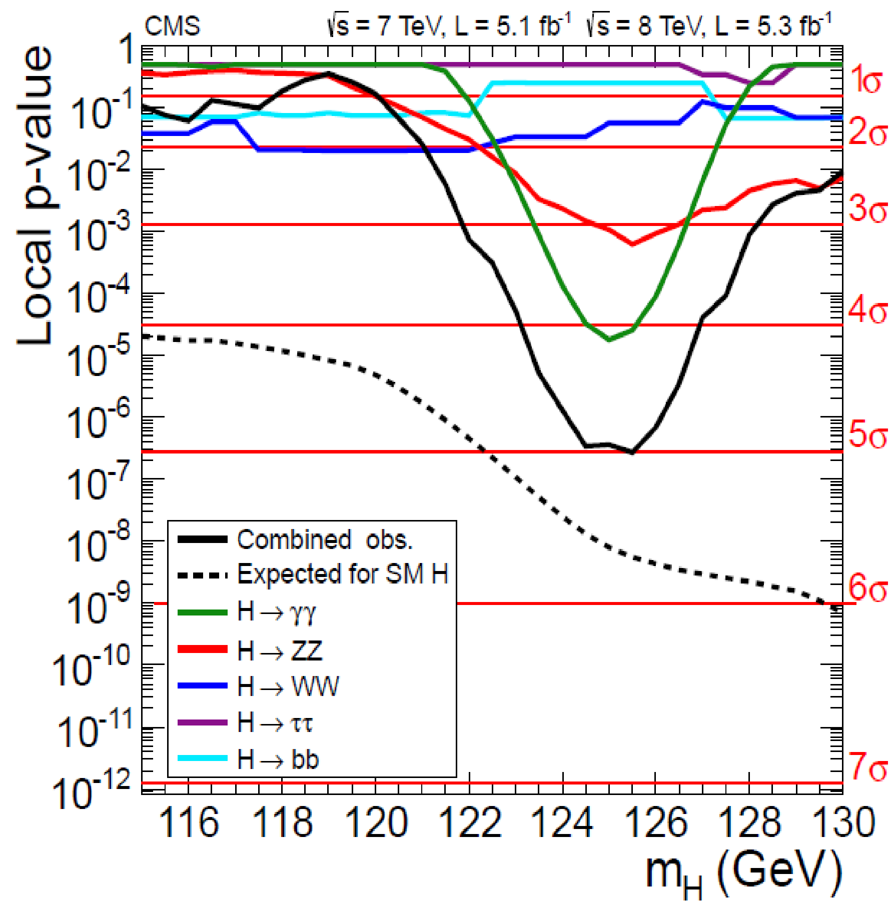


ATLAS exclusion:
132-527 GeV

CMS exclusion:
127-600 GeV

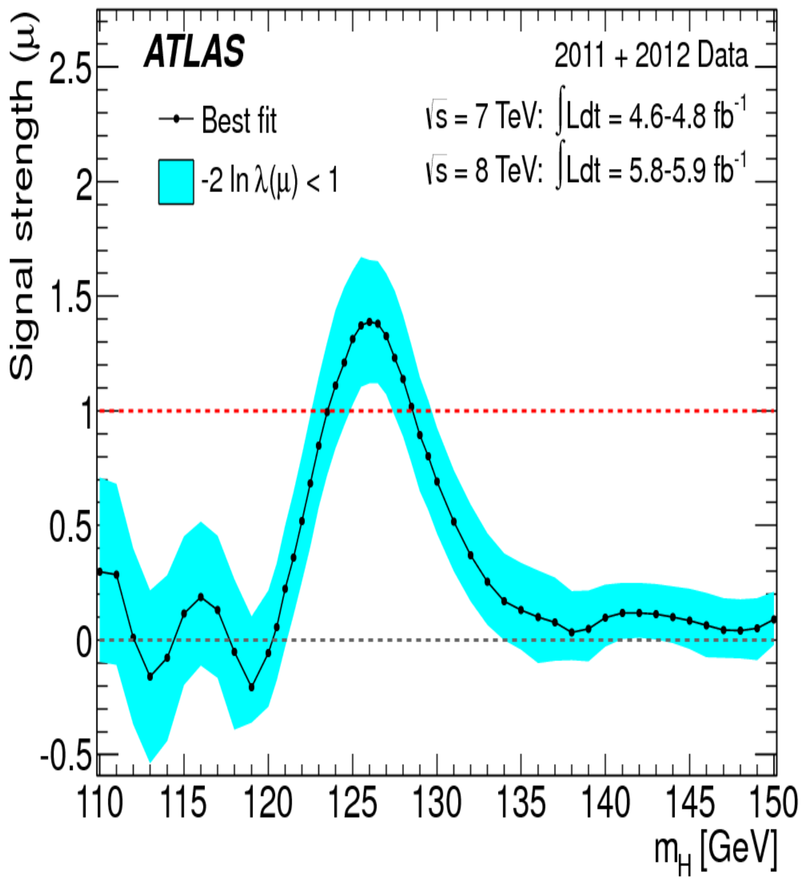
Fluctuation probability

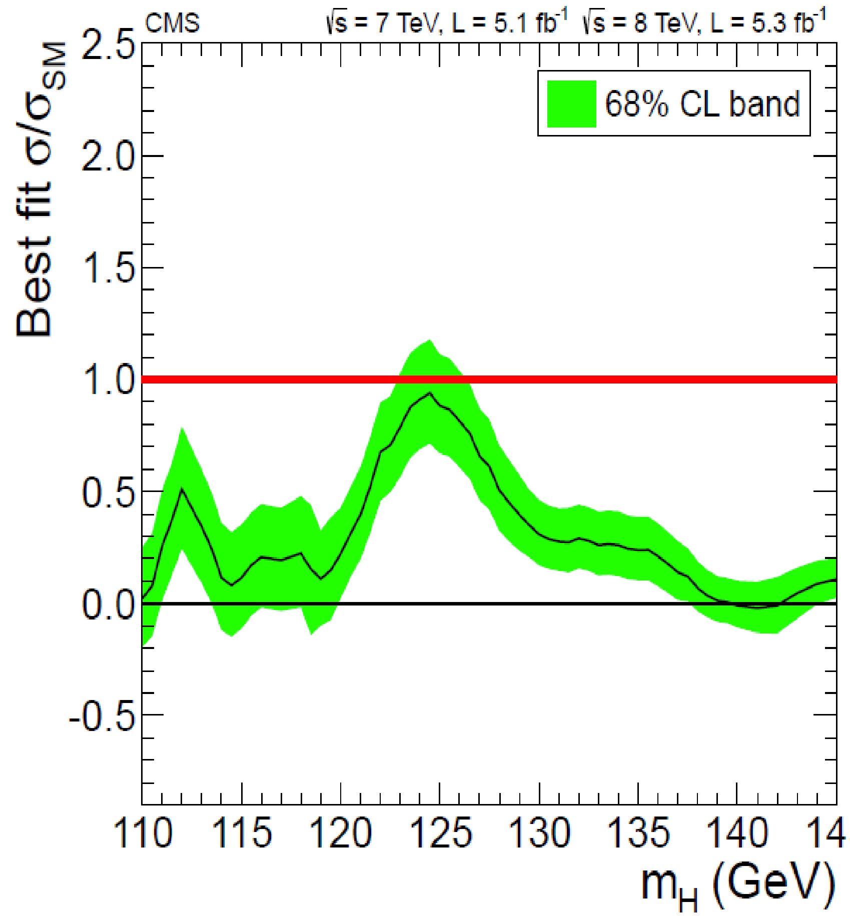




ATLAS: 6.0σ ($3\cdot10^{-9}$) **CMS: 5.0σ ($3\cdot10^{-7}$)**

