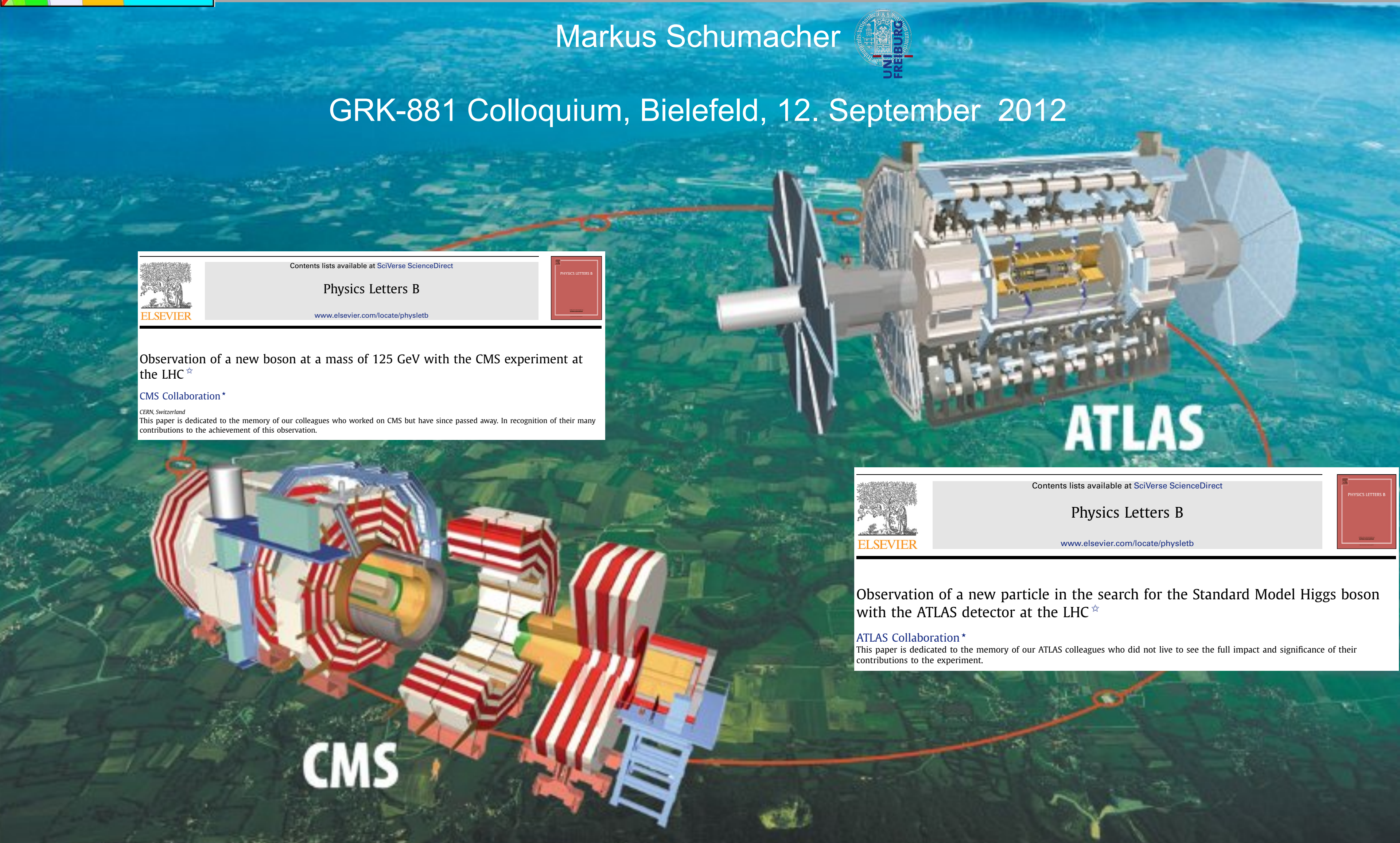
Observation of a New Particle in the Search for the Standard Model Higgs Boson at the LHC

Markus Schumacher

GRK-881 Colloquium, Bielefeld, 12. September 2012



Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *
CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

The Problem with Elementary Particle Masses

Interactions described via local gauge theories

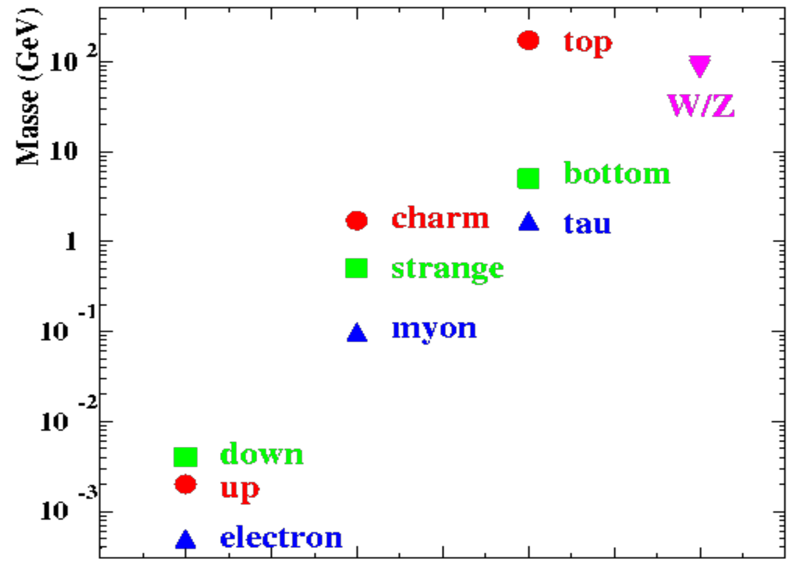
gauge groups of SM forbid masses for
- weak gauge bosons: W and Z
- fermions (l= doublet, r = singlet)

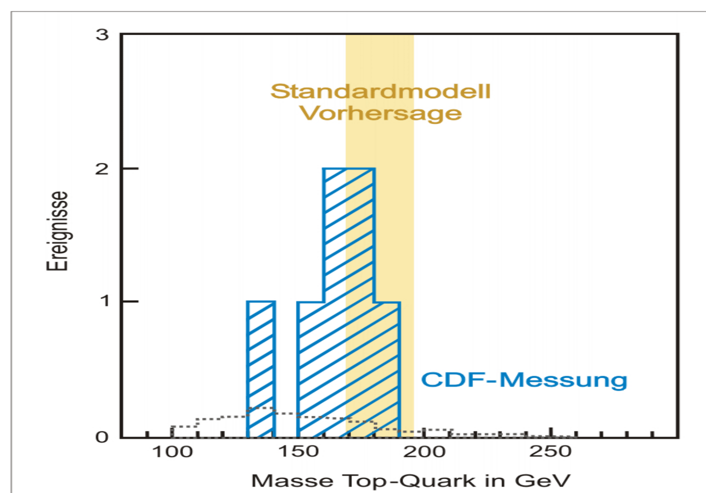
Bosonen	8 Gluonen	W^+, W^-, Z	γ
Gruppe	SU(3)	SU(2)	U(1)
Theorie	starke Kraft QCD	schwache Kraft	elektro-magnetische Kraft QED

„ad hoc“ mass terms destroy:

- renormalizibility → no precision predictions
- probability interpetation of cross sections
  e.g. unitaritaty violation in $W_L W_L$ scattering

Experiment: all particles massive except gluon and photon

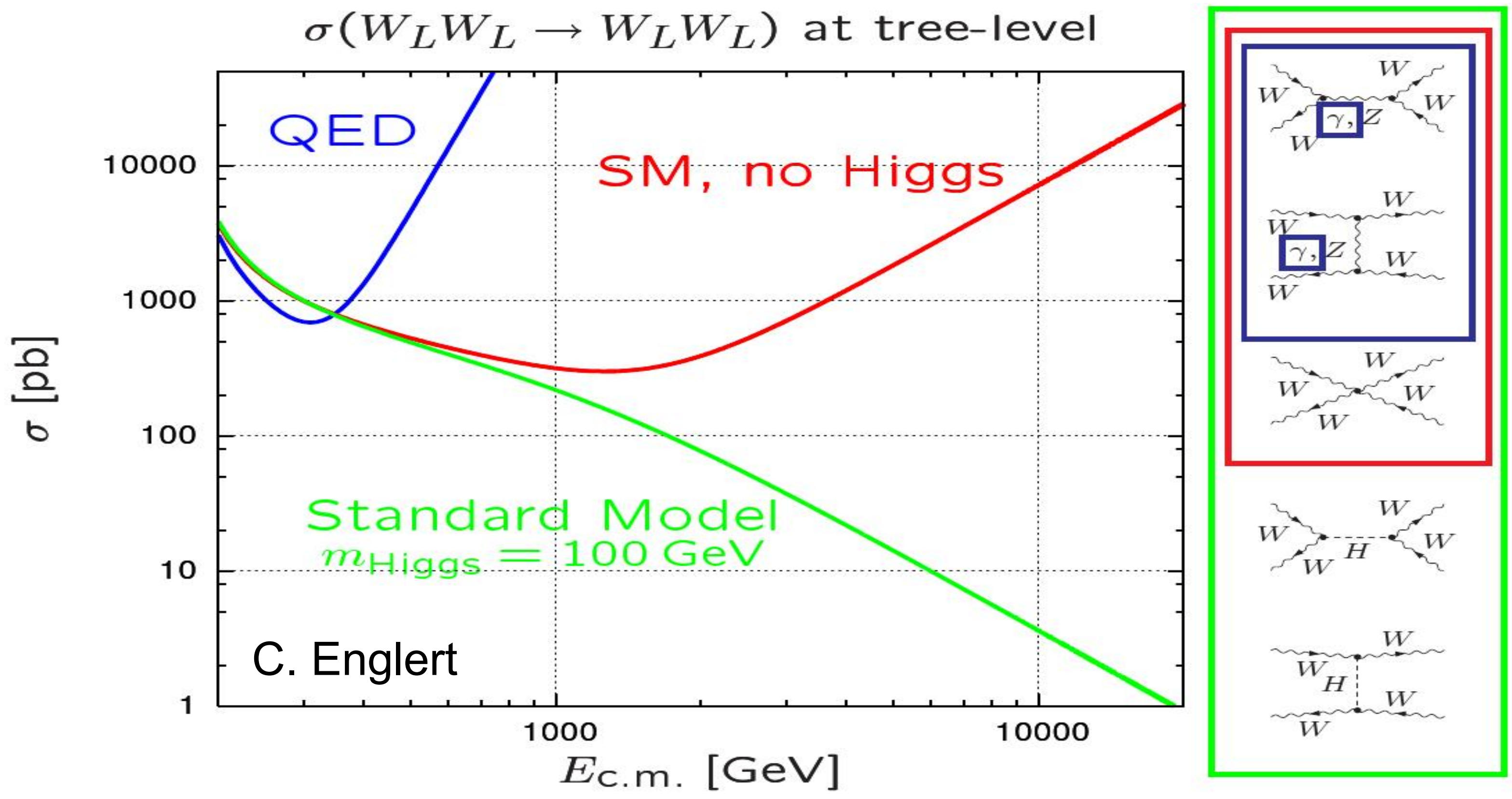




Violation of Unitarity in WW→WW

massive gauge boson: 1 longitudinal + 2 transversal degrees of freedom (d.o.f.)

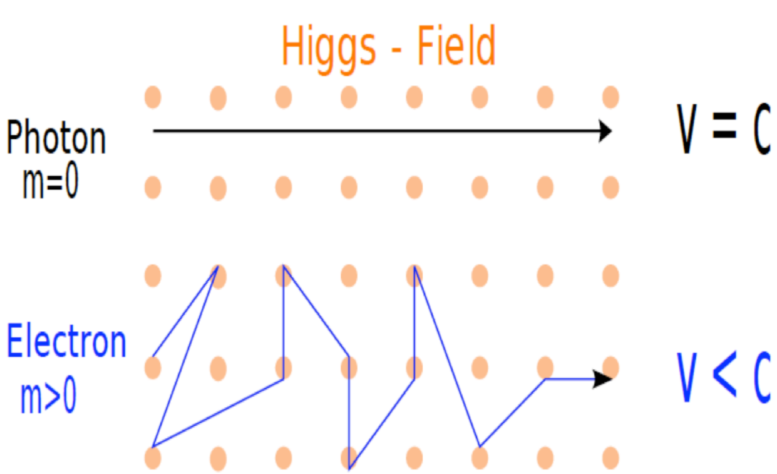
massless gauge boson: only 2 transversal degrees of freedom (d.o.f.)



SM w/o Higgs boson violates unitarity at energies ~1.2 TeV

Scalar boson H restores unitarity, if $g_{HPP} \sim m_P$ and m_H not too large

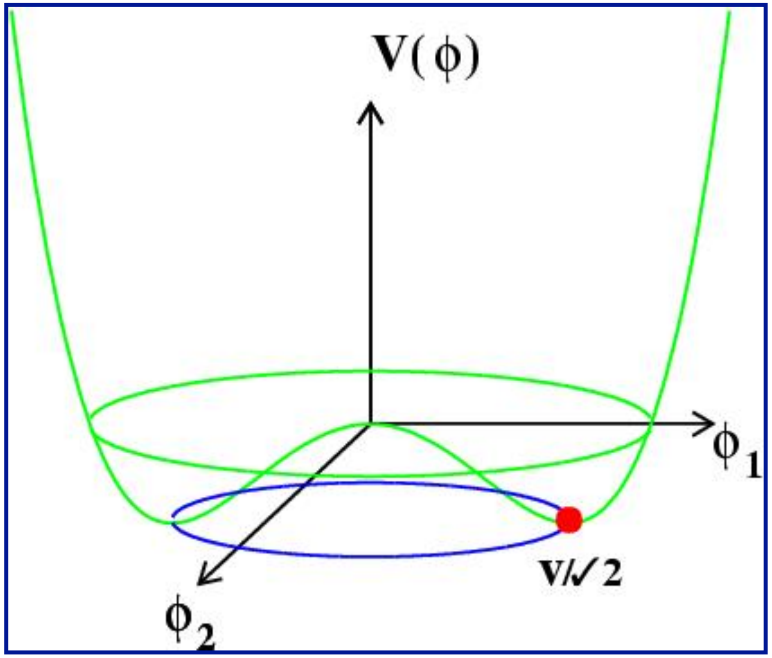
Mass Description and Higgs-(EBHGHK)-Mechanism



effective mass through interaction with omnipresent condensate of scalar field

value of condensate strength
(vacuum expactation value vev)
known from G_F

mass of particles = coupling x vev

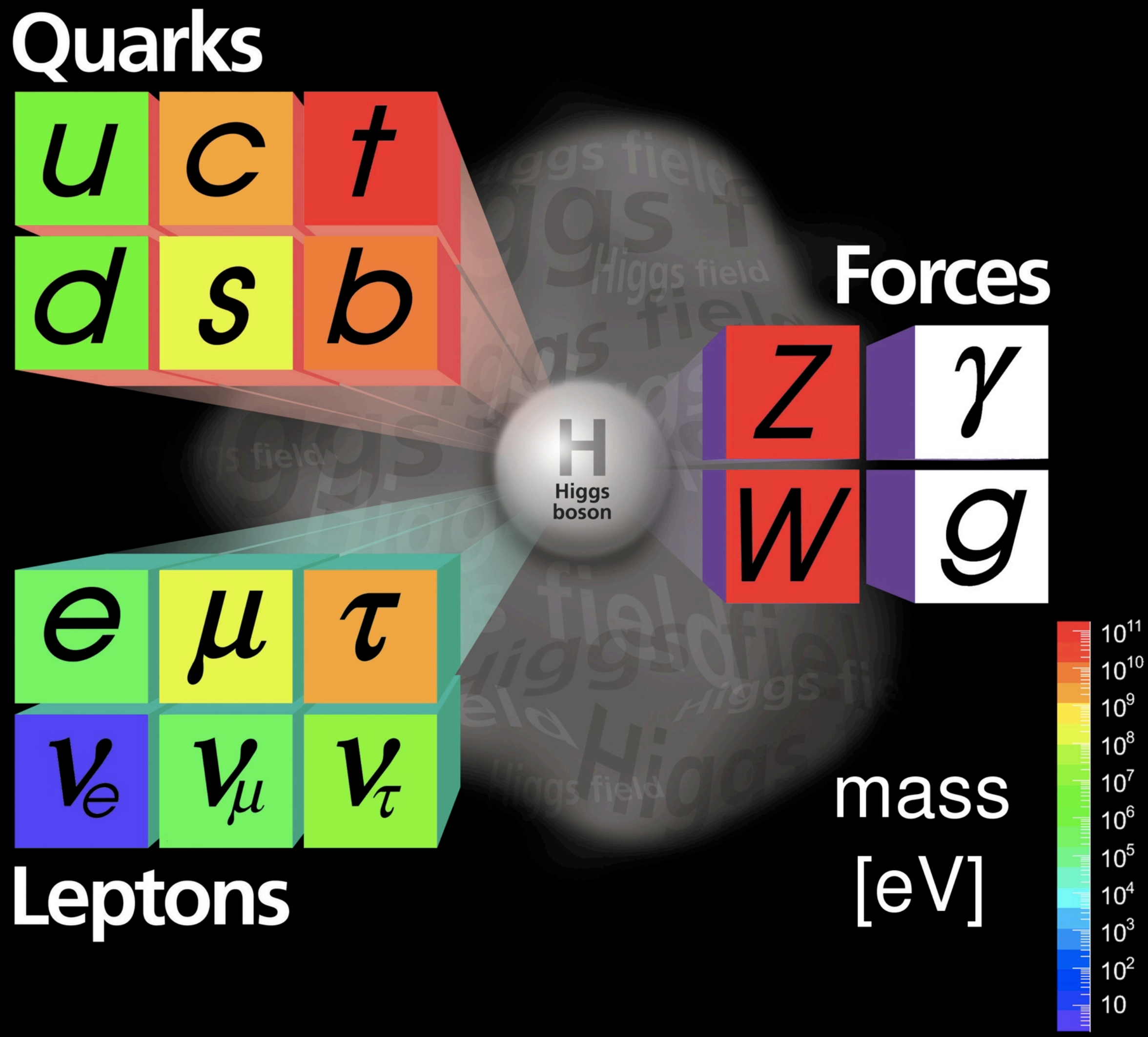


economical solution in SM: 4 scalar d.o.f
with gauge-invariant, renormalizable potential

minimum of V not at $\phi=0$
→ spontaneous symmetry breaking → vev
3 massless excitations → 3 long. d.o.f for W^{+-}, Z
1 massive excitation → physical Higgs-Boson

Higgs field has two components:
- homogenous condensate vev= 247 GeV
- Higgs-Boson H with unknown mass M_H

