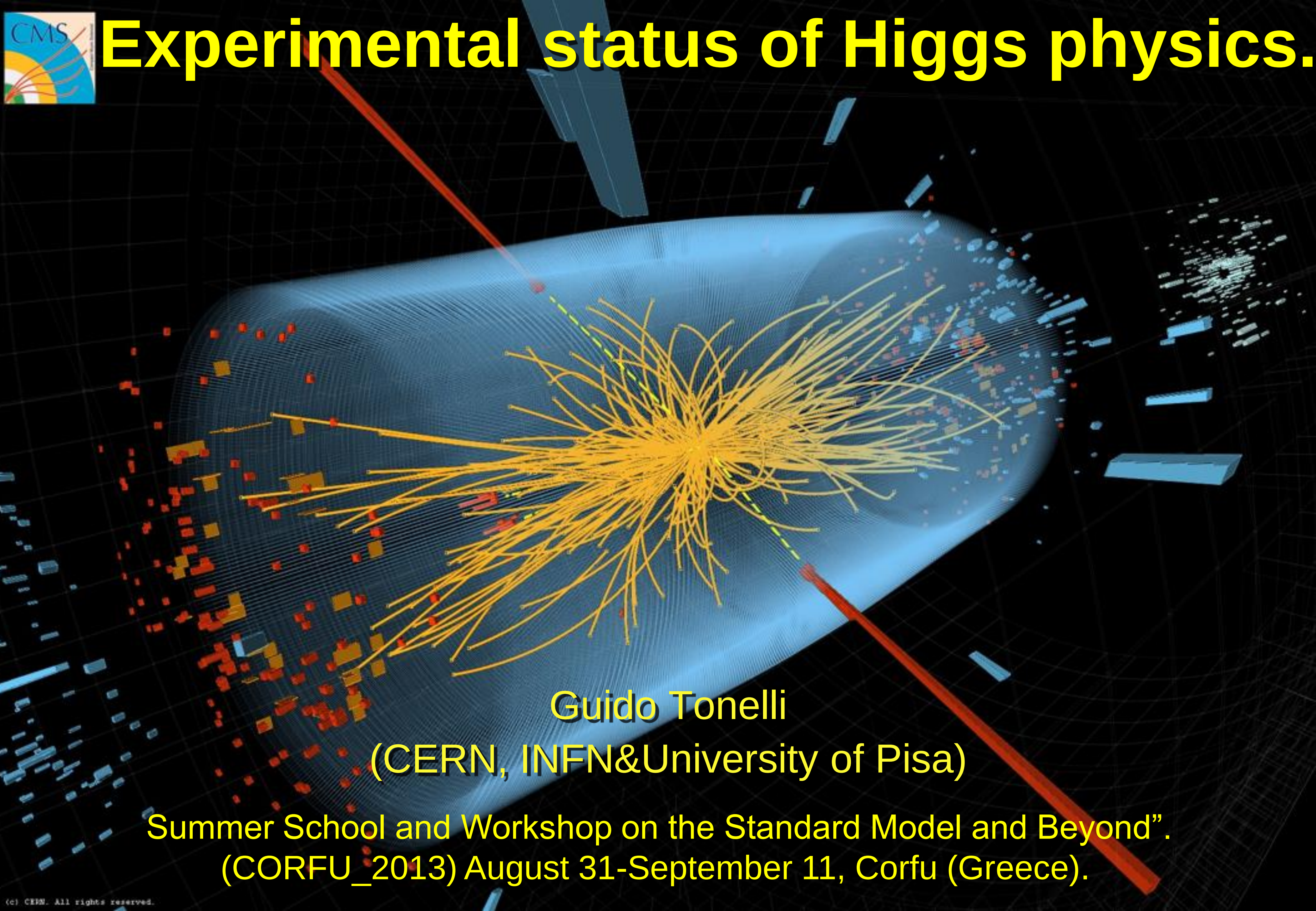
# Experimental status of Higgs physics.

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Summer School and Workshop on the Standard Model and Beyond”.

(CORFU_2013) August 31-September 11, Corfu (Greece).