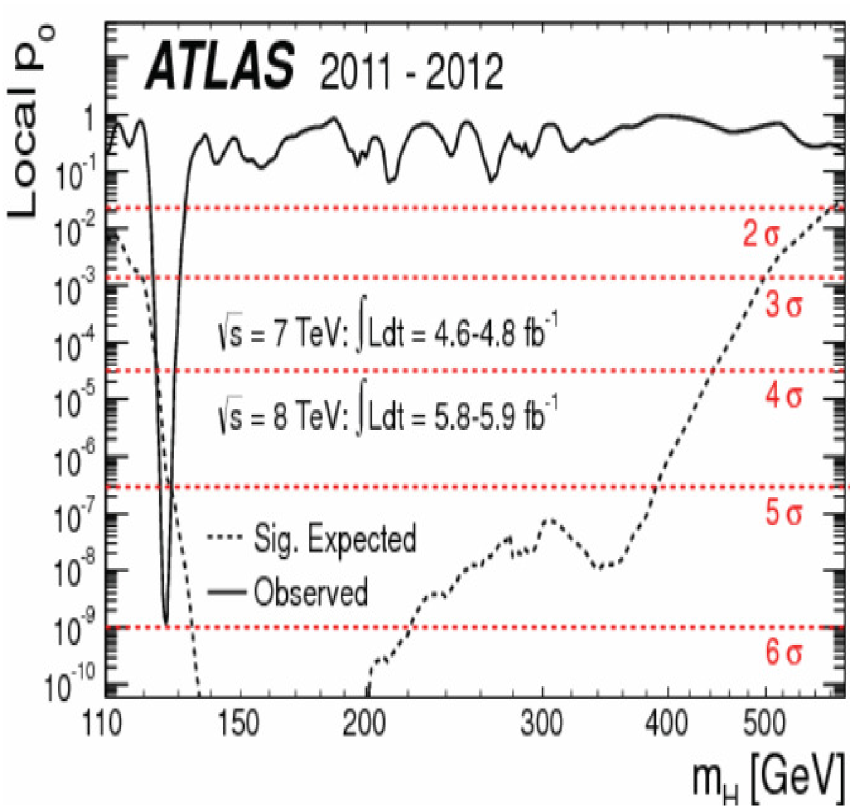
Signal strength

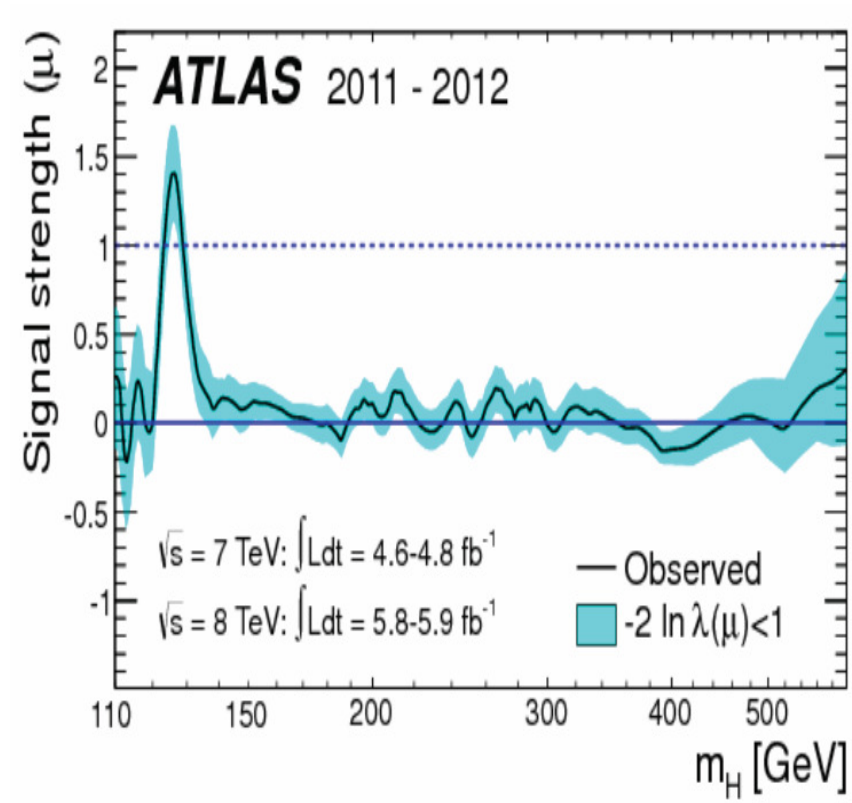




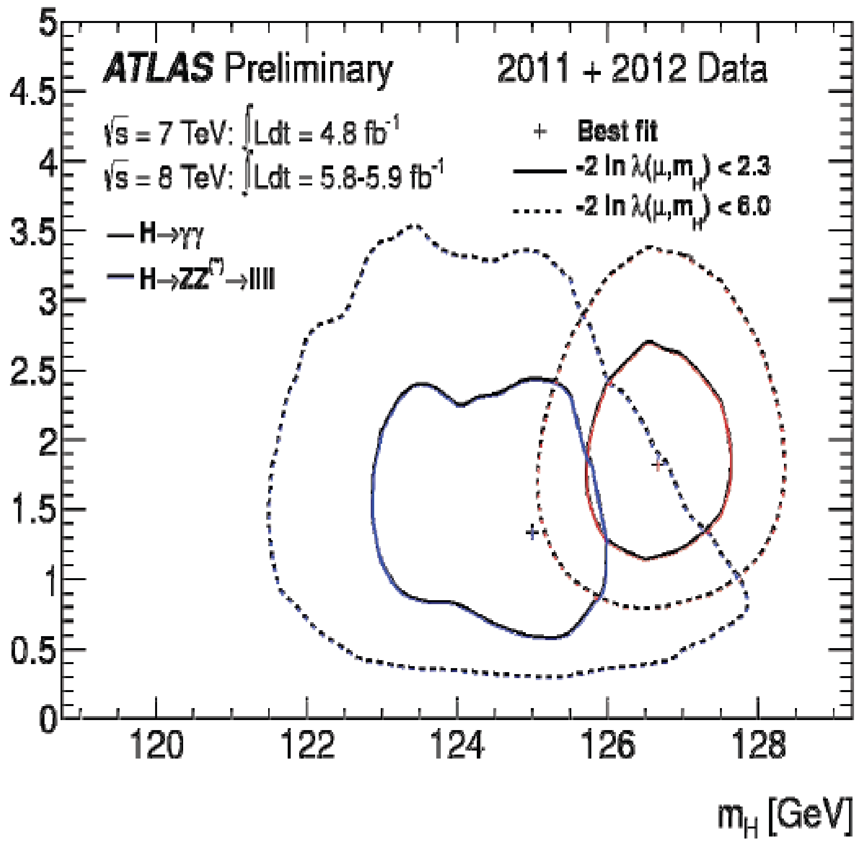
ATLAS: μ=1.4 ± 0.3 **CMS: μ=0.87 ± 0.23**

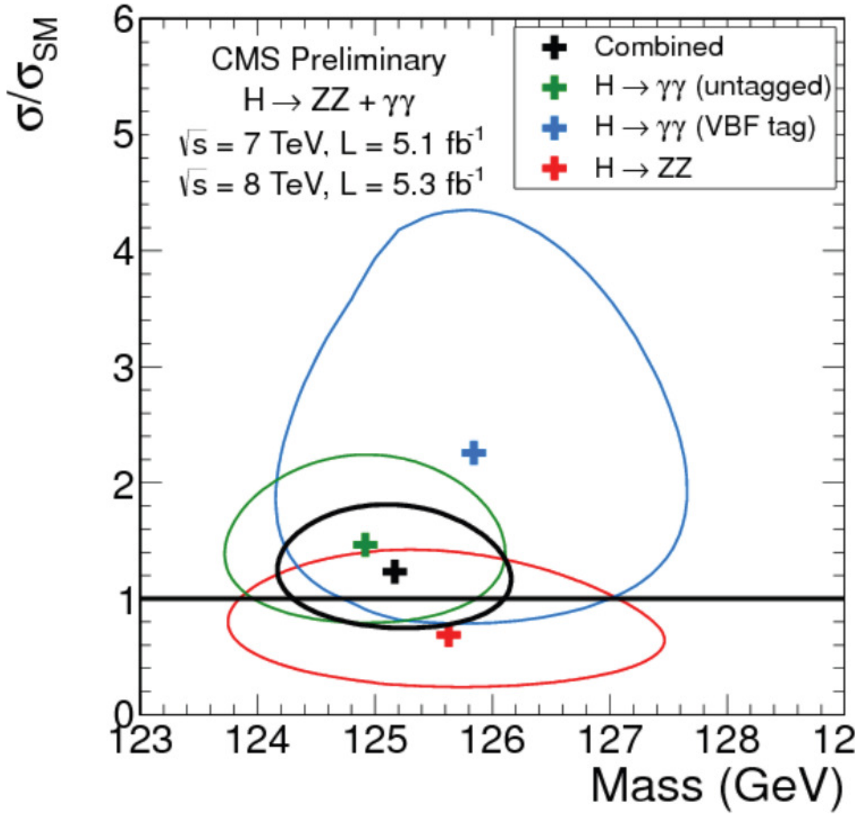
Anything at large masses???





