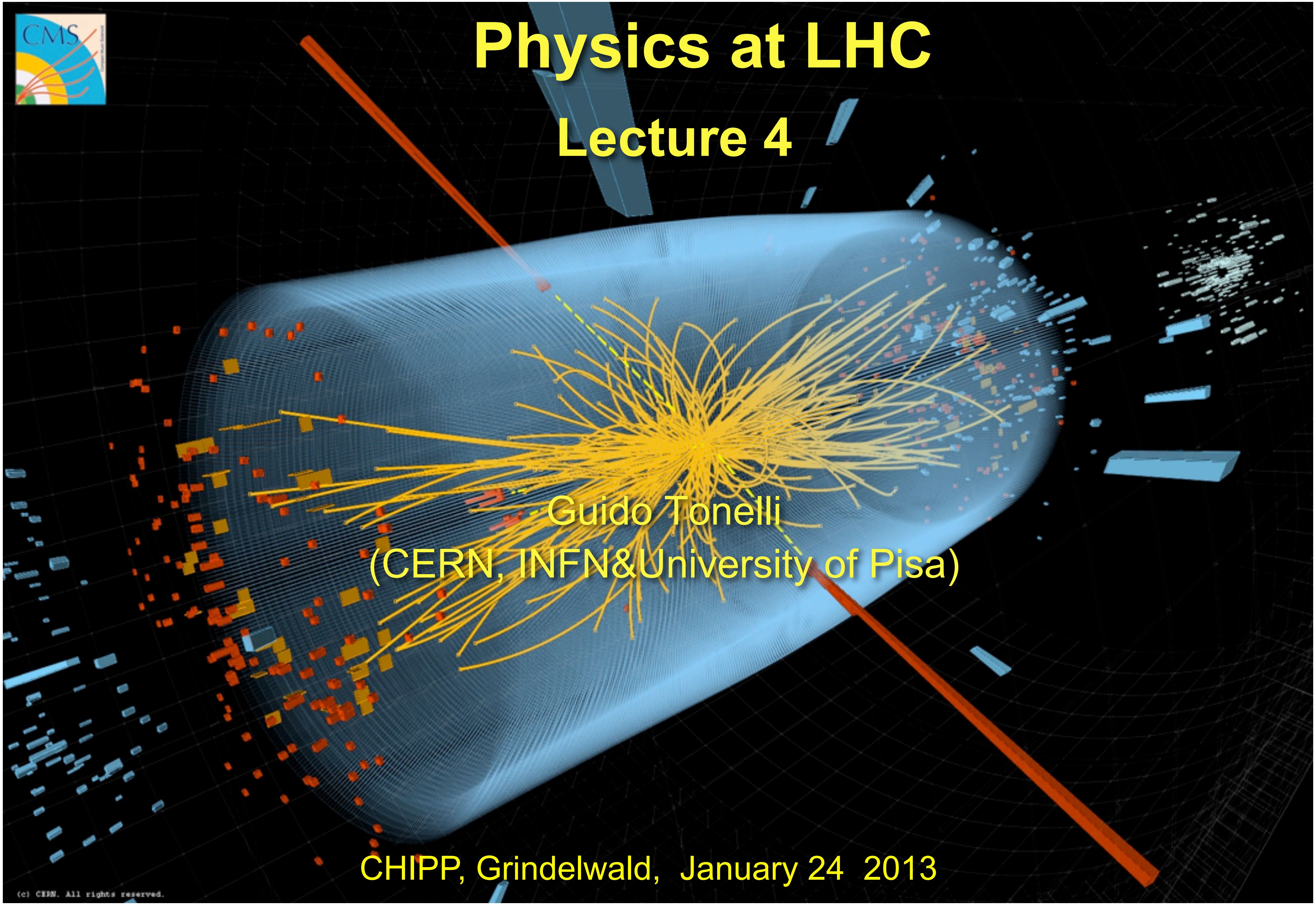


Physics at LHC

Lecture 4

Guido Tonelli
(CERN, INFN&University of Pisa)

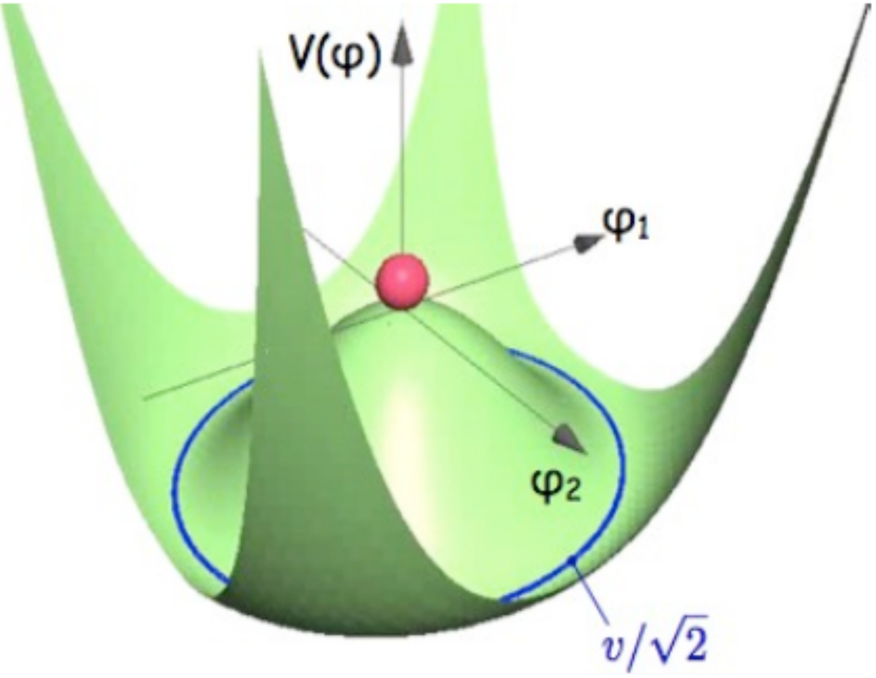
CHIPP, Grindelwald, January 24 2013

The discovery of the Higgs boson was high in the list

The SM Higgs has been proposed to provide an elegant solution for the ElectroWeak Simmetry Breaking mechanism.

It introduces a scalar field with a non-vanishing value at zero. The scalar boson appears as an excitation of the field above its ground state.

Horizontal excitation→ massless mode.
Vertical excitation →massive mode.
W and Z become massive while the photon remains massless.



$$\boxed{M_Z \cos\theta_W = M_W = \frac{1}{2} v g}$$

$$g^2 = 4\sqrt{2} M_W^2 G_F$$

Unfortunately, the theory does not predict precisely the mass of the boson

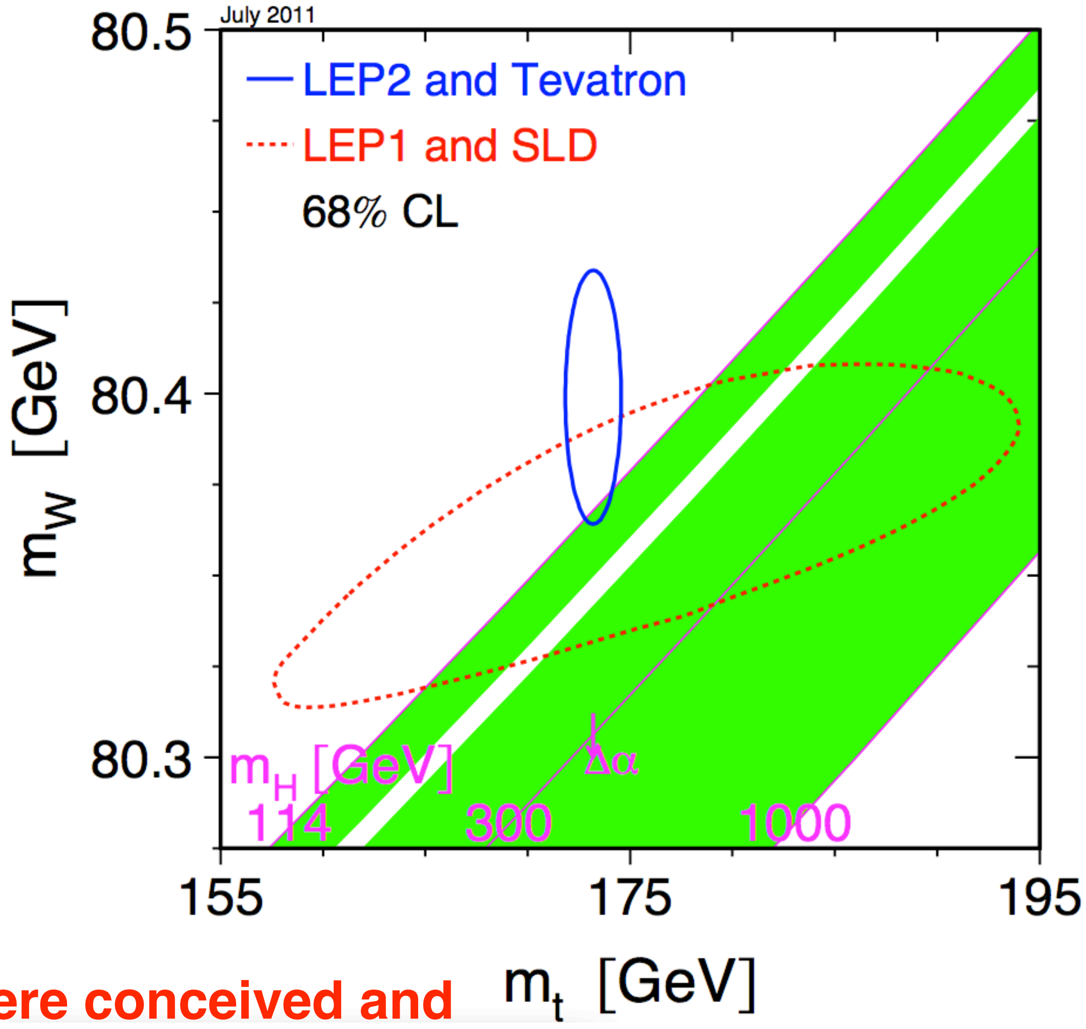
M_H is a free parameter $M_H^2 = 2\lambda v^2$
g=0.6574; v=246GeV

The state of the art before LHC

The global fit of the Electroweak parameters can be used to correlate, through radiative corrections, the mass of the Higgs to the mass of the W and of the Top.

Though electroweak data seem to favour a light mass Higgs there are logarithmic dependances so the constrains are not so strong.

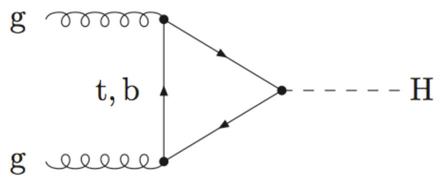
Before the LHC results the Higgs boson was allowed to sit anywhere between 114GeV/c^2 and ~1TeV/c^2 apart a narrow band between 158 and 175 GeV/c^2 directly escluded by the Tevatron Collider.



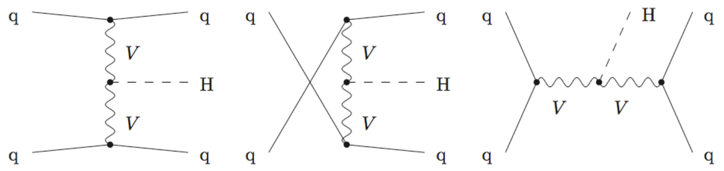
The LHC and its major experiments were conceived and built to explore in depth the multi-TeV region and solve in a way or another this major puzzle of particle physics.

SM Higgs production at LHC

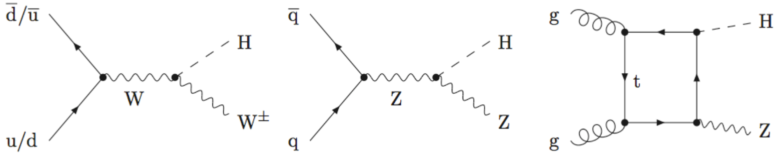
Gluon-gluon fusion



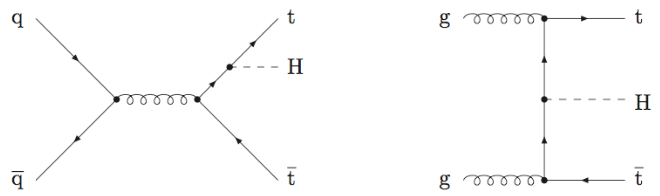
Vector bosons fusion

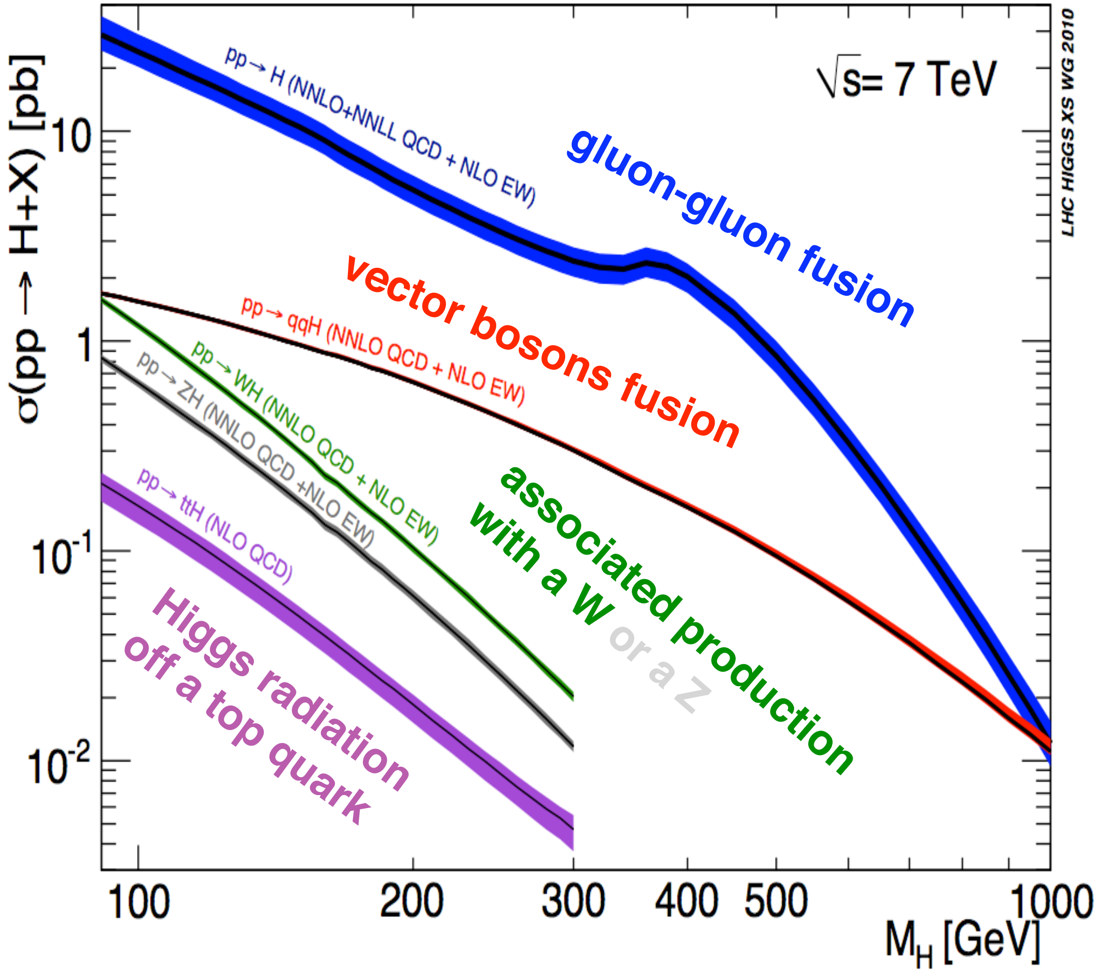


Associated production with W or Z

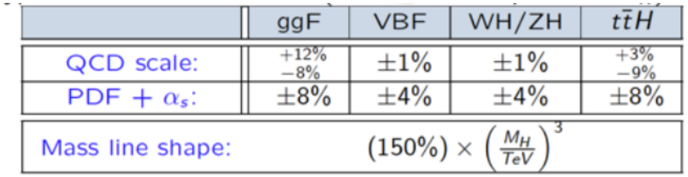


Higgs radiation off a top quark





Typical size of the uncertainty (there is also a dependance on the mass)



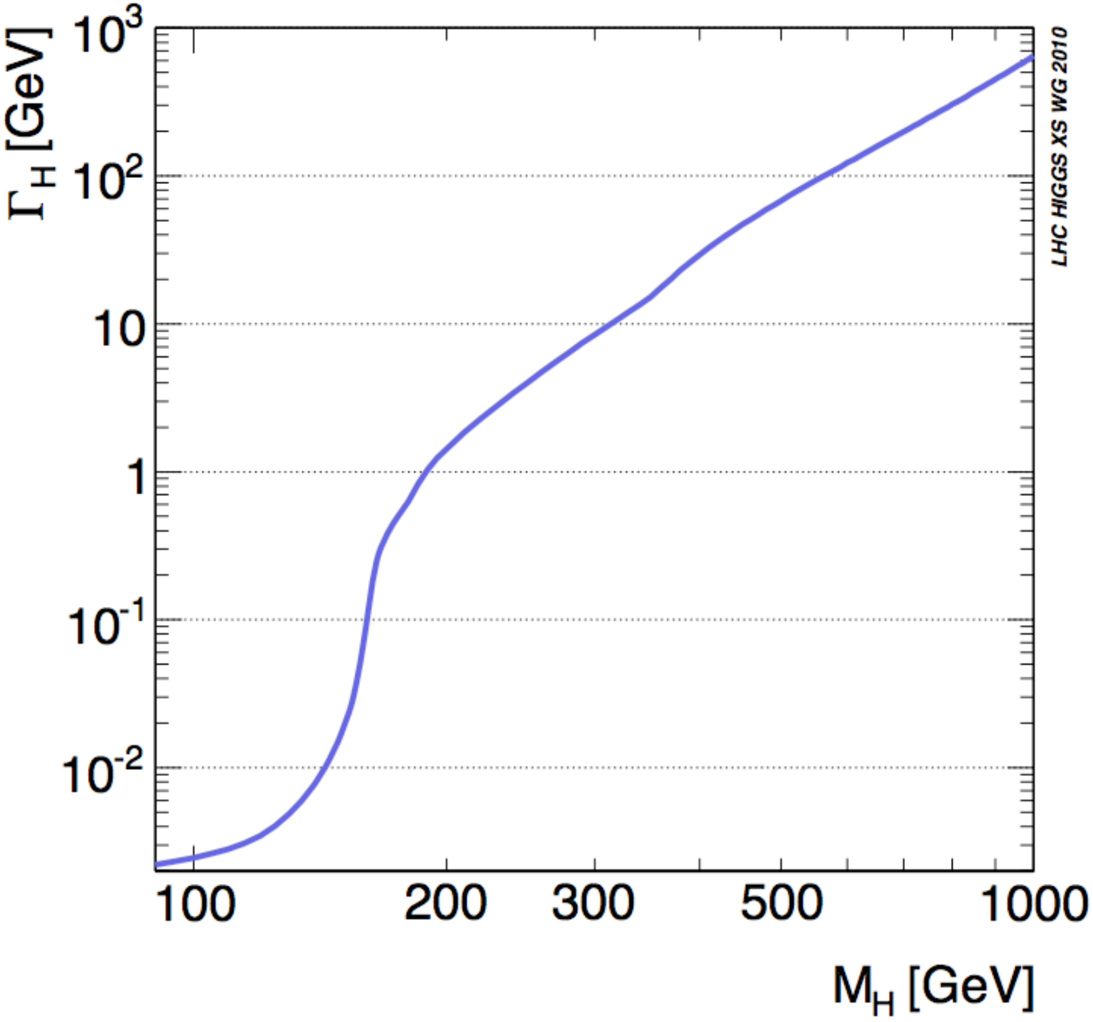
	ggF	VBF	WH/ZH	$t\bar{t}H$
QCD scale:	$^{+12\%}_{-8\%}$	$\pm1\%$	$\pm1\%$	$^{+3\%}_{-9\%}$
PDF + α_s:	$\pm8\%$	$\pm4\%$	$\pm4\%$	$\pm8\%$
Mass line shape:	$(150\%) \times \left(\frac{M_H}{TeV}\right)^3$			

SM Higgs boson width

Very narrow resonance at low mass: ~4MeV at 125GeV/c^2

The width grows rapidly with the mass.

Around 1TeV the width of the boson becomes comparable to its mass i.e the concept of particle fades away.



SM Higgs boson width vs mass under the relativistic Breit-Wigner assumption

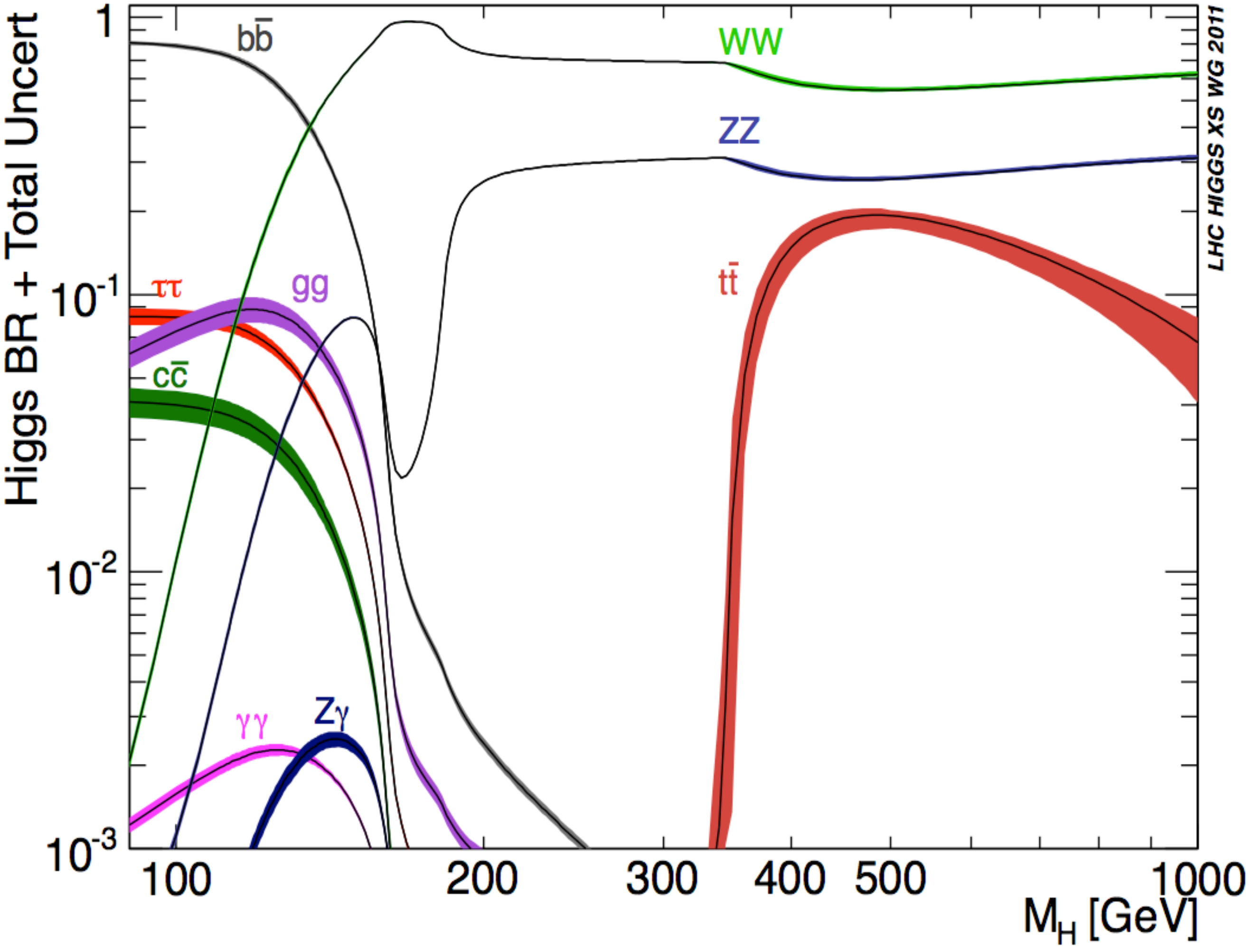
SM Higgs decay modes vs mass

Higgs couples to mass

$\Gamma_{Hff} \sim m_f^2$
$\Gamma_{HVV} \sim m_V^4$

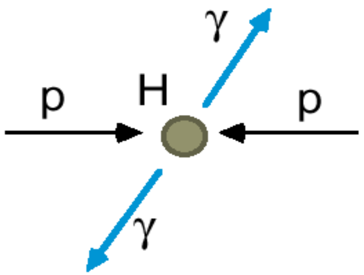
Different decay channels are used to explore the low and the high mass region.