# Outline of the talk

1. Short introduction on LHC, ATLAS and CMS

2. Higgs hunting basics.

3. Highlights of the discovery.

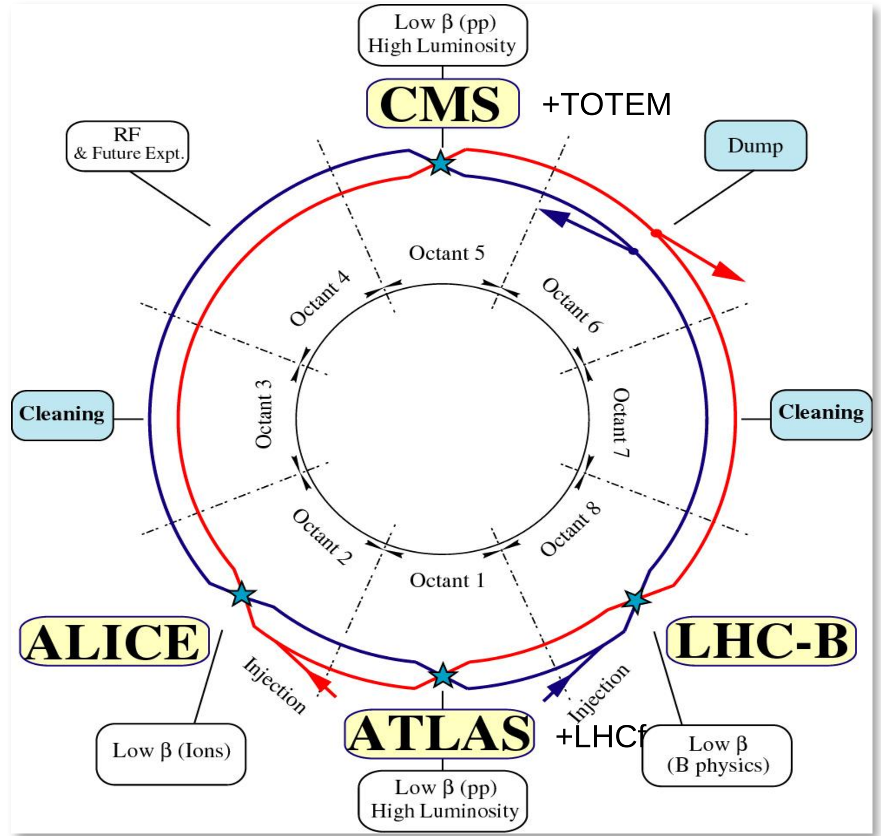
1. Latest results.