Without the Higgs Boson the SM is Not Complete



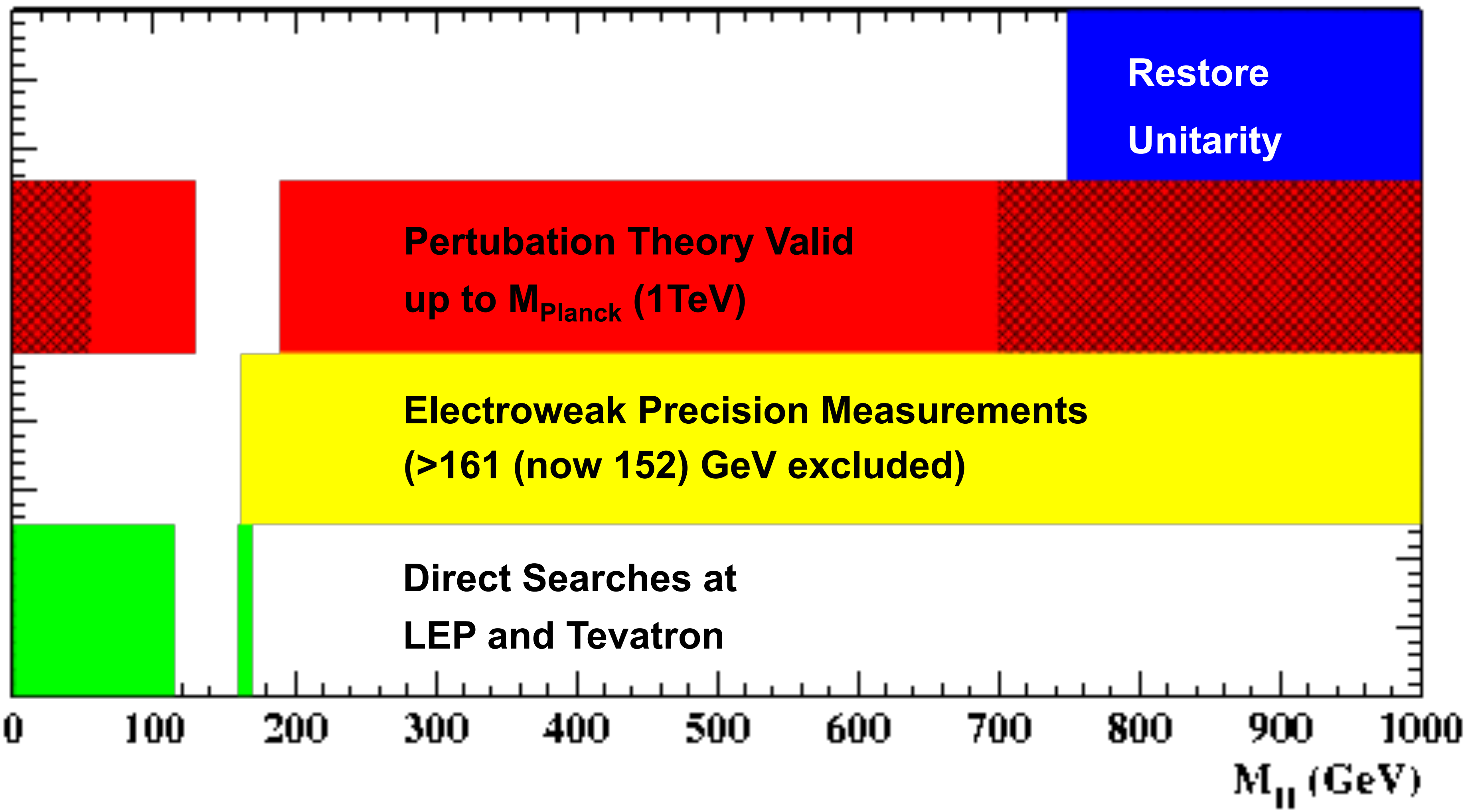
in SM the profile of the Higgs boson is fixed once we assume M_H

M_H is the last unknown parameter of the SM

whether a Higgs boson is realized in nature is unclear

consistent description of massive particles in gauge theories by Englert,Brout,Higgs, Guralnik,Hagen,Kibble in 1964

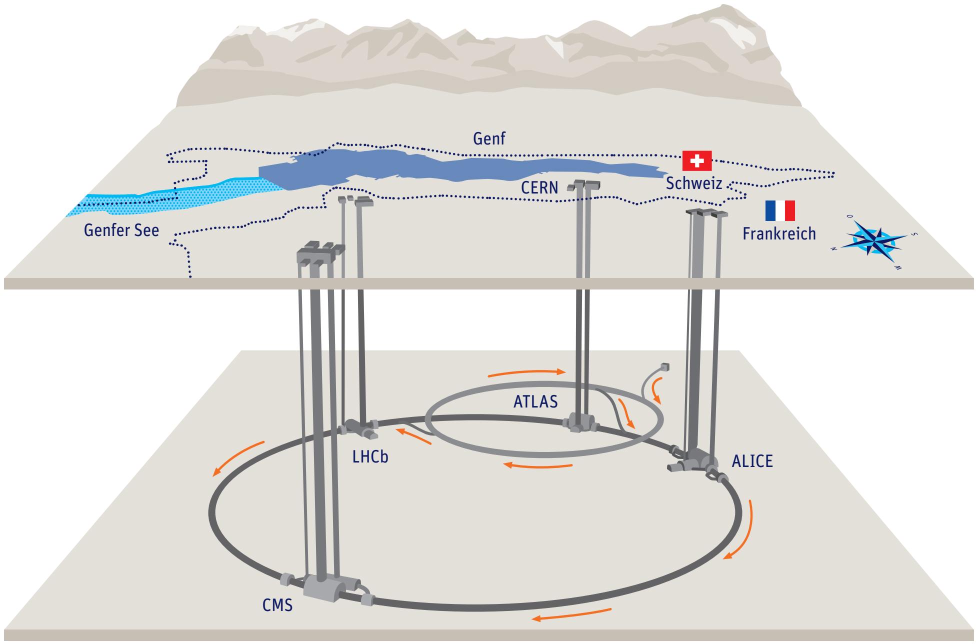
Knowledge about M_H in SM before LHC

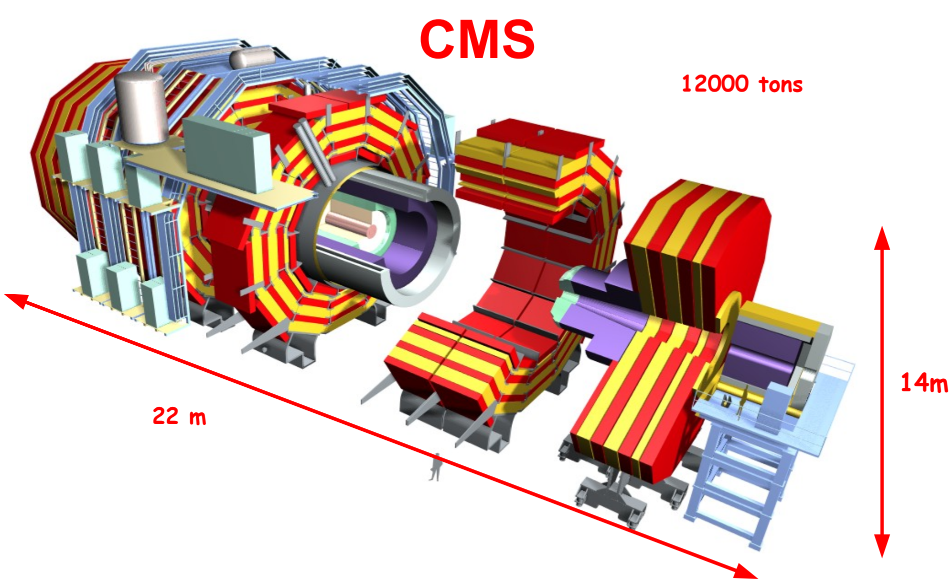


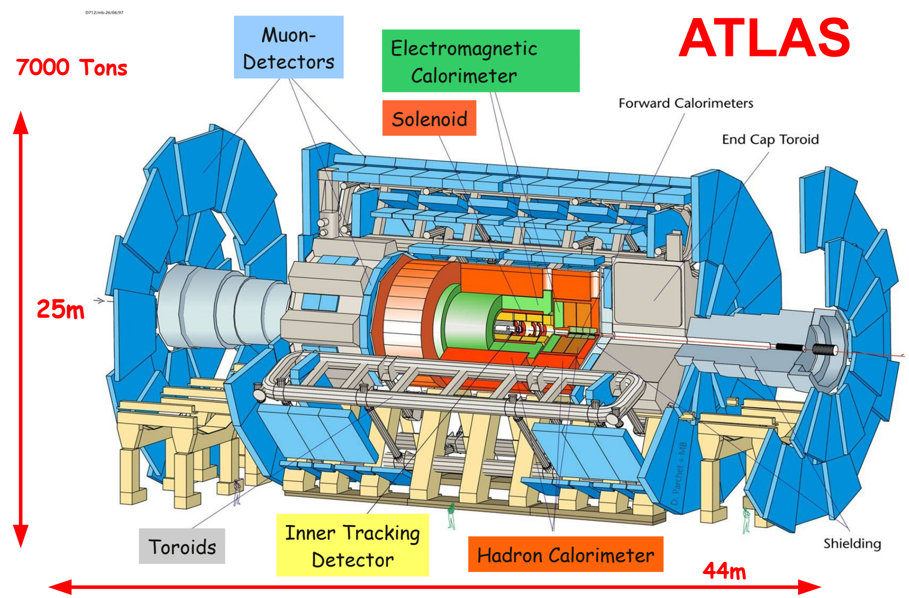
the Standard Model prefers a light Higgs boson

LHC and its experiments designed to probe the full mass range from LEP limit to 1 TeV

LHC, ATLAS and CMS





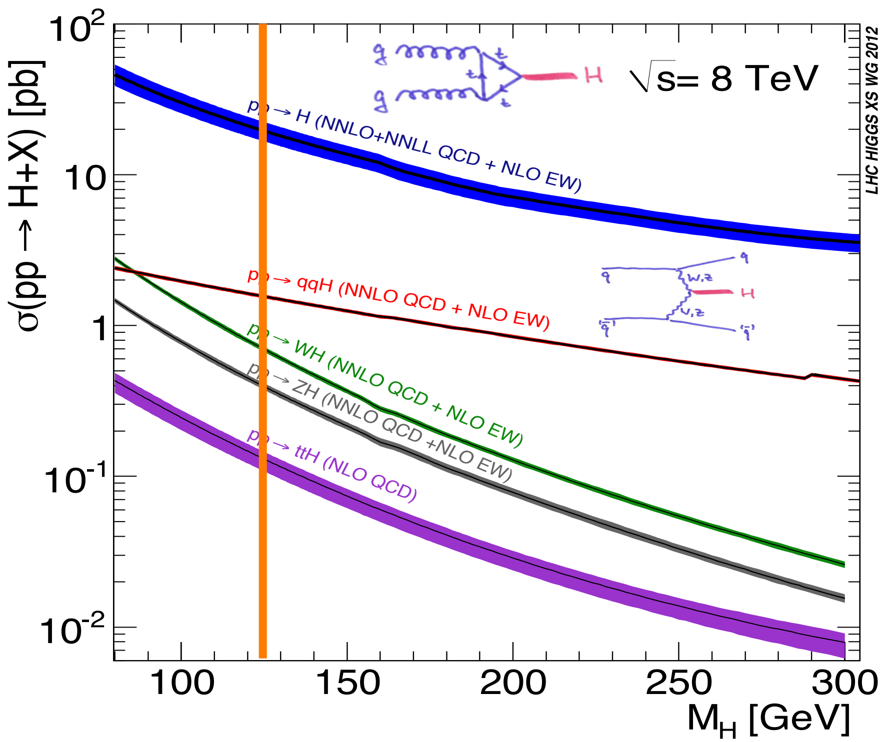


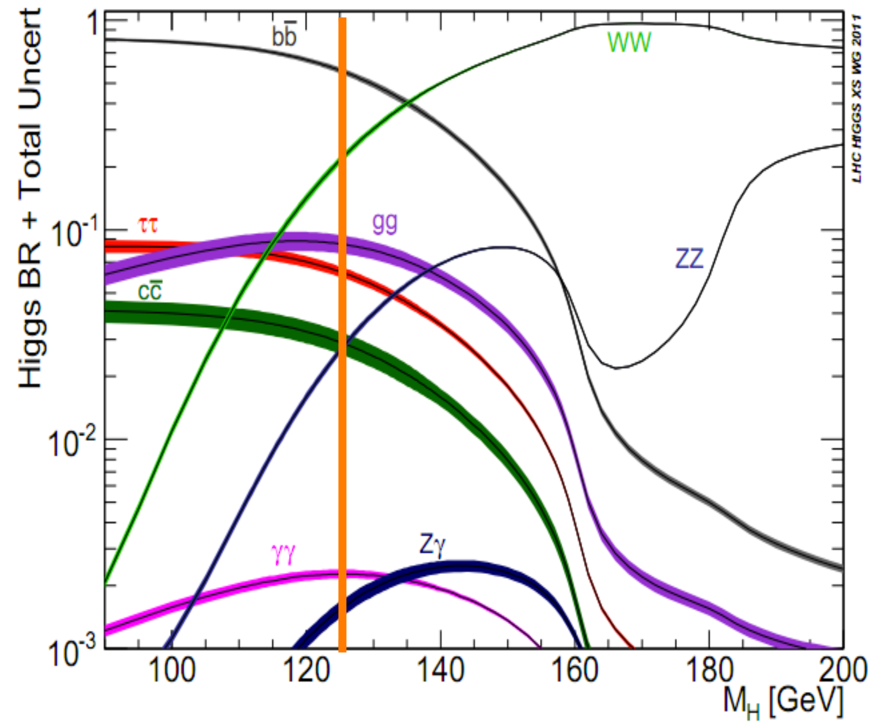
LHC, ATLAS and CMS

The success of 4th July 2012 is due to the excellent work of more than 10000 people over several decades in designing, building, commissioning and operating LHC and its pre-accelerators, CMS and ATLAS.

and due to excellent calculations by and cooperation with our friends from the theory community.

SM Higgs Boson Production and Decay

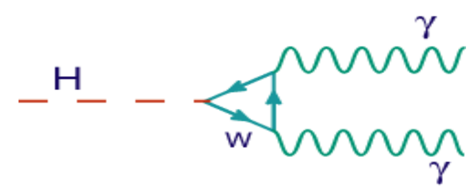




8 to 7 TeV: ~30% larger σ_{prod} at 125 GeV

E_{CM}	σ incl.	GGF	VBF
7 TeV	17.5 pb	15.3 pb	1.2 pb
8 TeV	22.3 pb	19.5 pb	1.6 pb

H→ 2 photons loop induced

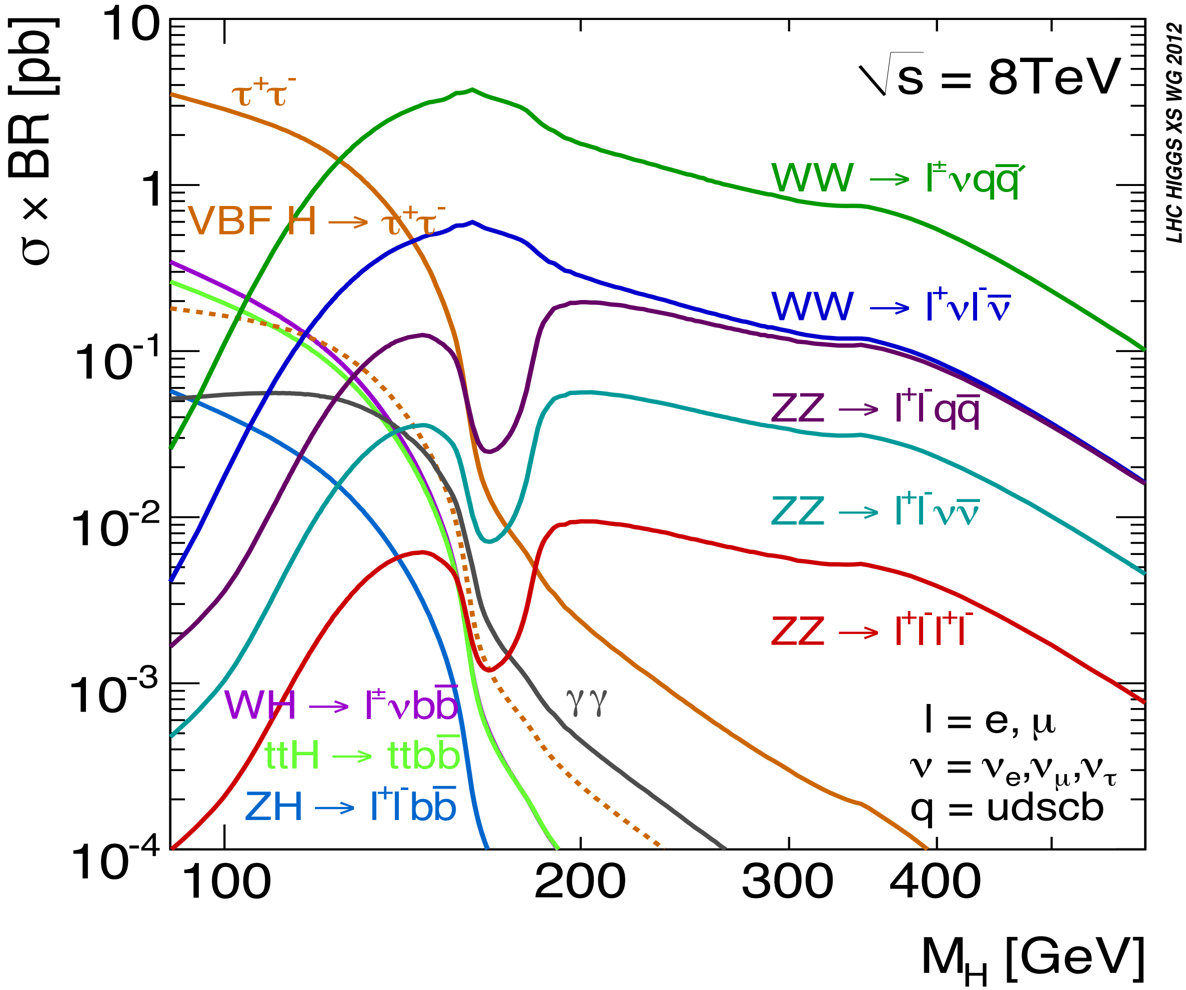


BR (125 GeV) = 0.2 %

H→ ZZ→4 leptons (l=e,μ)

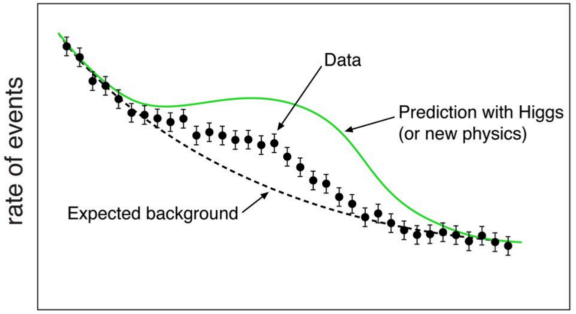
BR (125 GeV) = 0.013 %

Production Rates in Detectable Final States



rule of thumb:
need ~3 signal events after selecton to exclude hypothesis (for background =0)

criteria:
- sufficient signal rate
- „triggerable“ → e,μ,γ,(τ)
- background reducible
- good mass resolution