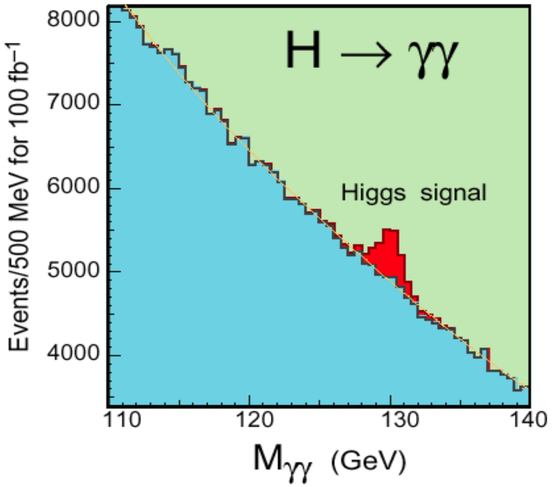
All available channels are combined to increase the sensitivity.

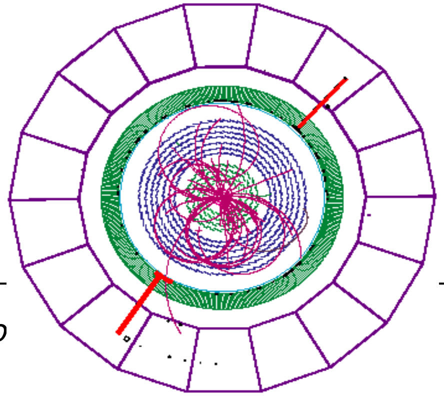


Higgs Boson Searches

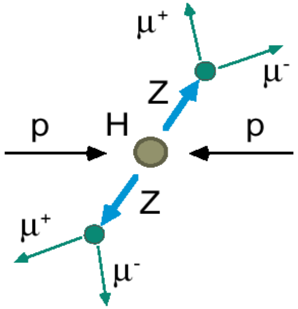
Low $M_H < 140$ GeV/c²

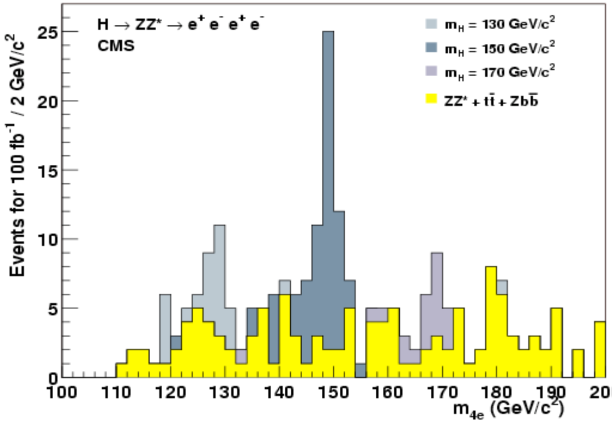




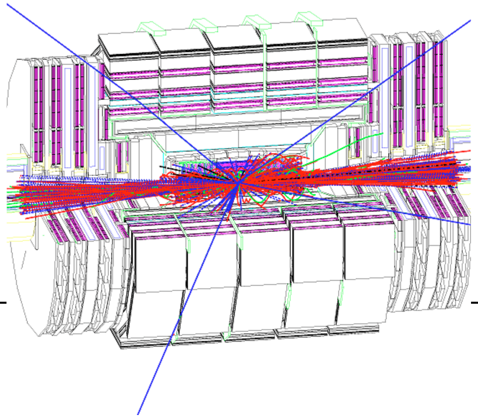


Medium $130 < M_H < 500$ GeV/c²

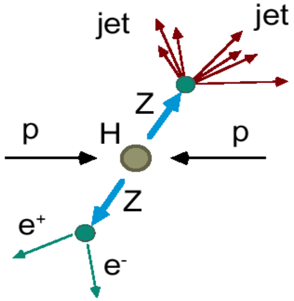


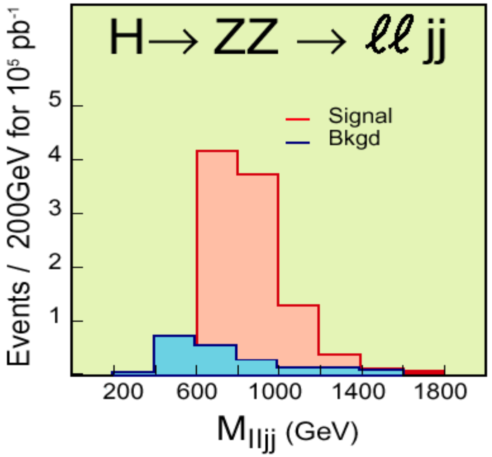


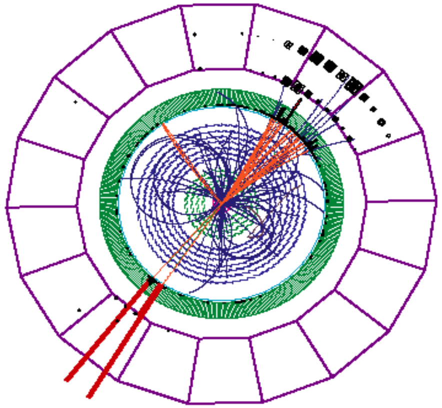
H (150 GeV) → Z^0Z^{0*} → 4μ



High $M_H >$ ~500 GeV/c²

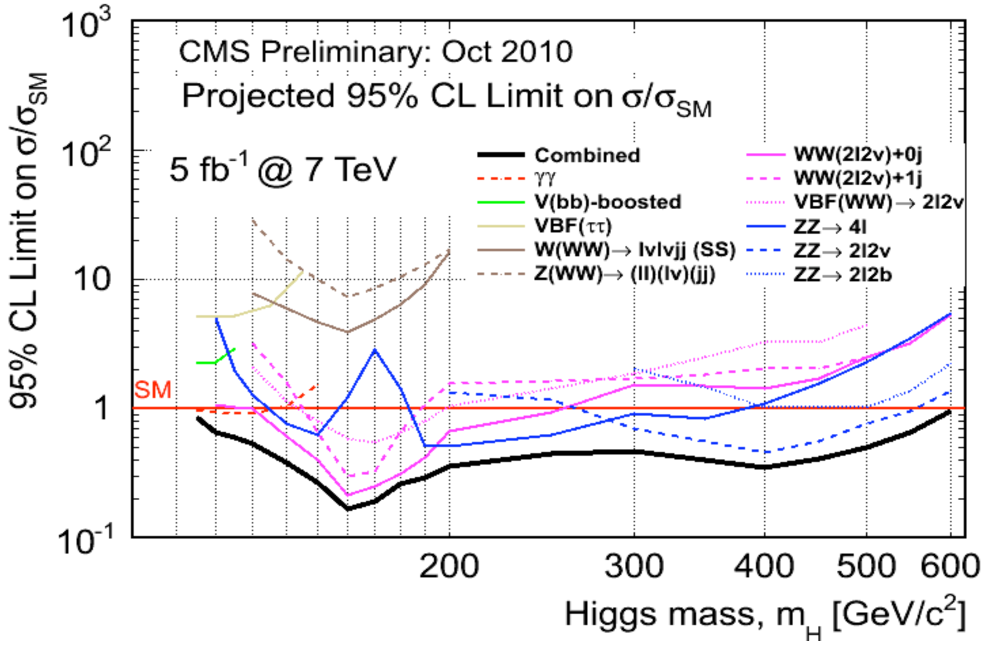




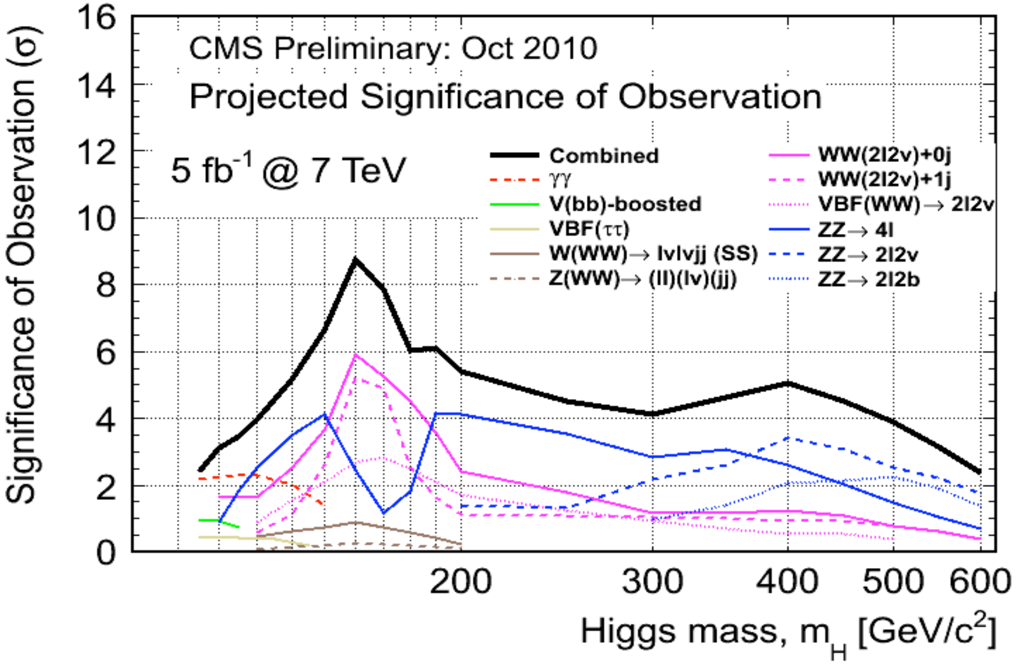


The challenge

CMS Projected Sensitivity @5fb^{-1}



CMS Projected Significance @5fb^{-1}

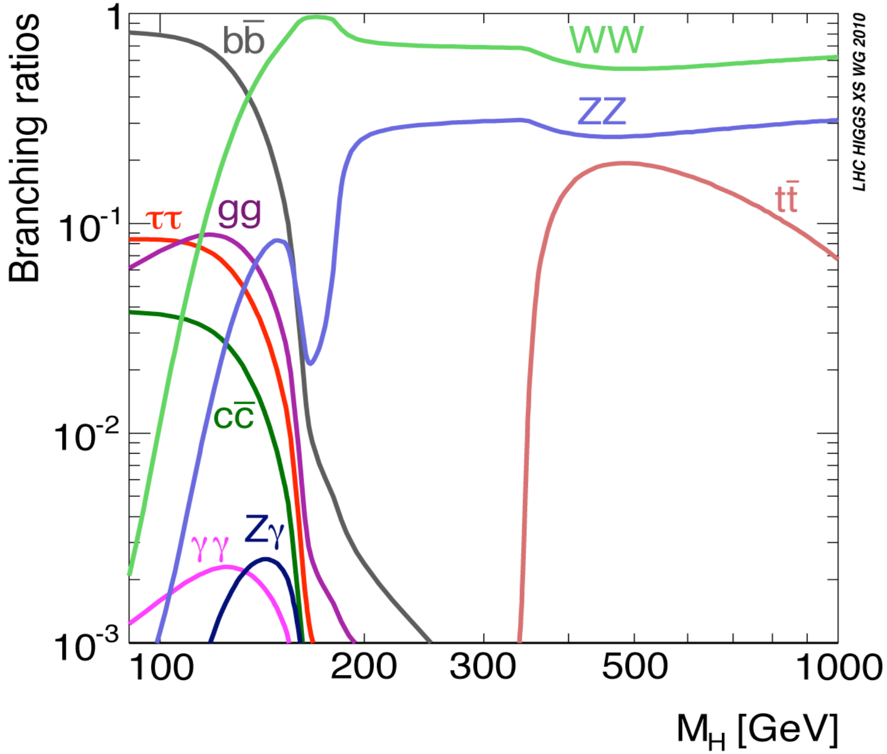


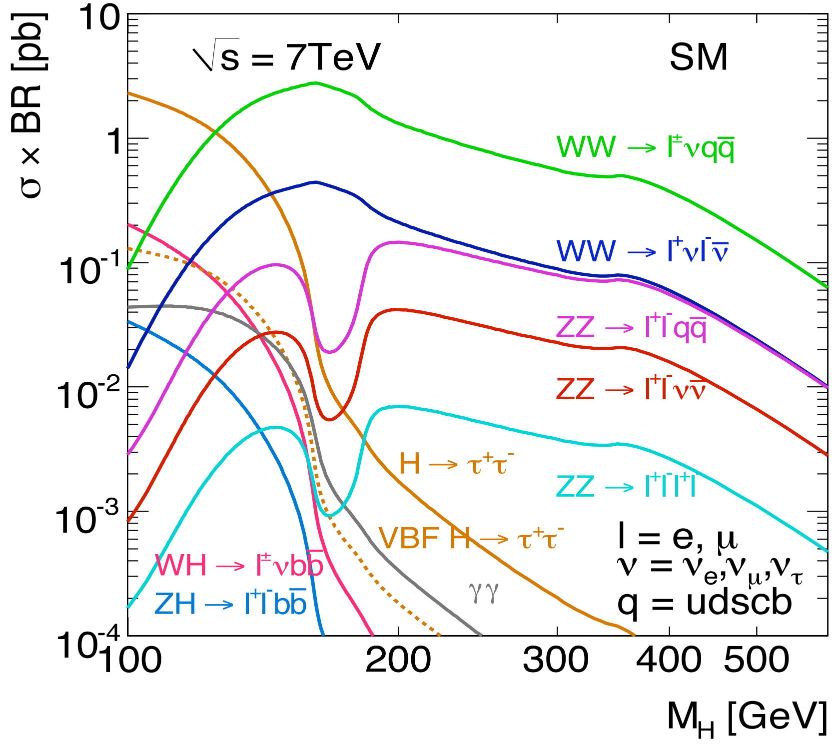
October 2010: with 5fb^{-1} delivered by LHC we could reach a sensitivity below 1xSM in the full mass range.

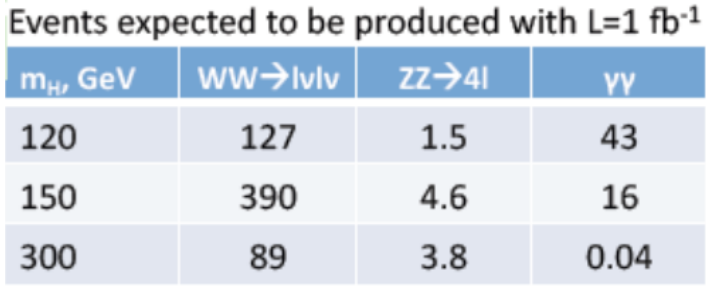
If the SM Higgs boson would be hidden in the low mass region we could start seeing excesses with a significance of 2-3 sigma.

Every single channel, particularly in the low mass region, brings very important information.

SM Higgs Decay Modes Vs Mass







Events expected to be produced with L=1 fb^{-1}

m_H, GeV	WW→lνlν	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

High mass searches: based on H→WW and H→ZZ decay modes reconstructed in several channels; i.e H→WW→lνjj + H→WW→lνlν

Low mass searches: H→γγ ; H→bb; H→ ττ, H→ZZ→4leptons, H→WW→lνlν.

Discover the Higgs at 7 TeV

This was the “mission impossible” that was set up in July 2010.

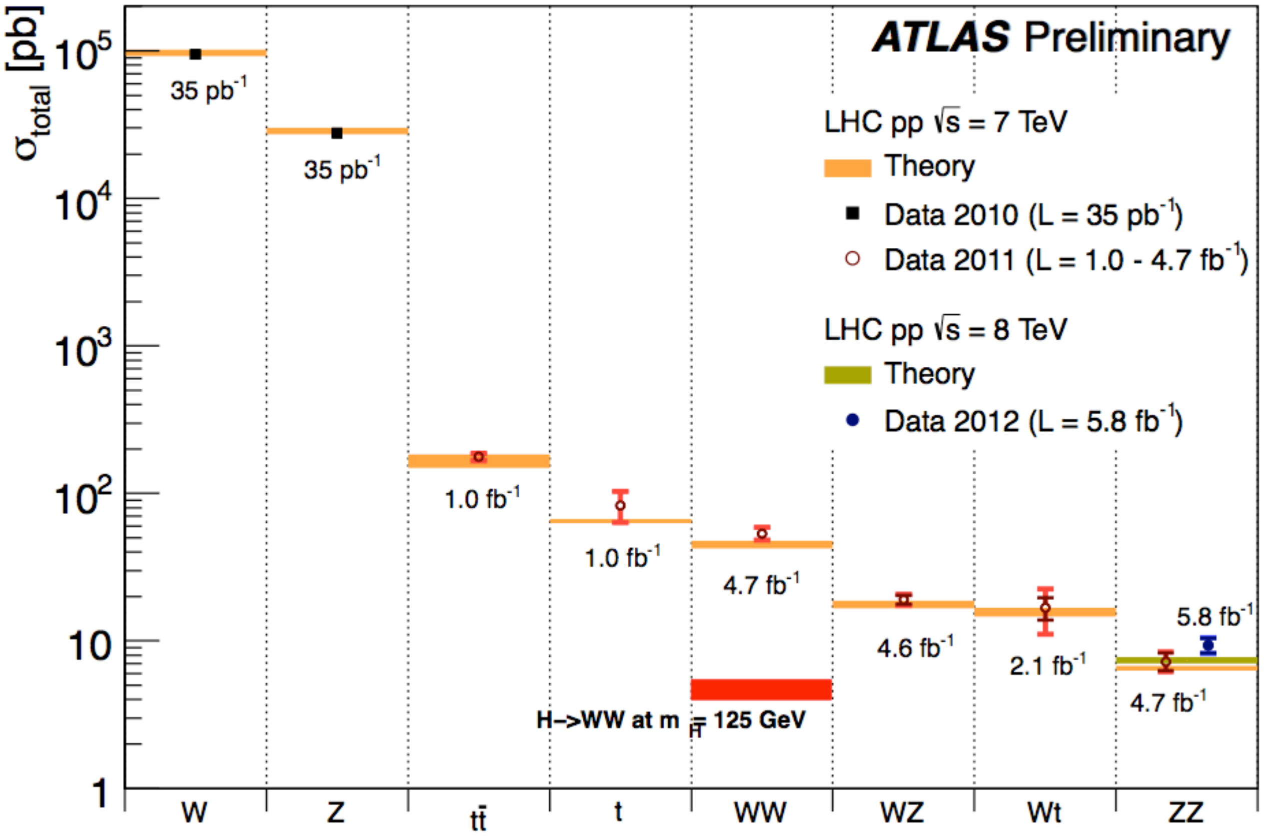
“We’ll discover the SM higgs boson-or exclude it forever- before entering the long shut-down needed to run LHC at 14TeV”

After the terrible incident of LHC and the decision **to run at 7 TeV** in 2010 nobody really believed that we could have seriously addressed the discovery of the Higgs boson before the repair of the splices of LHC to **run at 13-14TeV**.

If we are here today it is just because, in the last two years, an incredible effort has been put together basically from scratch.

New ideas, completely new approaches, very aggressive and modern analysis tools.

EWK measurements are SM Higgs background



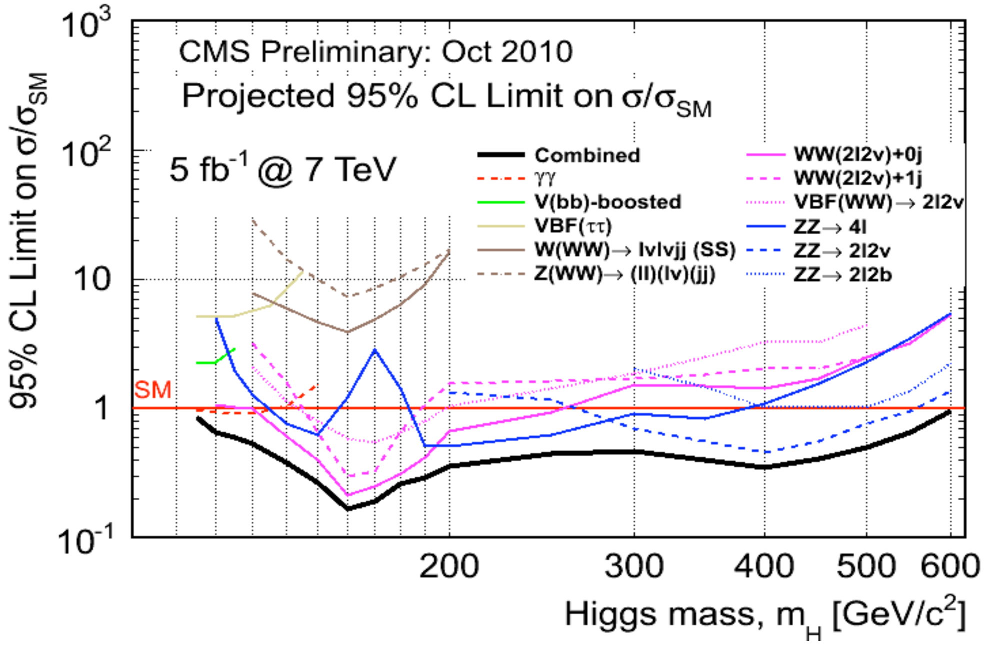
$\sigma(pp) \rightarrow H$ (with m_H=125GeV) =17.5pb

Same order of manitude of the diboson (WW,WZ,ZZ production).

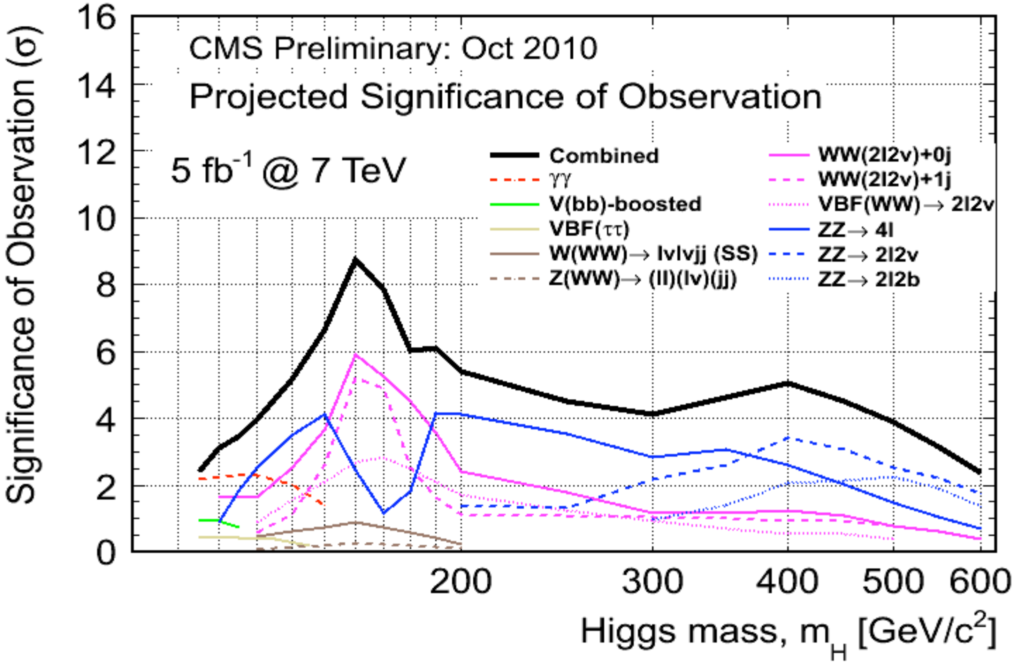
These measurements are also very important to validate detector/physics simulation, object reconstructions, event selections and in general the analysis techniques.

The challenge in 2010

CMS Projected Sensitivity @5fb^{-1}



CMS Projected Significance @5fb^{-1}



October 2010: with 5fb^{-1} delivered by LHC we could reach a sensitivity below 1xSM in the full mass range.

If the SM Higgs boson would be hidden in the low mass region we could start seeing excesses with a significance of 2-3 sigma.

The goal: discover the SM Higgs boson (or exclude it over the full mass range) before the long shutdown needed to repair the LHC splices.