Signal strength vs mass





ATLAS: M_H=126.0±0.4±0.4 **CMS: M_H=125.3±0.4±0.5**

Unofficial average: 125.7 ± 0.4 GeV

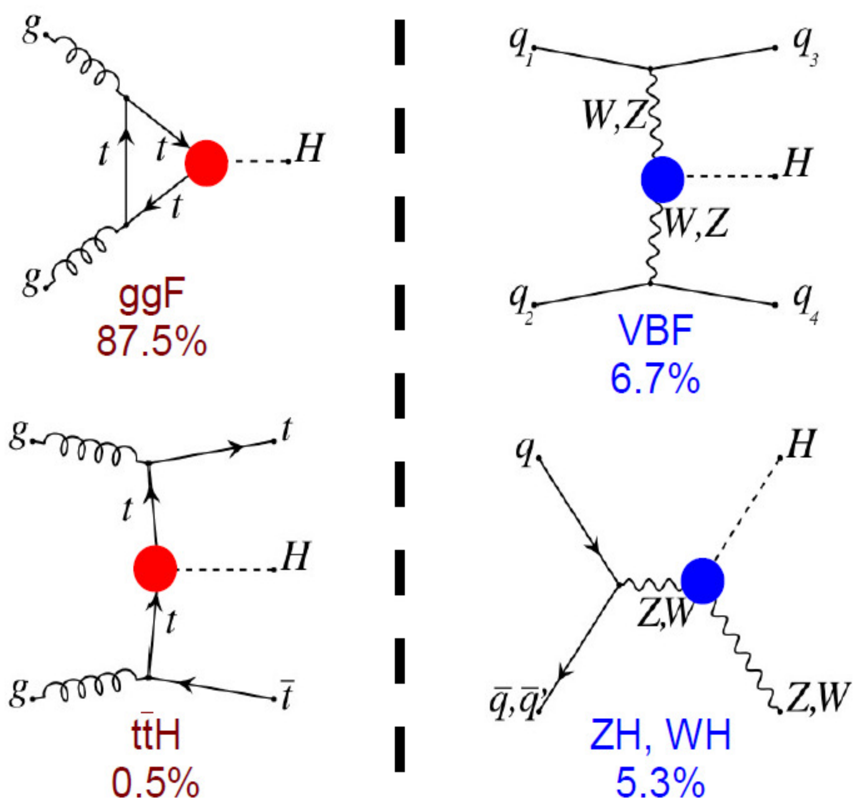
Chronology of the discovery

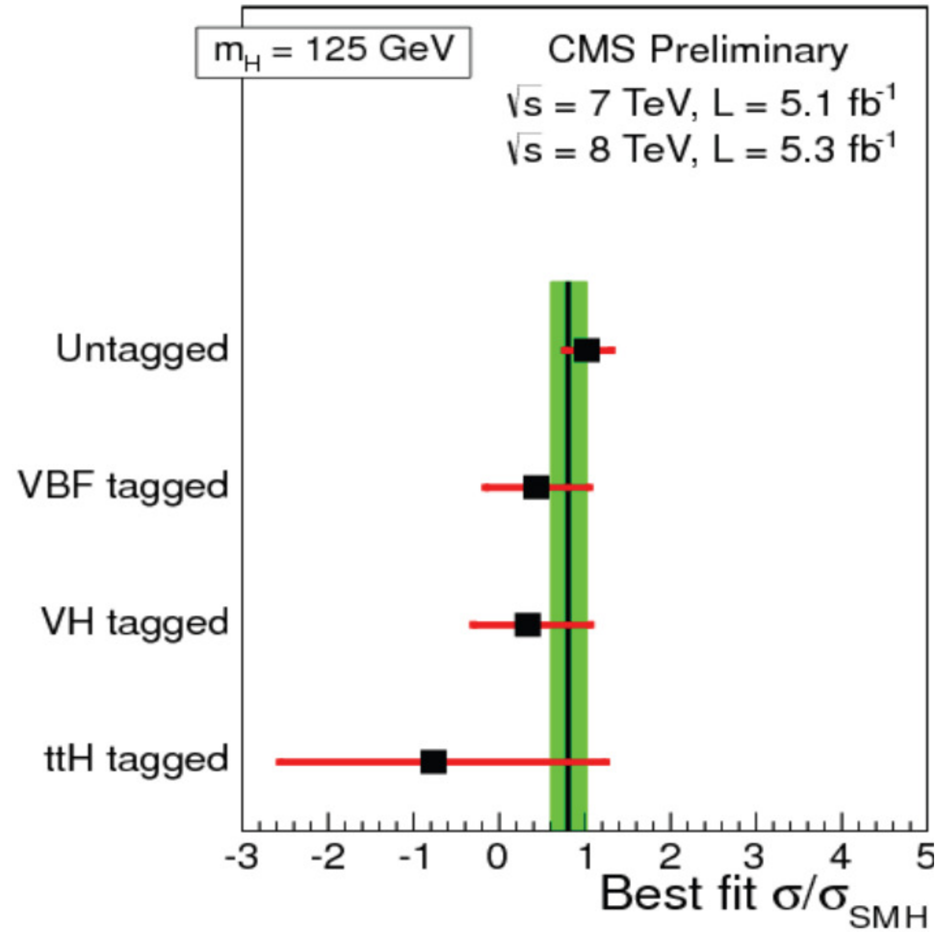
	Tevatron	ATLAS	CMS
July 2011	1 σ	2 σ	1.5 σ
Dec 2011		3.6 σ	2.5 σ
Mar 2012	2 σ	2.5 σ	2.8 σ
July 2012	2.8 σ	5.0 σ	4.9 σ
Aug 2012		6.0 σ	5.0 σ

What we know by now

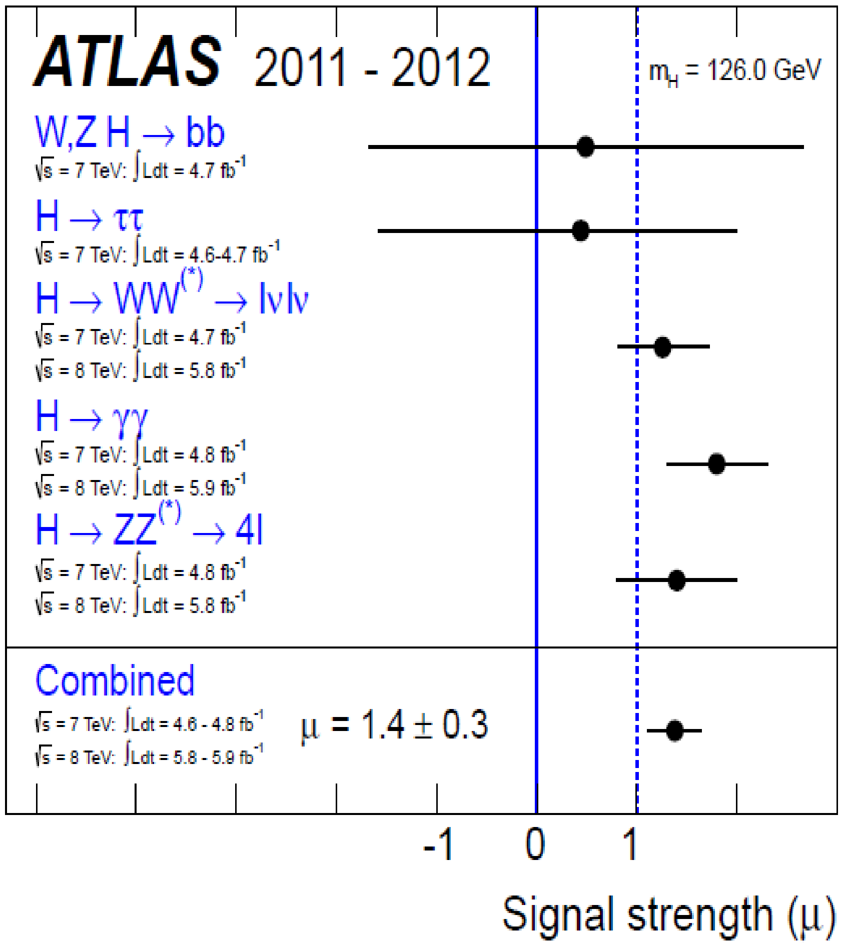
- Did we discover a new particle?
  - Yes, certainly.
- Is it a Higgs boson?
  - We don't know yet!
- Is it a *Standard Model Higgs*?
  - We don't know yet!
- Is it a boson?
  - Yes! (Integer spin)
- Is it a vector boson?
  - No! $S \neq 1$
- Is it a scalar boson?
  - We don't know yet! $S=0$ or 2