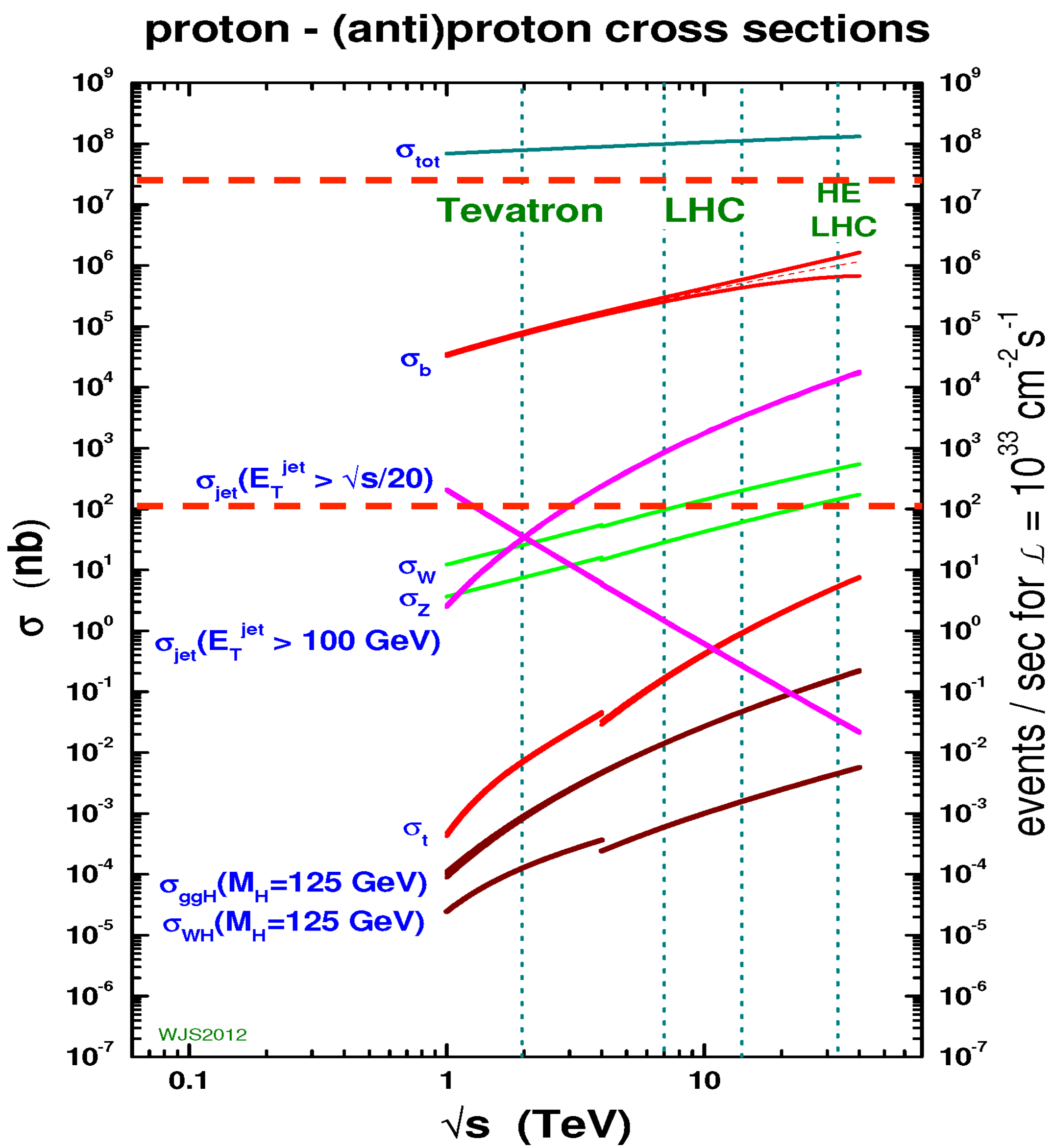
Mass of decay products

no fully hadronic final states, not gg→H with H→bb,→ZZ(WW)→4quarks

H→bb only in W(Z)H with W→lν oder Z→ll

for small M_H not H→ZZ→llqq und H→WW→lν qq

The Challenge



collision rate: 20 MHz

→ three staged trigger system

recording rate: o(200) HZ

→ still: 3 PetaByte/Year

analysed data ~10 to 11 fb^{-1}

(~50% at 7 TeV in 2011

+ ~50% at 8TeV in 2012)

this corresponds to:

~ 10^{15} collisions

~ 200000 produced Higgs bosons (125 GeV)

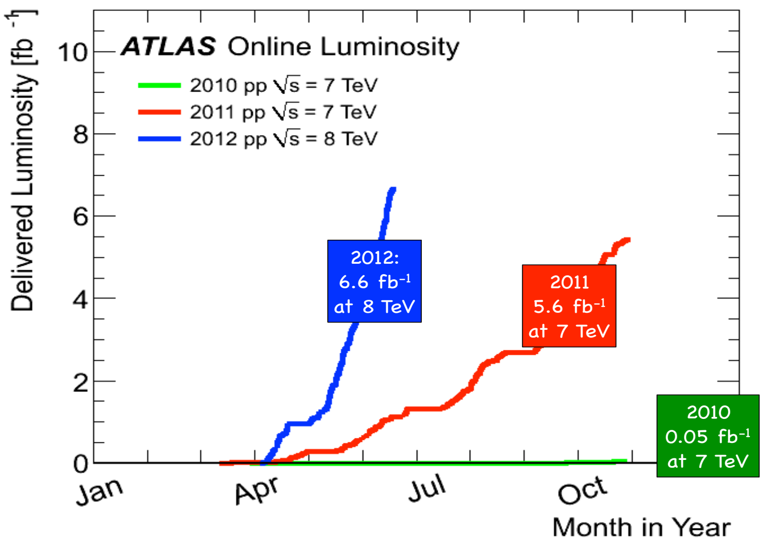
but only

~400 decaying via H→γγ

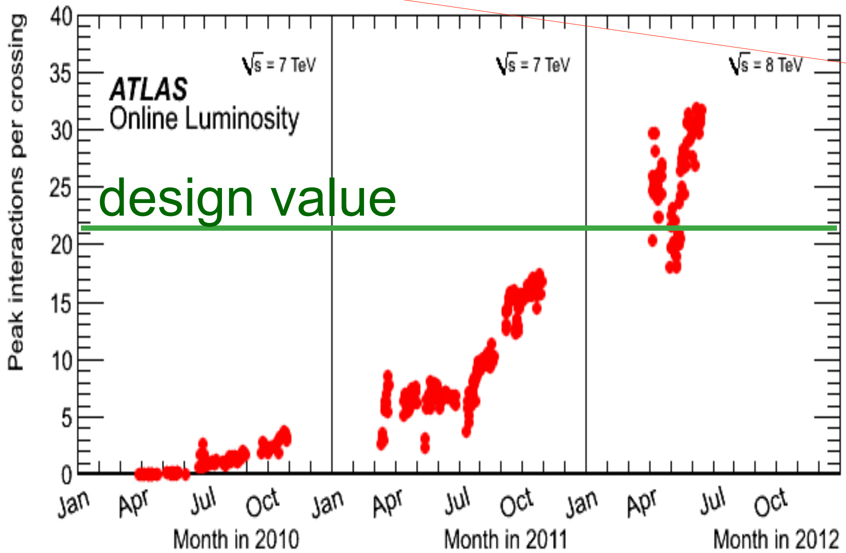
~30 decaying via H→ZZ→4l

Excellent Performance of the LHC

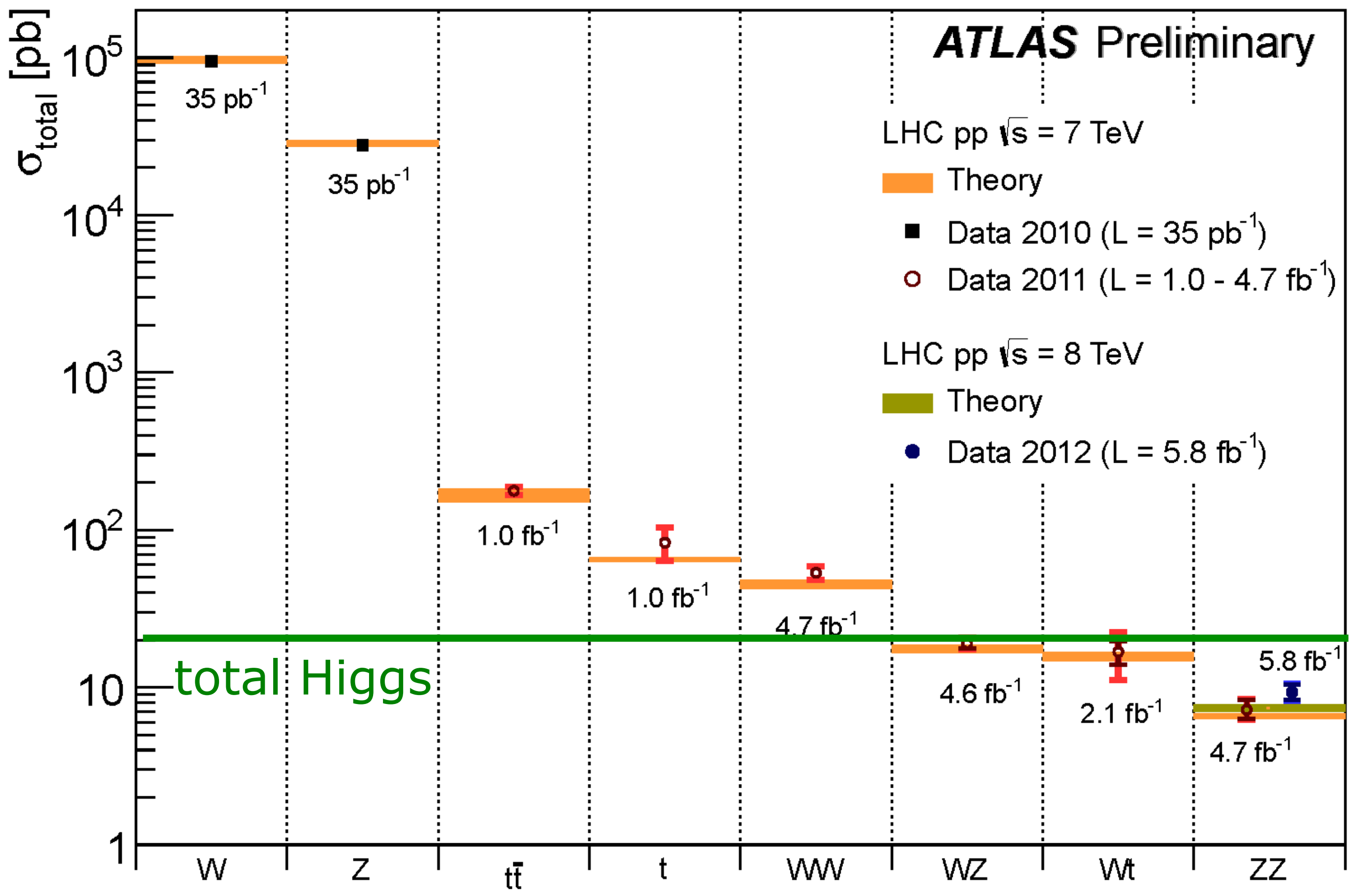
LHC exceeds all expectations



the price to pay: „Pile up“

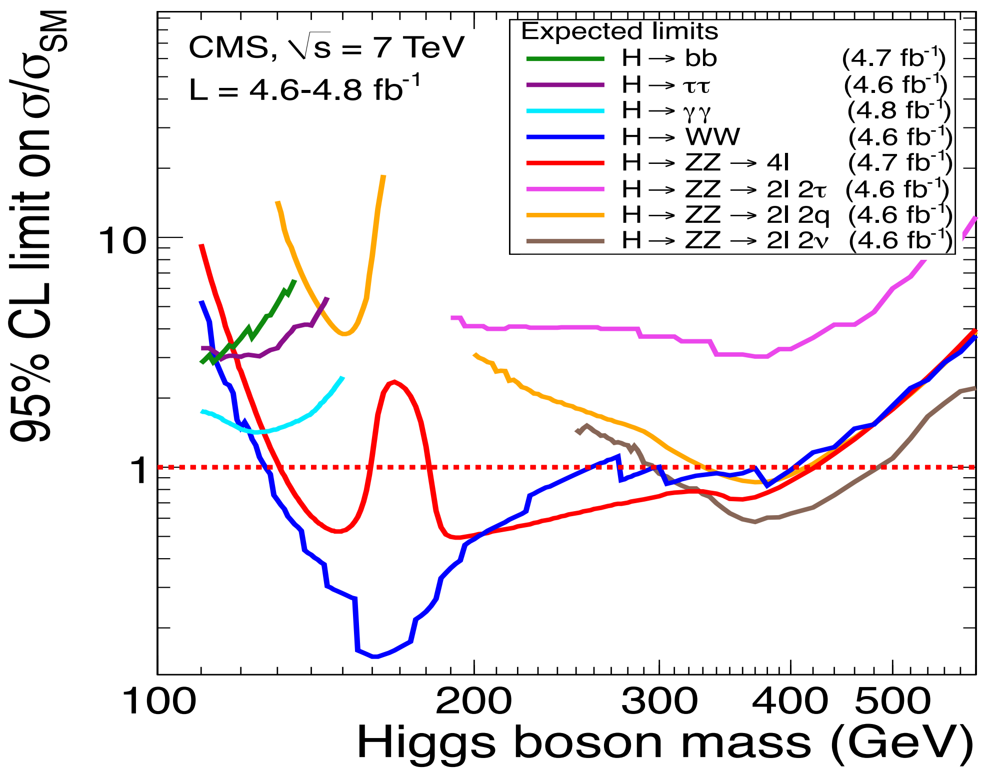


Understanding the Background Processes



Excellent agreement between theory prediction and measurement due to very precise calculations and good understanding of detector performance

Expected Exclusion Sensitivity with 2011 Data



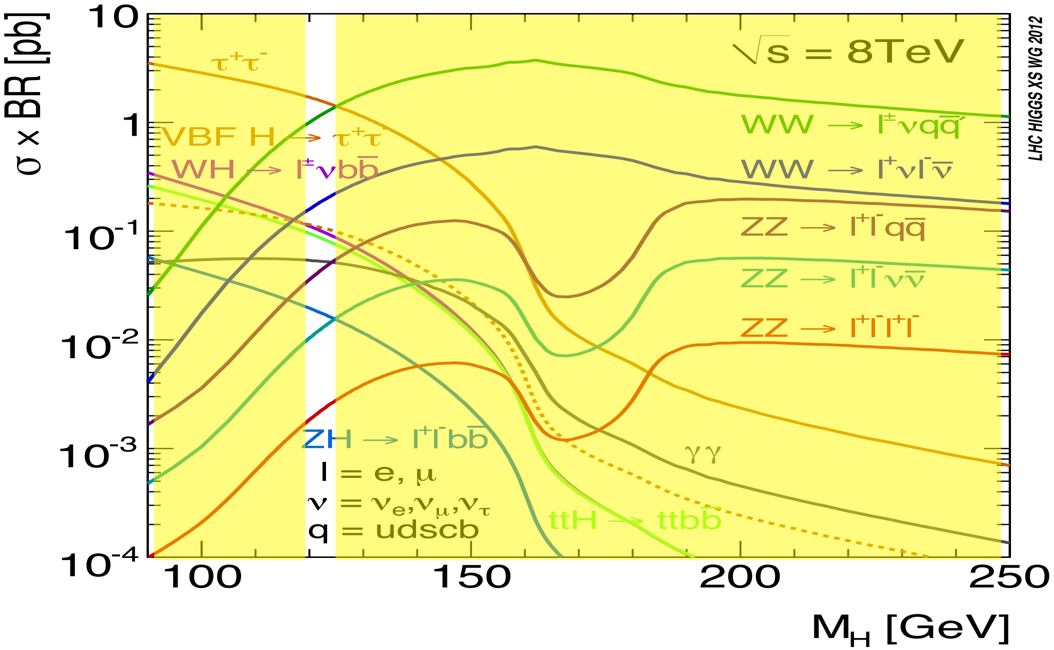
m_H> 200 GeV: H → ZZ → 4l, llνν, lljj H →WW->lνlν, lνjj

150 < m_H < 200 GeV: H → WW(*)->2l2ν, H → ZZ*->4l, (H→ZZ*→2l2q)

m_H < 150 GeV: H → 2γγ , H→ZZ*→4l,H→ WW*→lνlν, H → ττ, H → bb in VH

σ_m /m~1– 2%, σ_m/m~10-20%, no mass reconstruction

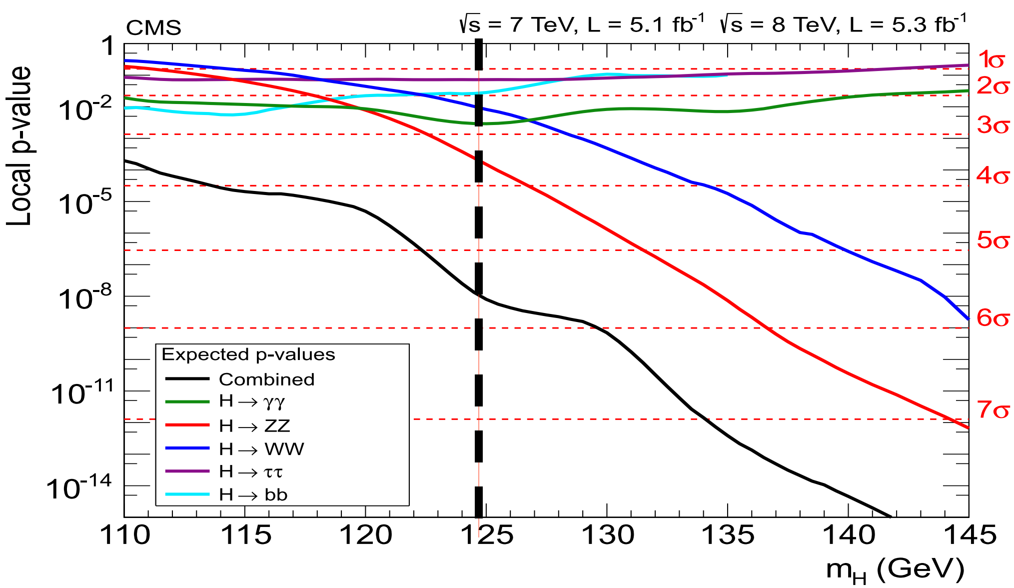
Status after Analysis of 2011 Data



only small M_H window left

from 117.5 to 118.4 GeV
and 122.7 to 127.5 GeV

excess at M_H~125 GeV
of ~3σ per experiment



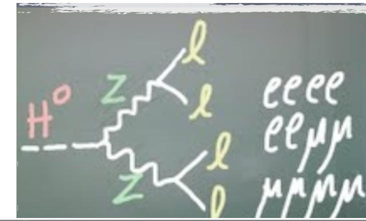
concentrate on small M_H in 2012

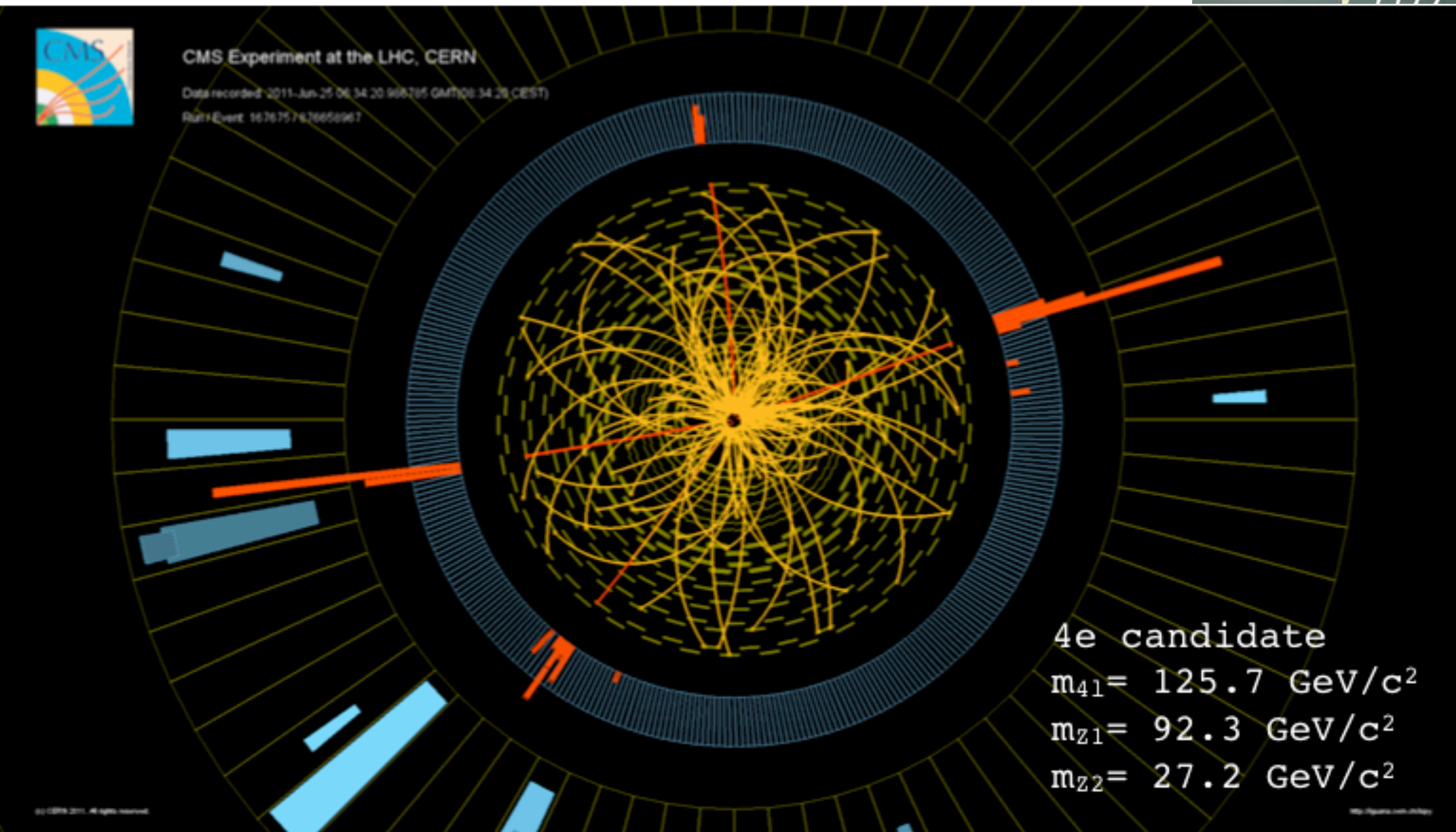
- good mass resolution, small rate
  H→γγ H→ZZ*→4l (ATLAS+CMS)
- no mass reconstruction, high rate
  H→WW*→lνlν (ATLAS+CMS)
- limited mass resolution:
  H→ττ, H→bb (so far only CMS)