Higgs hunting basics: μ and CL_S

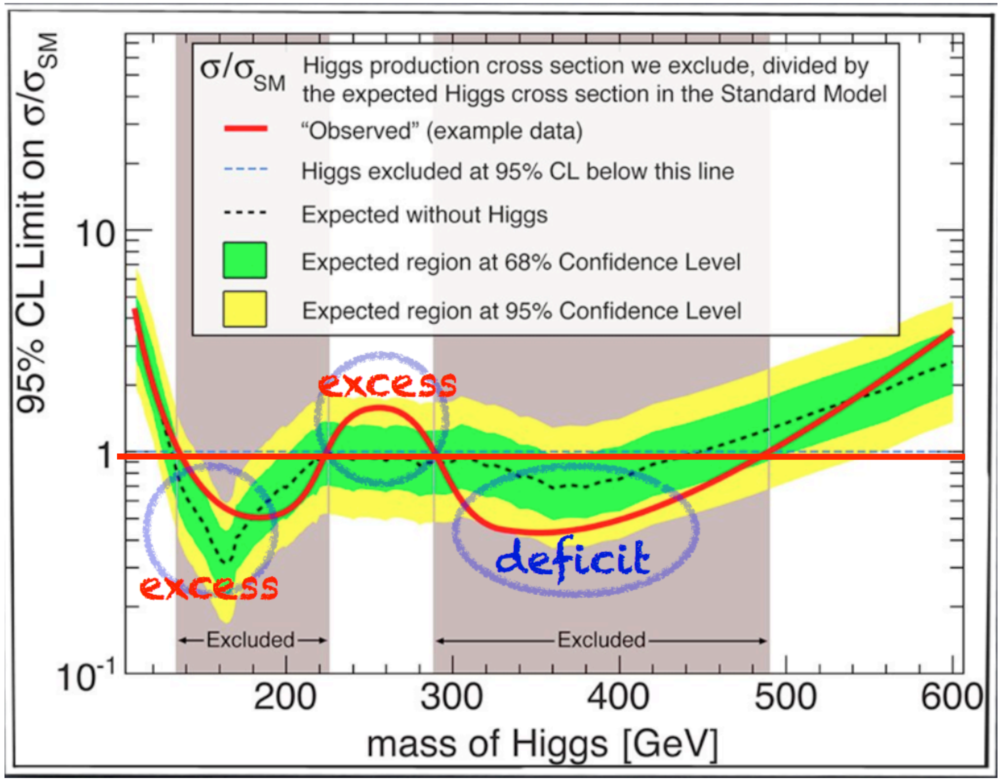
Understanding the yellow and green bands.

μ is the ratio between the measured cross section at a given mass assuming the presence of a SM Higgs signal and the expected cross section at that mass.

$$\mu = \frac{\sigma_{meas}}{\sigma_{SM}(m_H)}$$

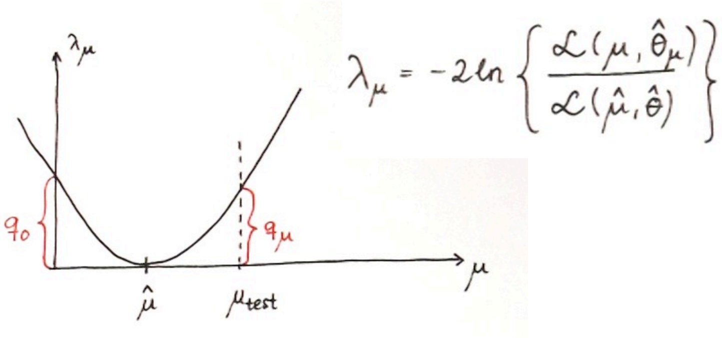
CLs measures the compatibility of the data with the signal hypothesis.

If CLs<5% the signal hypothesis is excluded at the 95% CL.



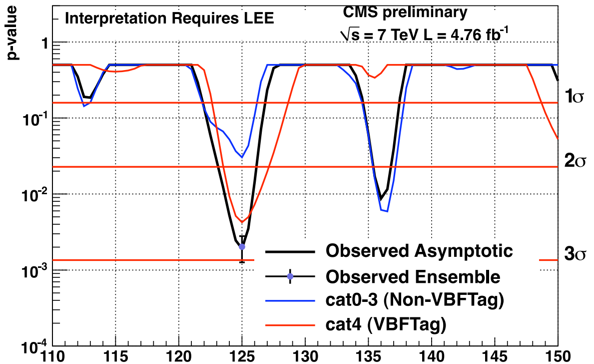
μ_{up} is the signal strength for which CLs=5%. If, for a given mass hypothesis, m_H, μ_{up} <1 then $\sigma_{meas}<\sigma_{SM}$ and m_H is excluded at 95% CL.

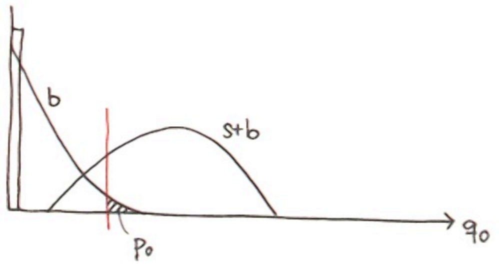
Profile likelihood Ratio, p_0 and CL_s



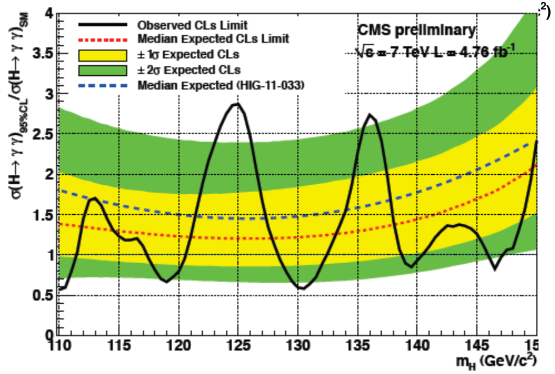
$$\lambda_\mu = -2\ln\left\{\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}_\mu)}{\mathcal{L}(\hat{\mu},\hat{\theta})}\right\}$$

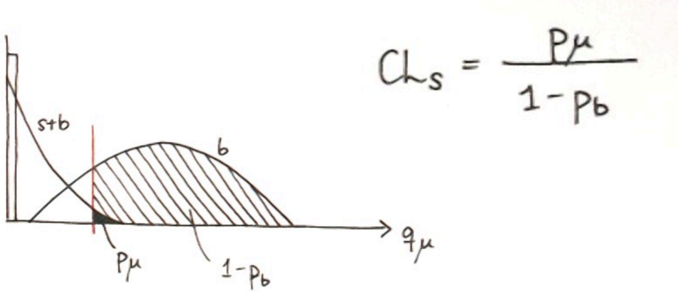
- local significance p_0 to test background hypothesis





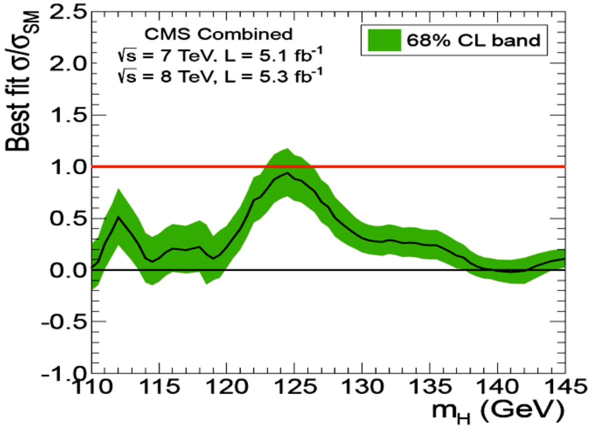
- $CL_s = CL_{s+b}/CL_b$ (log-likelihood ratio) to test signal hypothesis





$$CL_s = \frac{p_\mu}{1-p_b}$$

- $\hat{\mu}$ to estimate the signal strength (relative to the SM expectation)



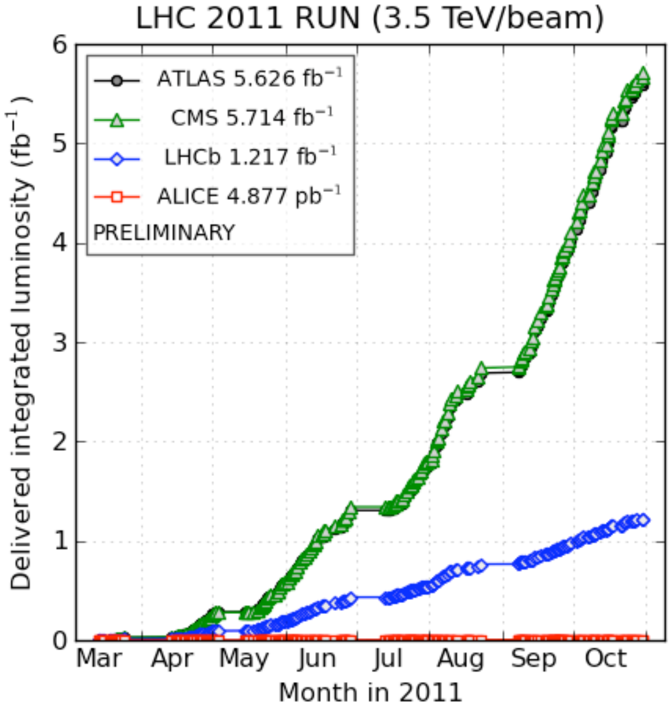
The first breakthrough.

>5.5 fb^{-1} delivered in pp mode at 7 TeV in 2011 (1fb^{-1} was the official goal for the machine).

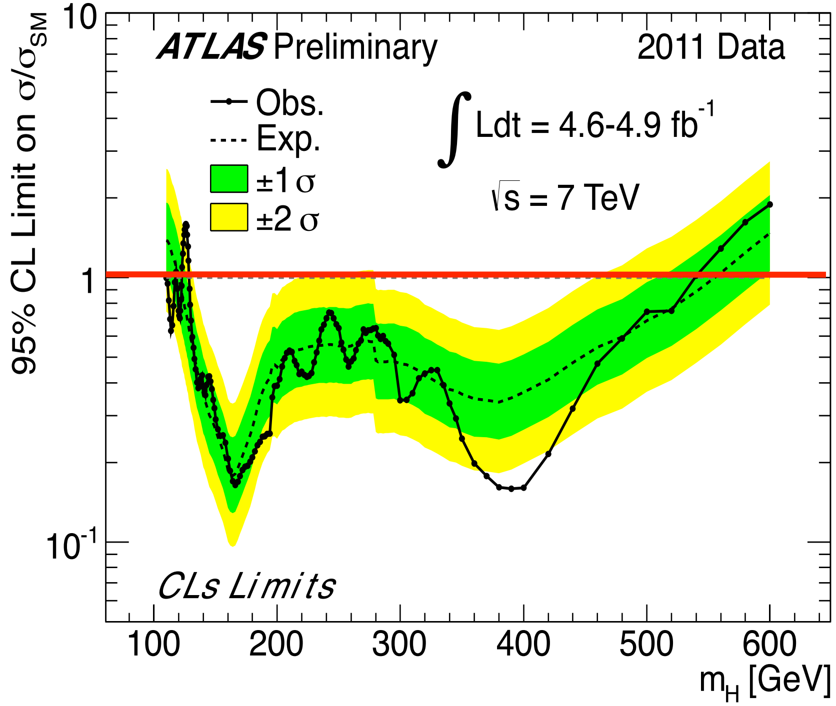
ATLAS and CMS detectors recorded typically **90-95%** of the delivered luminosity and about **85-90%** was good quality data for physics.

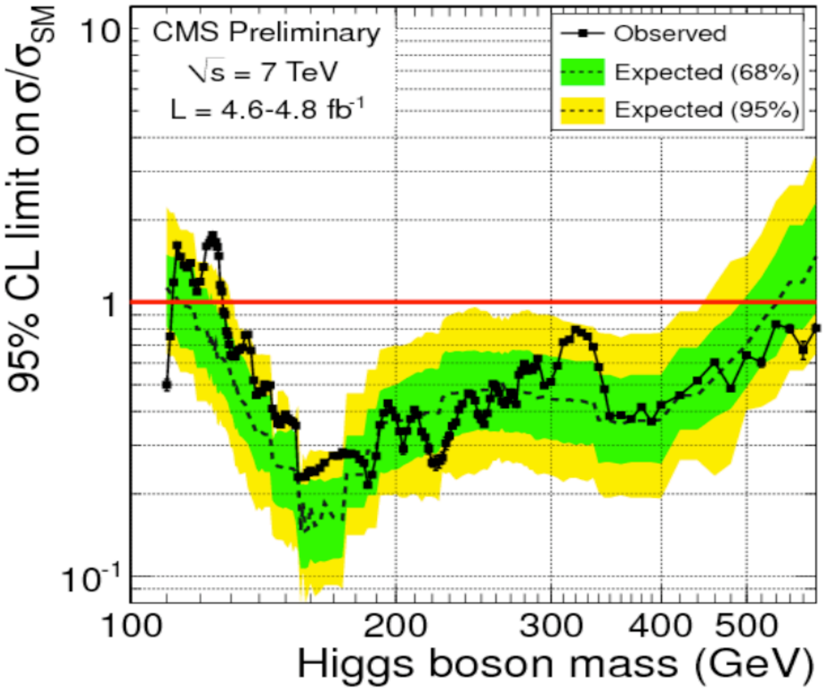
Average fraction of operational channels per subsystem typically >98%.

For the first time the amount of data large was enough to allow experiments to say something significative on the Higgs boson search in the full mass region.



December 13, 2011: 1st special seminar at CERN.





Expected exclusion 120-555GeV.

Observed exclusion 110-117.5, 118.5-122.5, 129-539GeV.

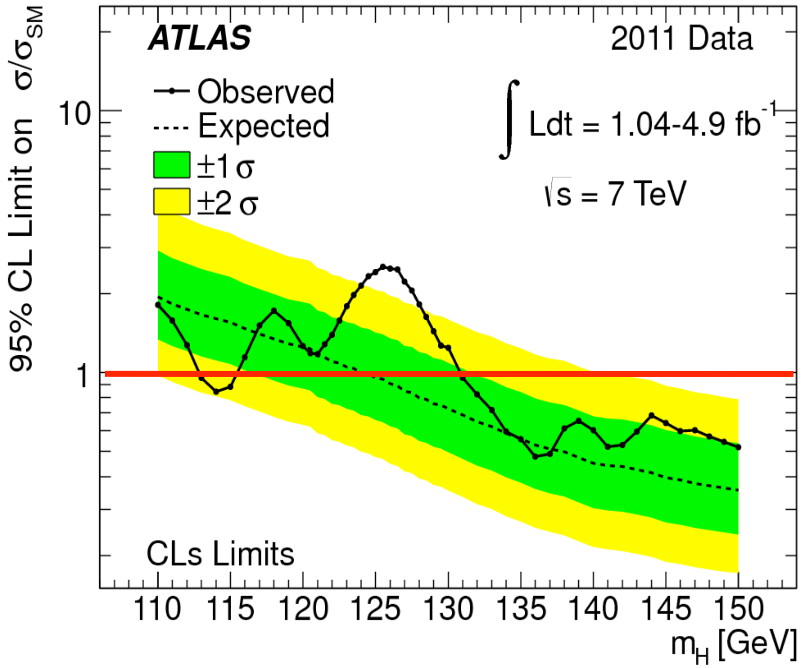
We have not been able to exclude the presence of the SM Higgs boson below **129GeV** due to the presence of **an excess of events** in the low mass region.

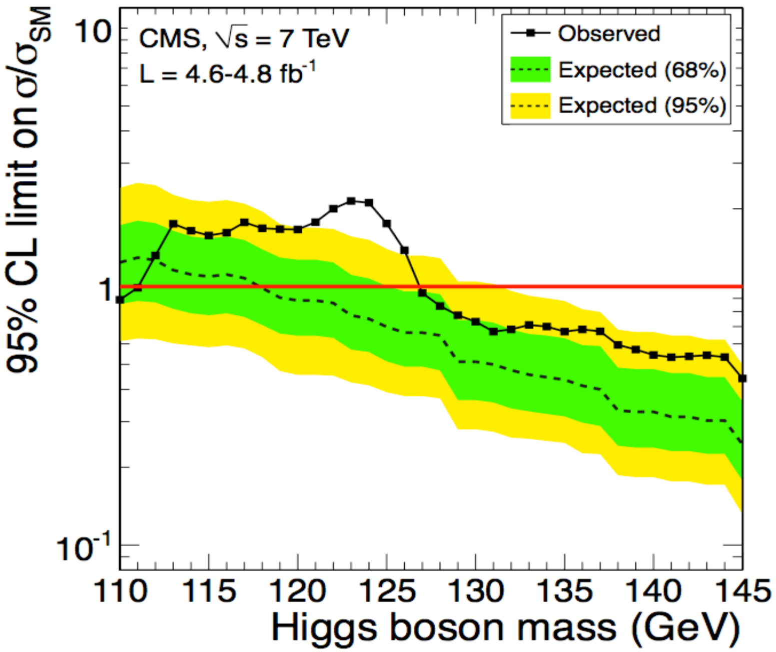
Expected exclusion 114.5 - 543 GeV

Observed exclusion 127.5 - 600 GeV.

We have not been able to exclude the presence of the SM Higgs boson below **127.5 GeV** due to **the presence of an excess of events** in the low mass region.

The first evidence of an “excess” at 125GeV





ATLAS : “We observe **an excess of events around m_H~ 126 GeV**: local significance **3.6 σ** SM Higgs expectation: 2.4 σ local → observed excess compatible with signal strength within +1σ; the global significance (taking into account Look-Elsewhere-Effect) is 2.3 sigma”

CMS : “We observe **an excess of events** which is most compatible with a SM Higgs hypothesis **in the vicinity of m_H~ 124 GeV**, but the statistical significance (**2.6σ** local and 1.9σ global after correcting for the LEE in the low mass region) is not large enough to say anything conclusive.

Since then, new data at 8 TeV and blind analyses.

- A lot of improvements in the analyses
- Better understanding of the detector
- Optimal selection criteria to improve the sensitivity.

but, to avoid any kind of scientific or even psychological bias, everything was done blindly, without looking at the data.

- Analysts were allowed to use only control regions far away from the possible "signal region".
- **The data were unblinded on June 15 as soon as the LHC delivered an additional 5fb^{-1} of data at 8 TeV.**

Un-blinding the data in CMS

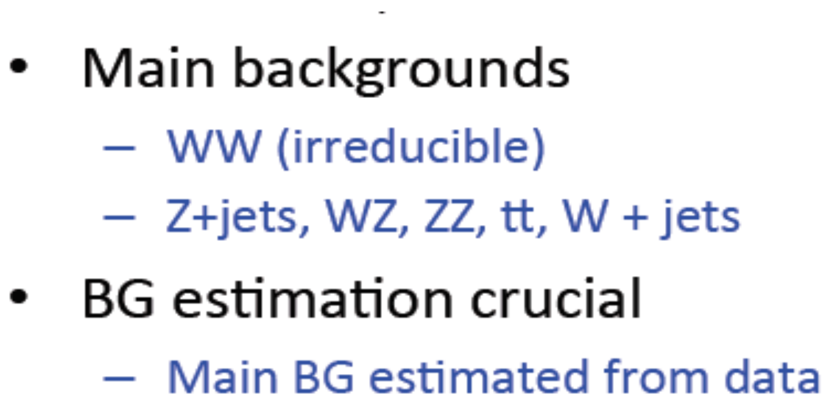
About 700 participants (400 persons in a room at CERN, rest by video)

That day we would have known whether we would have had a discovery or not.

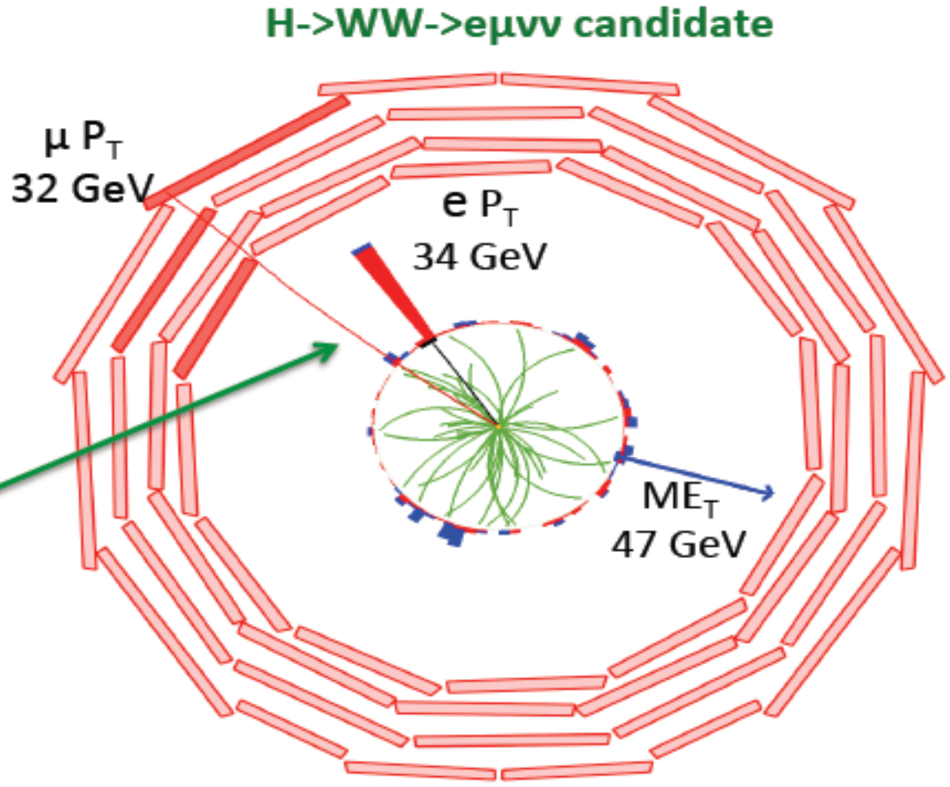
If the signal in new data would have appeared around 125GeV…..

H→WW→lνlν

- This channel contributes in the whole mass region but the presence of the two neutrinos yields a poor mass resolution (~20%): expect a broad excess and no narrow mass peak in presence of signal.
- Search: Two isolated leptons with p_T>20/10 GeV + MET>~40 GeV

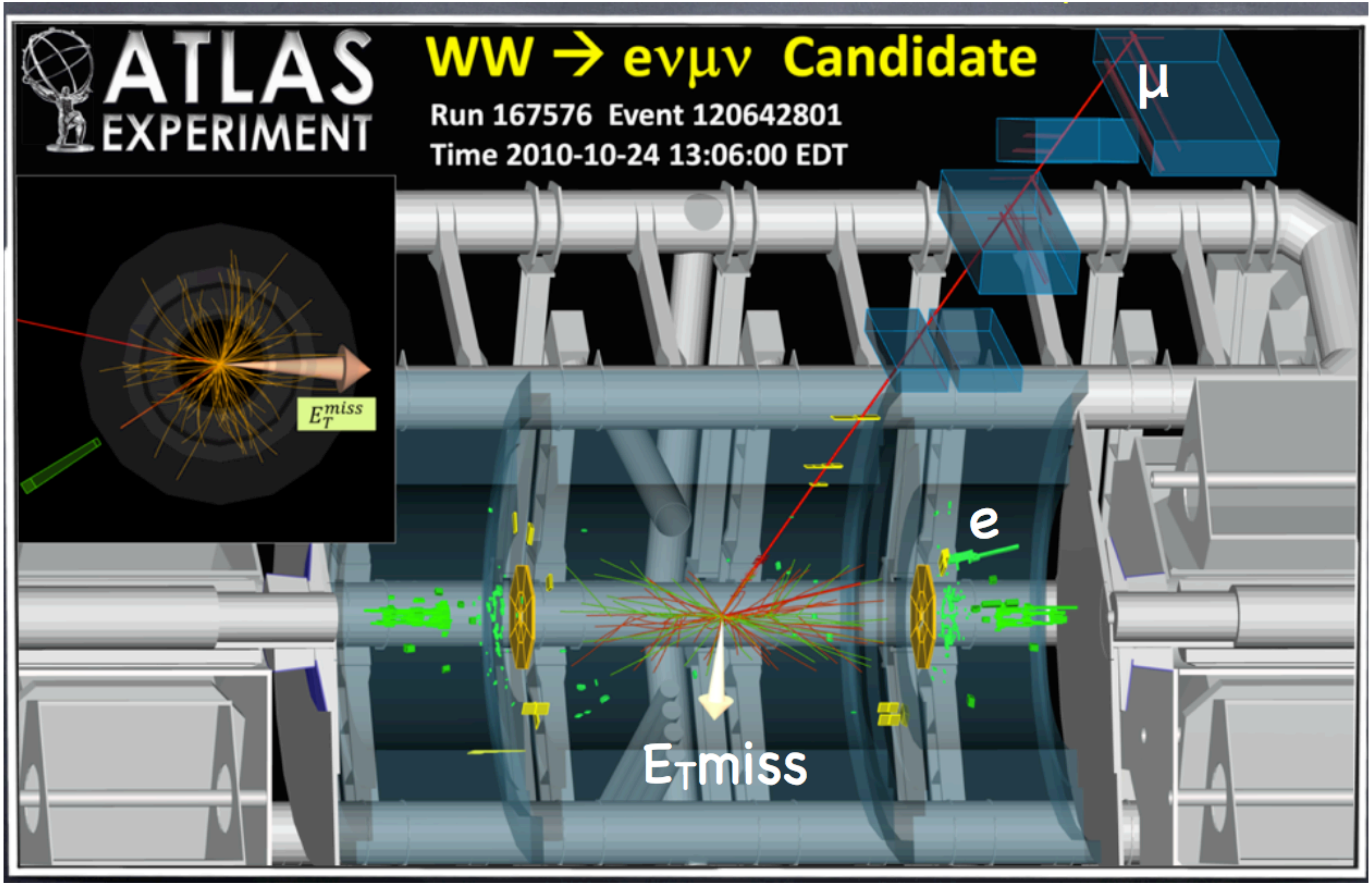


- Main backgrounds
  - WW (irreducible)
  - Z+jets, WZ, ZZ, tt, W + jets
- BG estimation crucial
  - Main BG estimated from data