2. Preliminary results on the properties.

1. Conclusion.

# 1. Short introduction on LHC, ATLAS and CMS.

# The LHC : design parameters



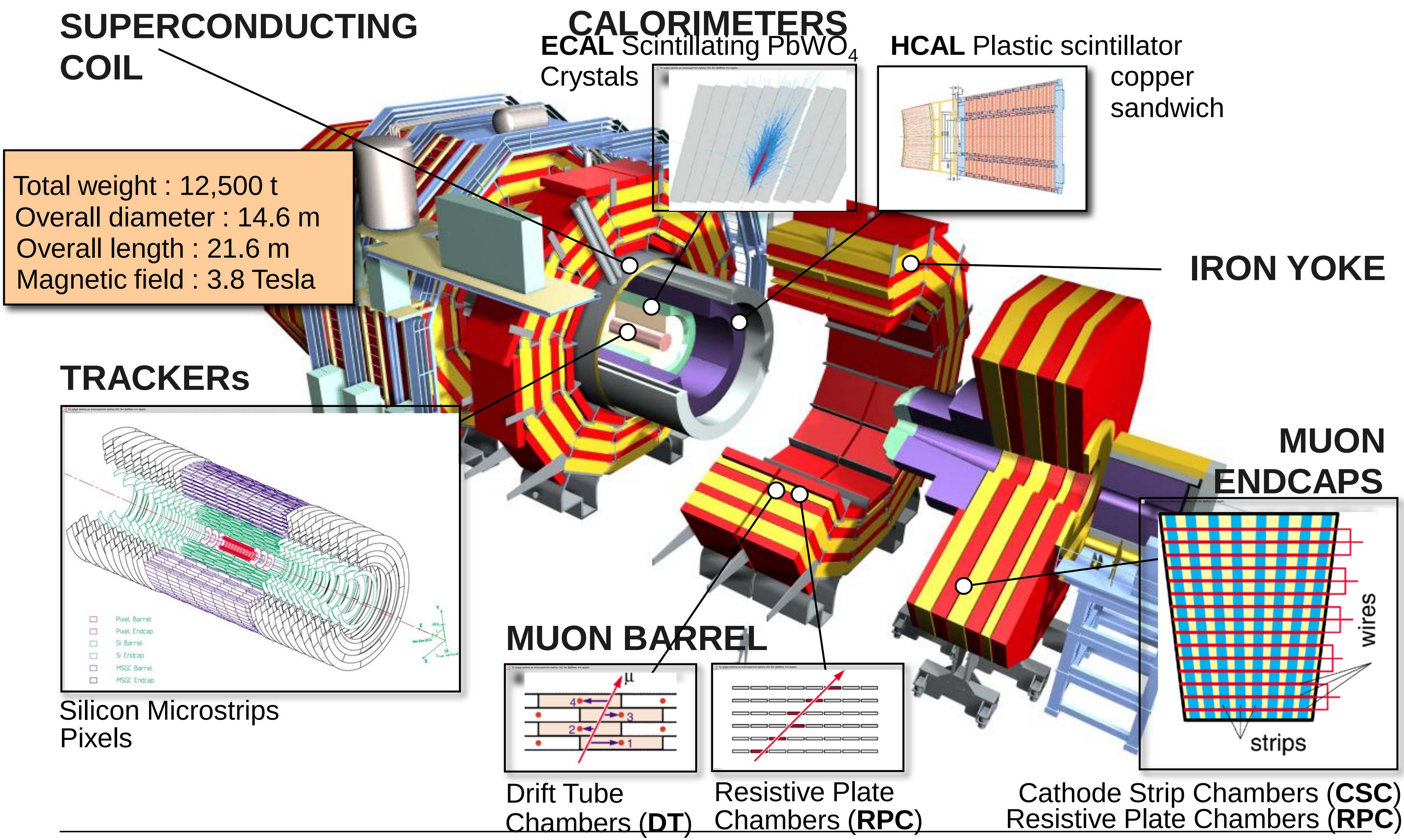

1232 superconducting dipoles
15m long at 1.9 K, B=8.33 T
Inner coil diameter = 56 mm

| | | |
|---|---|---|
| Max. beam-energy | **7 TeV** | ( 7xTEVATRON) |
| Design Luminosity | **$10^{34}$ cm$^{-2}$s$^{-1}$** | (>100x TEVATRON) |
| Bunch spacing | **24.95 ns** | |
| Particles/bunch | 1.1 $10^{11}$ | |
| Stored E/beam | 362 MJ | |

Also : Lead Ions operation
Energy/nucleon 2.76 TeV / u
Total initial lumi $10^{27}$ cm$^{-2}$ s$^{-1}$

**After the incident on the splices in 2008**
**3.5-4 TeV max beam energy**
**50ns bunch spacing, high "pile-up"**
**Max L~5-7x$10^{33}$ cm$^{-2}$s$^{-1}$**