The Golden Channel H → ZZ$^{(*)}$ → 4l

signature: 4 isolated leptons, 2 consistent with decay Z→2 l

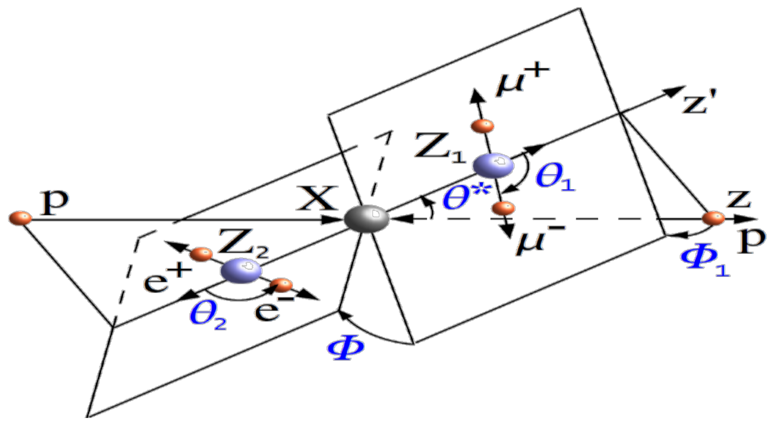
challenge: lepton reconstruction and identification
reconstruction of M_{4l}

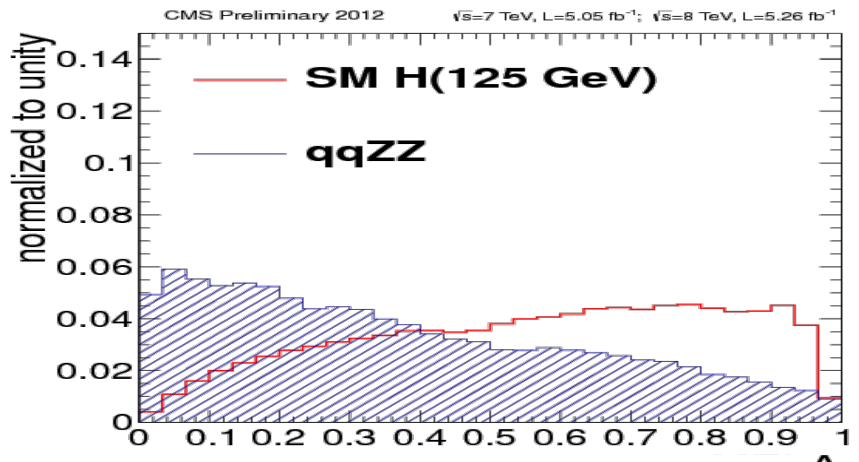




CMS: H→ZZ(*)→ 4 l   Angular Correlations

Exploit different angular correlations
for signal and irreducible ZZ background



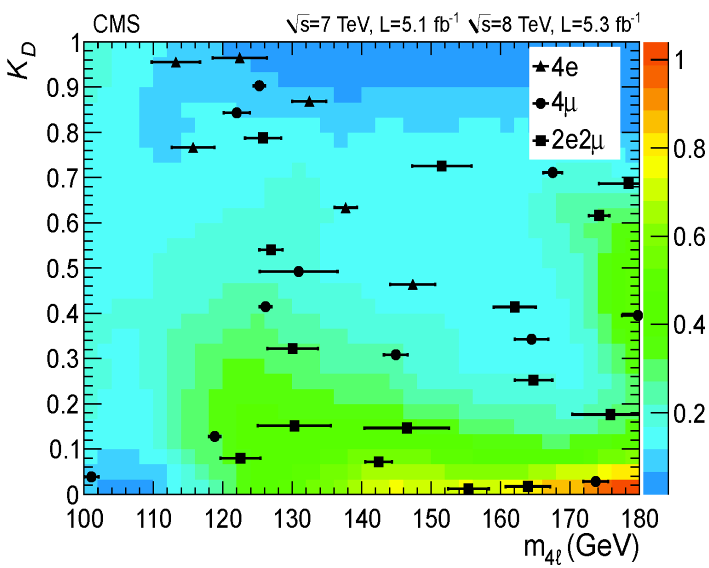


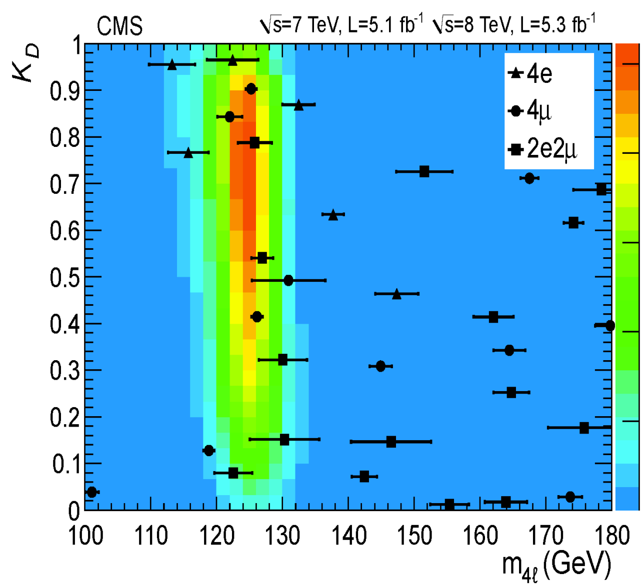
$$K_D = \mathcal{P}_{\rm sig}/(\mathcal{P}_{\rm sig} + \mathcal{P}_{\rm bkg})$$

Background

Signal (M=125 GeV)

final 2-dim. discriminant „M_{4l}-vs-K_D“



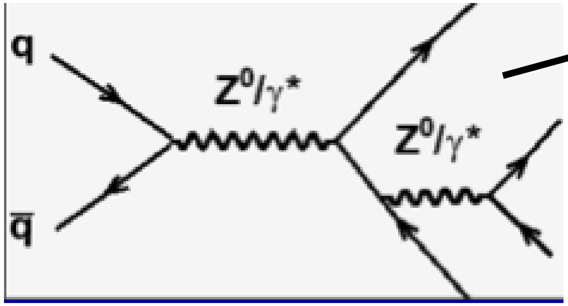


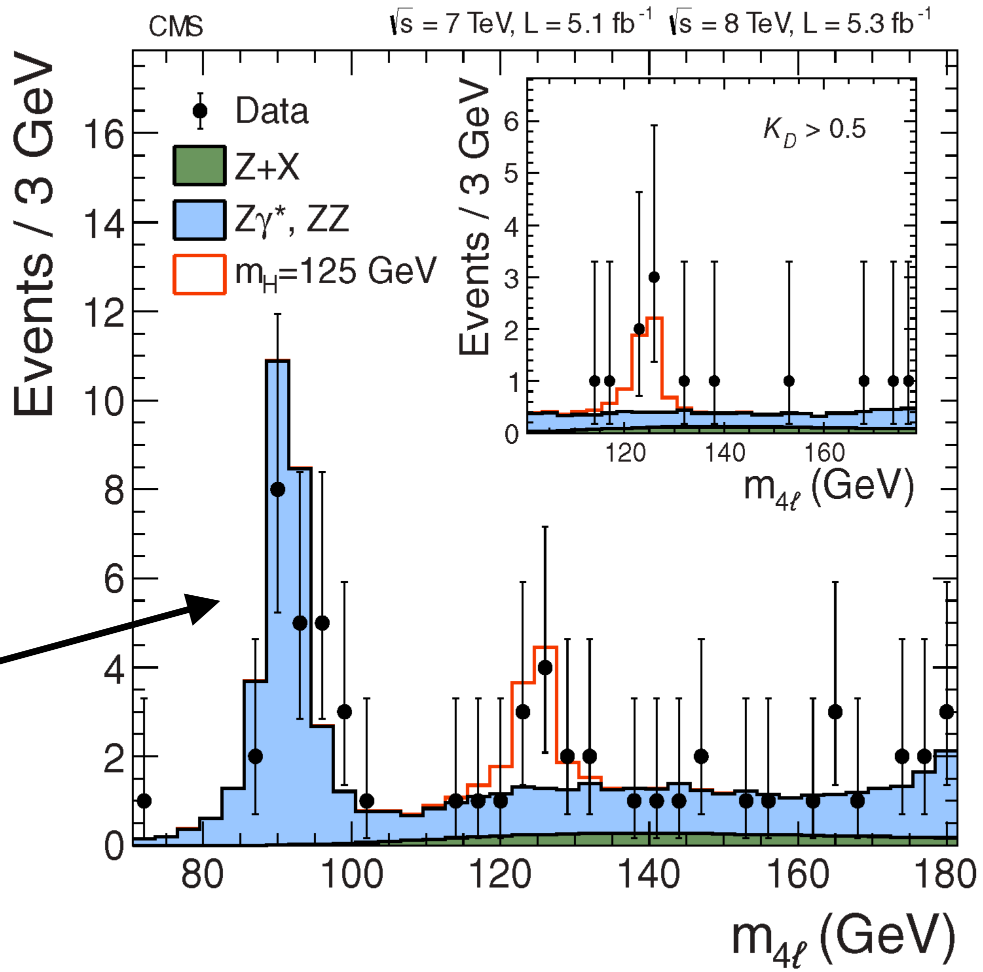
CMS: H→ZZ$^{(*)}$ → 4l - Results

event yields in mass window
from 121.5 to 130.5 GeV

Channel	4 e	4 μ	2 e2 μ	4 l
Bckgr.	0.7	1.3	1.9	3.8
Signal(125)	1.4	2.7	3.4	7.5
Data	1	3	5	9

a standard „candle“



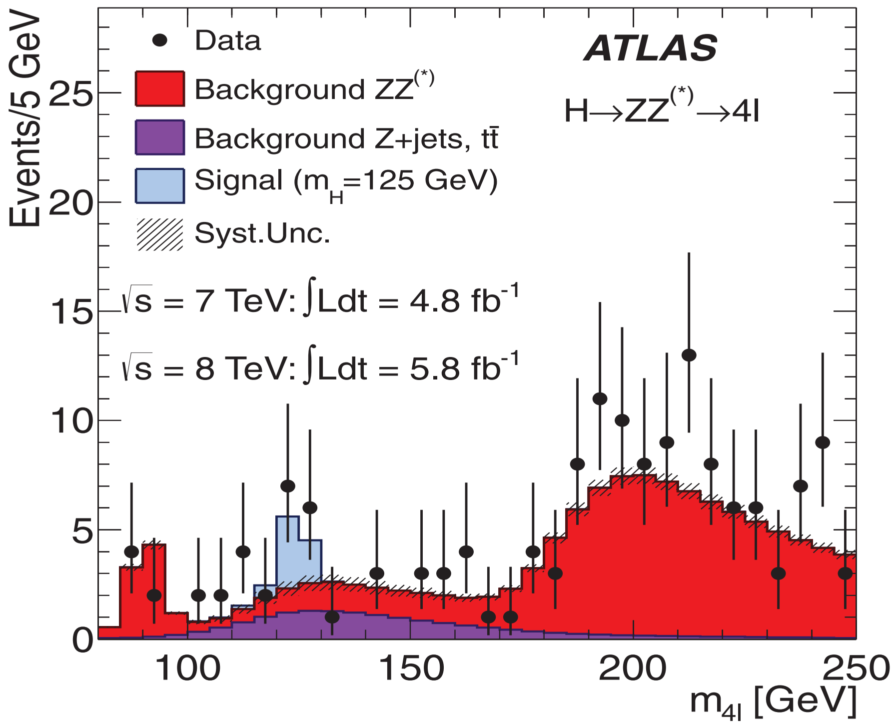


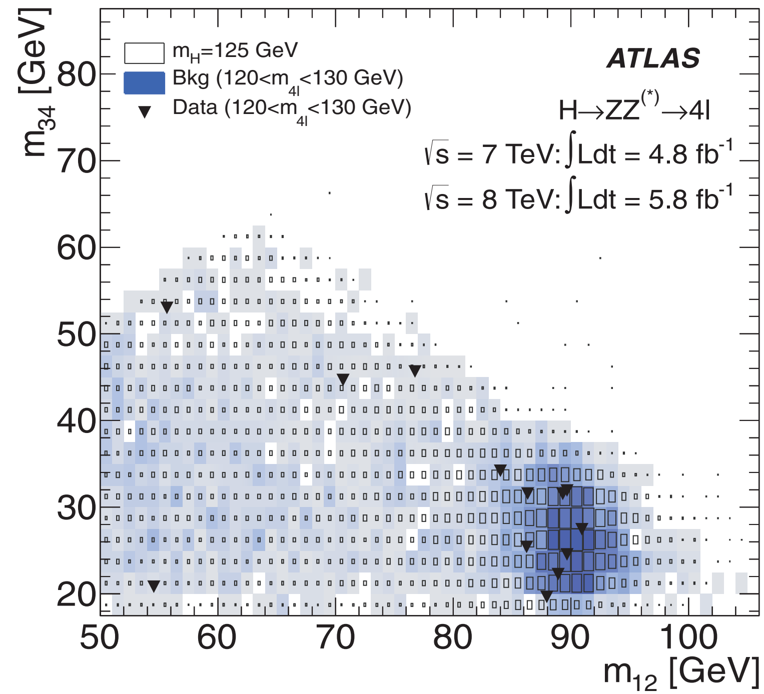
dominant ZZ→4l background
estimated from theory + simulation
(var. theo. uncertainties considered)

significant excess at M_{4l} = 125.6 GeV

signal strength 0.7±0.35 x SM

ATLAS: H→ZZ$^{(*)}$→4 l - Results





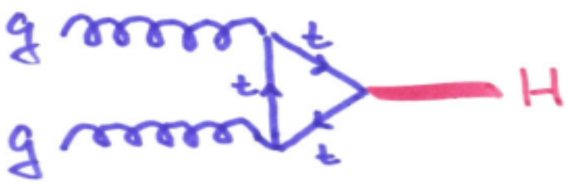
events in ±5 GeV mass window at 125 GeV

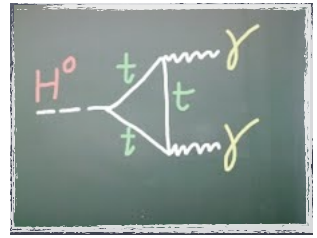
Channel	4 e	4 μ	2 e2 μ	4 l
Bckgr.	1.6	1.3	2.2	5.1
Signal(125)	0.9	2.1	2.3	5.3
Data	2	6	5	13

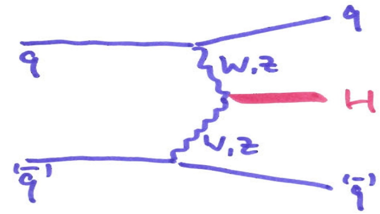
significant excess at M_{4l} = 125 GeV
signal strength 1.4±0.6 x SM

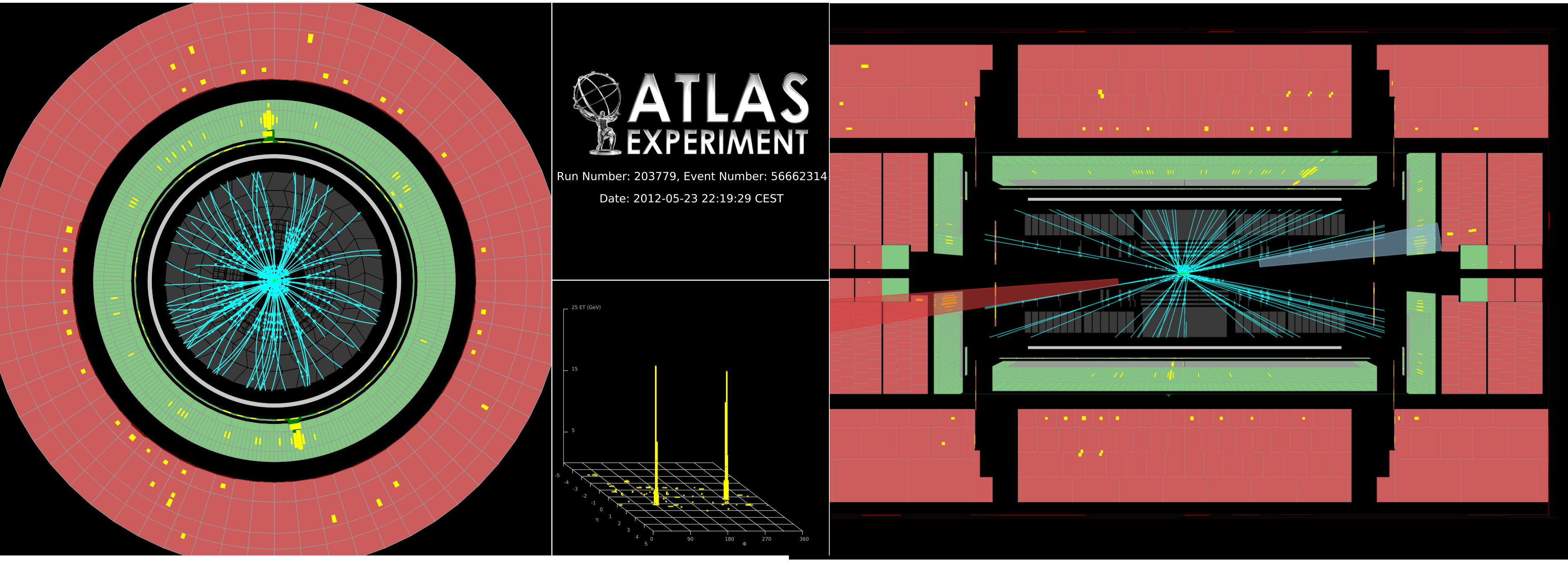
mild excess for M_{4l} > 180 GeV
consistent with σ_{ZZ} measurement
no influence on findings for low mass