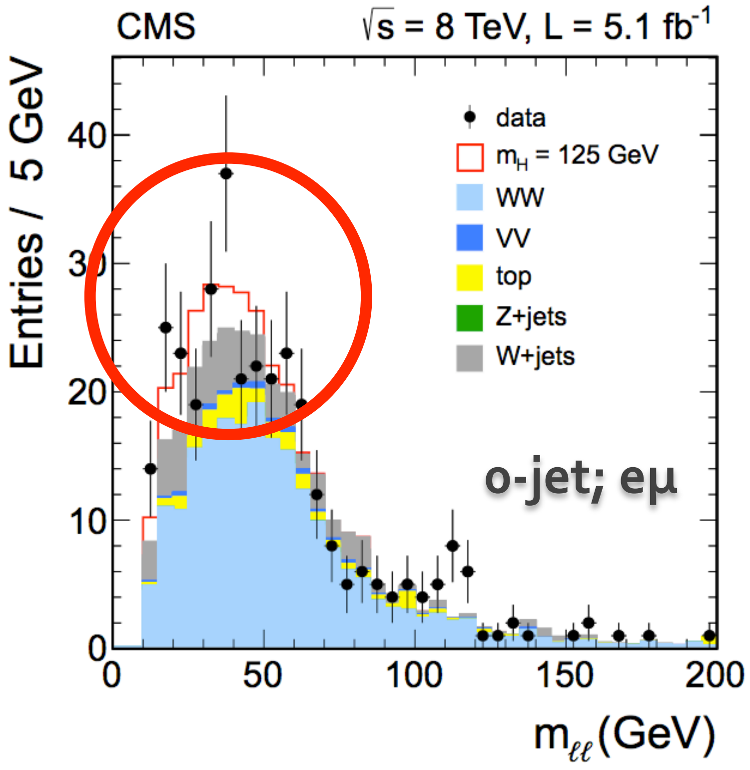
The scalar Higgs boson and the V-A structure of the W decay favors a small opening angle between the two charged leptons

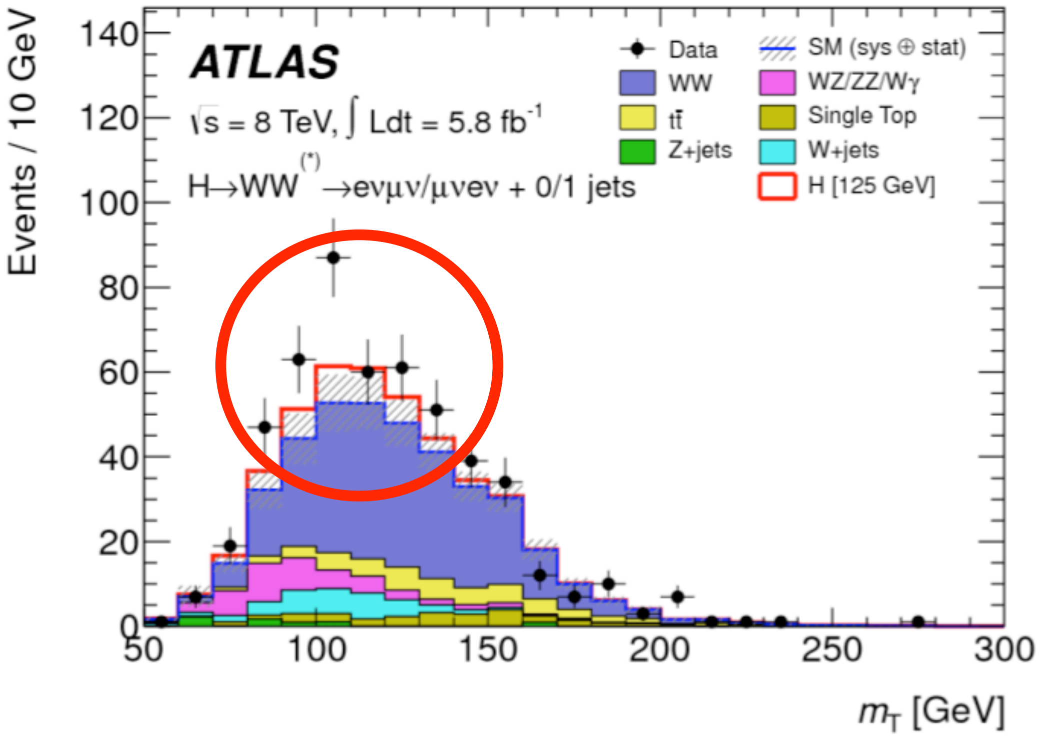
$H \rightarrow WW \rightarrow 2l2\nu$



Results on $H \rightarrow WW \rightarrow 2l2\nu$

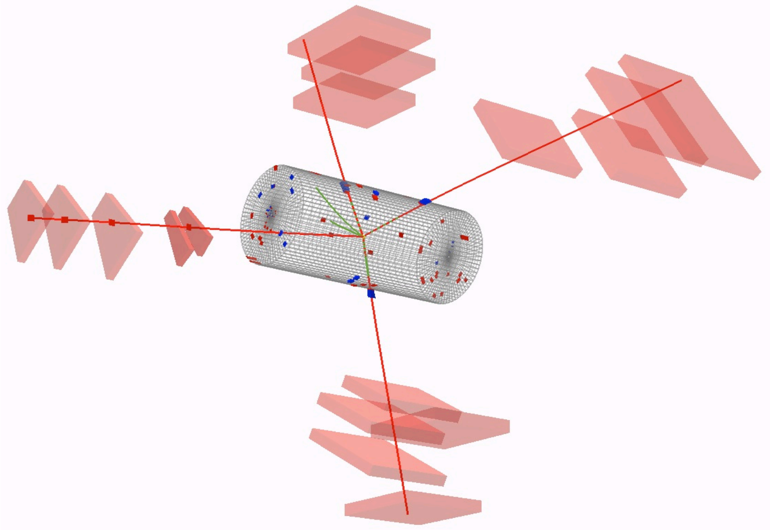
We cannot expect to see a narrow peak in the distributions for the presence of neutrinos (missing transverse energy) in the decay.

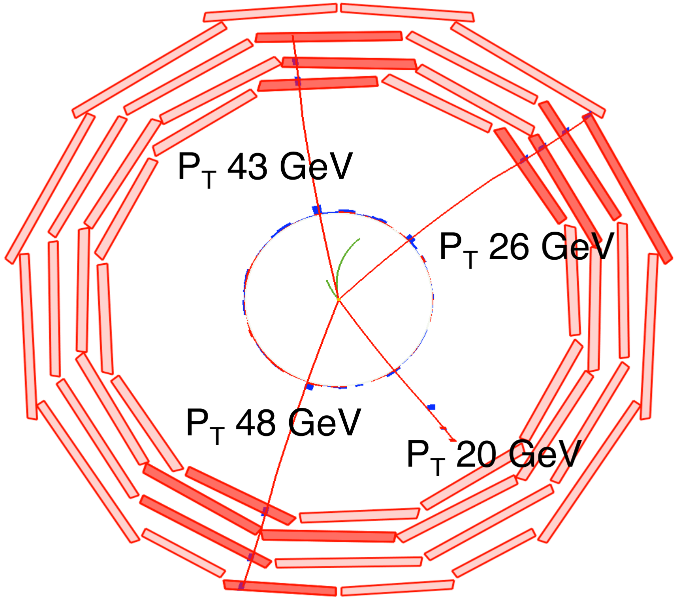




The presence of a SM Higgs boson at 125GeV would appear as a broad excess of events in the low mass end of the invariant mass distribution of the two leptons or in the transverse mass distribution.

H → ZZ →4e, 4μ, 2e2μ: The Golden Channel





Signature: Two pairs of same flavor high pT oppositely charged isolated leptons. One or both pairs with invariant mass compatible with the Z.

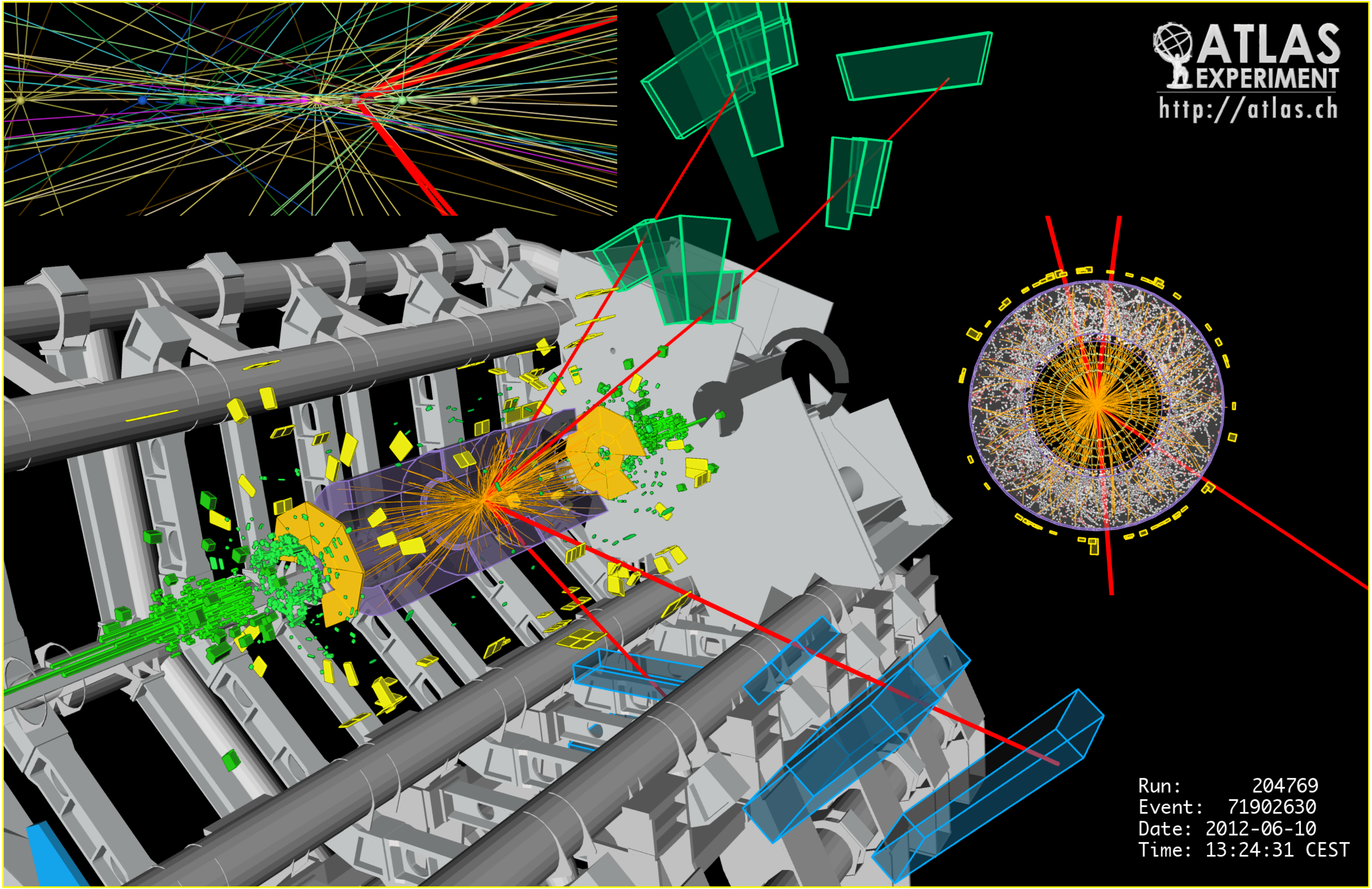
Extremely clean, high resolution channel (1-2%) but very low rate (σ~2-5fb).

Kinematics fully available: reconstruction of the invariant mass of the system.

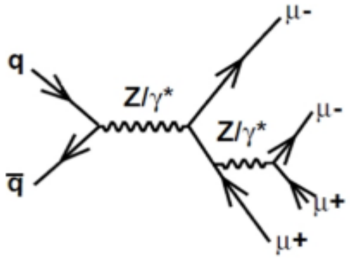
Main backgrounds: ZZ* (irreducible) for $m_H<2m_Z$, Zbb, Z+jets, tt

Suppress backgrounds with isolation and impact parameters cuts on two softest leptons.

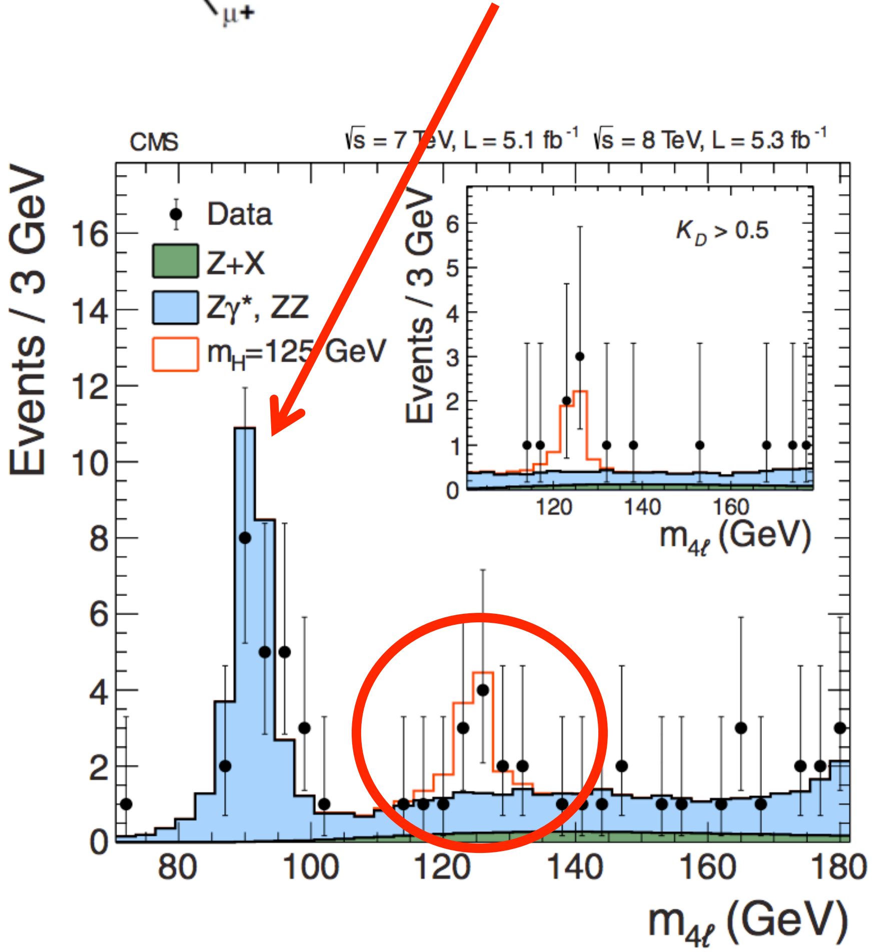
H→ZZ→4 leptons

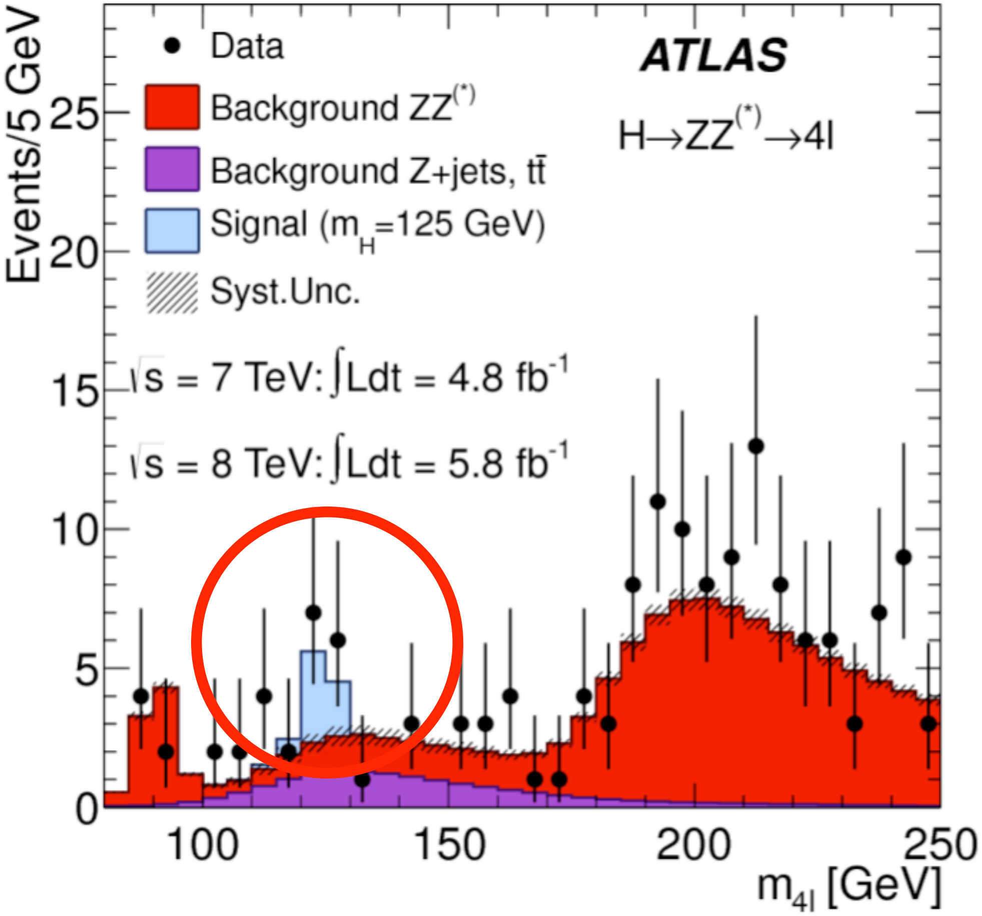


Results on H→ZZ→4 leptons



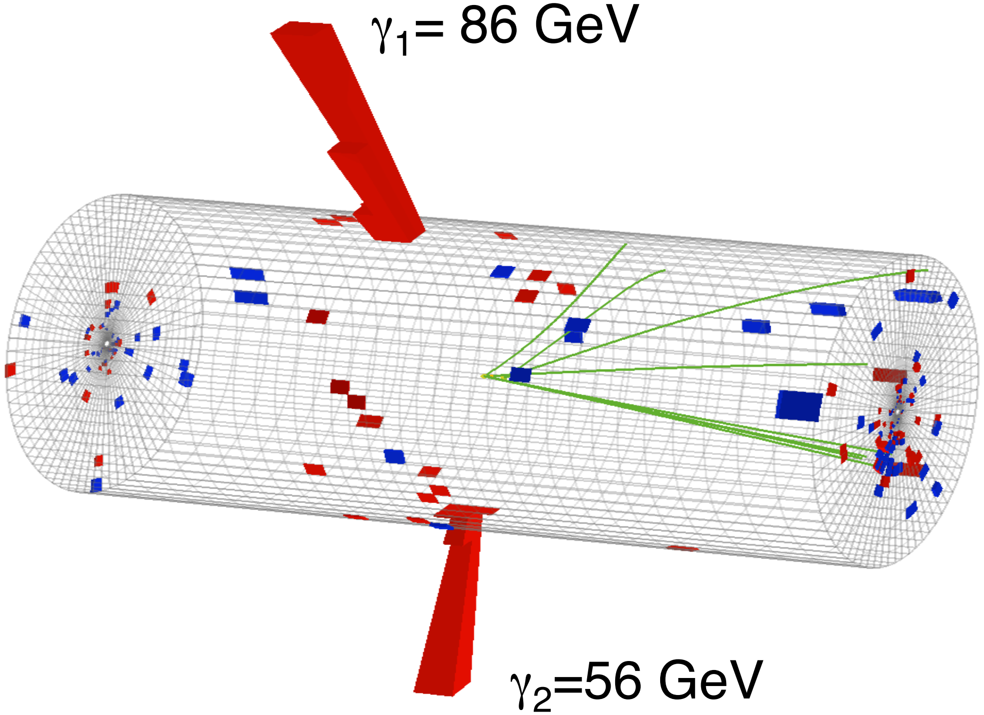
Very rare EWK process used for calibration purposes.





The specialist of the Low Mass: H→ $\gamma\gamma$

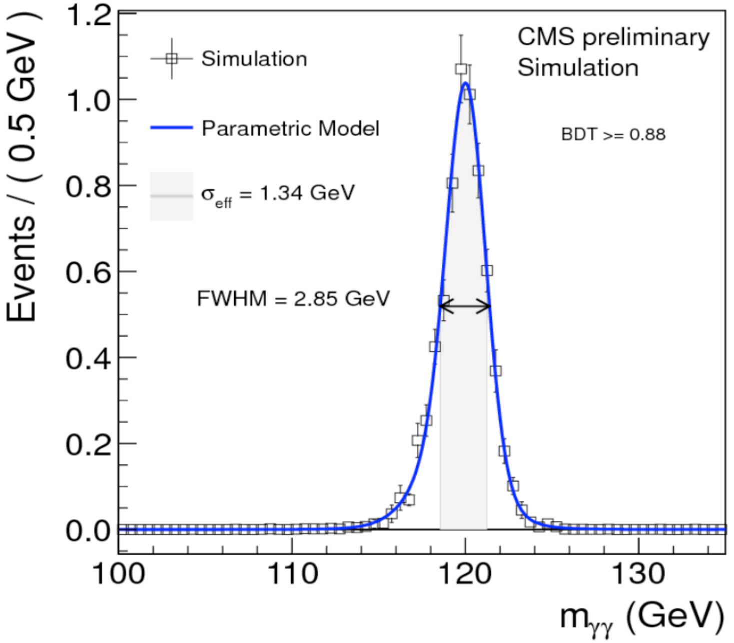
Signal: two energetic, isolated γ. Search for a narrow mass excess over a smoothly falling background.



Excellent resolution: 1-2%

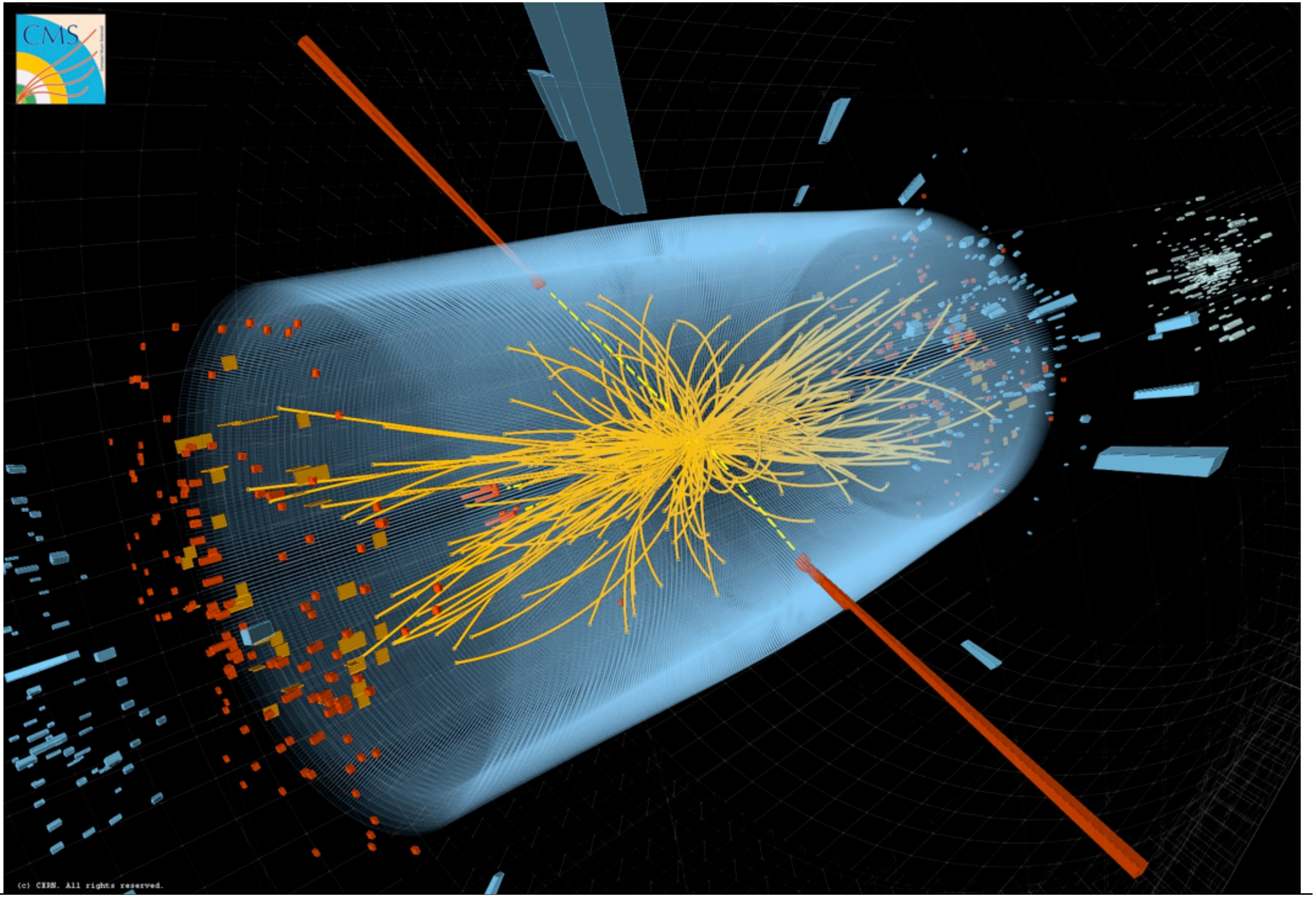
Challenges: vertexing with PU, calibration of the electromagnetic calorimeters.