# The Compact Muon Solenoid (CMS)

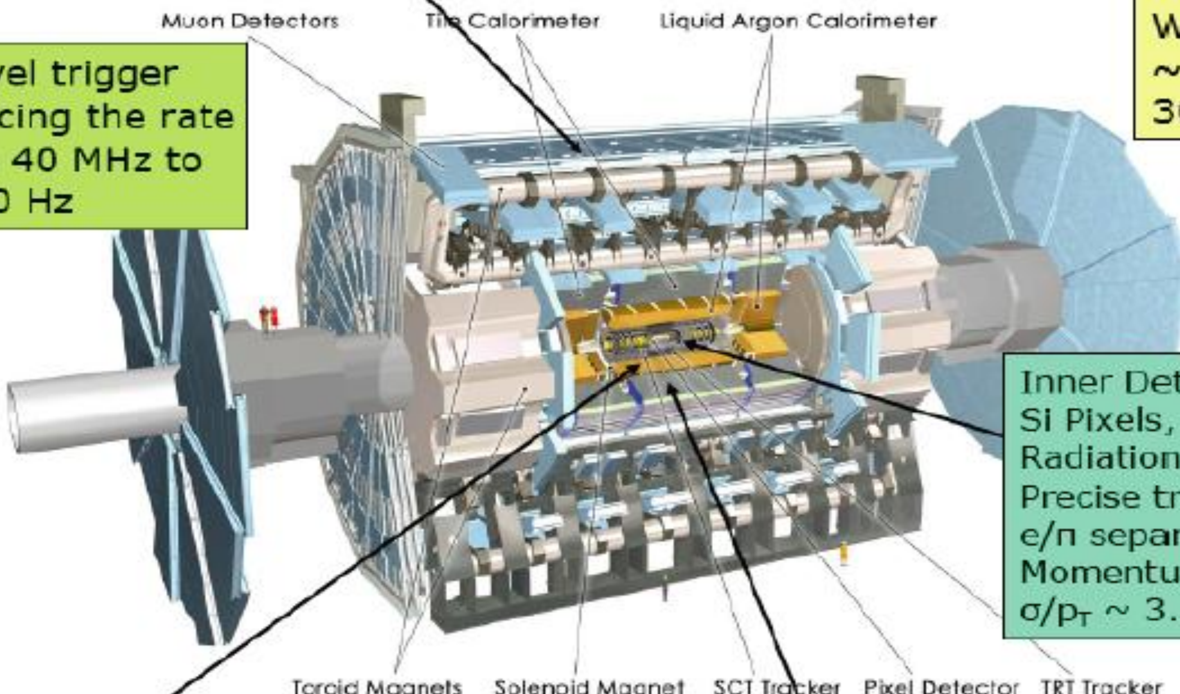


# The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu$ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~$10^8$ electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz




Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

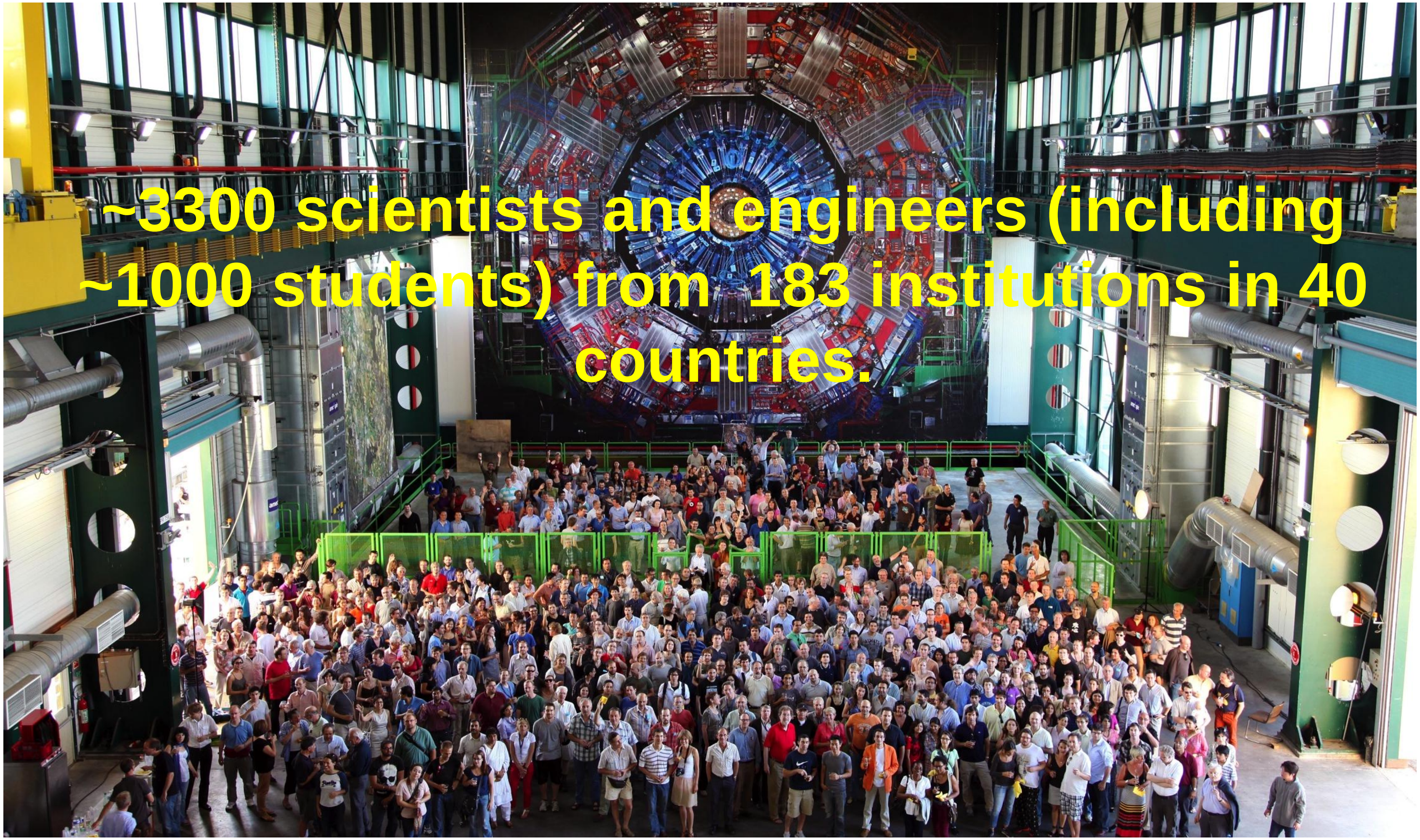
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing $E_T$
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