H → 2 Photons





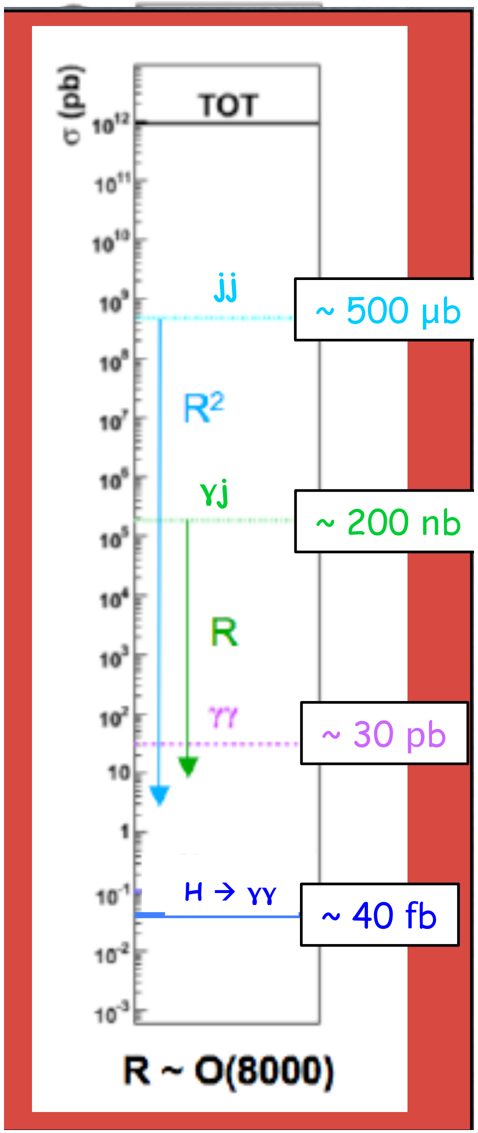




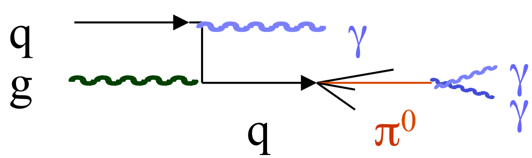
challenges: - identification of hight p_T photons with high purity
- reconstruction of invariant di-photon mass
(in both experiments contribution from angle btw. photons negligible)

enhance sensitivity by splitting in analysis categories

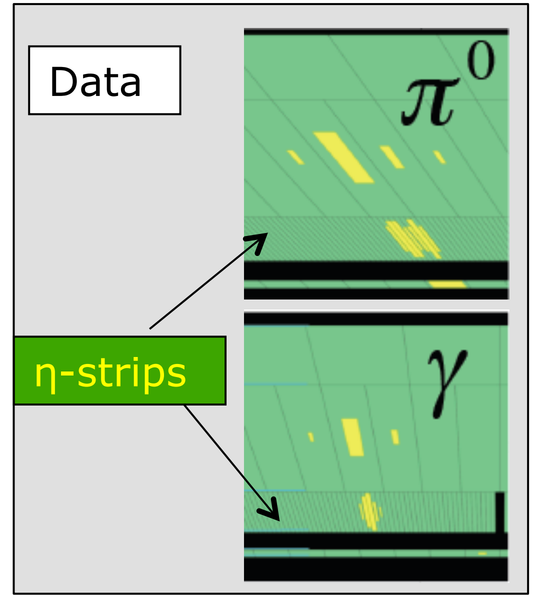
H→ 2 Photons: Background suppression



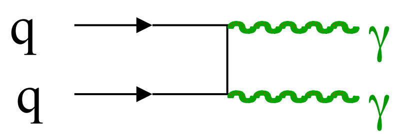
reducible background: γ-jet , jet-jet



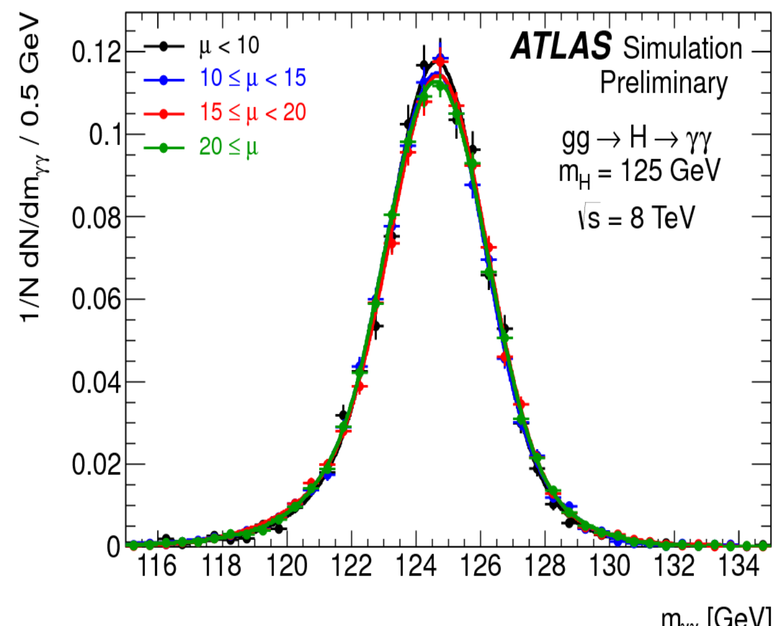
discriminate γ and jet (π^0)



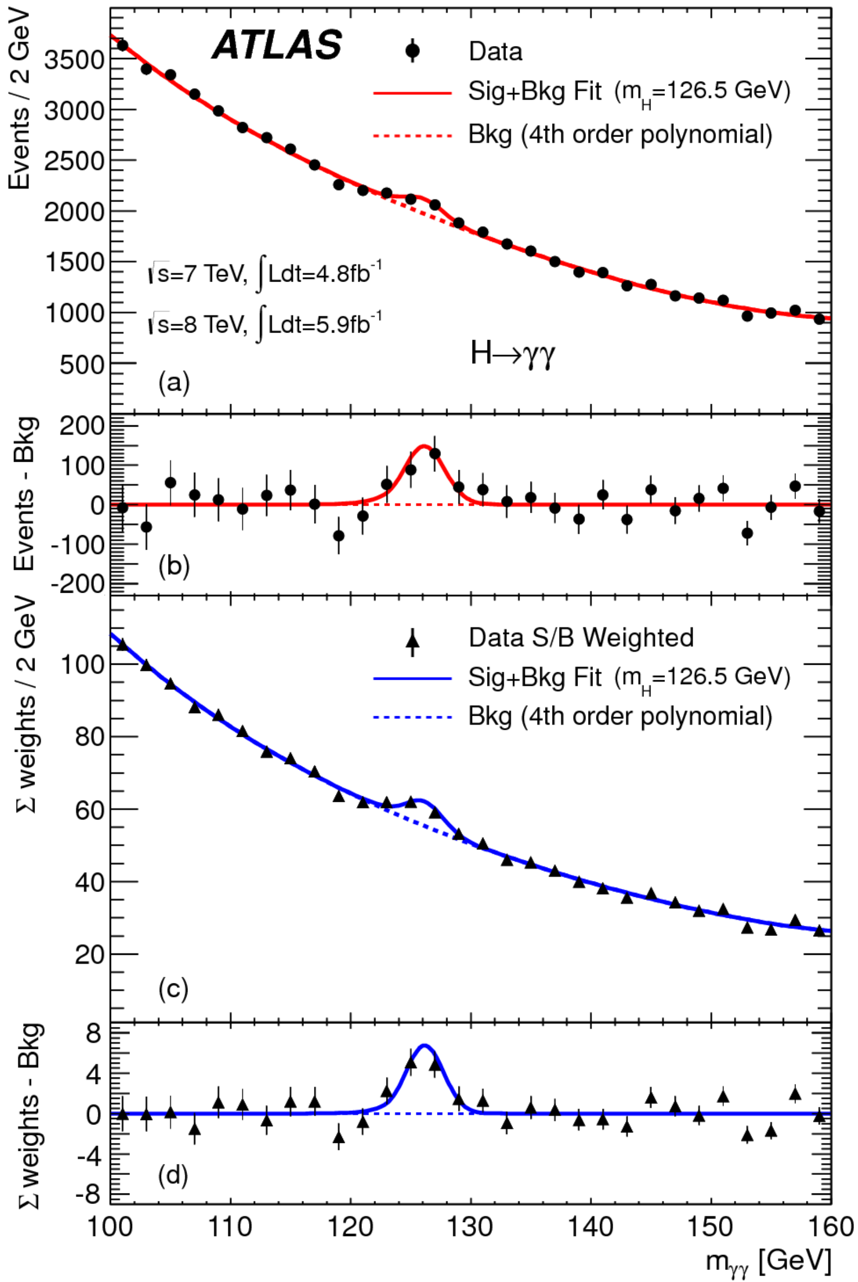
irreducible background:



excellent reconstruction of di-photon mass $M_{\gamma\gamma}$ robust against „pile-up"



ATLAS: H→γγ Mass Spectrum + Categories



VBF + 9 inclusive categories
(un-)converted, central/forward,…

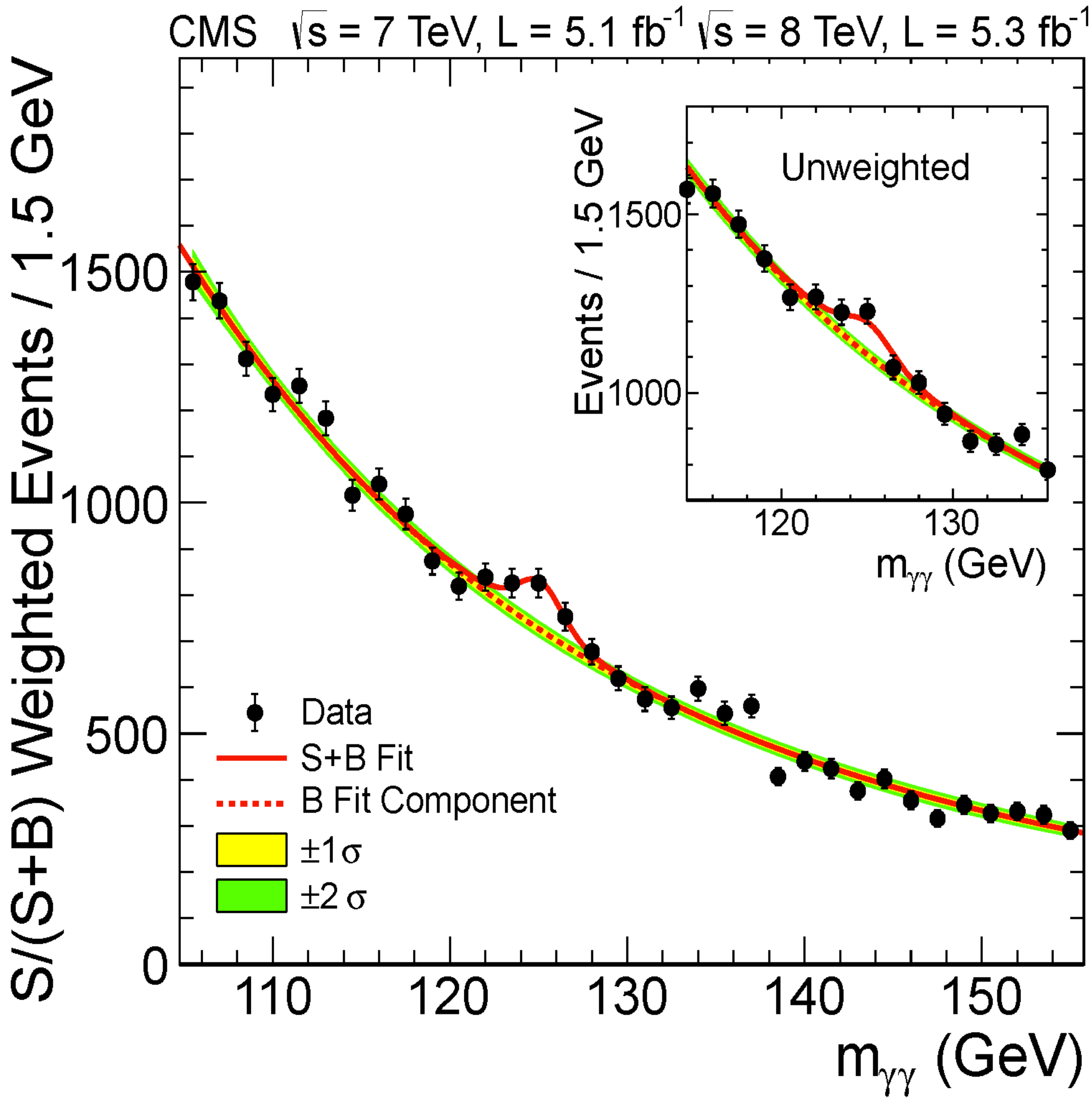
category	Signal/Bckg	σ_M (Gev)
inclusive	1 / 36	1.63
best	1 / 6	1.37
worst	1 / 75	2.65
VBF	1 / 4.5	1.57

category weight = ln (1+ s/b)
s/b evaluated in mass window
containing 90% of signal yield

analytic model for signal a. background

significant excess at $M_{\gamma\gamma}$= 126.5 GeV
signal strength 1.8±0.5 x SM

CMS: H→ 2 Photons Mass Spectrum



5 (6) categories:
2 (1) VBF (in 2011)
+ 4 inclusive based on „Boosted Decision Tree"-output

category weight = s/(s+b) in 2 σ_M mass window

significant excess at 125 GeV

signal strength: 1.6±0.4 x SM

Test of Signal+BG-Hypothesis → Exclusion

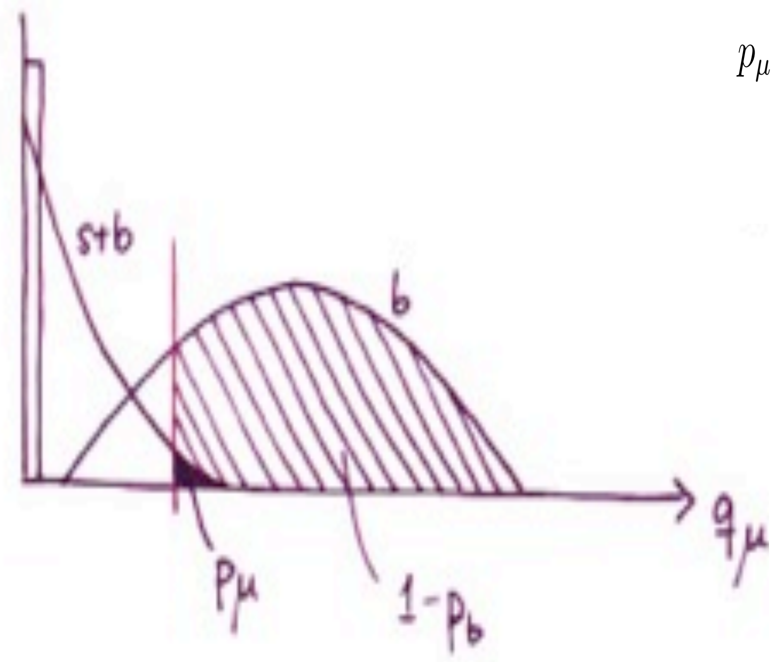
test statistic used at LHC: ratio of "*profiled likelihoods*"

L = likelihood to observe data for signal strength μ

(μ = $\sigma_{signal}/\sigma_{SM\text{-}H}$, θ = systematic uncertainties)

$$q_\mu = -2\ln\frac{\mathcal{L}(\mathrm{obs}\,|\,\mu\cdot s+b,\,\hat{\theta}_\mu)}{\mathcal{L}(\mathrm{obs}\,|\,\hat{\mu}\cdot s+b,\,\hat{\theta})}$$

p-value quantifies consistency with null hypothesis (here signal+background)



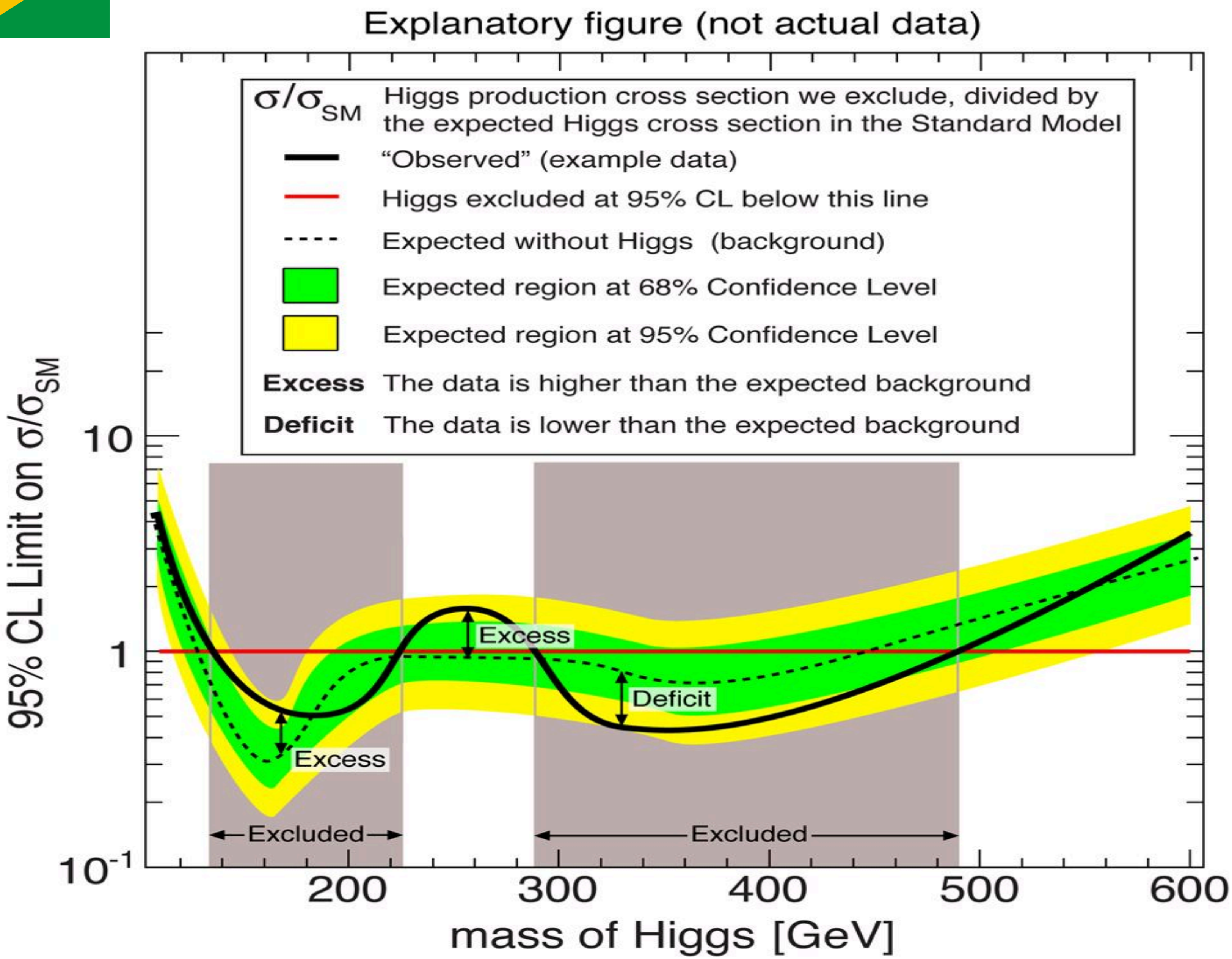
$$p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs}\,|\,\mathrm{signal{+}background}) = \int_{\tilde{q}_\mu^{\mathrm{obs}}}^{\infty} f(\tilde{q}_\mu|\mu,\hat{\theta}_\mu^{\mathrm{obs}})\,d\tilde{q}_\mu$$