Calibration constants derived from Z→ee data.

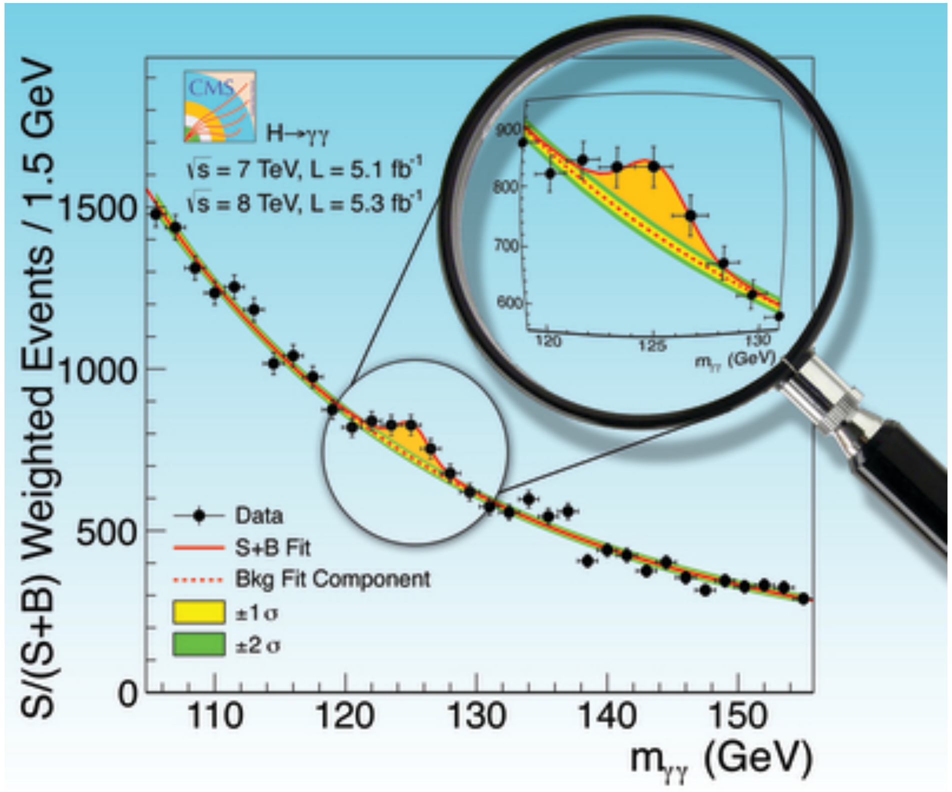


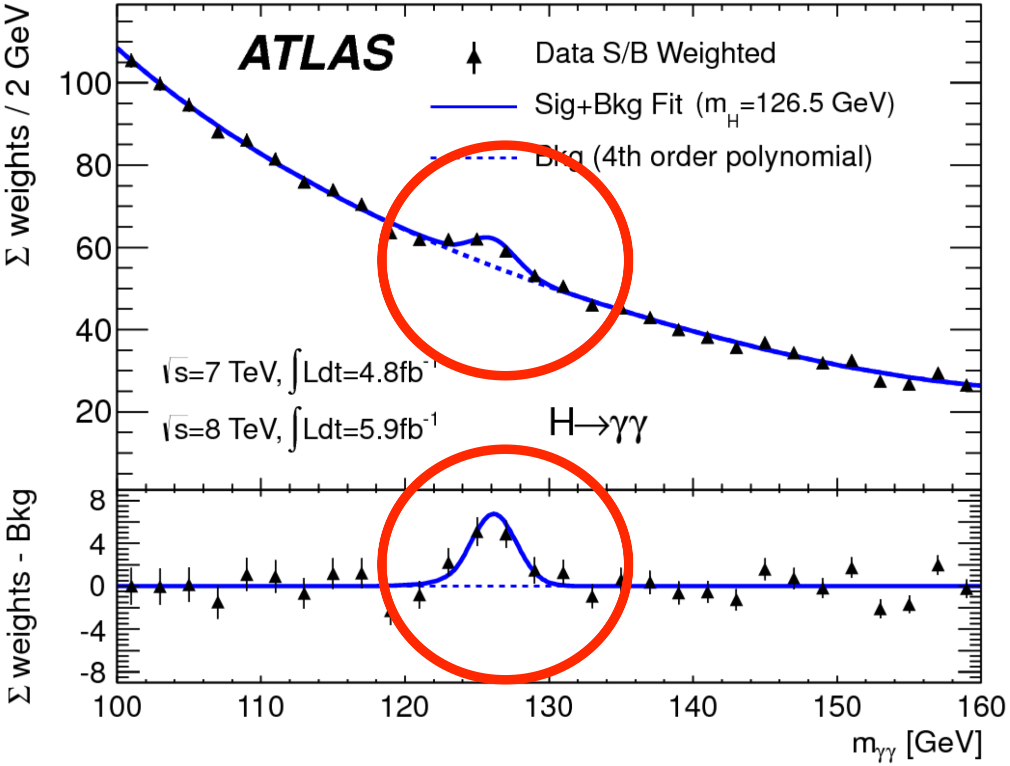
Background: Large and mostly irreducible QCD di-photons. Measured from $M_{\gamma\gamma}$ sidebands in data

$H \rightarrow \gamma\gamma$



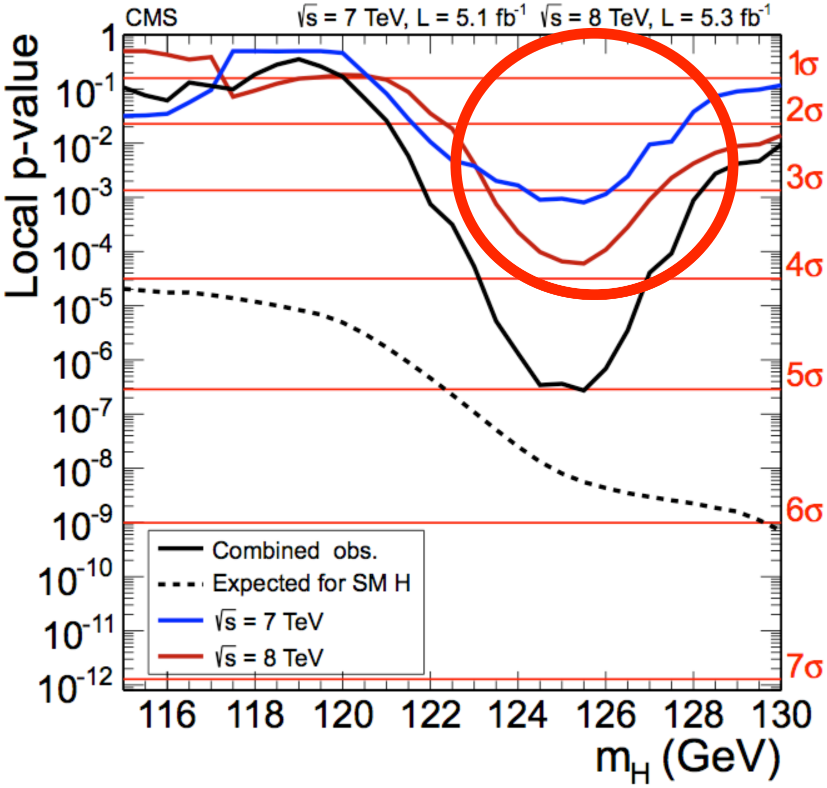
Results on H→γγ

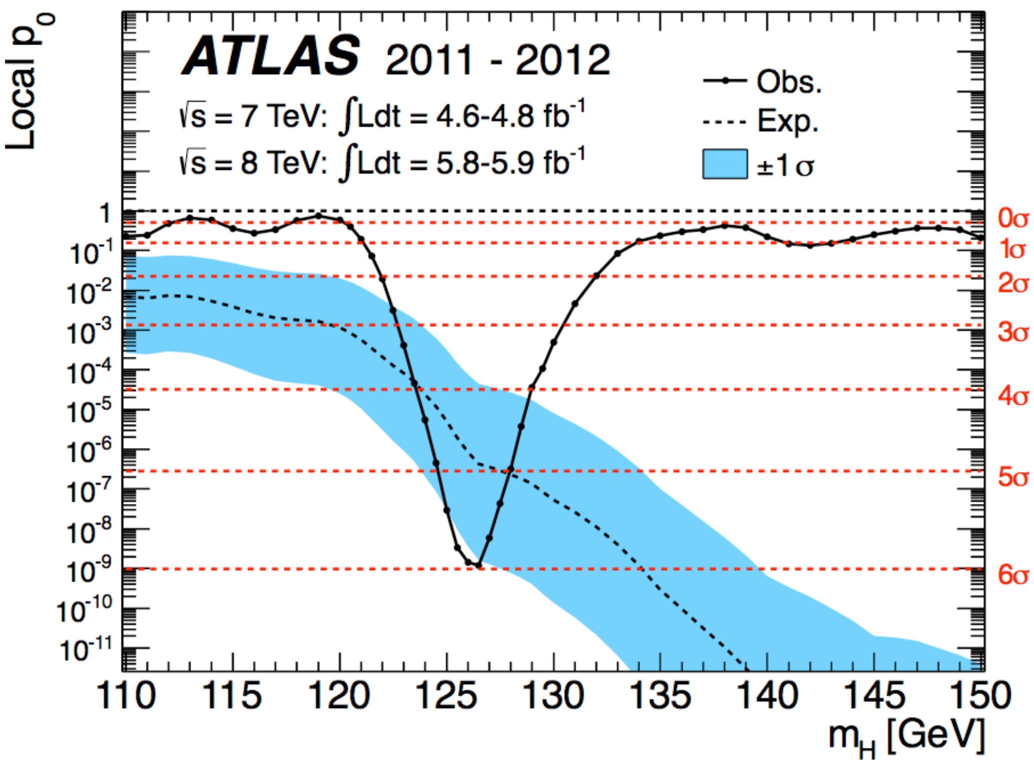




Discovery of a Higgs-like boson.

Combined significance 5.0σ for CMS and 5.9σ for ATLAS



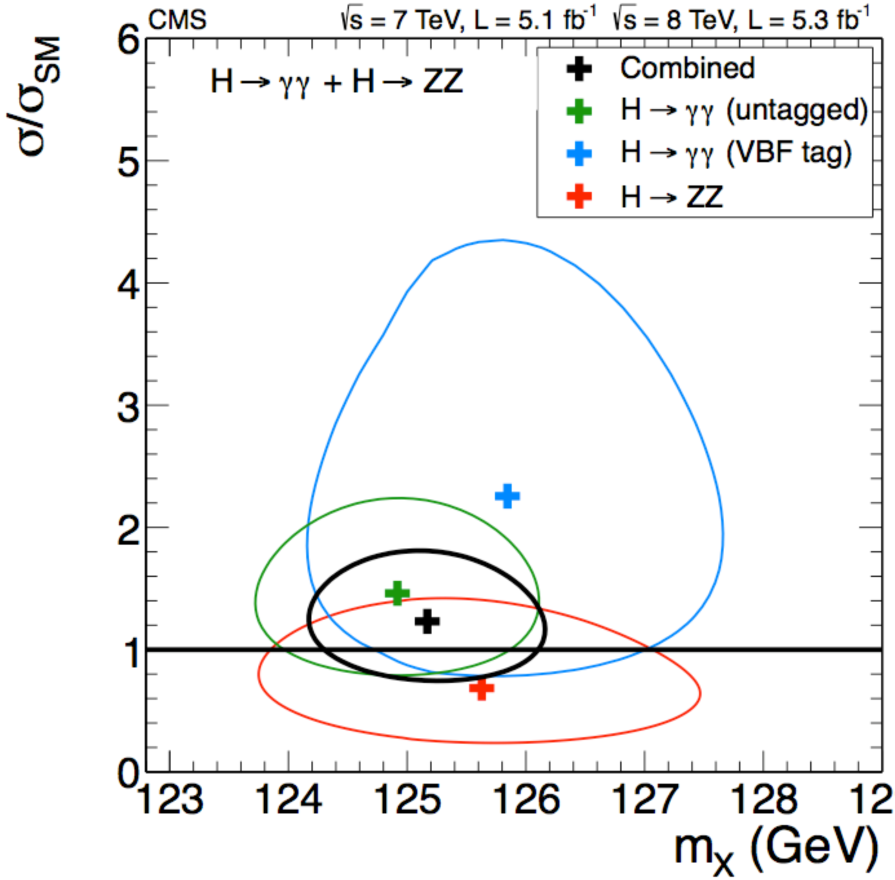


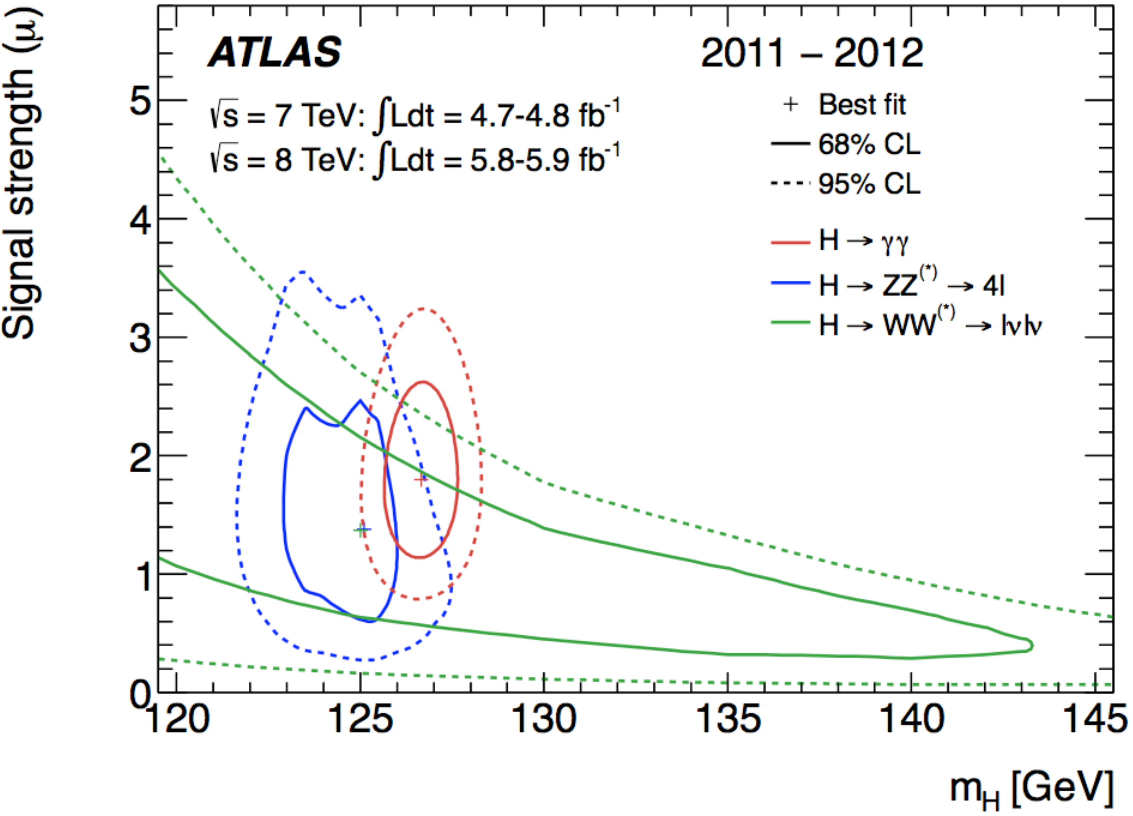
2nd Special Seminar at CERN, July 4th 2012.

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC arXiv: 1207.7214v1.

Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at LHC arXiv 1207.7235v1

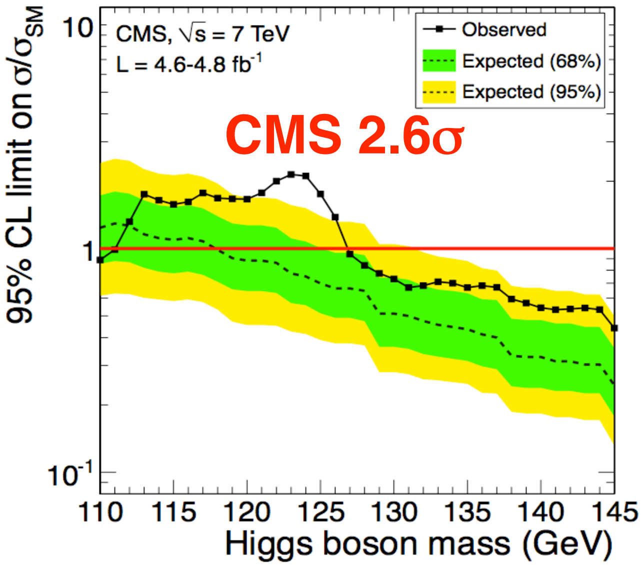
First measurements of the mass





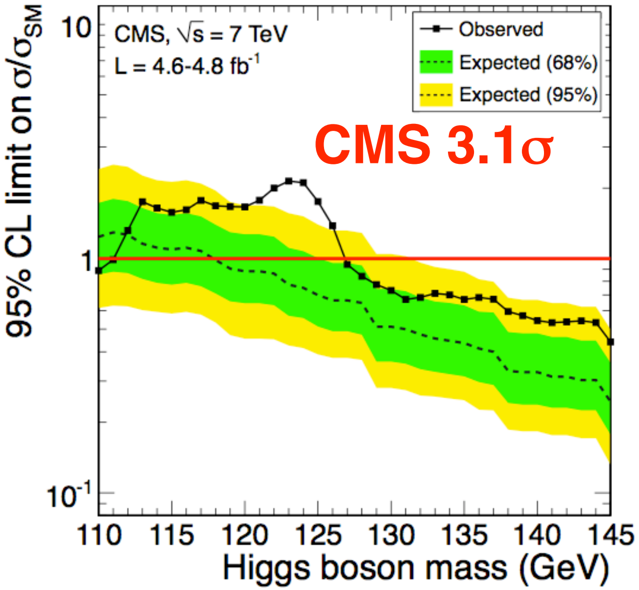
m_H=125.3±0.4(stat)±0.5(syst)GeV **m_H=126.0±0.4(stat)±0.4(syst)GeV**

The 7 months that changed physics



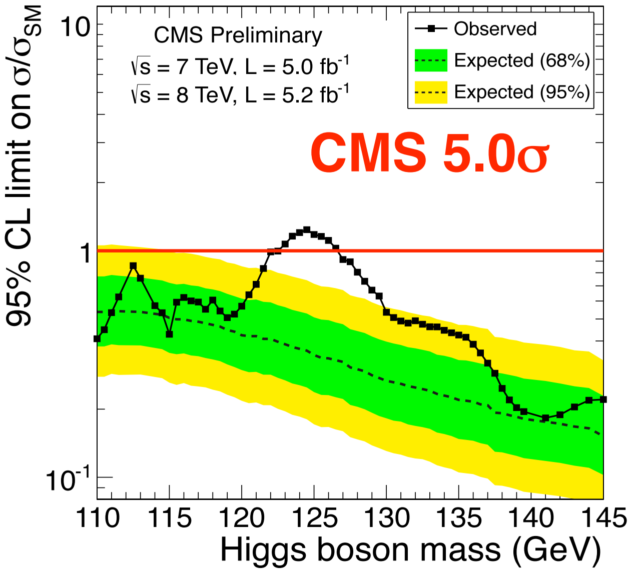
CMS 2.6σ

13 Dec 2011 CERN Seminar



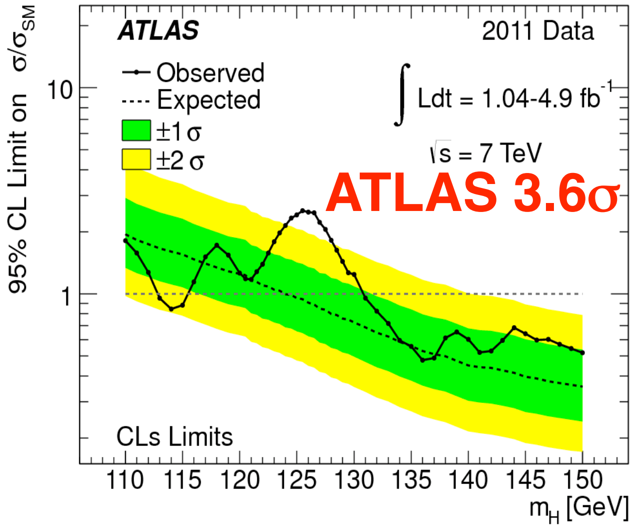
CMS 3.1σ

7 Feb. 2012 arXiv:1202.1488v1/v3

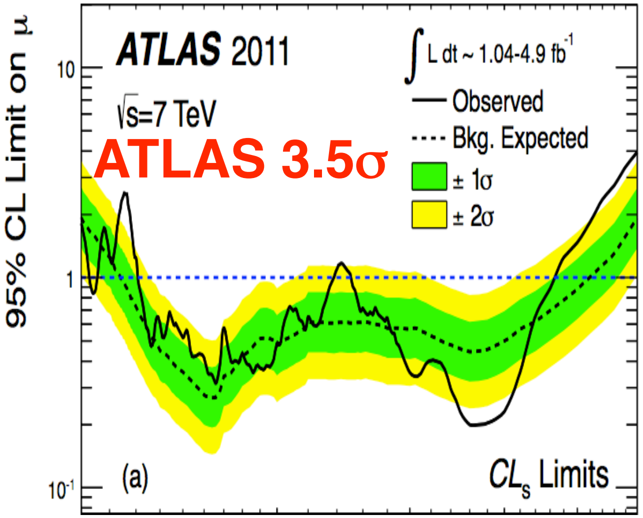


CMS 5.0σ

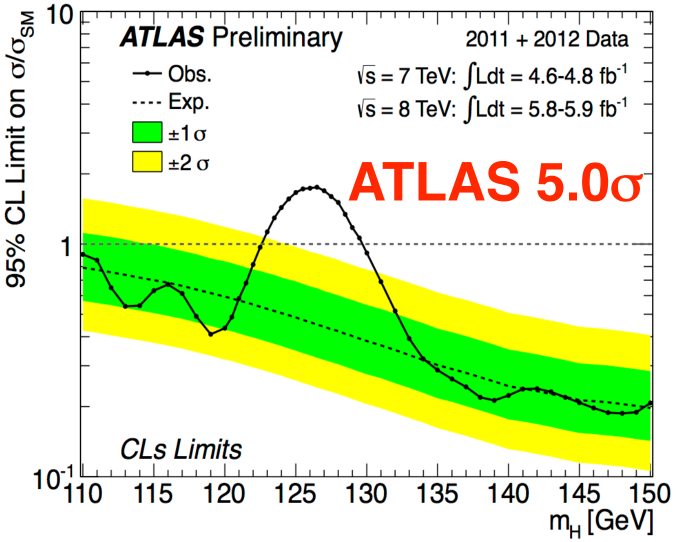
4 Lug 2012 CERN Seminar



ATLAS 3.6σ



ATLAS 3.5σ



ATLAS 5.0σ

To be noted

•This discovery has arrived with LHC running at **7/8 TeV: 1/2 of its design energy !!!**

•The discovery was announced when ATLAS and CMS had collected **~10fb^{-1}: 1/3 of the minimal amount considered necessary at the time of our Physics TDR 2007!!!**

This is the result of the ‘mission impossible” set-up just in 2010:

“We’ll discover the SM higgs boson-or exclude it forever- before entering the long shut-down needed to run LHC at 14TeV”

Key components: beautifully working detectors, a reliable accelerator and hundreds of enthusiastic young physicists willing to take the challenge.

Implications of the discovery

Is it really the SM Higgs or do we see already deviations from the SM?