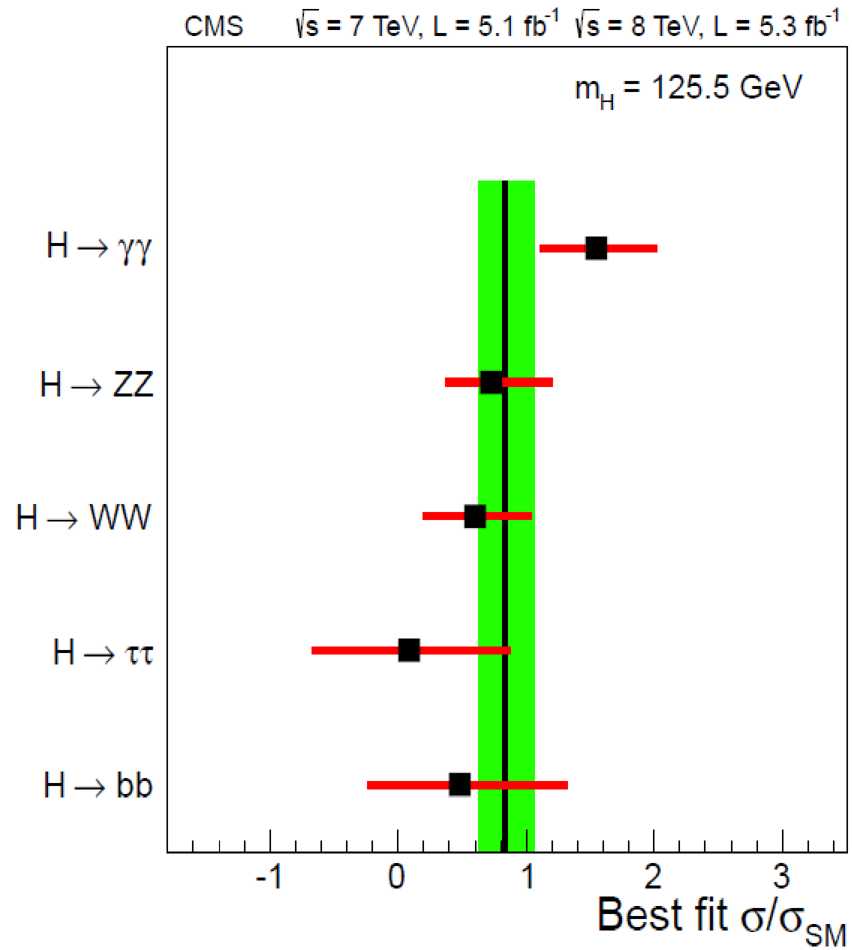
First test of production mechanism



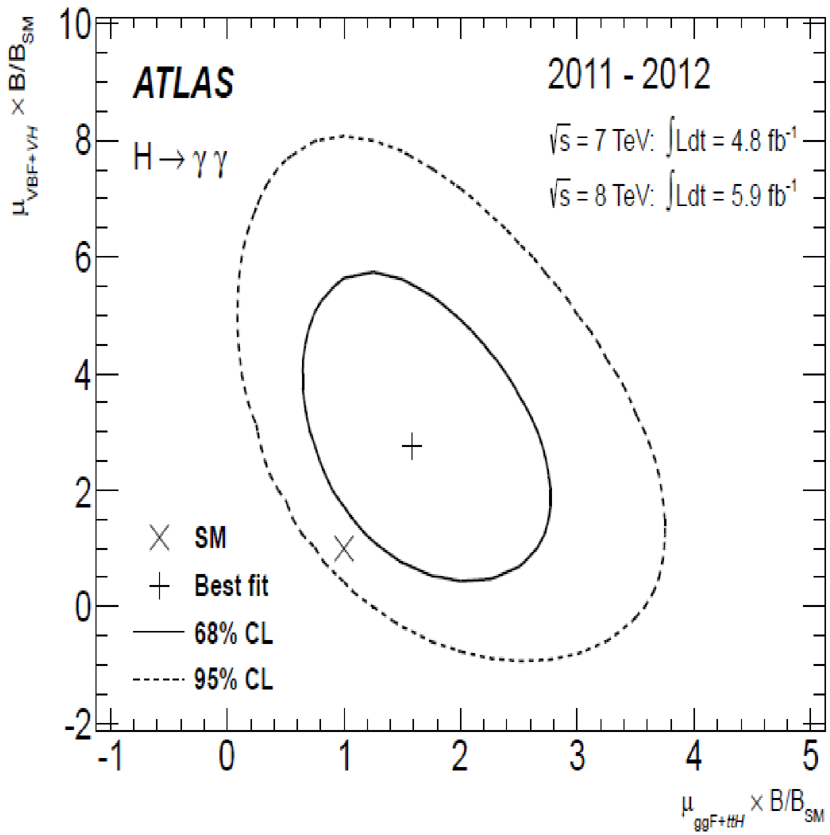


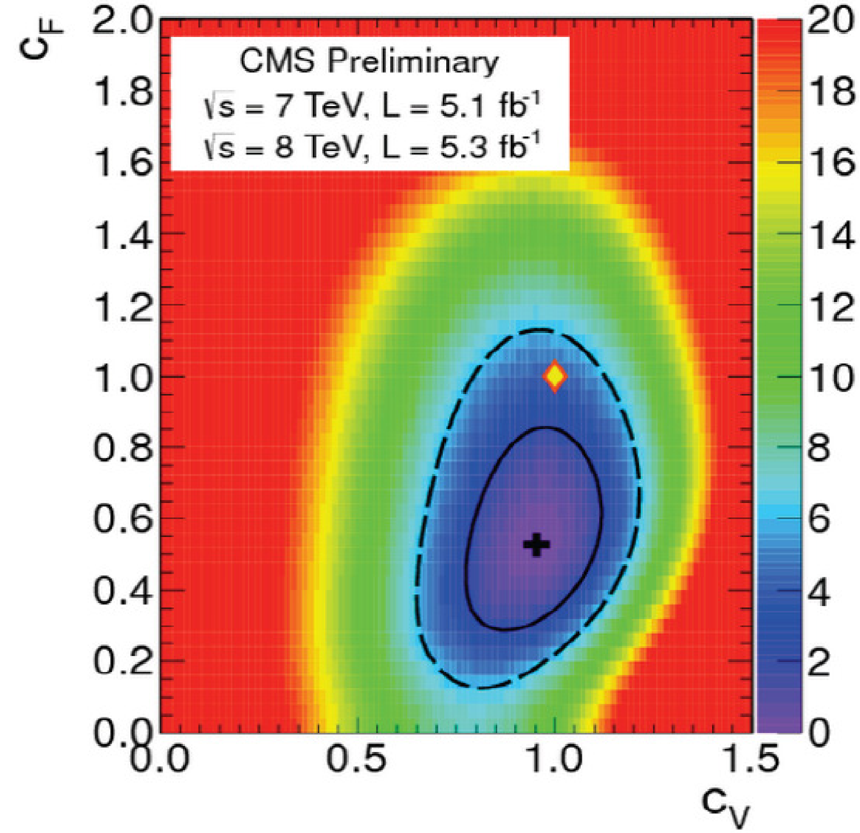
Test of decay branching ratios





Higgs couplings: bosonic vs fermionic





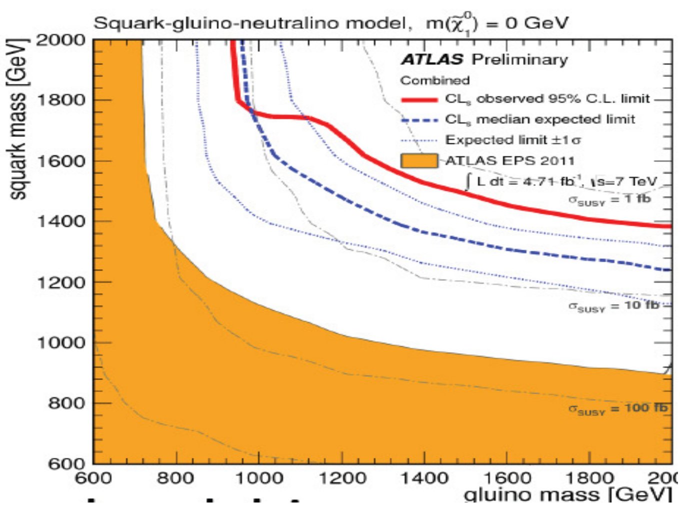
Other searches

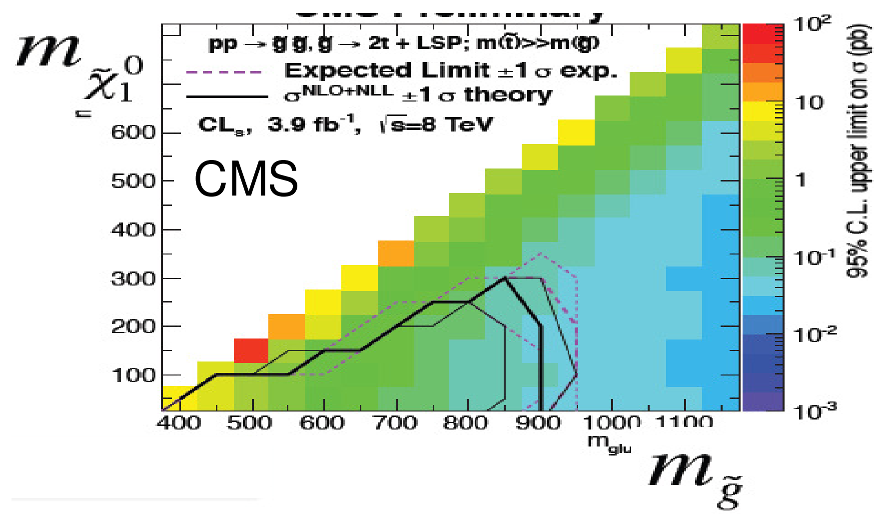
- Non-Standard Model Higgs
  - Fermiophobic Higgs
  - SUSY Higgs
  - Exotic Higgs (e.g. double charged)
- Supersymmetry
- Exotics (everything else)