CL_s method: $$CL_s = p_\mu/(1-p_b)$$

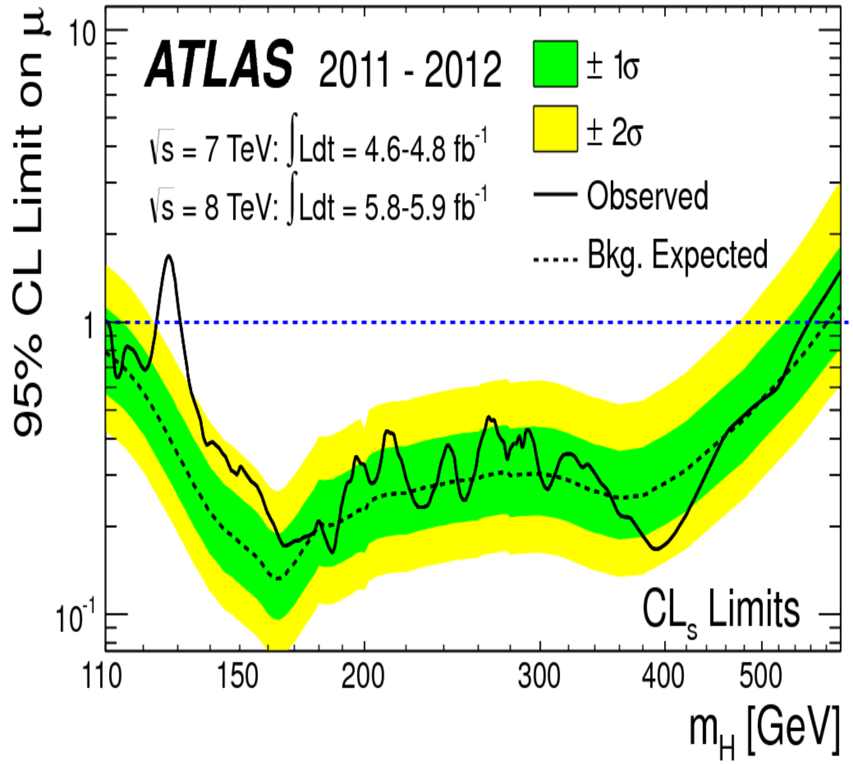
"ad-hoc" correction to avoid exclusion w/o sensitivity due to downwards fluctuation of background

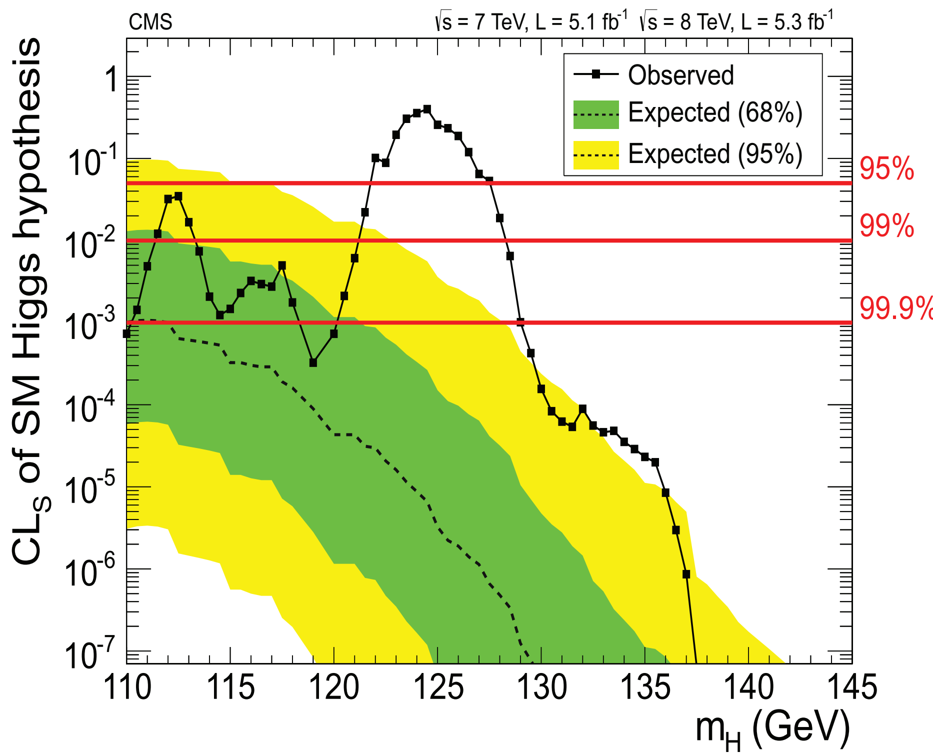
Signal hypothesis μ excluded at 95% CL, if $CL_s \leq \alpha = 5\%$ holds

Understanding the “Brazil” Figures



Combined Exclusion Limits (95% CL)





Observed : 111 < M_H < 122 GeV and 131 < M_H < 559 GeV

110 < M_H < 121.5 GeV and 128 < M_H < 600 GeV

Expected: 110 < M_H < 582 GeV

110 < M_H < 600 GeV

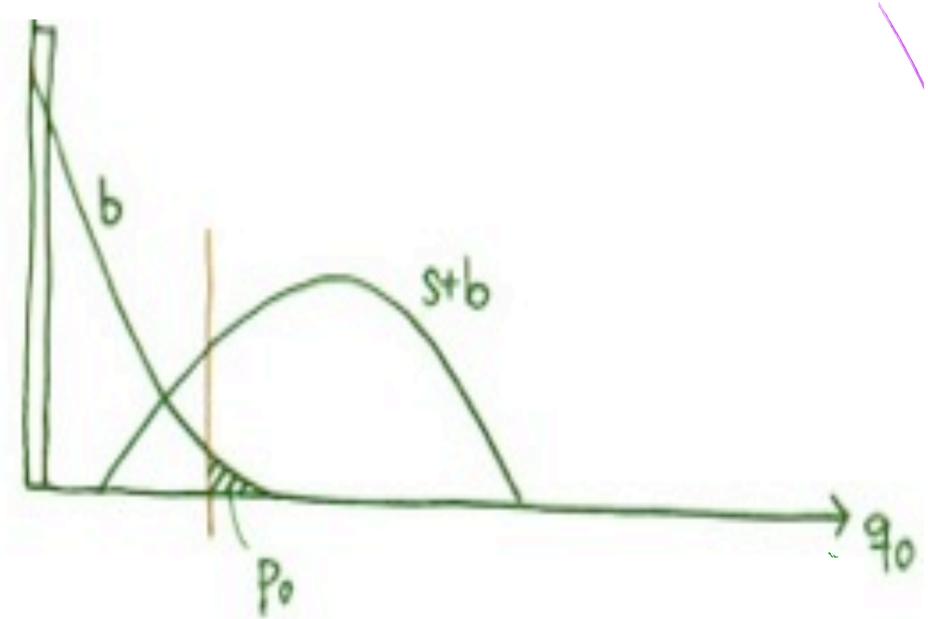
in both experiments exclusion is weaker than expected

in significant mass range ~ 0.2 σ_{SM} excluded

Test of Background-Only-Hypothesis → Discovery

different test statistic, as μ=0 under background-only hypothesis

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{obs} \,|\, b,\, \hat{\hat{\theta}}_0)}{\mathcal{L}(\text{obs} \,|\, \hat{\mu} \cdot s + b,\, \hat{\theta})}$$



$$p_0 = \mathrm{P}(q_0 \geq q_0^{obs} \,|\, \mathrm{b})$$

Significance Z from standard Gauss

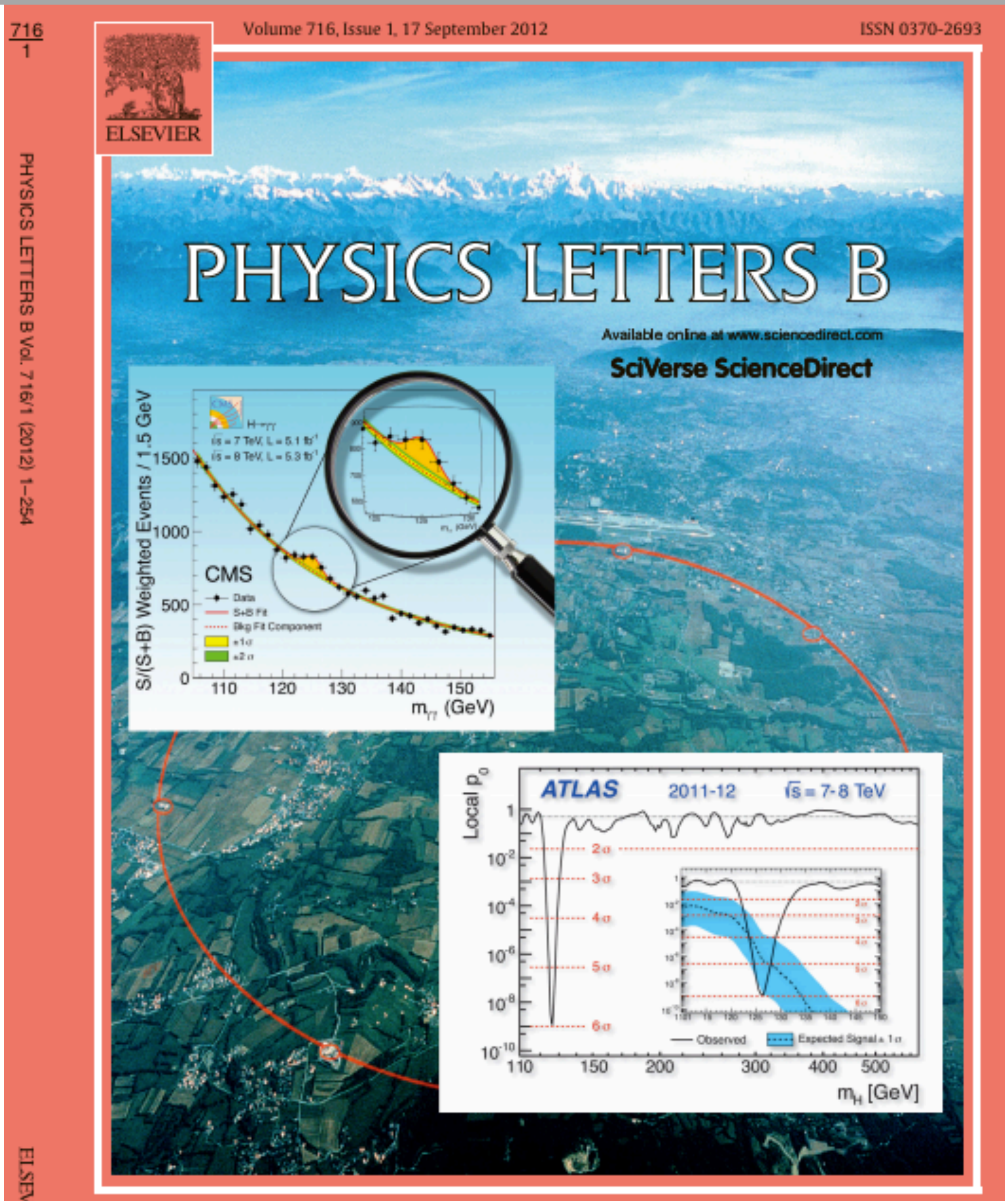
$$p_0 = \int_Z^{+\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)\, \mathrm{d}x$$

discovery: $p_0 \leq 2.85\text{x}10^{-7}$
significance $Z \geq 5$

"Look Elsewhere Effect" (LEE)

so far: deviation from "background-only" for fixed M_H → local p-value
now: what is probability to observe an excess at least as large as observed one anywhere in spectrum? → global p-value

Discovery of a New Particle



open presentation on 4th July

in special CERN seminar:

CMS 4.9 σ (all channels)

ATLAS 5.0 σ (only →ZZ→4l ,→$\gamma\gamma$)

submission to PLB on 31st July

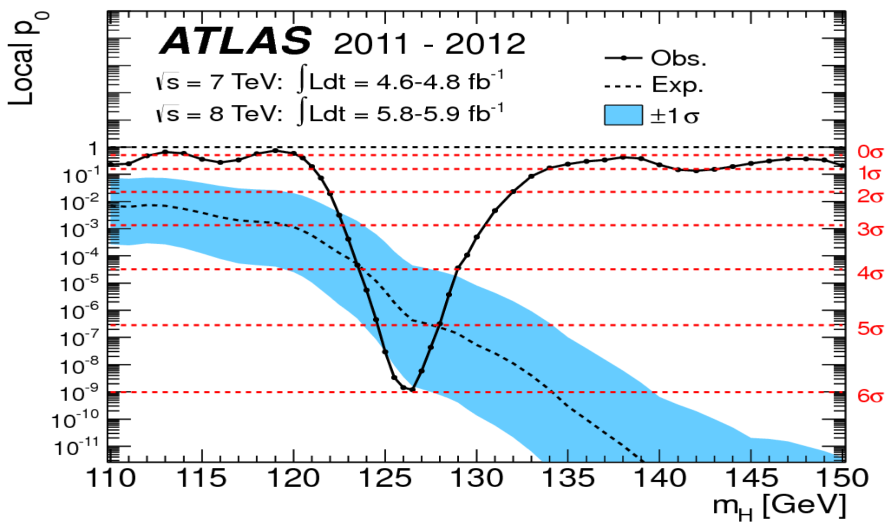
CMS 5.0 σ (all channels)

ATLAS 5.9 σ (→WW→e$\mu\nu\nu$,

→ZZ→4l,→$\gamma\gamma$)

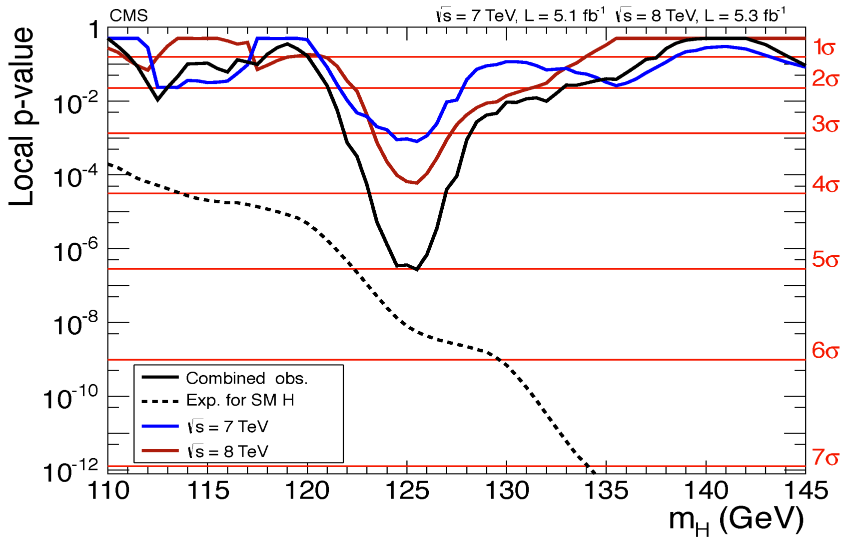
Discovery of a New Particle

5.9 σ for m_H~126.5 GeV



w/ LEE: 5.1(5.3)σ in 110<M_H<600(150) GeV

5.0 σ for m_H~125.5 GeV



4.6(4.5) σ in 110 < M_H <130 (145) GeV

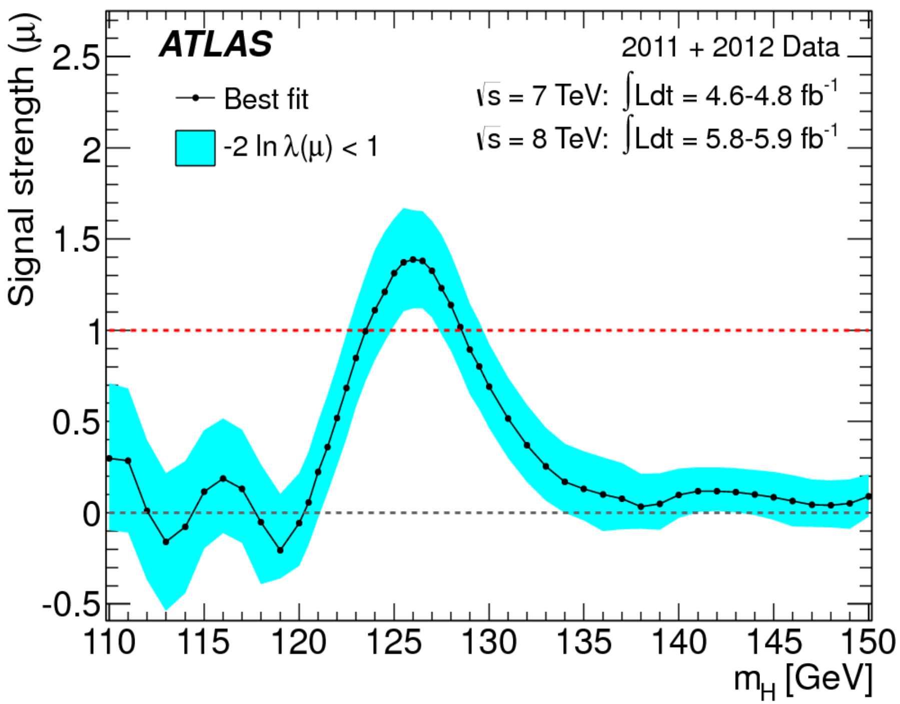
Channel	Significance(exp)	Mass with mininmal p_0
H→ZZ→4l	3.4 (2.7)	125.0 GeV
H→γγ	4.5 (2.5)	126.5 GeV
H→WW→eνμν	2.8 (2.3)	125.0 GeV
Combined	5.9 (4.9)	126.5 GeV

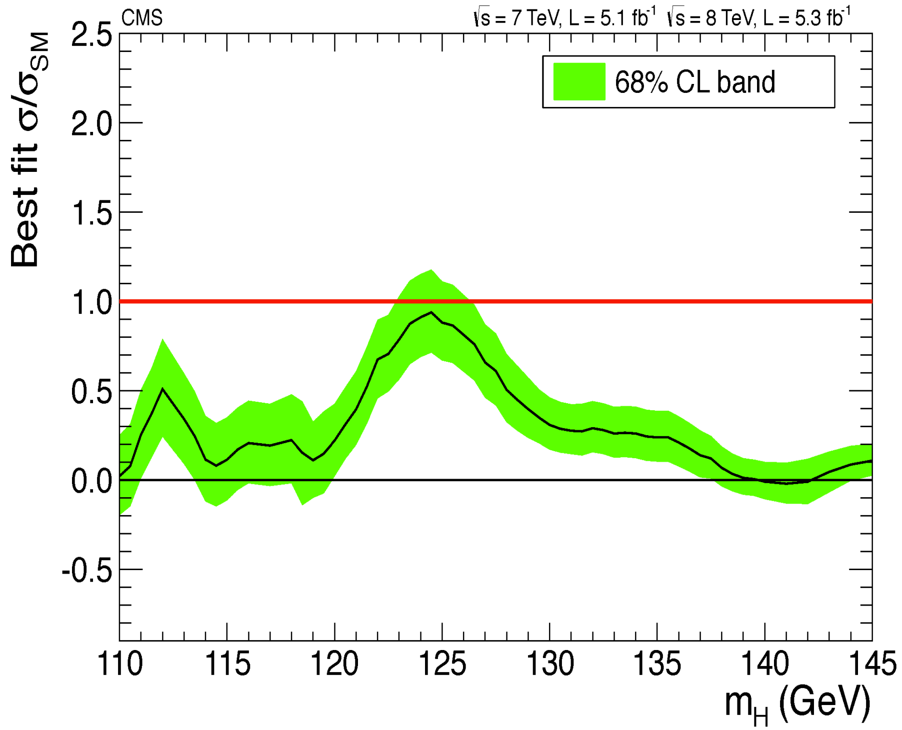
Channel	Significance(exp)	Mass with minimal p_0
H→ZZ→4l	3.2 (3.8)	125.6 GeV
H→γγ	4.1 (2.8)	125 GeV
H→WW→lνlν	1.6 (2.4)	--
H→bb + ττ	0.4 (2.4)	--
Combined	5.0 (5.8)	125.5 GeV