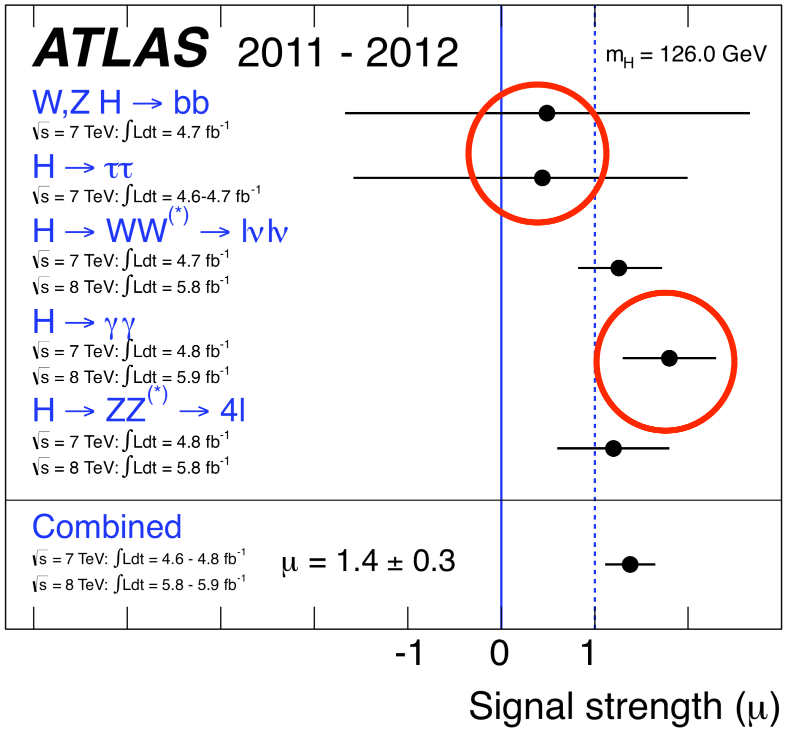
The strength of its interactions with all other particles and with itself are precisely the ones predicted by the SM?
Is it alone or accompanied? Is it "elementary" or "composite"?

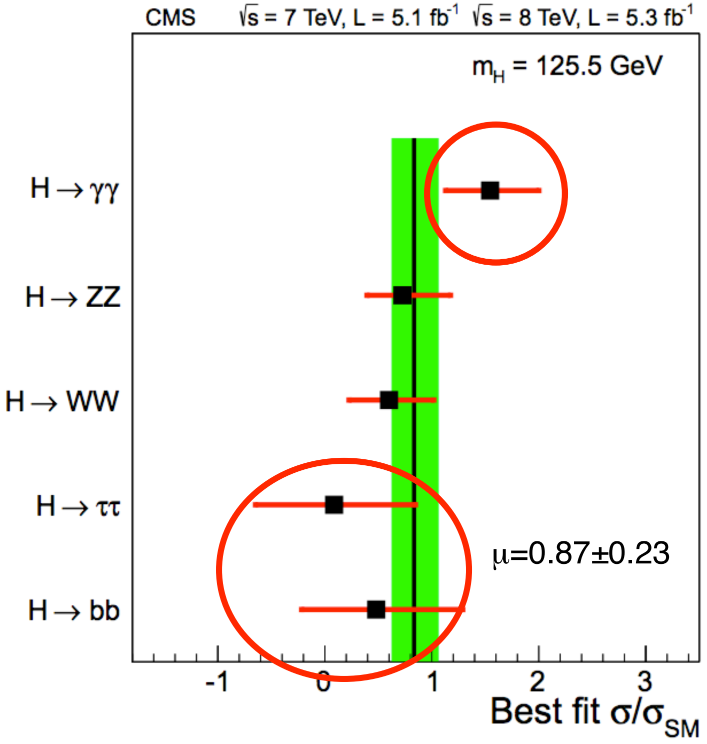
What are the implications for the search for new physics?

A new field has been opened by the discovery: precision measurement of the "Higgs-like particle" properties as a possible path to BSM physics.

Higgs "factories": HL-LHC, ILC ?

"It walks like a duck, it quacks like a duck…"

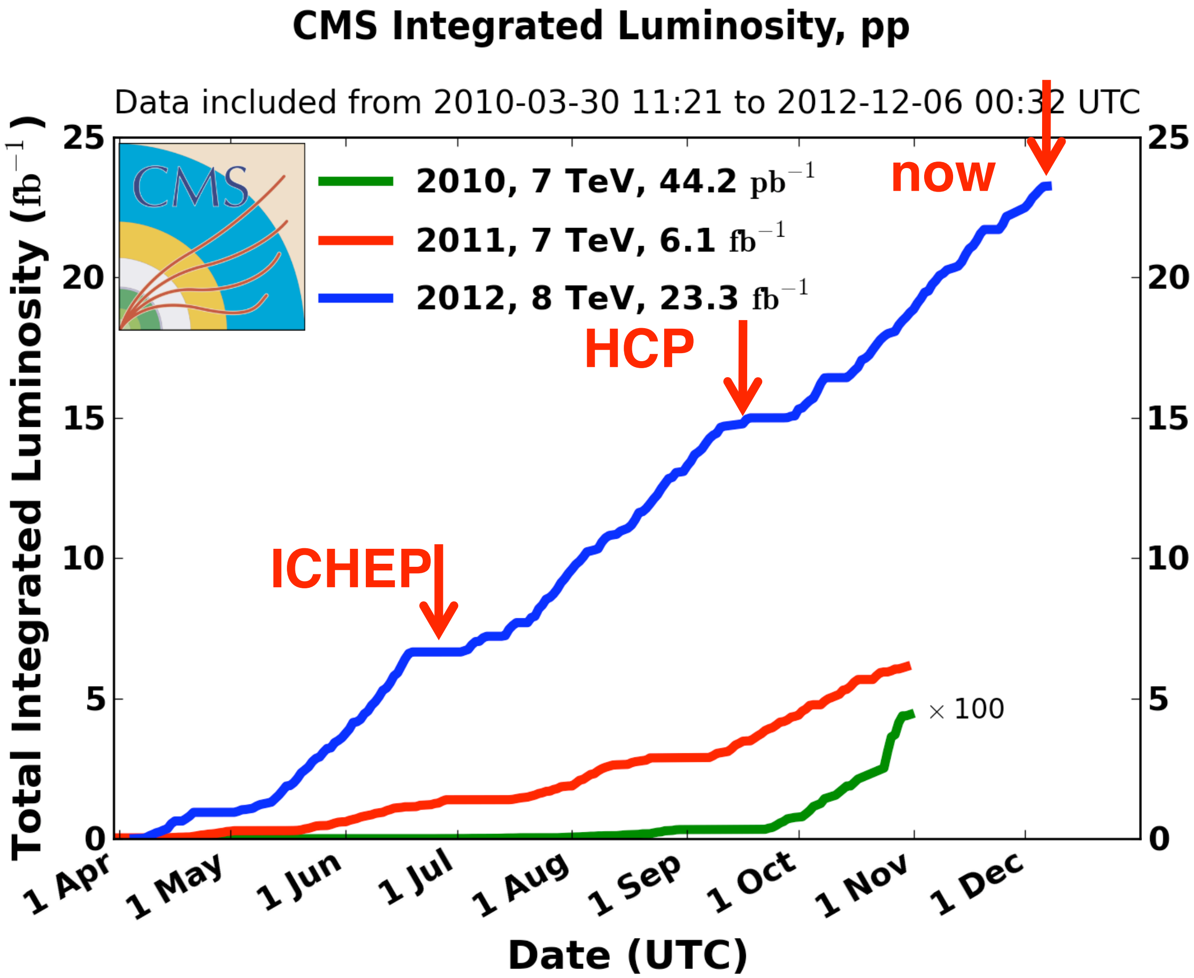




Signal strength σ/σ_{SM} in different modes is consistent with the hypothesis that the observed new particle is the SM Higgs boson, but…

- Some modes (i.e. ττ, bb) would simply require more data to distinguish a SM signal from background or could hint to a problem in the Yukawa coupling.
- **There is a hint of an excess in H2GG both in ATLAS and CMS. Additional data would be needed to understand what is happening there.**

New data collected since the discovery.

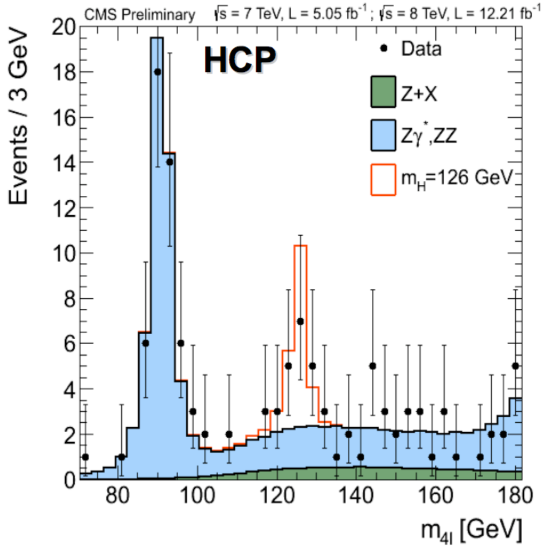


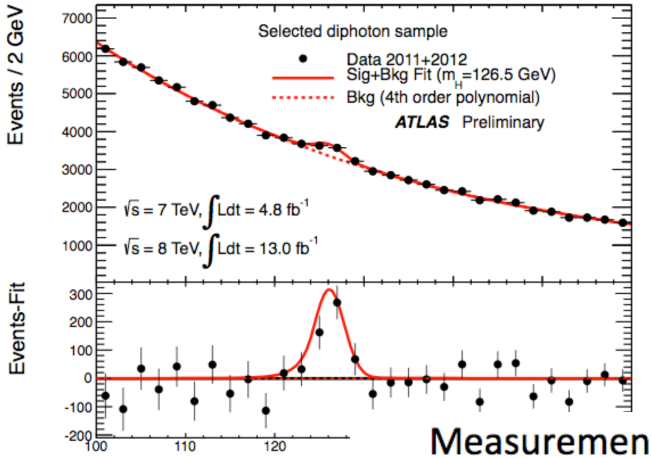
New results presented at the Hadron Collider Physics Conference in Kyoto in November and at the CERN Council Seminar in December.

The signal is gaining strength

New H→ZZ→4l results shown by CMS at HCP

New H→γγ result: ATLAS at the CERN Council

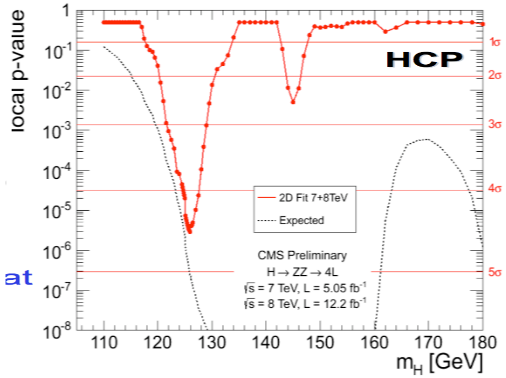


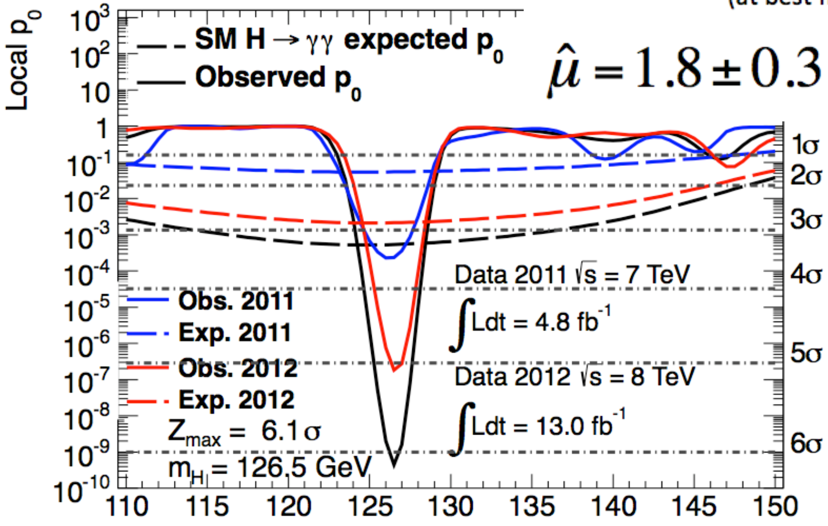


Measurement of signal strength :

(at best fit mass 126.5 GeV)

$$\hat{\mu} = 1.8 \pm 0.3\ (stat)^{+0.29}_{-0.21}\ (syst)$$

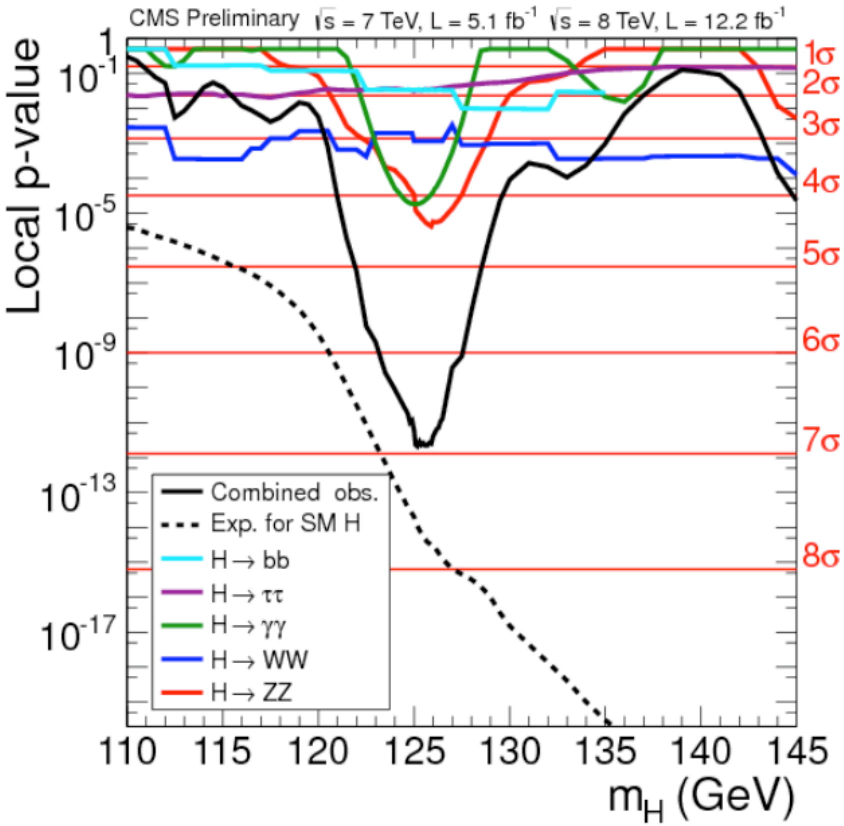


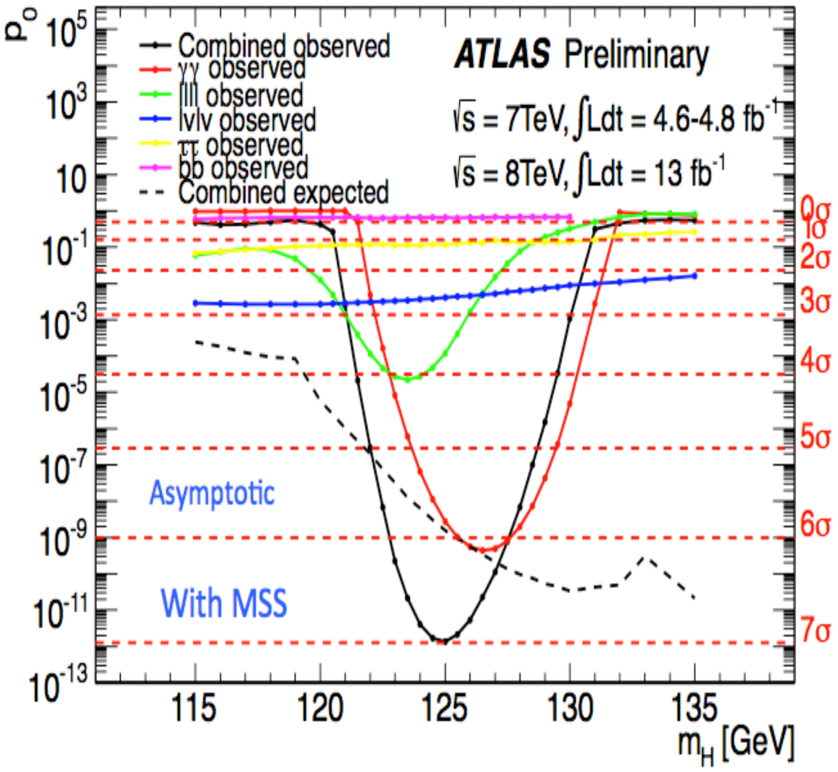


Local significance: 4.6σ

Local significance: 6.1σ

The signal is gaining strength



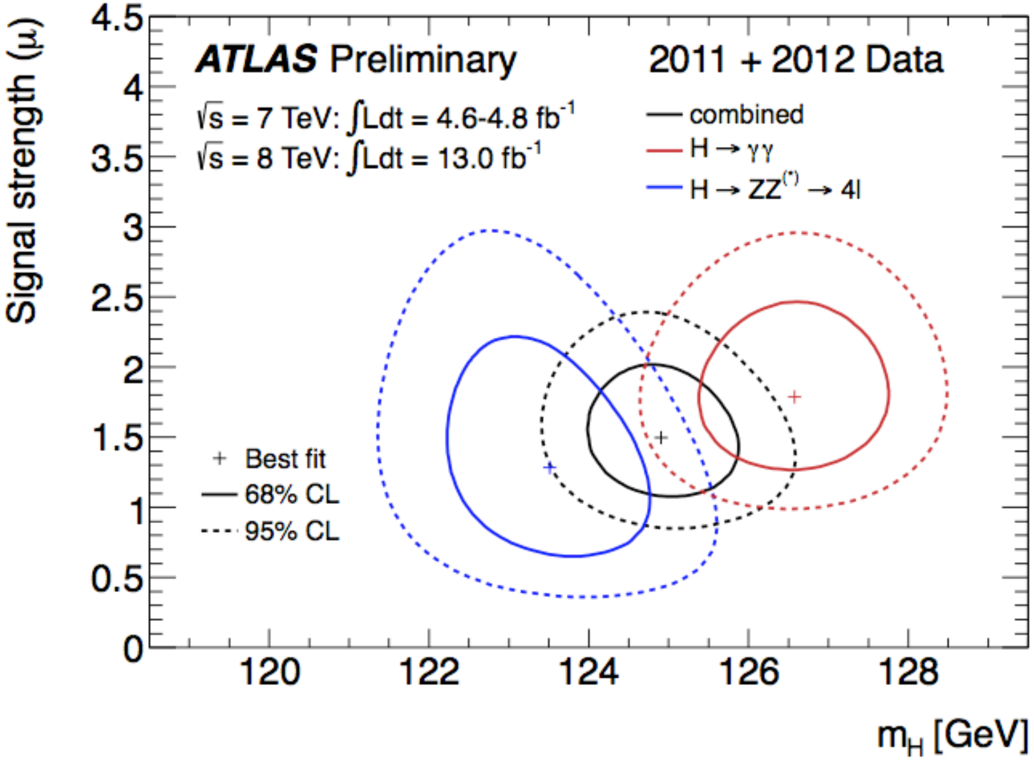


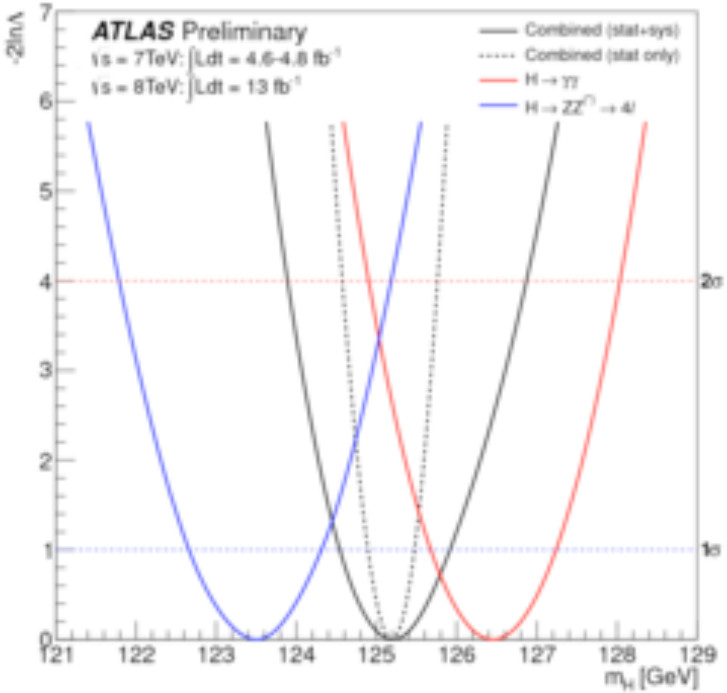
Stronger signal: 6.9σ (CMS) **7.0σ (ATLAS).**

Compatible masses:

m_H=125.8±0.4(stat)±0.4(syst)GeV **m_H=125.2±0.3(stat)±0.6(syst)GeV**

Is ATLAS observing a doublet of Higgs bosons?





$$m_H = 123.5 \pm 0.9\ (stat)\ {}^{+0.4}_{-0.2}\ (syst)\ \mathrm{GeV} \quad m_H = 126.6 \pm 0.3\ (stat) \pm 0.7\ (syst)\ \mathrm{GeV}$$

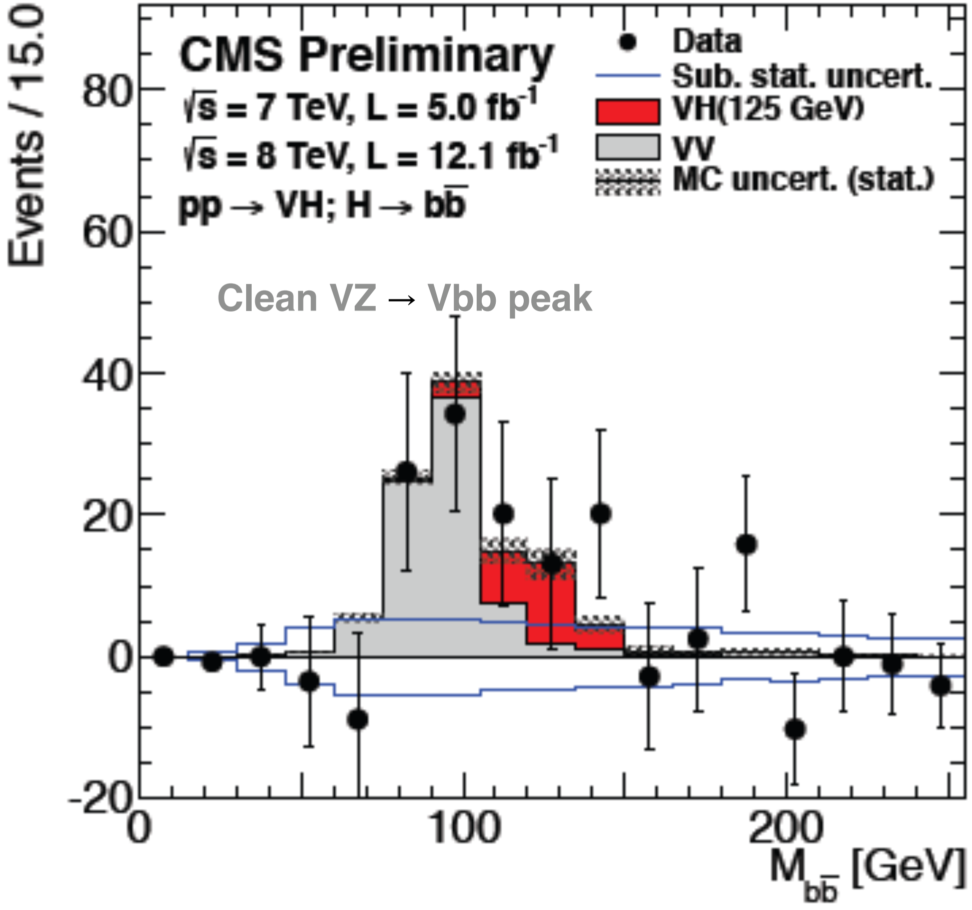
$$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)\ \mathrm{GeV}$$

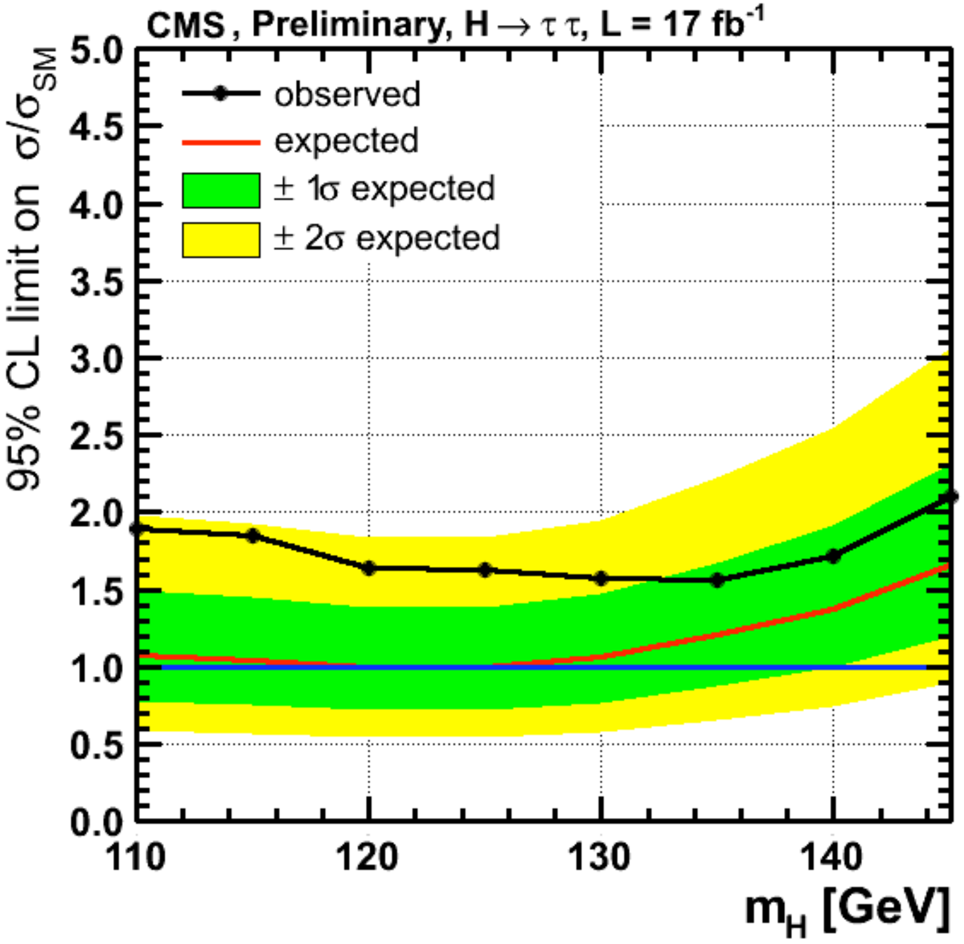
NO the measurements of the mass in the two channels are each other compatible (2.3-2.7σ) and everything is compatible with what CMS observes.