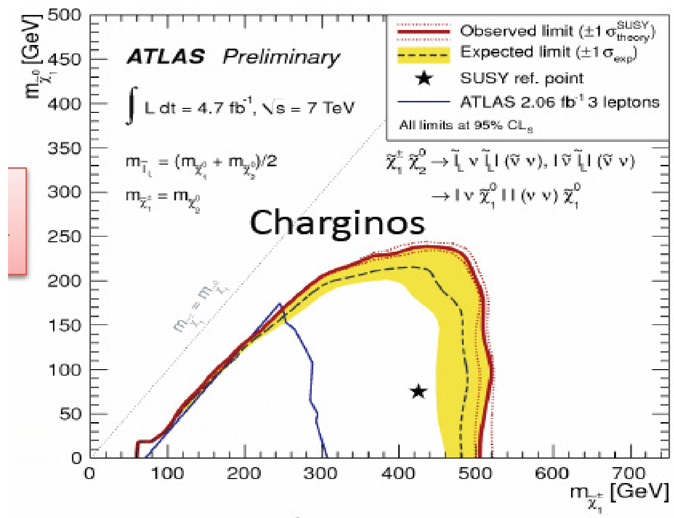
Supersymmetry

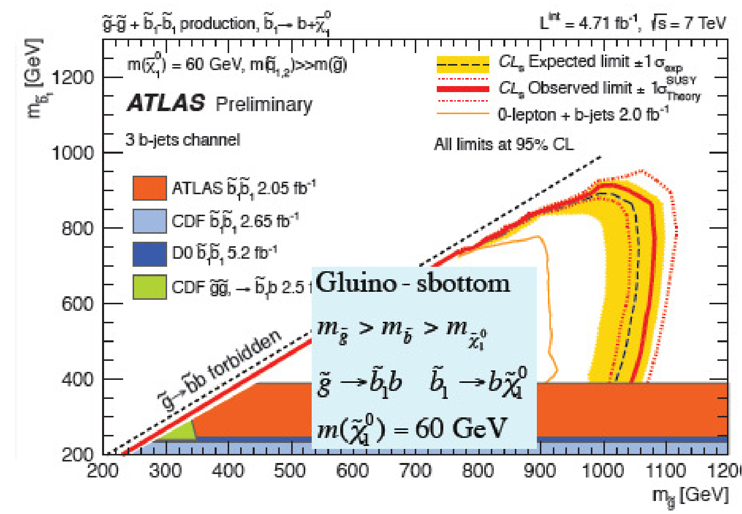
- Observation of a Higgs boson at 125 GeV is consistent both with SM and SUSY
- SUSY signal is expected in a wide variety of channel and topologies. Typical predicted mass spectrum is 100-1000 GeV. Experimental signature relatively easy - difficult to miss!
- But: not a single hint so far!
- It is nearly impossible to exclude SUSY decisively, because of too wide spectrum of possible scenarios

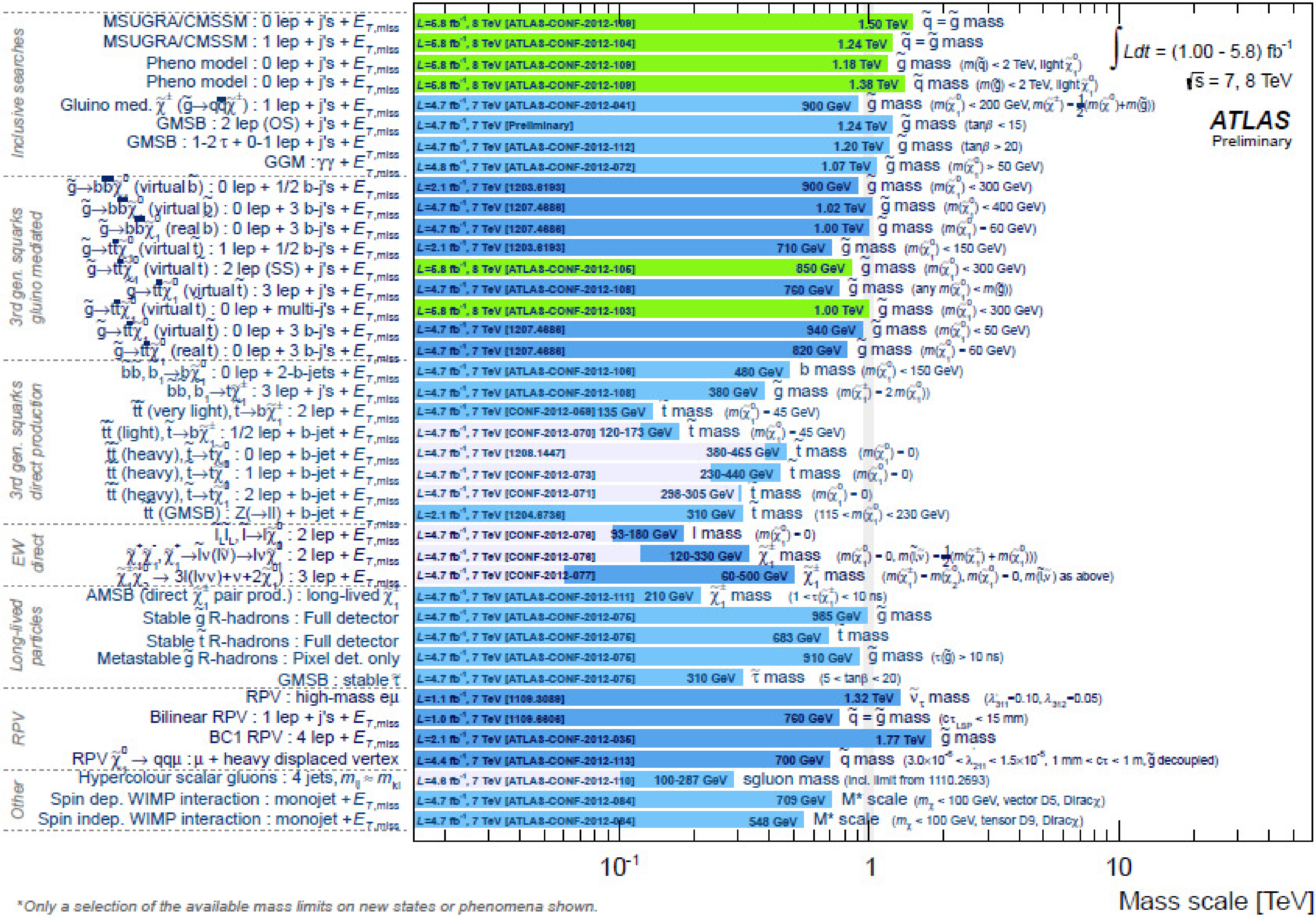
Few examples









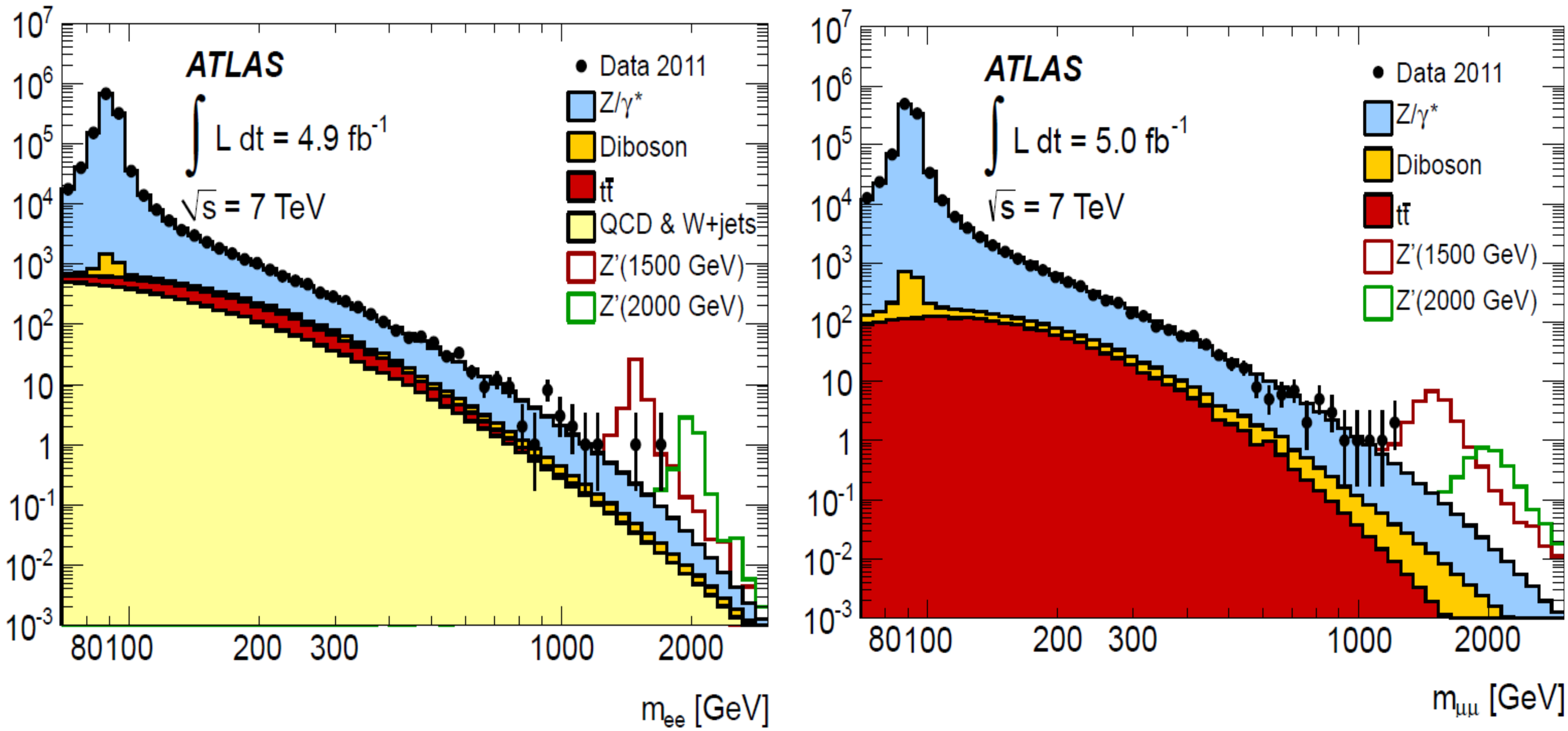


*Only a selection of the available mass limits on new states or phenomena shown.