Anatomy of the New Particle: Overall Signal Strength

Determination of the “best” signal strength $\mu = \sigma_{obs}/\sigma_{SM}$ for each hypothetical M_H

assumption: ratio of production cross-sections and BRs as predicted in SM





largest signal strength at m_H= 126.0 GeV

μ = 1.4 ± 0.3

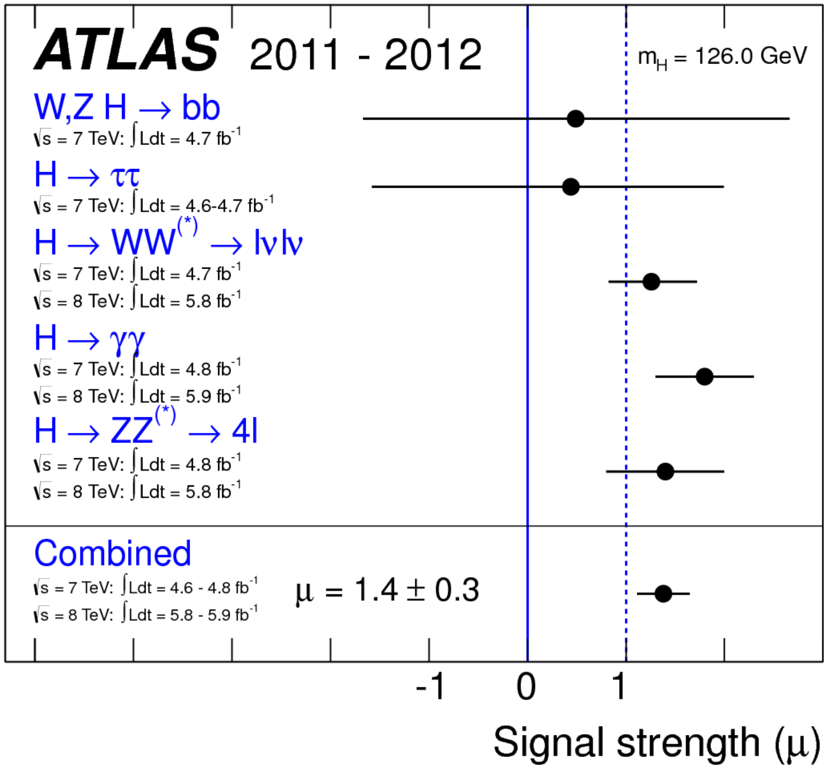
largest signal strength at m_H= 125.5 GeV

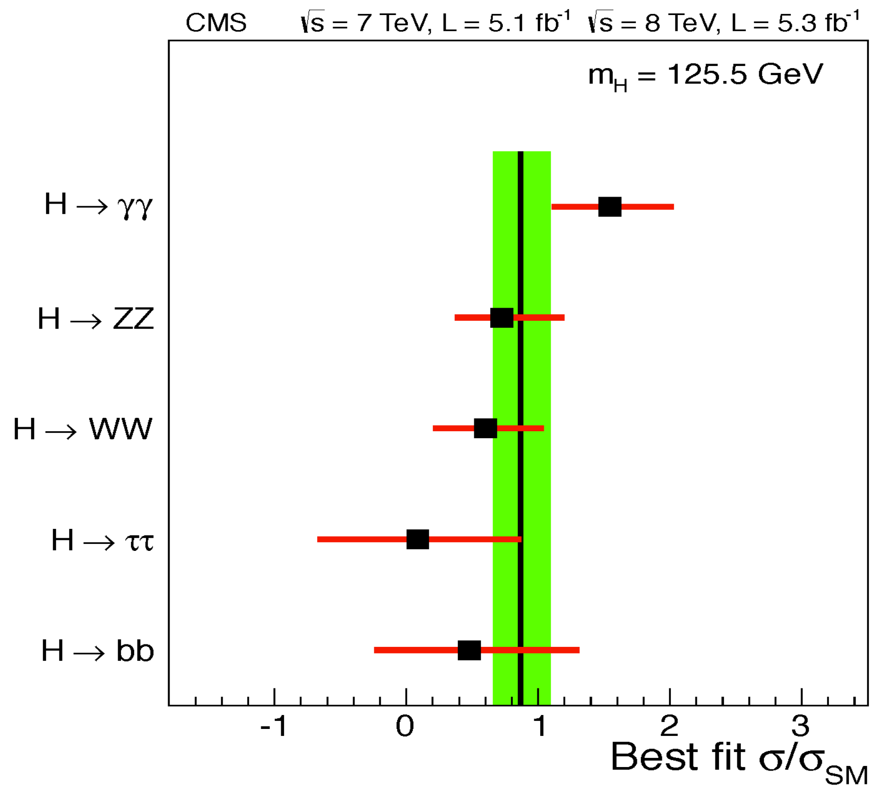
μ = 0.87 ± 0.23

consistent with expectation in Standard Model

Signal Rate in Various Decay Modes

Assumption: ratio of production cross-section as predicted by SM





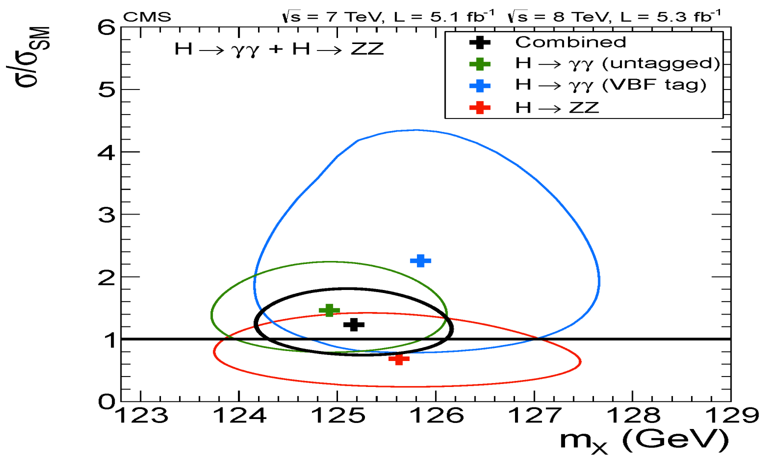
Signal strengths in individual decay modes consistent with SM prediction
(Some people like to see already here a tension esp. in $H \rightarrow \gamma\gamma$)

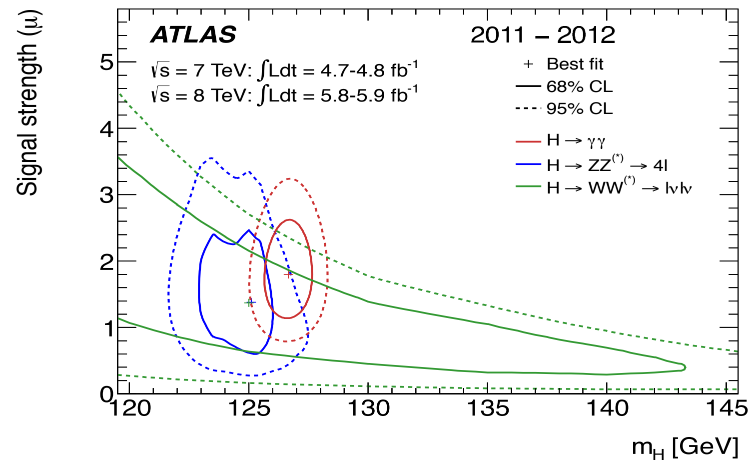
Tevatron observes a ~3σ excess in $H \rightarrow bb$ search.
Factor of 2.5 high w.r.t to SM at 125 GeV, but consistent within 2 standard deviations

Mass and Signal Strength

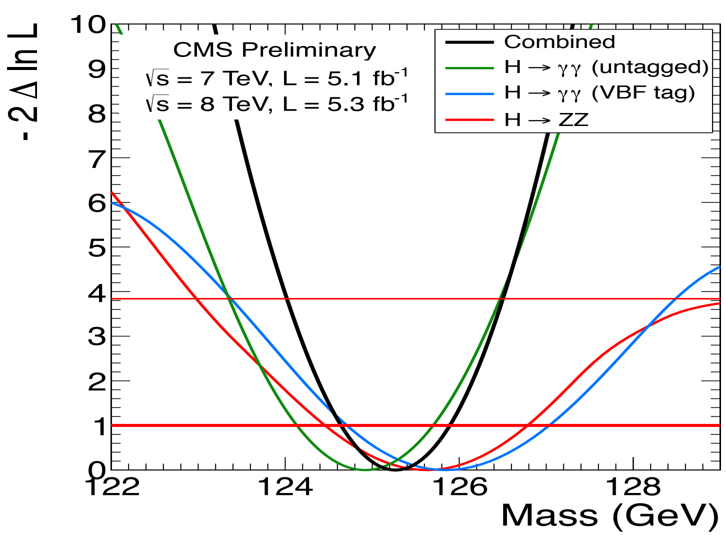
in each final state: assumes SM ratio for different production mechanisms contributing

CMS: combined fit assumes SM ratio of different final states





ATLAS: probability to observe a difference or larger as seen in H→γγ and H→4l is 8%



CMS: M_{new}= 125.3 ± 0.4(stat) ± 0.5(sys) GeV

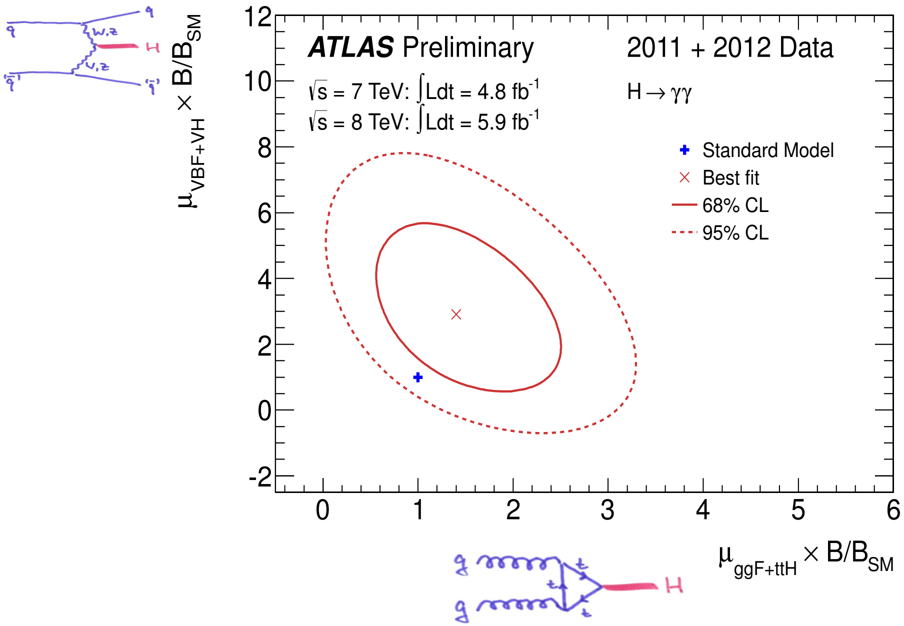
ATLAS: M_{new}= 126.0 ± 0.4(stat) ±0.4 (sys) GeV
from H→γγ and H→ZZ→4l

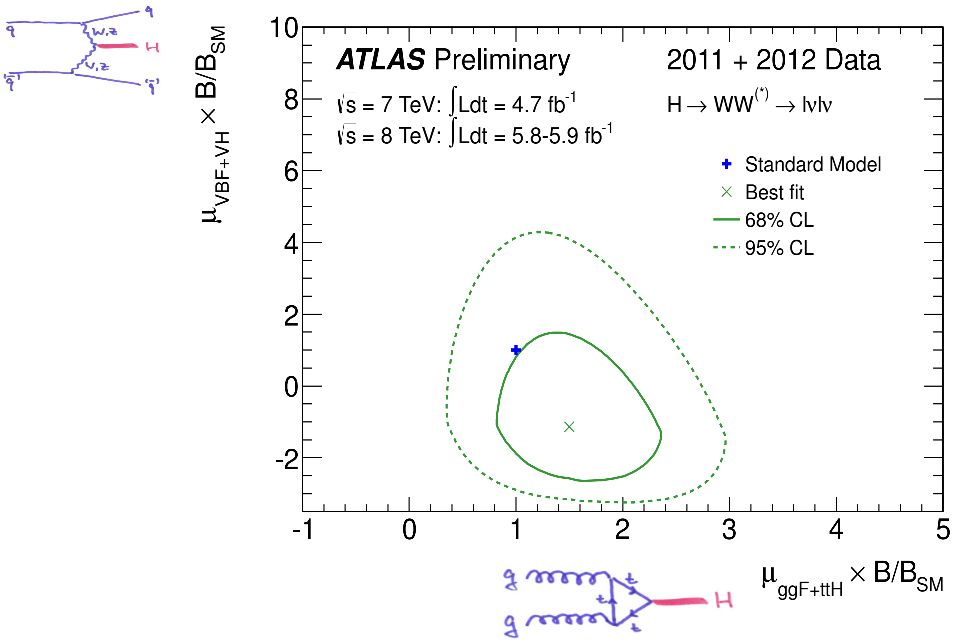
μs for each final state are nuisance parameters

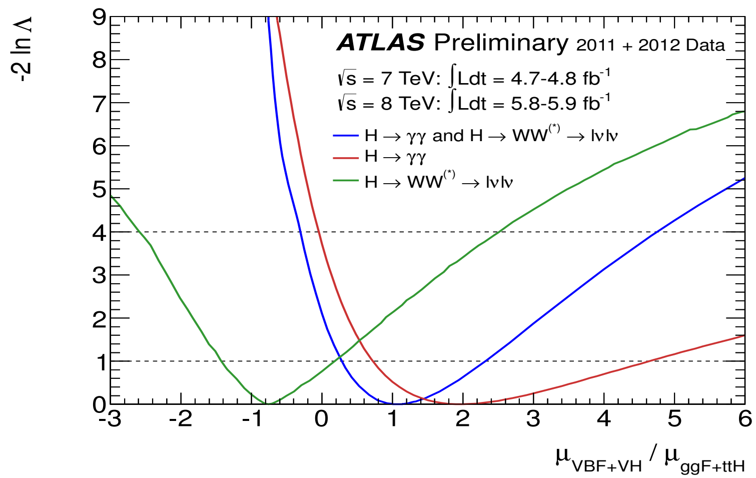
dominant sys. uncertainty from e/γ energy scale

Rates in Different Production Modes

analysis split up in jet categories → different contributions from gluon fusion and VBF







fit ratio of signal strength
and consider BRs as free parameters

ratio of signal strengt between
gluon fusion and VBF
consistent with SM

Ratio of Partial Width

in narrow width aproximation (for CP-even Higgs boson) event rates described by:

$$\boxed{\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}}$$

κ_i^2 scaling factors for partial (total width), e.g.

$$\boxed{(\sigma \cdot \mathrm{BR})\,(gg \to \mathrm{H} \to \gamma\gamma) \quad = \quad \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}}$$

total width not measurable at LHC → no coupling determination w/o theory input

→ only ratio of partial width or scaling factors $\boxed{\lambda_{ij} = \kappa_i/\kappa_j}$

Ratio of Partial Width (examples)

fermion and vector couplings

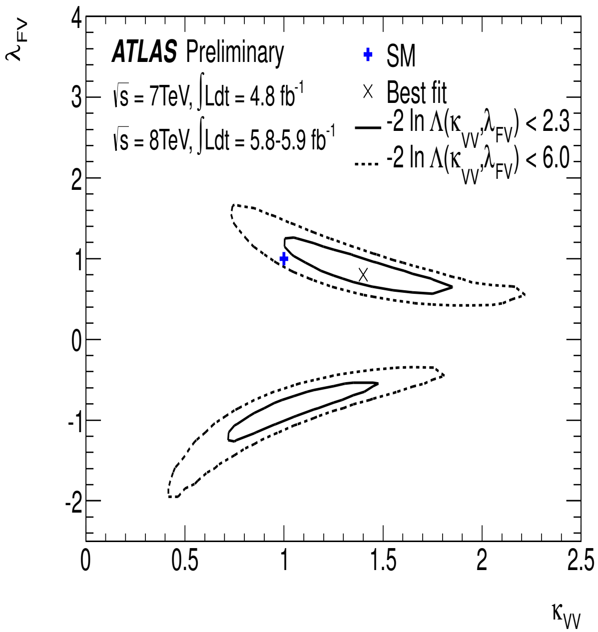
$$\lambda_{FV} = \kappa_F/\kappa_V$$
$$\kappa_{VV} = \kappa_V \cdot \kappa_V/\kappa_H$$

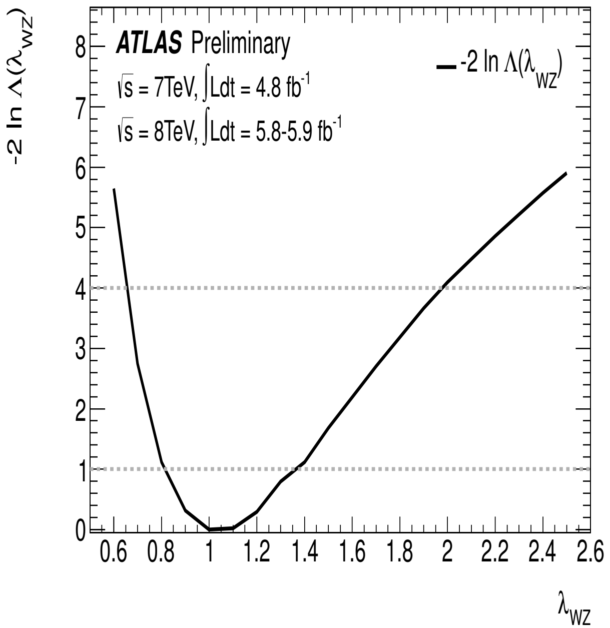
W/Z coupling

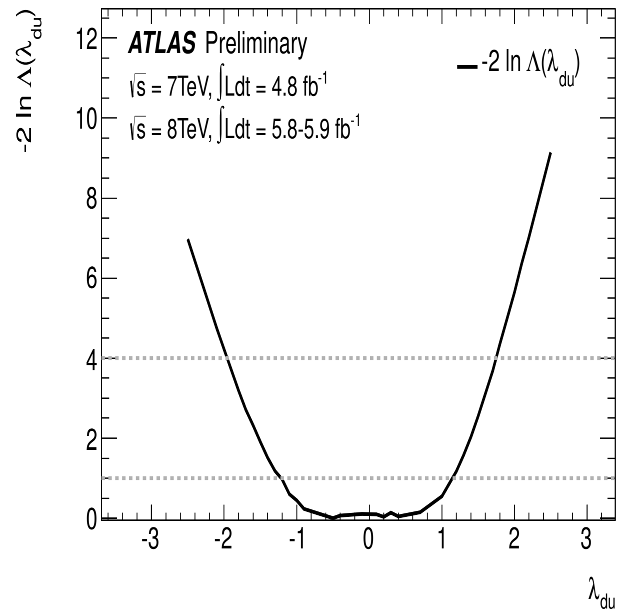
$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z/\kappa_H$$
$$\lambda_{WZ} = \kappa_W/\kappa_Z$$
$$\lambda_{FZ} = \kappa_F/\kappa_Z$$

u/d coupling

$$\kappa_{uu} = \kappa_u \cdot \kappa_u/\kappa_H$$
$$\lambda_{du} = \kappa_d/\kappa_u$$
$$\lambda_{Vu} = \kappa_V/\kappa_u$$







$$\lambda_{FV} \in [-1.1, -0.7] \cup [0.6, 1.1]$$

$$\lambda_{WZ} = 1.07^{+0.35}_{-0.27}$$

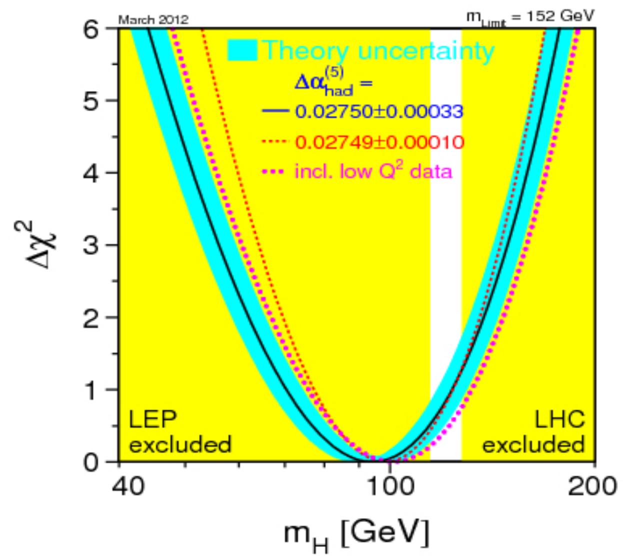
$$\lambda_{du} \in [-1.2, 1.2]$$

no deviation from prediction for a SM Higgs boson

Status of Knowledge about New Particle

mass: 126.0 ± 0.4 ± 0.4 GeV (ATLAS)
125.3 ± 0.4 ± 0.5 GeV (CMS)

consistent with preferred range in SM

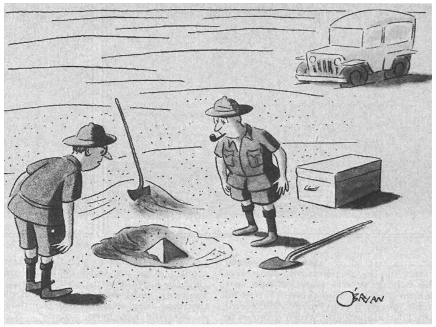


decays into 2 particles with identical spin
and charge sum=0

→ discovery of a neutral boson

spin=1 hypothesis very unlikely

decay in two massless vector bosons ($H \rightarrow \gamma\gamma$)
excludes spin=1 (Landau-Yang theorem)
(could be $Y \rightarrow XX$, $X \rightarrow 2\gamma$, but disfavoured by specific ATLAS analysis)



"This could be the discovery of the century. Depending, of course, on how far down it goes."

overall signal strength and strength in individual decay modes
consistent with SM prediction within still large uncertainties

selection strategy makes use of predictions for spin=0 and CP = + particle
e.g. CMS k_D discrimant in $ZZ^* \rightarrow 4l$

Is it a Higgs Boson and if yes which one?