CMS coupling to fermions

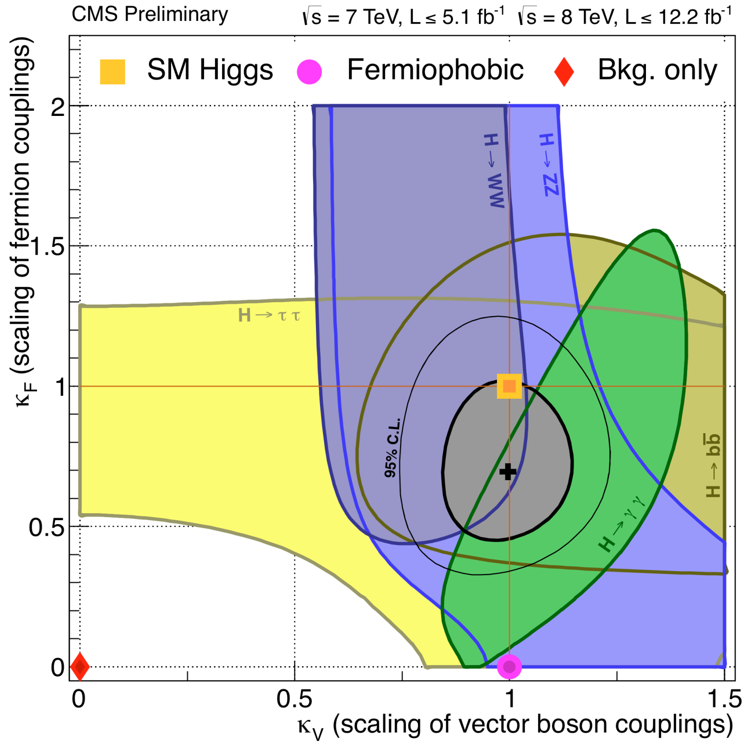
$H \rightarrow bb$: 2σ "excess"

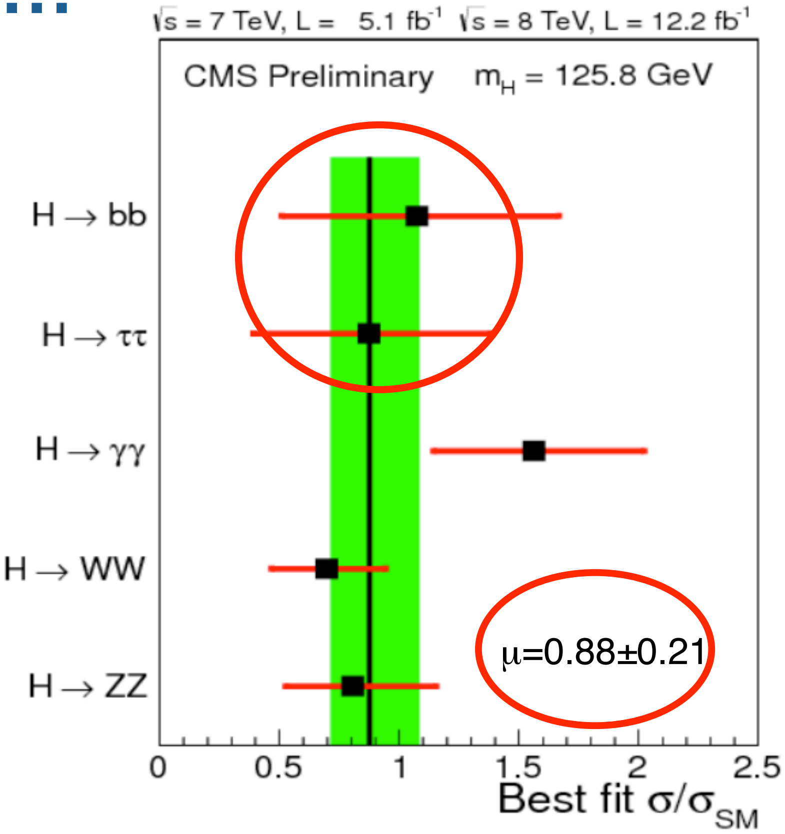
$H \rightarrow \tau\tau$: > 1σ "excess"





"It continues to walk like a duck, and to quack like a duck…"





μ=0.88±0.21

Signal strength σ/σ_{SM} in different modes is consistent with the hypothesis that the observed new particle is the SM Higgs boson.

- **New data in the H→bb and H→ ττ shown by CMS in HCP slightly strengthens the consistency with the SM hypothesis.**

Have we observed a scalar?

Spin ⇆ angular distribution of final decay products

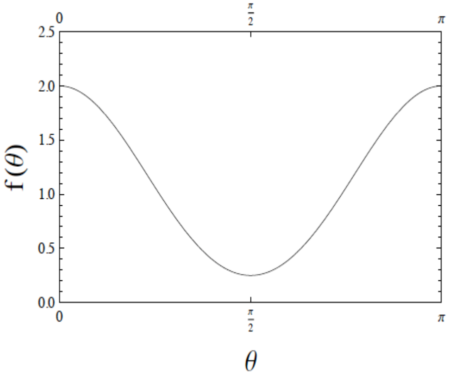
Since it decays to two photons: spin 1 is forbidden by Bose symmetry (Landau-Yang theorem).

1) gg →X→γγ qq →X→γγ Gao et al. 2010

spin-0: flat in cosθ*

spin-2: quartic in cosθ*

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$$

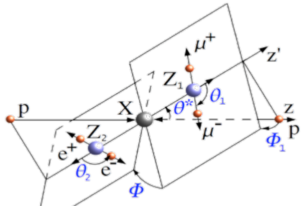


2) gg →X→ZZ*→4ℓ Choi et al. 2002, De Rujula et al 2010

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

arXiv:1001.5300

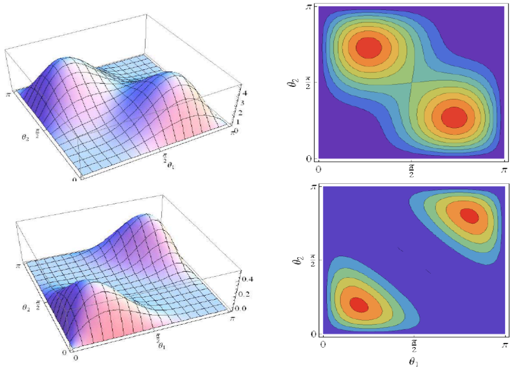
3) gg →X→W⁻W⁺ →ℓ⁻ℓ⁺νν Ellis et al. 2012

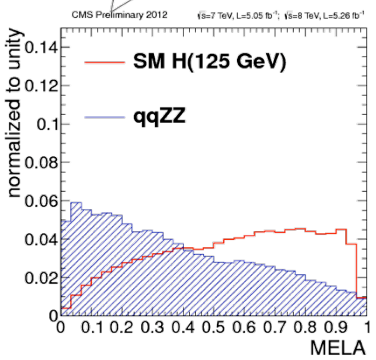


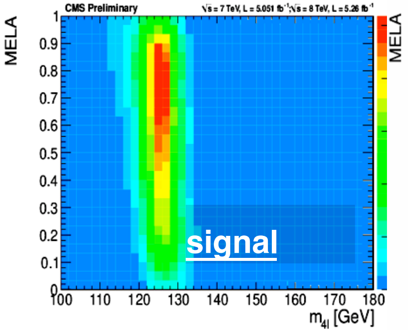
Polar angle distribution for $X_2 \to W^+W^-$

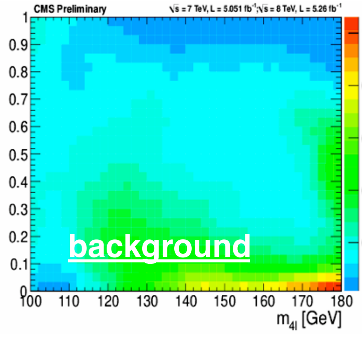
Polar angle distribution for $X_0 \to W^+W^-$

(for $\phi = \pi$)

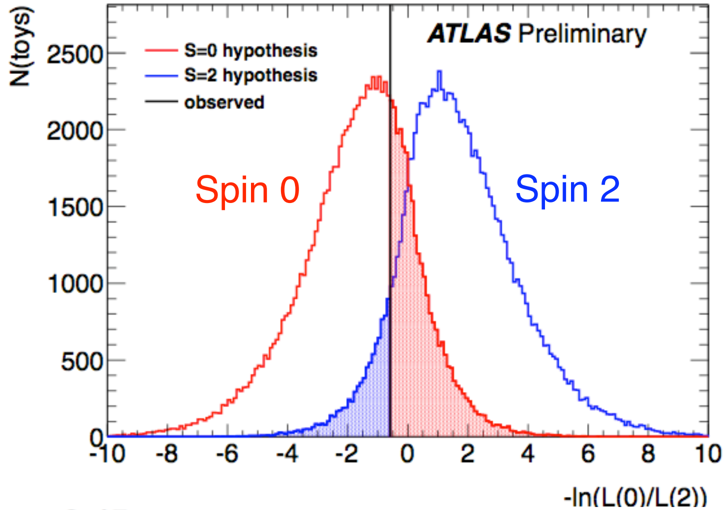


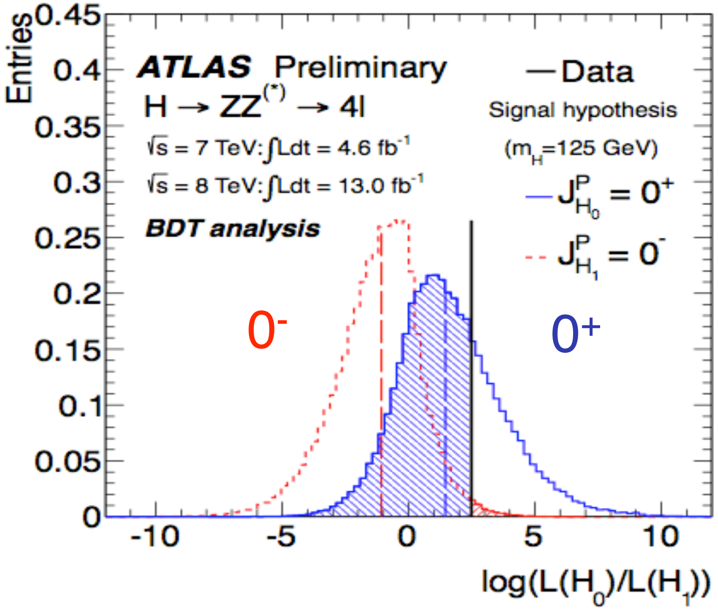


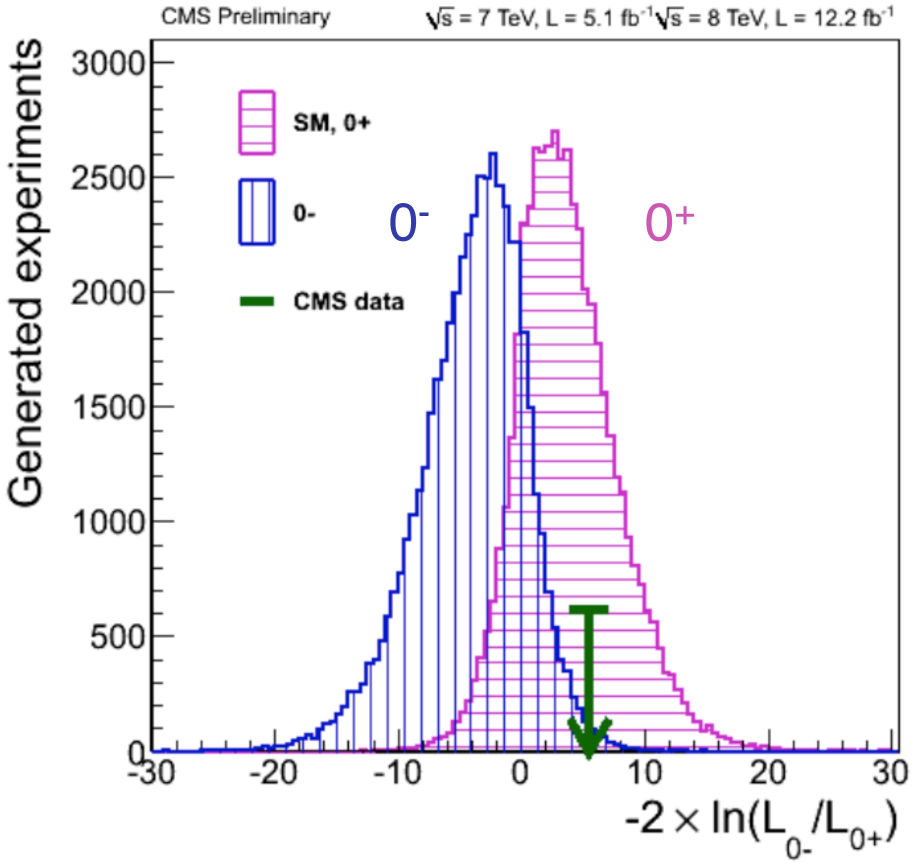




Quantum numbers prelim. results







Preliminary results on scalar/pseudo-scalar; observation consistent with 0^+ (0^-) within **0.5 (2.45) σ.**

Quantum numbers: perspectives

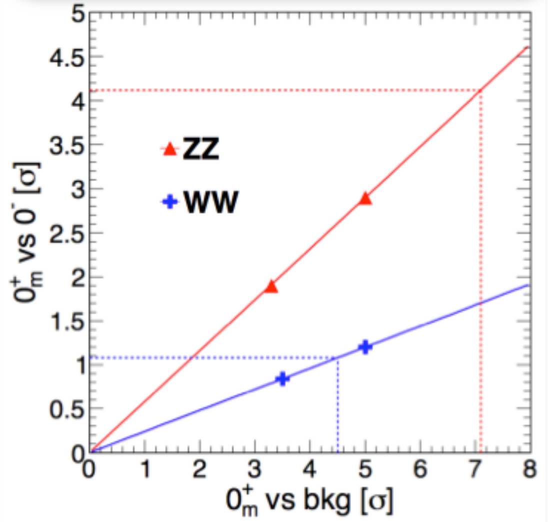
Spin and parity J^P

J^P: currently using angular correlations in ZZ*, WW* and γγ. By the end of 8 TeV run, assuming a total of $25 fb^{-1}$ per experiment.
~4σ separation of 0^+ vs 0^- and 0^+ vs 2^+

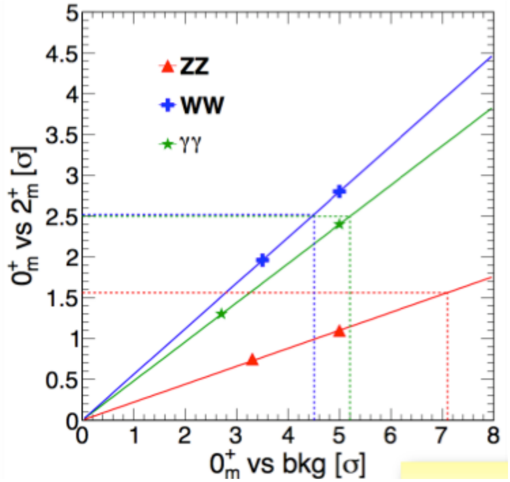
It will be sorted out by early next year, maybe, by combining 2011-12 ATLAS+CMS results.

CP: even, odd or a mixture? More tricky.
If focus at LHC stays on WW*, ZZ* and VBF: limited sensitivity to distinguish pure CP-even state from a mixture of CP-even and CP-odd components.

Linear collider: threshold behaviour of e+e-→ttH gives precision measurement of CP mixing.

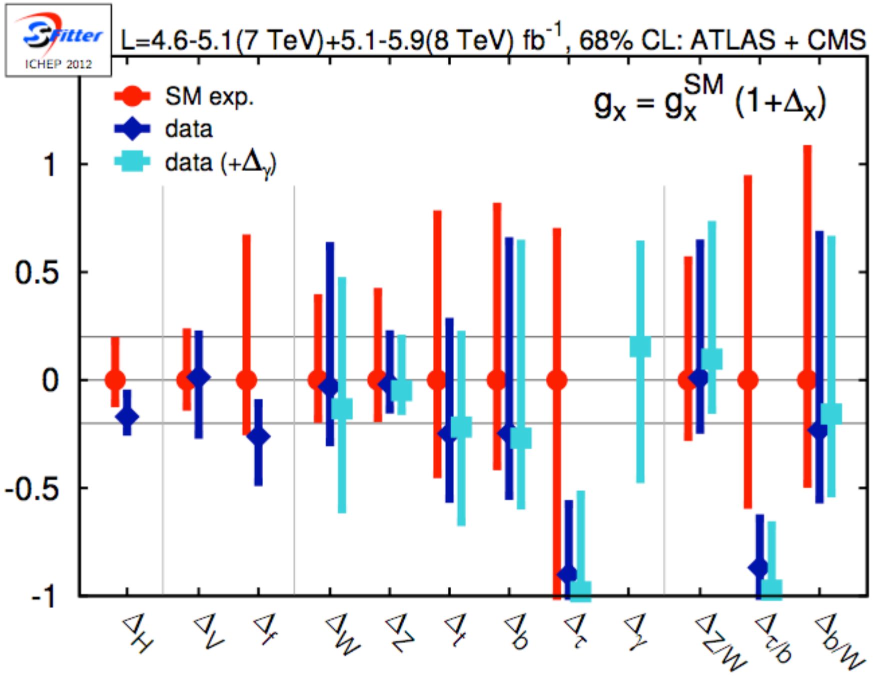


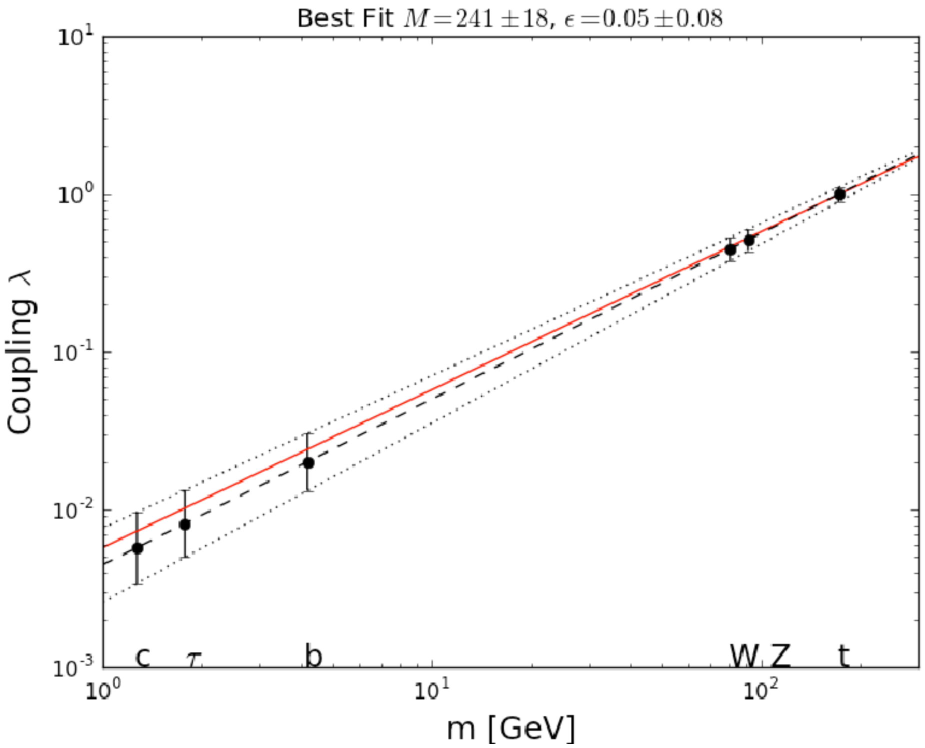
Expected hypothesis separation Significance vs signal observation. arXiv:1208.4018v1, Bolognesi et al.



Current status

- **Coupling to vector bosons:**
- Is this boson related to EWSB, and how much does it contribute to restoring unitarity in $W_L W_L$ scattering
- **Couplings to fermions** - is Yukawa interaction at work? - contribution to restoring unitarity? couplings proportional to mass ?