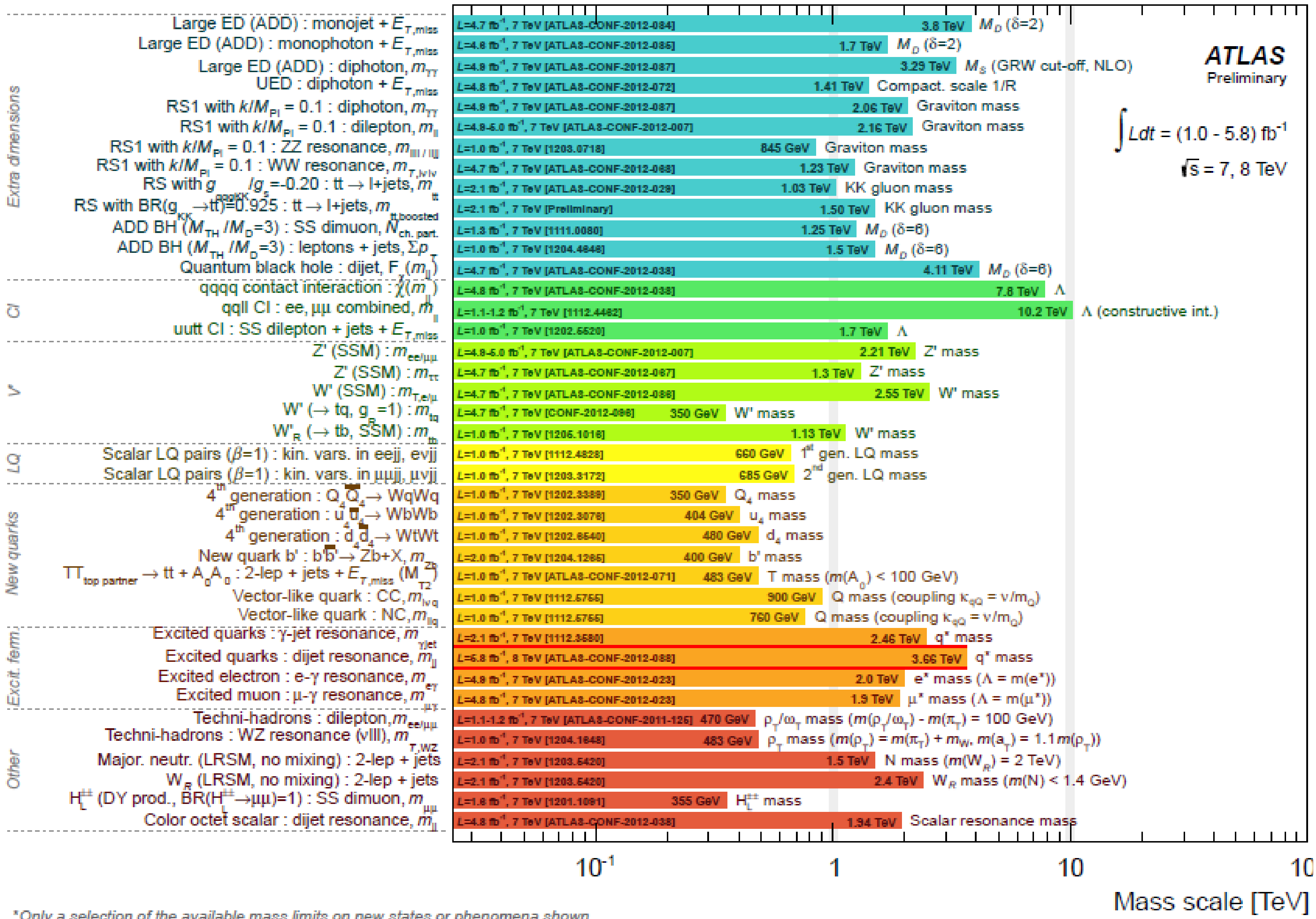
Exotics

- New vector bosons (W′, Z′)
- 4th generation quarks
- New leptons
- Gravitons, monopoles, leptoquarks
- Black holes
- Double charge, fractonal charge particles
- Just any unexpected deviation from SM