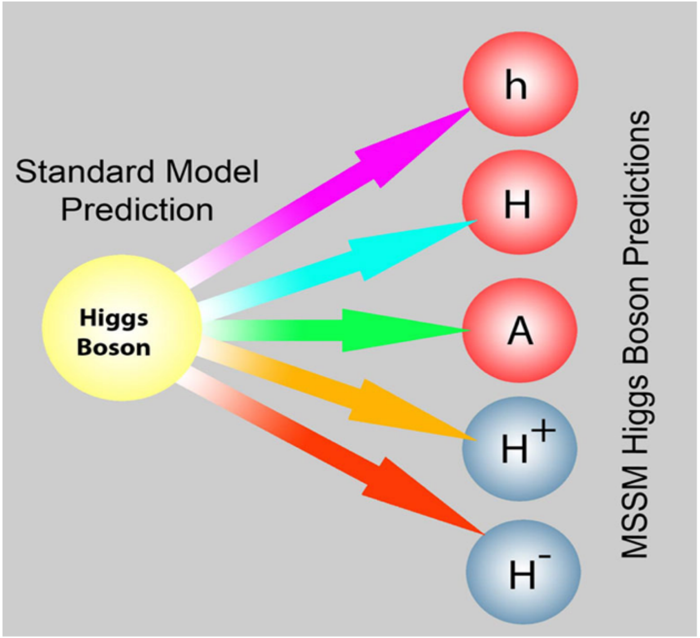
next steps with more data:

verify that it is a scalar boson and hence can be companion of the condensate
excude spin 2 (and 1) by end of year from angular correlations in production and decay

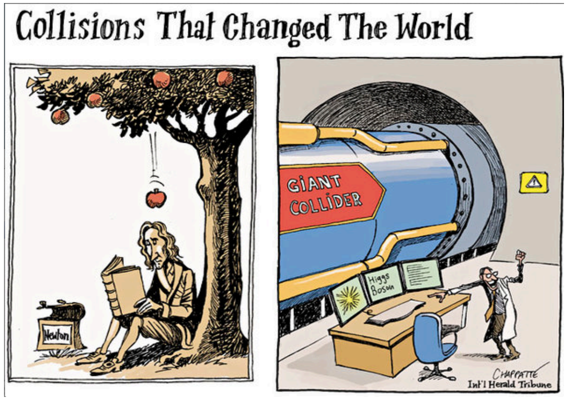
CP nature, pure state, mixed state?
determine dominant component until end of year
CP admixtures need more data and studies
CP-odd Higgs boson only couples to gauge bosons at loop level
→need observation of fermion coupling

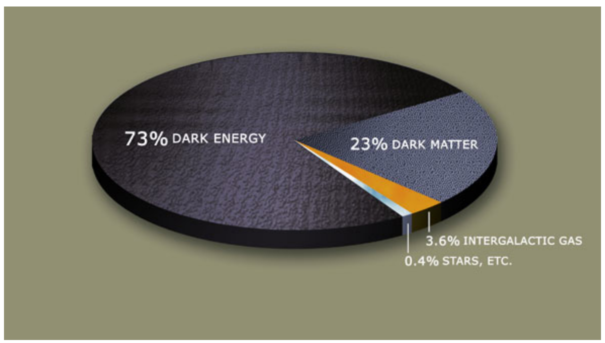
continue to measure partial width and couplings
(w/ „mild“ theory assumptions)

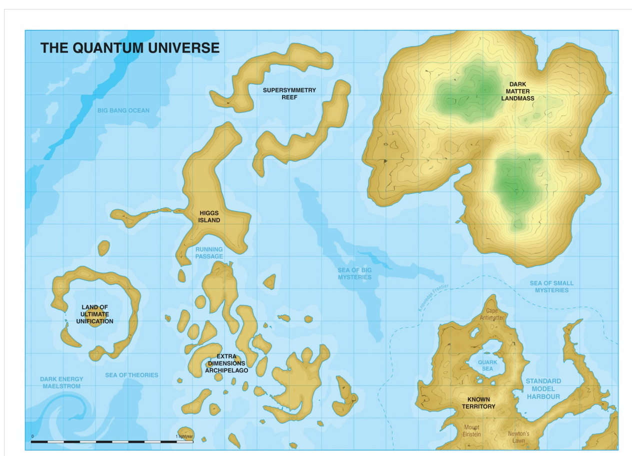
search for additional Higgs bosons
other masses, decay and production modes



Few Final Words







A new neutral boson with mass ~126 GeV has been discovered by ATLAS and CMS.
This is a milestone in physics!

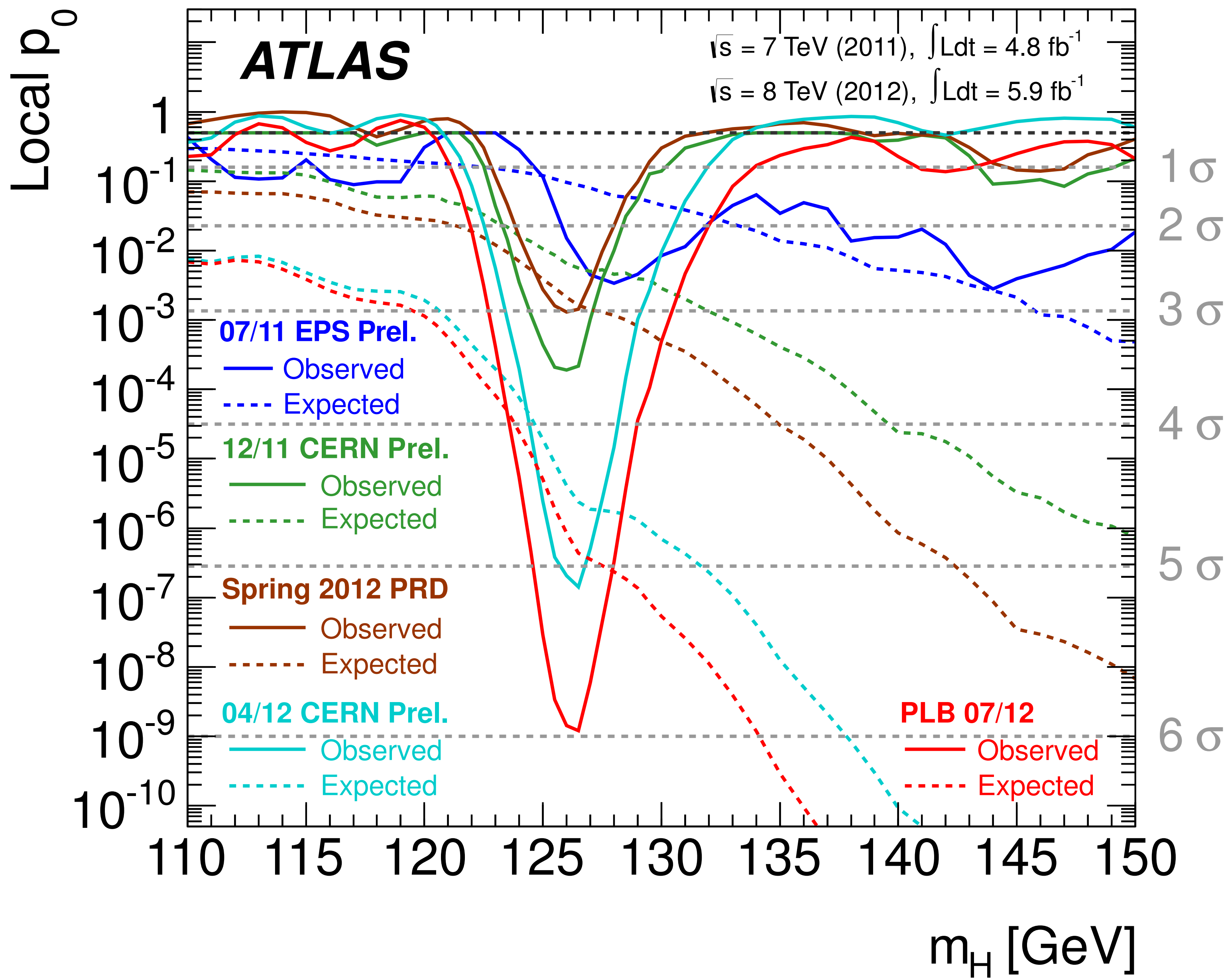
So far observed properties consistent with predictions for SM Higgs Boson,
but also a plentitude of extended models can accomodate the findings

Still many open questions in particle physics, e.g.:
- nature of dark matter
- unification of forces
- flavour/generation problem
- ...

Observation of a Higgs-like particle marks NOT the end of particle physics BUT just the entrance to a new, fascinating era!

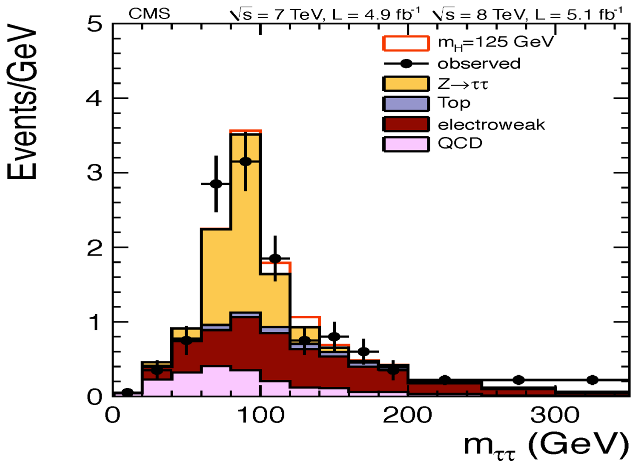
Hopefully many further (unexpected?) discoveries waiting for us at the LHC!

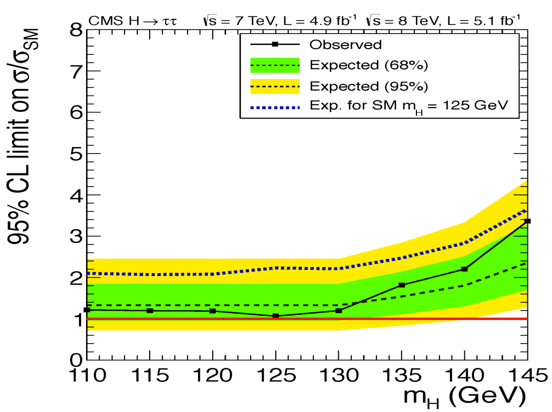
ATLAS Significance: Evolution with Time



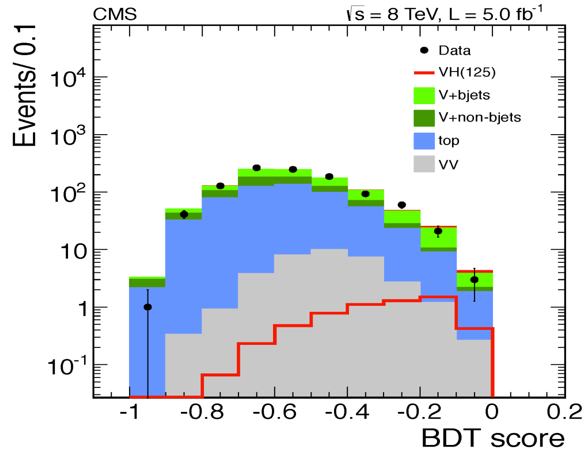
CMS H→ ττ, →bb and →WW→lνlν

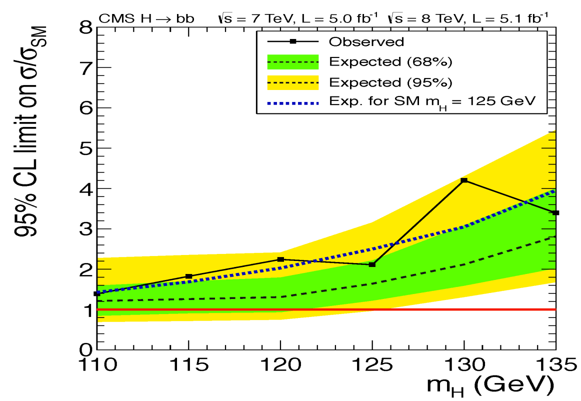
H→ττ



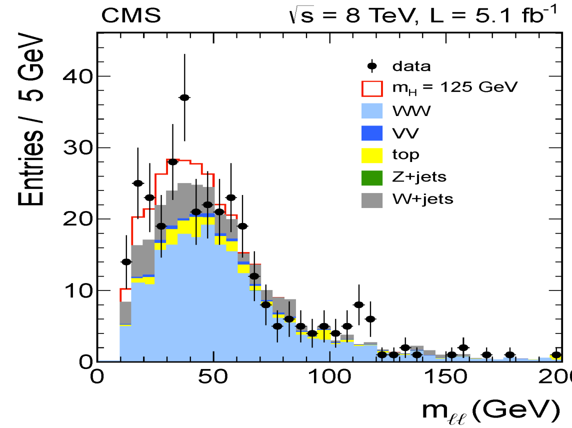


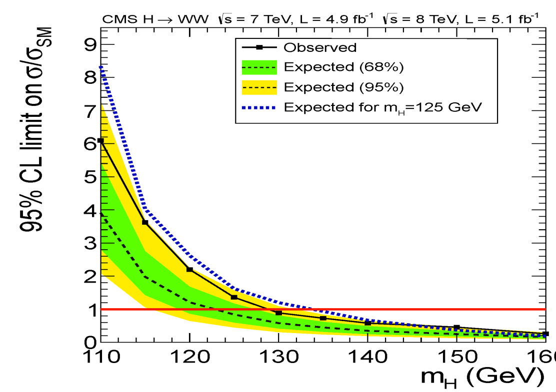
VH, H→bb





H→WW→lνlν





observed (expected) sensitivities at M_H=125 GeV

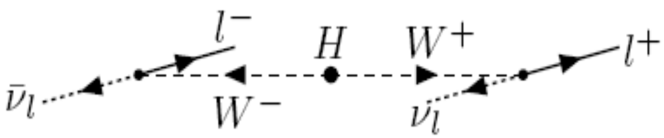
limit: 1.1 (1.3 exp)
significance: 0 (1.4 exp)

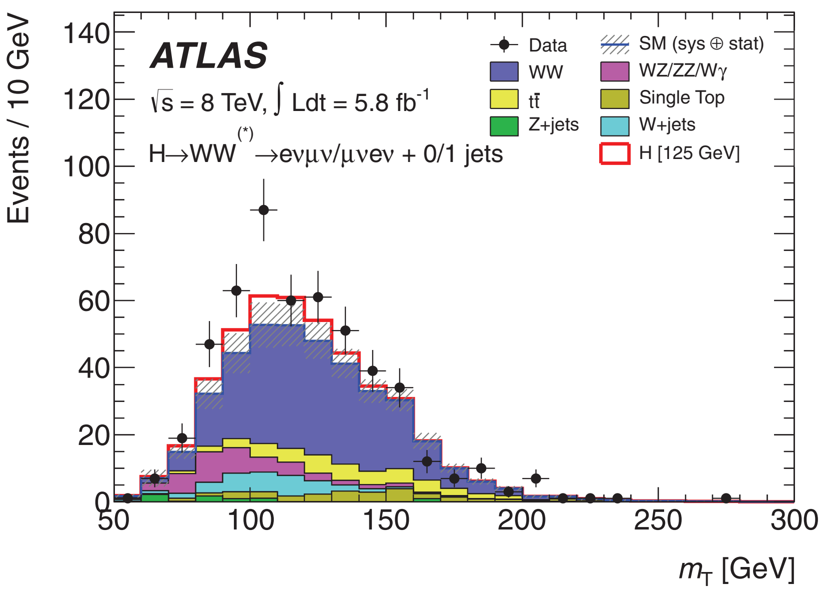
limit: 2.1 (1.6 exp)
significance: 0.7 (1.9 exp)

significance: 1.6 (2.4 exp)

ATLAS: H→ WW→eνμν in 2012

only eμ final state in 2012 due to pile-up
selection exploits spin=0 nature of Higgs boson
(idea by Dittmar and Dreiner)





$$0.75\, m_H \ < \ m_{\mathrm{T}} \ < \ m_H \ \text{for} \ m_H \ = \ 125 \text{ GeV}.$$

	0-jet	1-jet	2-jet
Signal	20 ± 4	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
$t\bar{t}$	8 ± 2	6 ± 2	0.15 ± 0.10
$tW/tb/tqb$	3.4 ± 1.5	3.7 ± 1.6	-
$Z/\gamma^* +$ jets	1.9 ± 1.3	0.10 ± 0.10	-
$W +$ jets	15 ± 7	2 ± 1	-
Total Background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed	185	38	0

$$m_T = \sqrt{2\ P_T{}^{\ell\ell} \not{E}_T\ (1 - \cos\Delta\varphi)}$$

significant excess observed (1.9±0.7 x SM in 2012)

final discriminant: transverse mass (5 (3,1) bins in 0 (1,2) jet category