The problematic triumph of the Standard Model

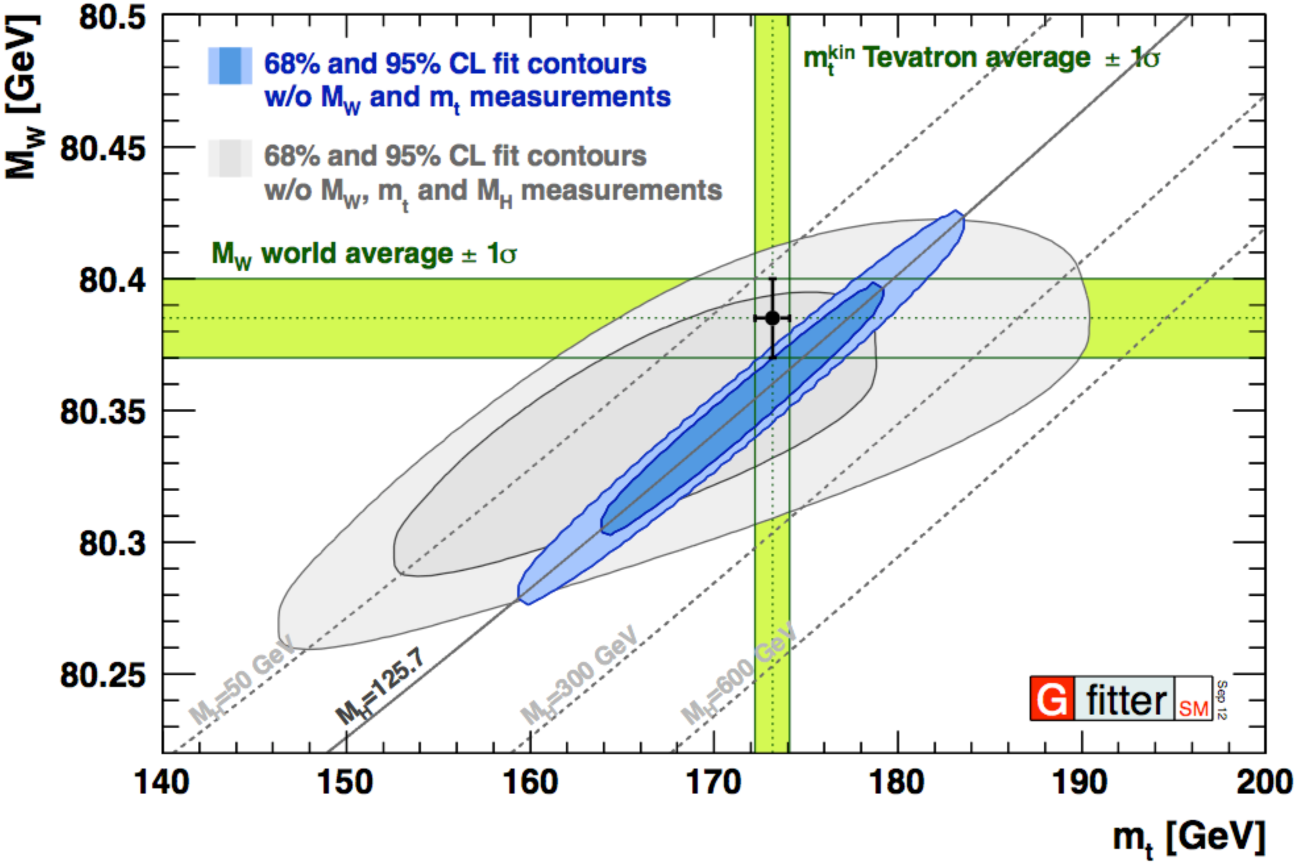
Despite this further success, we know that the SM is not complete since it does not explain several important observations:

- **Dark matter.**
- **Dark energy.**
- **The mechanism responsible for inflation.**
- **The unification of forces and the role of gravity.**
- **Neutrinos masses and hierarchy.**
- **Matter anti-matter asymmetry**
- **Leptogenesis and bariogenesis**
- **…**

To understand all this we need to look for physics beyond the Standard Model; **but at which energy scale?**

Implications on the search for new physics

New Electroweak fit



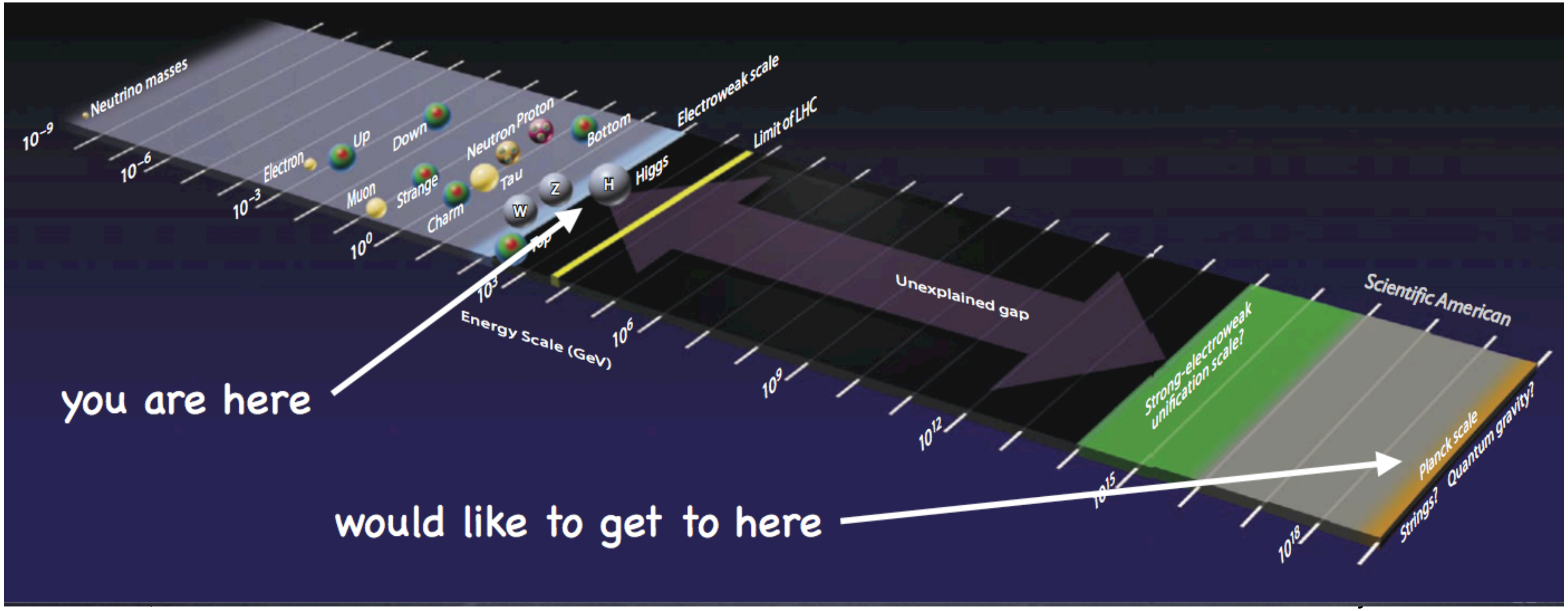
No much room left for physics beyond the Standard Model.

New physics, if it does exists, appears to be weakly coupled to the Electroweak scale

A 125GeV boson is a very special object

A light boson, could in principle rule its self-interaction and the Yukawa interactions with fermions in such a way that the theory could remain weakly coupled up to the Planck scale without any dynamics appearing beyond the EWK scale.

This would be in itself an outstanding discovery: for the first time we would have seen a phenomenon that could be described by the same theory over 15 orders of magnitude in energy.

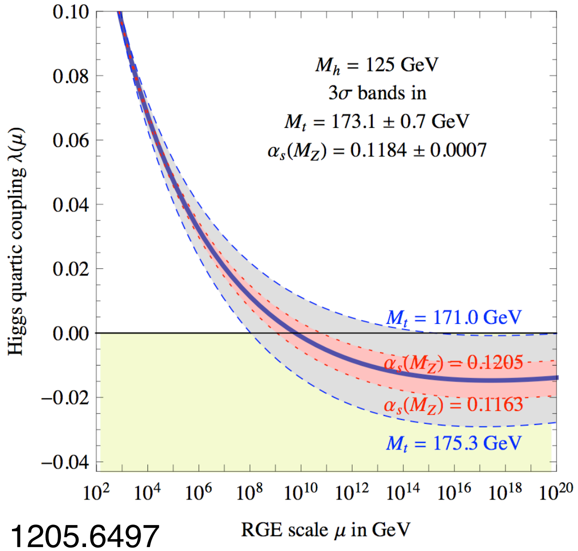


The importance of precision measurements

Is the Higgs potential vanishing at M_{Pl} ?

EWSB determined by Planck physics? absence of new energy scale between the Fermi and the Planck scale? Anthropic or natural EWSB?

$$\lambda(M_{\rm Pl}) = -0.0144 + 0.0028\left(\frac{M_h}{\rm GeV} - 125\right) \pm 0.0047_{M_t} \pm 0.0018_{\alpha_s} \pm 0.0028_{\rm th}$$



arXiv: 1205.6497

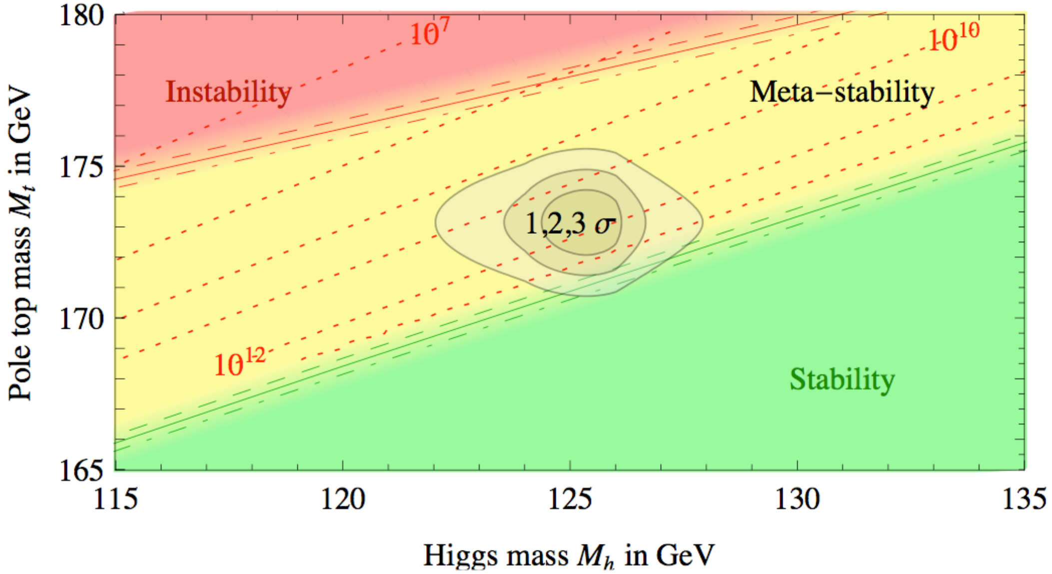
Although possible, this scenario would be severely constrained by the need that the couplings of the boson must be finely tuned to very well predicted values.

Precision measurements of the couplings could lead to unambiguous hints of the presence of New Physics beyond the EWK scale.

The Higgs boson properties must be studied in great detail with the goal of a <1% accuracy in the couplings.

Is the EWK vacuum stable ?

With a heavy top quark and a 125GeV Higgs the EWK vacuum in our Universe appears to be in a meta-stable state. The Higgs potential could develop an instability around **$10^{11\text{-}12}$ GeV**, with a lifetime still much longer than the age of the Universe. However, taking into account theoretical and experimental errors, stability up to the Planck scale cannot be excluded.



arXiv: 1205.6497

if $m_H > M_{stability}$, the Higgs could serve as an inflaton

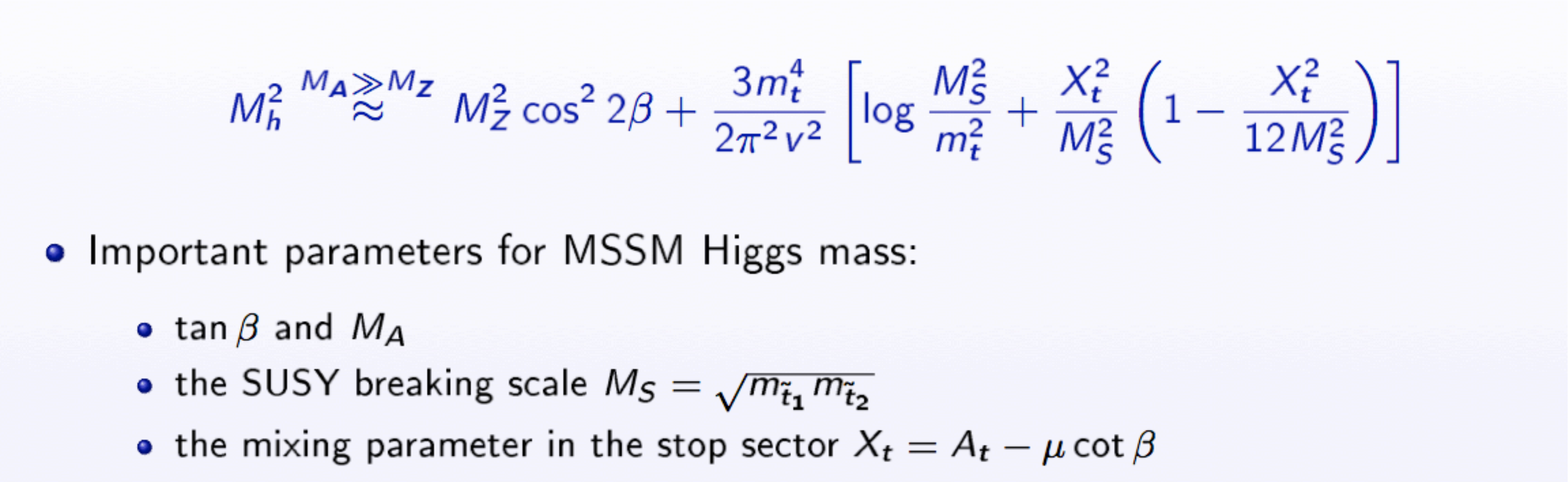
if $m_H = M_{stability}$ the SM is asymptotically safe, ie consistent up to arbitrary high energy

Precise determination of the Higgs mass as well as a new round of measurements of the top mass will be key ingredients of this game. Implications on the mass of RH neutrinos, temperature reheating after the inflation, leptogenesis etc.

SUSY and a 126GeV scalar

In the SM, the Higgs mass is essentially a free parameter.
In the MSSM, the lightest CP-even Higgs particle is bounded from above:
$M_h^{max} \approx M_Z |\cos 2\beta| +$ radiative corrections $\leq 110\text{–}135$ GeV

Imposing M_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections.

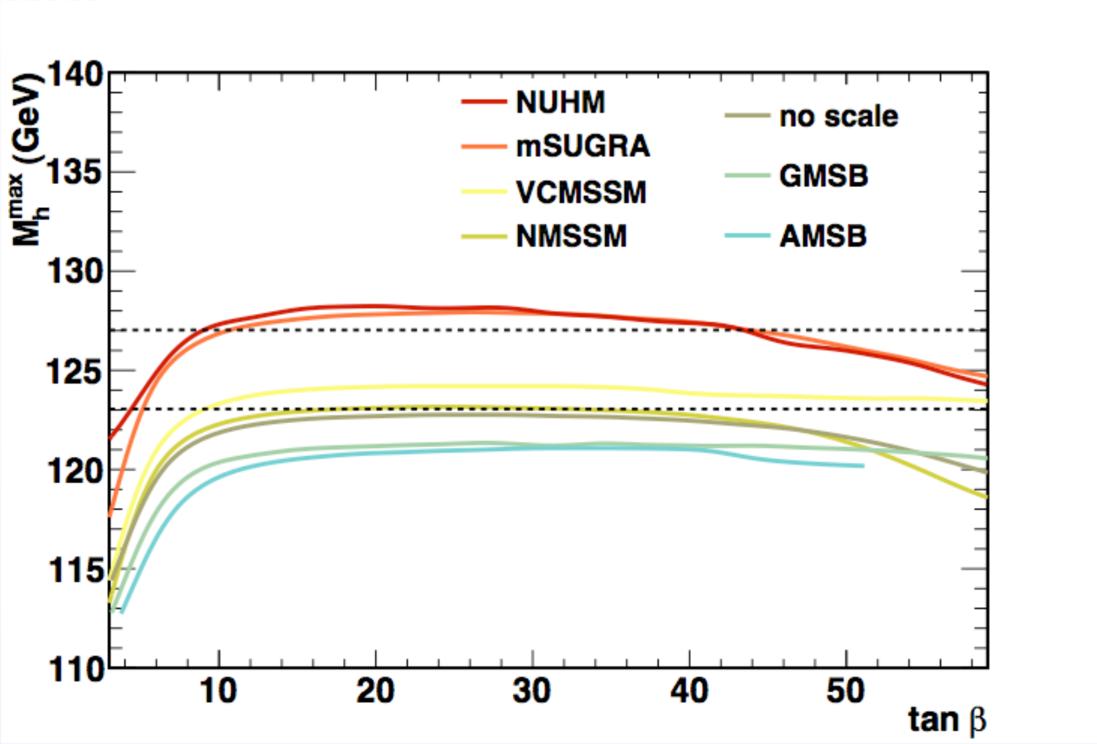


$$M_h^2 \overset{M_A \gg M_Z}{\approx} M_Z^2 \cos^2 2\beta + \frac{3 m_t^4}{2\pi^2 v^2}\left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu \cot\beta$

SUSY models compatible with a 126GeV scalar

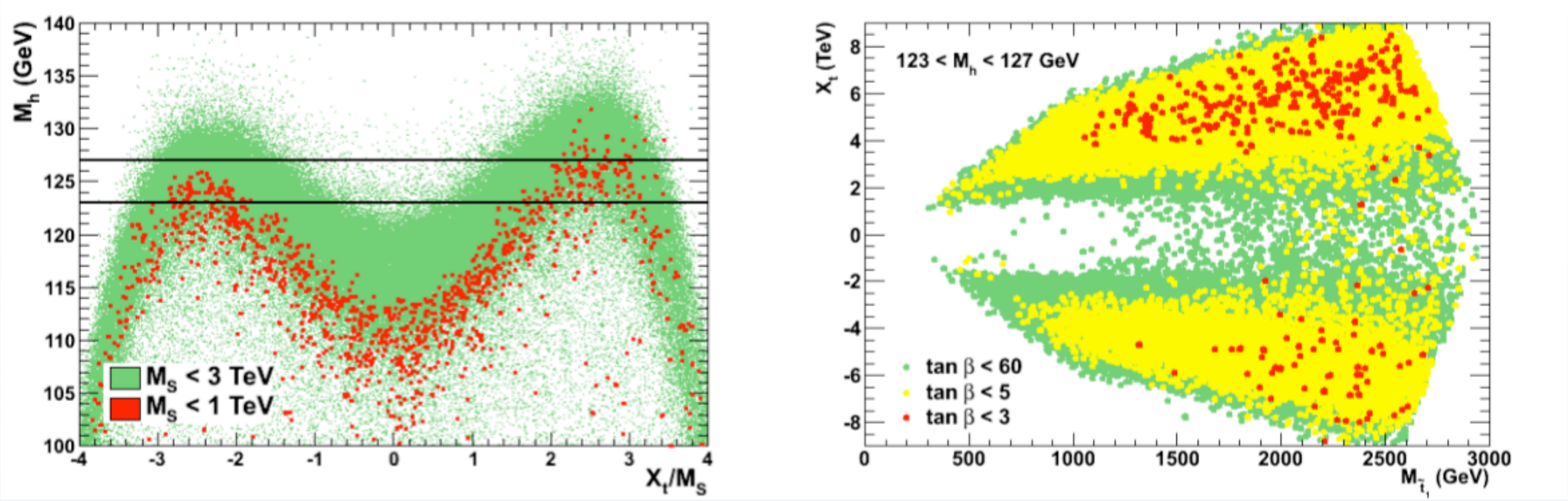
Maximal Higgs masses



A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
$M_h^{\max}$	121.0	121.5	128.0	123.0	123.5	124.5	128.5

Still a not negligible part of pMSSM survives



A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

A large part of the pMSSM still survives

No mixing cases ($X_t \approx 0$) excluded for $M_S < 1$ TeV

Small stop masses still allowed

20 % of the points passing all constraints are compatible with a 123GeV<M_H <127GeV

The LHC plans

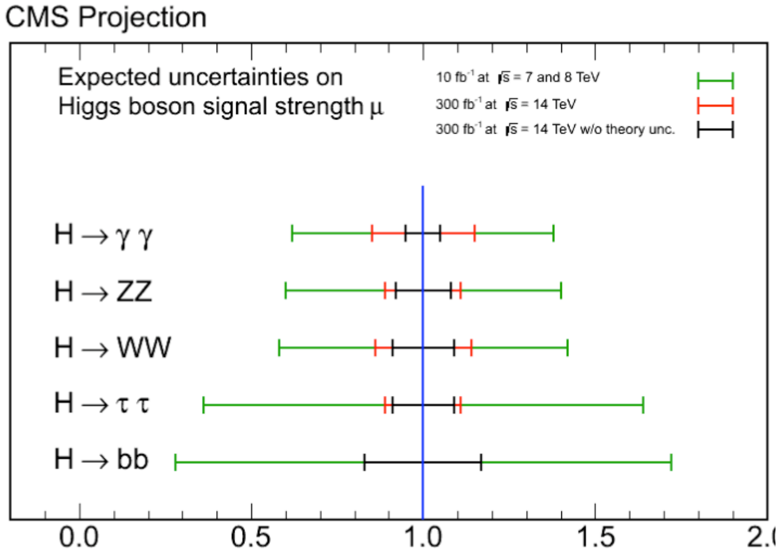
- **LHC RUN I**: 2012 run ended with ~23fb^{-1}
  - Combined with 2011 run (5.6fb^{-1}), a total **~25fb^{-1}**

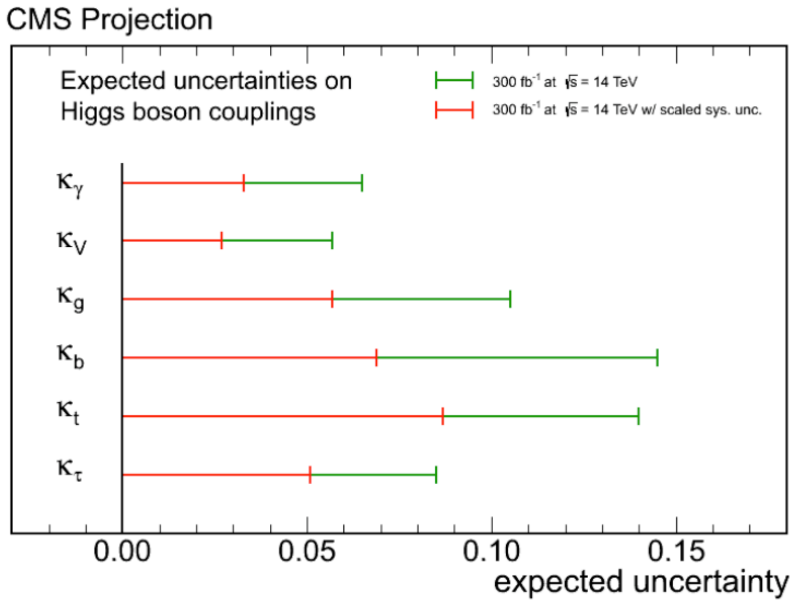
- Spring 2013 – 2014: shutdown (**LS1**) to go to 13TeV.
- **LHC RUN II a)**: 2015 – 2017: 13TeV, $\mathcal{L}$~10^{34}, **~100fb^{-1}**

- 2018: Shut-down (**LS2)**
- **LHC RUN II b)**: 2019 – 2021: 13TeV, $\mathcal{L}$~2x10^{34}, **~300fb^{-1}**

- 2022 – 2023: Shut-down (**LS3**)
- **LHC RUN III:** 2023 – 2030: 13TeV, $\mathcal{L}$~5x10^{34} (**HL-LHC**), **~3000fb^{-1}**

Projection on the couplings: 300fb^{-1}-3000 fb^{-1}





5-10%@LHC 14TeV and 300fb^{-1}.

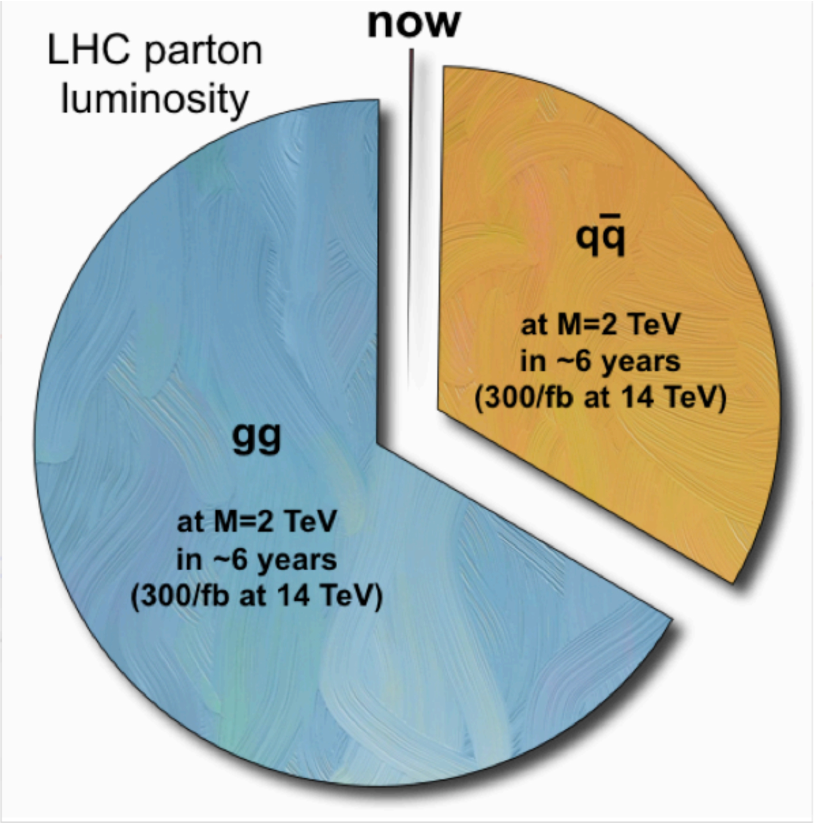
< 5%@LHC 14TeV and 3000fb^{-1}, only if systematics can be drastically reduced.

Scenario 1: no improvements in systematics

Scenario 2: theory uncertainties halved and systematics scaling as 1/sqrt of the integrated luminosity.

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

..but surprises might arrive at any moment



G. Dissertori Crakow 2012

Conclusion.

- By analysing the 2011 and 2012 data, we have discovered a new boson around a mass of 126GeV/c^2. The result is consistent, within uncertainties, with expectations for a standard model Higgs boson. The collection of further data will enable a more rigorous test of this conclusion and an investigation of whether the properties of the new particle imply physics beyond the standard model.

- As a consequence of this observation a significant re-tuning of our search strategies for new physics is ongoing.

We are just at the beginning of the exploration of the TeV region. Stay tuned!