Example: sequential Z′ boson



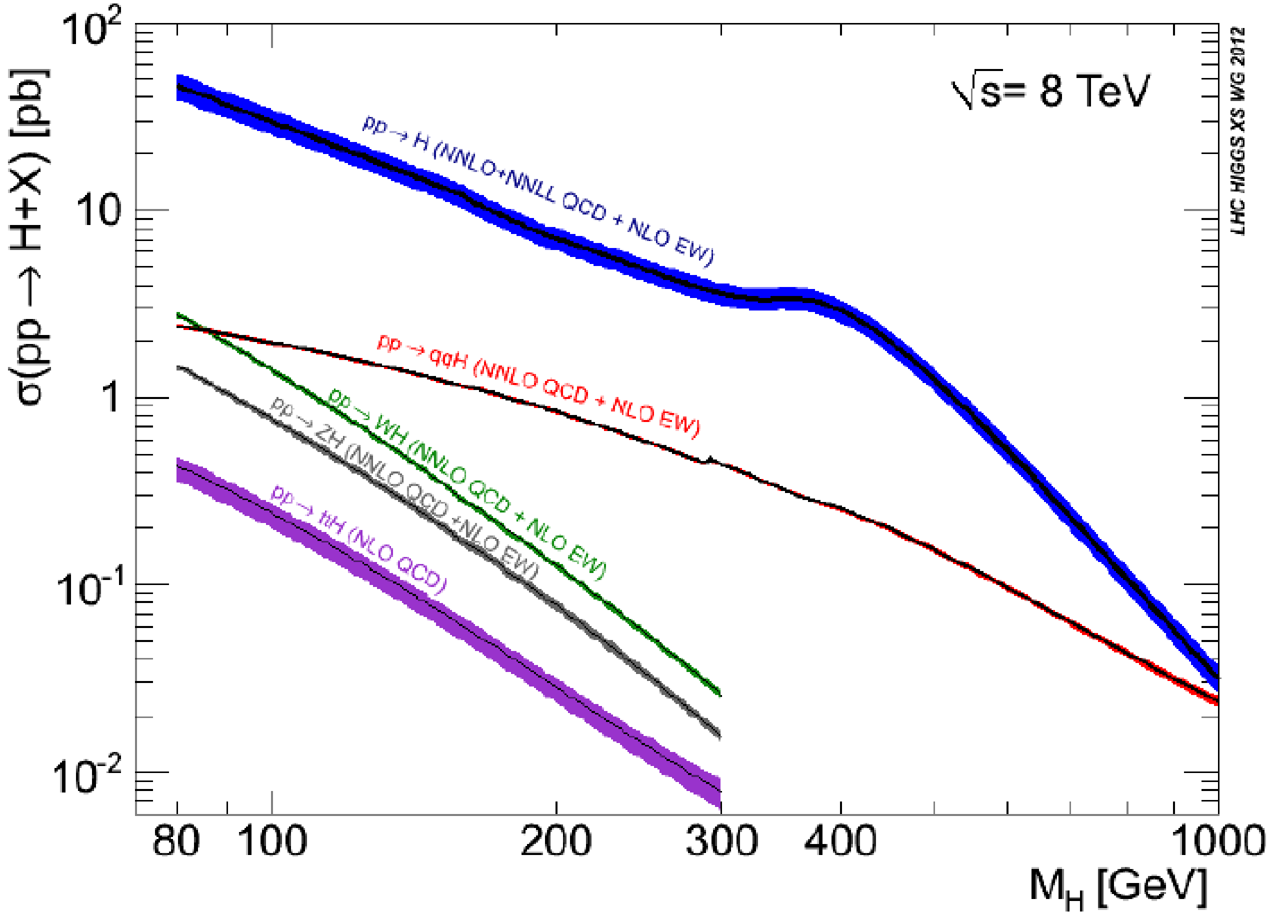
$M_{Z'} > 2220$ GeV


ATLAS
Preliminary
∫Ldt = (1.0 - 5.8) fb⁻¹
√s = 7, 8 TeV
Extra dimensions
CI
V'
LQ
New quarks
Excit. ferm.
Other
Large ED (ADD) : monojet + E_T,miss
L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2012-084] 3.8 TeV M_D (δ=2)
Large ED (ADD) : monophoton + E_T,miss
L=4.6 fb⁻¹, 7 TeV [ATLAS-CONF-2012-085] 1.7 TeV M_D (δ=2)
Large ED (ADD) : diphoton, m_γγ
L=4.9 fb⁻¹, 7 TeV [ATLAS-CONF-2012-087] 3.29 TeV M_S (GRW cut-off, NLO)
UED : diphoton + E_T,miss
L=4.8 fb⁻¹, 7 TeV [ATLAS-CONF-2012-072] 1.41 TeV Compact. scale 1/R
RS1 with k/M_Pl = 0.1 : diphoton, m_γγ
L=4.9 fb⁻¹, 7 TeV [ATLAS-CONF-2012-087] 2.06 TeV Graviton mass
RS1 with k/M_Pl = 0.1 : dilepton, m_ll
L=4.9-5.0 fb⁻¹, 7 TeV [ATLAS-CONF-2012-007] 2.16 TeV Graviton mass
RS1 with k/M_Pl = 0.1 : ZZ resonance, m_llll / lljj
L=1.0 fb⁻¹, 7 TeV [1203.0718] 845 GeV Graviton mass
RS1 with k/M_Pl = 0.1 : WW resonance, m_T,lνlν
L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2012-068] 1.23 TeV Graviton mass
RS with g_qqKK/g_s=-0.20 : tt → l+jets, m_tt
L=2.1 fb⁻¹, 7 TeV [ATLAS-CONF-2012-029] 1.03 TeV KK gluon mass
RS with BR(g_KK→tt)=0.925 : tt → l+jets, m_tt,boosted
L=2.1 fb⁻¹, 7 TeV [Preliminary] 1.50 TeV KK gluon mass
ADD BH (M_TH /M_D=3) : SS dimuon, N_ch. part.
L=1.3 fb⁻¹, 7 TeV [1111.0080] 1.25 TeV M_D (δ=6)
ADD BH (M_TH /M_D=3) : leptons + jets, Σp_T
L=1.0 fb⁻¹, 7 TeV [1204.4646] 1.5 TeV M_D (δ=6)
Quantum black hole : dijet, F_χ(m_jj)
L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2012-038] 4.11 TeV M_D (δ=6)
qqqq contact interaction : χ(m_jj)
L=4.8 fb⁻¹, 7 TeV [ATLAS-CONF-2012-038] 7.8 TeV Λ
qqll CI : ee, μμ combined, m_ll
L=1.1-1.2 fb⁻¹, 7 TeV [1112.4462] 10.2 TeV Λ (constructive int.)
uutt CI : SS dilepton + jets + E_T,miss
L=1.0 fb⁻¹, 7 TeV [1202.5520] 1.7 TeV Λ
Z' (SSM) : m_ee/μμ
L=4.9-5.0 fb⁻¹, 7 TeV [ATLAS-CONF-2012-007] 2.21 TeV Z' mass
Z' (SSM) : m_ττ
L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2012-067] 1.3 TeV Z' mass
W' (SSM) : m_T,e/μ
L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2012-086] 2.55 TeV W' mass
W' (→ tq, g_R=1) : m_tq
L=4.7 fb⁻¹, 7 TeV [CONF-2012-096] 350 GeV W' mass
W'_R (→ tb, SSM) : m_tb
L=1.0 fb⁻¹, 7 TeV [1205.1016] 1.13 TeV W' mass
Scalar LQ pairs (β=1) : kin. vars. in eejj, eνjj
L=1.0 fb⁻¹, 7 TeV [1112.4828] 660 GeV 1st gen. LQ mass
Scalar LQ pairs (β=1) : kin. vars. in μμjj, μνjj
L=1.0 fb⁻¹, 7 TeV [1203.3172] 685 GeV 2nd gen. LQ mass
4th generation : Q₄Q̄₄→ WqWq
L=1.0 fb⁻¹, 7 TeV [1202.3389] 350 GeV Q₄ mass
4th generation : u₄ū₄→ WbWb
L=1.0 fb⁻¹, 7 TeV [1202.3076] 404 GeV u₄ mass
4th generation : d₄d̄₄→ WtWt
L=1.0 fb⁻¹, 7 TeV [1202.6540] 480 GeV d₄ mass
New quark b' : b'b̄'→ Zb+X, m_Zb
L=2.0 fb⁻¹, 7 TeV [1204.1265] 400 GeV b' mass
TT_top partner → tt + A₀A₀ : 2-lep + jets + E_T,miss (M_T2)
L=1.0 fb⁻¹, 7 TeV [ATLAS-CONF-2012-071] 483 GeV T mass (m(A₀) < 100 GeV)
Vector-like quark : CC, m_lνq
L=1.0 fb⁻¹, 7 TeV [1112.5755] 900 GeV Q mass (coupling κ_qQ = v/m_Q)
Vector-like quark : NC, m_llq
L=1.0 fb⁻¹, 7 TeV [1112.5755] 760 GeV Q mass (coupling κ_qQ = v/m_Q)
Excited quarks : γ-jet resonance, m_γjet
L=2.1 fb⁻¹, 7 TeV [1112.3580] 2.46 TeV q* mass
Excited quarks : dijet resonance, m_jj
L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-088] 3.66 TeV q* mass
Excited electron : e-γ resonance, m_eγ
L=4.9 fb⁻¹, 7 TeV [ATLAS-CONF-2012-023] 2.0 TeV e* mass (Λ = m(e*))
Excited muon : μ-γ resonance, m_μγ
L=4.8 fb⁻¹, 7 TeV [ATLAS-CONF-2012-023] 1.9 TeV μ* mass (Λ = m(μ*))
Techni-hadrons : dilepton, m_ee/μμ
L=1.1-1.2 fb⁻¹, 7 TeV [ATLAS-CONF-2011-125] 470 GeV ρ_T/ω_T mass (m(ρ_T/ω_T) - m(π_T) = 100 GeV)
Techni-hadrons : WZ resonance (νlll), m_T,WZ
L=1.0 fb⁻¹, 7 TeV [1204.1648] 483 GeV ρ_T mass (m(ρ_T) = m(π_T) + m_W, m(a_T) = 1.1 m(ρ_T))
Major. neutr. (LRSM, no mixing) : 2-lep + jets
L=2.1 fb⁻¹, 7 TeV [1203.5420] 1.5 TeV N mass (m(W_R) = 2 TeV)
W_R (LRSM, no mixing) : 2-lep + jets
L=2.1 fb⁻¹, 7 TeV [1203.5420] 2.4 TeV W_R mass (m(N) < 1.4 GeV)
H_L^±± (DY prod., BR(H_L^±±→μμ)=1) : SS dimuon, m_μμ
L=1.6 fb⁻¹, 7 TeV [1201.1091] 355 GeV H_L^±± mass
Color octet scalar : dijet resonance, m_jj
L=4.8 fb⁻¹, 7 TeV [ATLAS-CONF-2012-038] 1.94 TeV Scalar resonance mass
10⁻¹
1
10
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

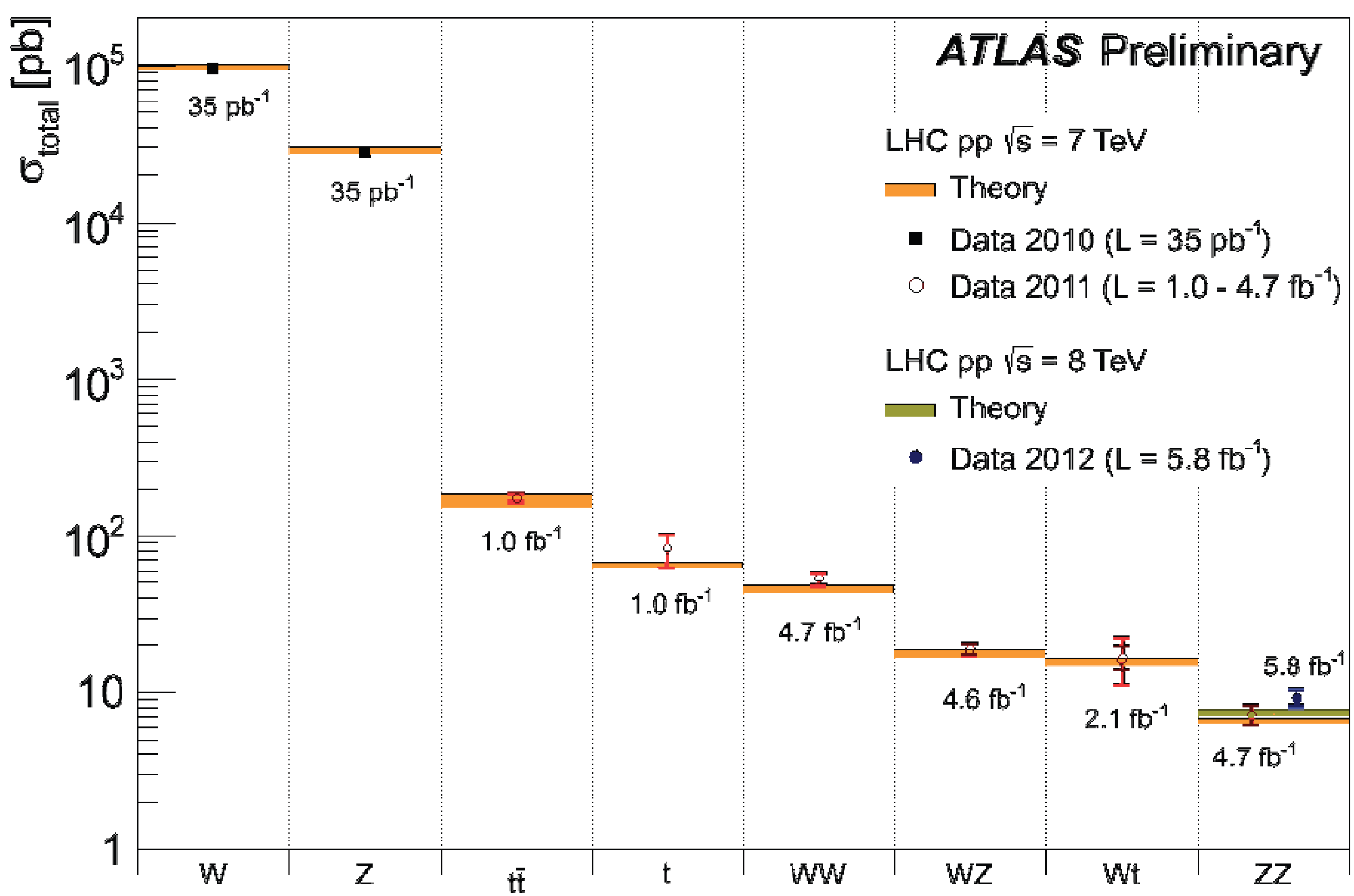
Summary

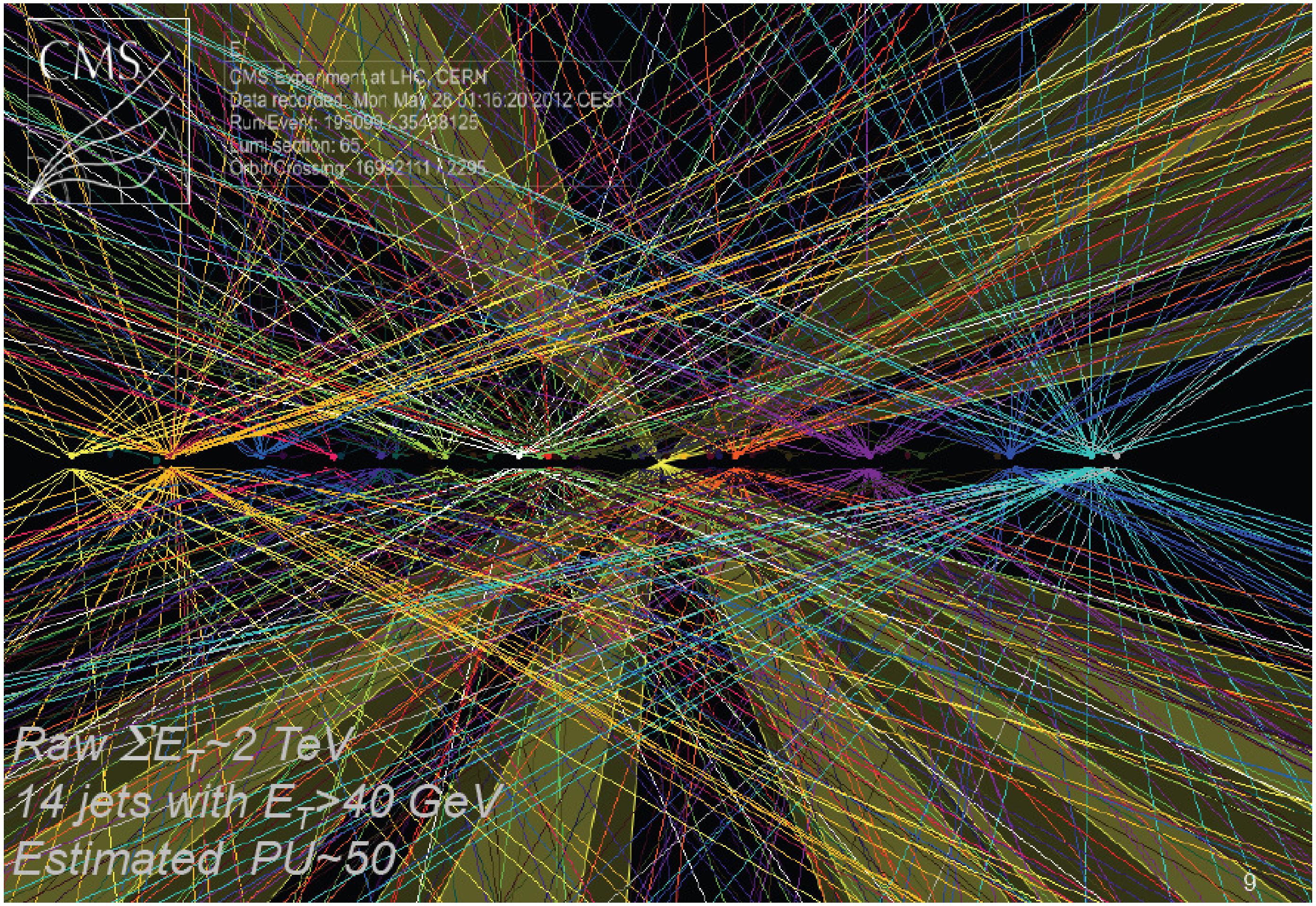
- A new 125 GeV particle has been discovered at LHC
- It perfectly fits the long-waited Higgs boson, but confirmation is needed
- Not a single hint of new physics beyond the Standard Model
- Still enormous amount of work ahead!

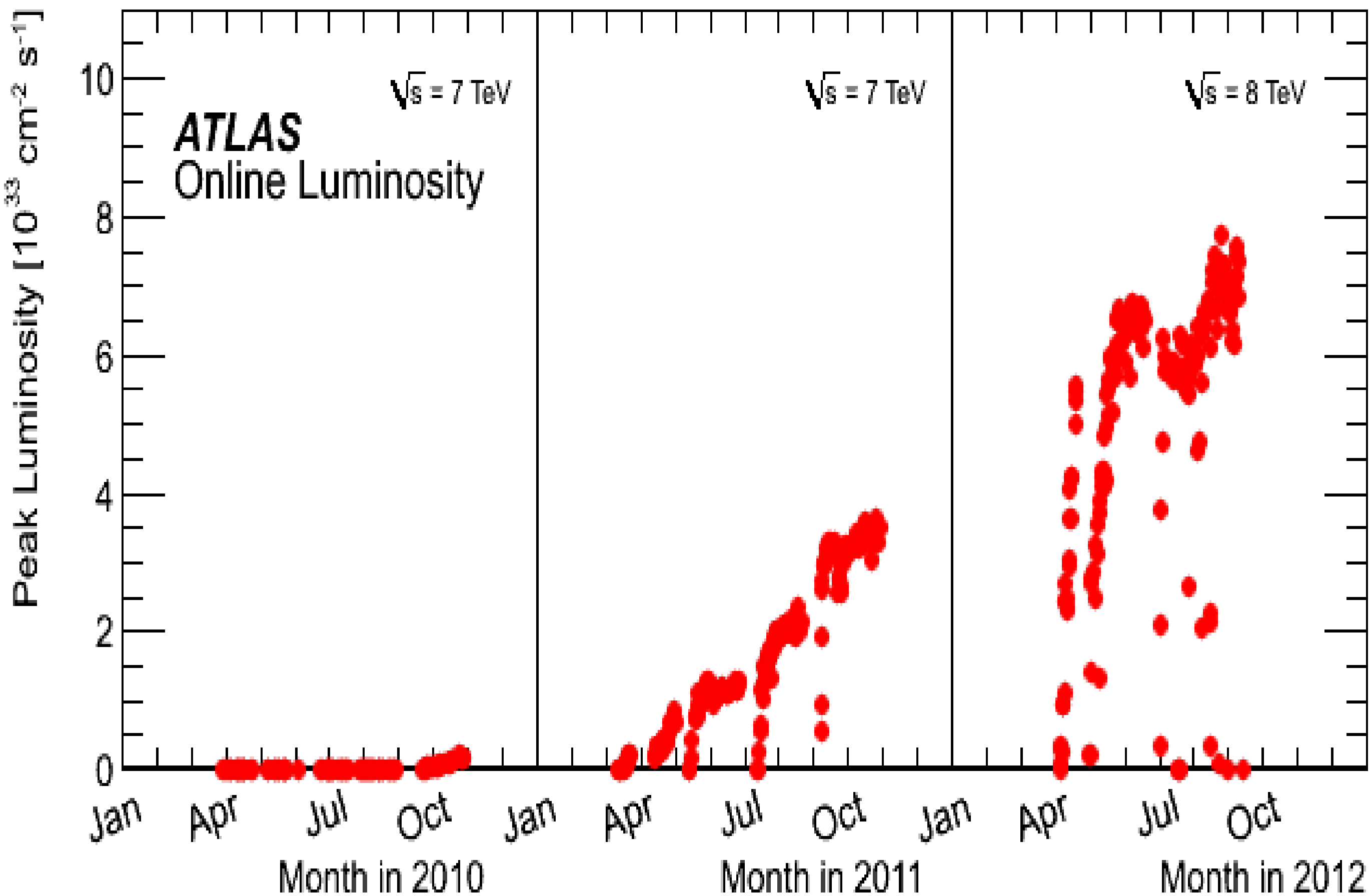
Spare slides



$\sqrt{s}$= 8 TeV
LHC HIGGS XS WG 2012
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
σ(pp → H+X) [pb]
M_H [GeV]
10^2
10
1
10^{-1}
10^{-2}
80
100
200
300
400
1000


ATLAS Preliminary
LHC pp √s = 7 TeV
Theory
Data 2010 (L = 35 pb-1)
Data 2011 (L = 1.0 - 4.7 fb-1)
LHC pp √s = 8 TeV
Theory
Data 2012 (L = 5.8 fb-1)
σtotal [pb]
35 pb-1
35 pb-1
1.0 fb-1
1.0 fb-1
4.7 fb-1
4.6 fb-1
2.1 fb-1
4.7 fb-1
5.8 fb-1
W
Z
tt̄
t
WW
WZ
Wt
ZZ


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
Raw ΣE_T~2 TeV
14 jets with E_T>40 GeV
Estimated PU~50
9


ATLAS
Online Luminosity
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
Peak Luminosity [10^{33} cm^{-2} s^{-1}]
0
2
4
6
8
10
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Month in 2010
Month in 2011
Month in 2012