# Many years of tough work

- The LHC project was approved in 1994.
- The Letters of Intent for ATLAS and CMS date back to 1992.
- It took many years of tough work by thousand of people facing un-precented challenges to complete the construction of LHC and of the two main general purpose detectors.

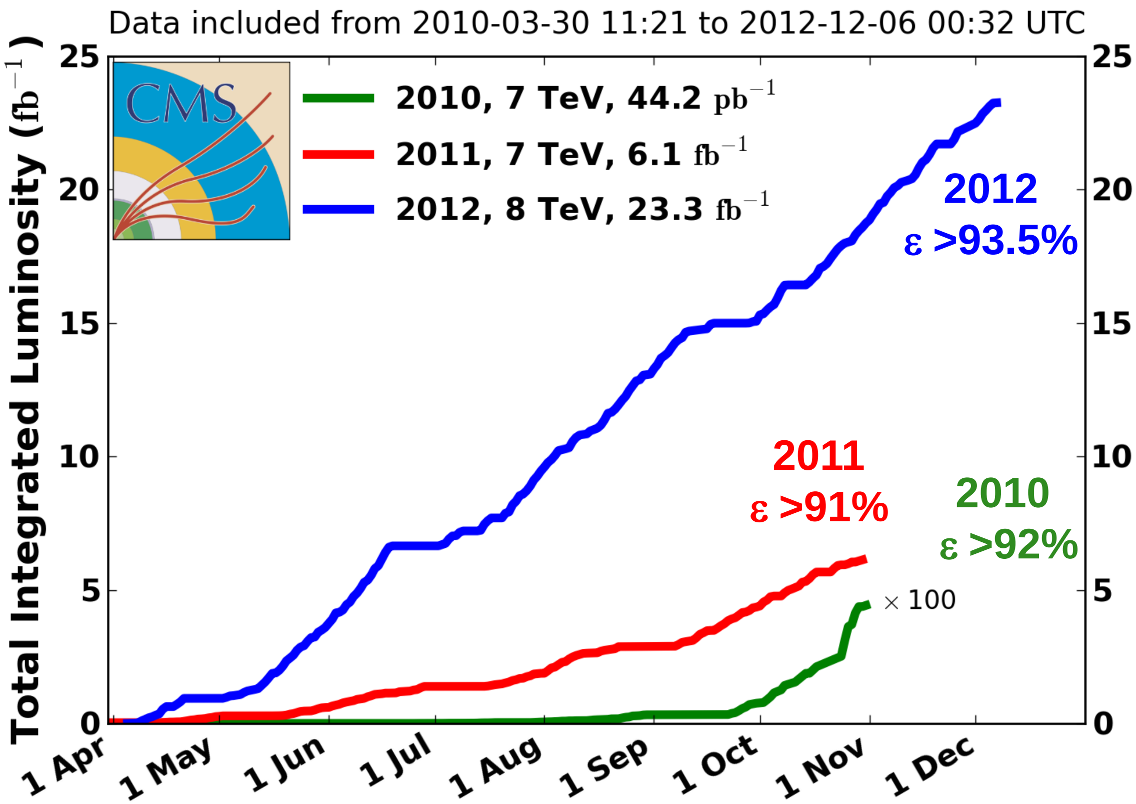
# Another key component: the people

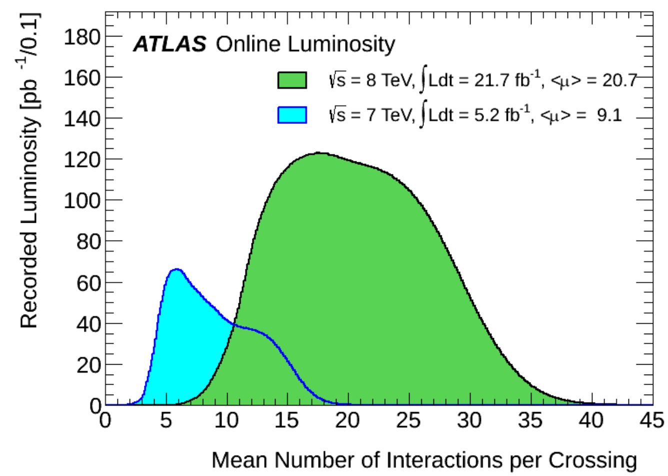



**Collaborations strong of ~1000 students and post-doc can do incredible things facing challenges that were once considered "mission impossible".**

# Detector operations in 2010-11-12

Excellent performance over the past three years.
Data taking efficiency in the range 91-94%.



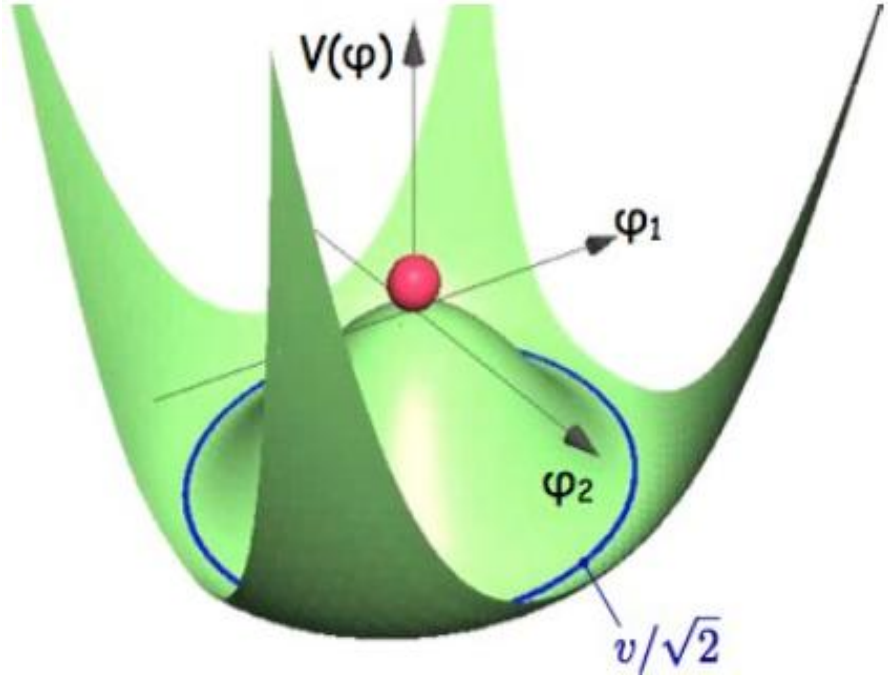

Excellent control of the effect of the pile-up on the main physics objects.

Record instantaneous luminosity **7.5x10$^{33}$ cm$^{-2}$s$^{-1}$**
Typical yields of physics quality data: 90-95% of the recorded data.

# 2. Higgs hunting basics.

# ElectroWeak Symmetry Breaking

The Brout- Englert-Higgs mechanism was proposed in 1964 to provide an elegant solution for the ElectroWeak Symmetry Breaking.




It introduces a scalar field with a non-vanishing value at zero. The Higgs 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.

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

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

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

**$M_H$ is a free parameter $M_H^2 = 2\lambda v^2$**

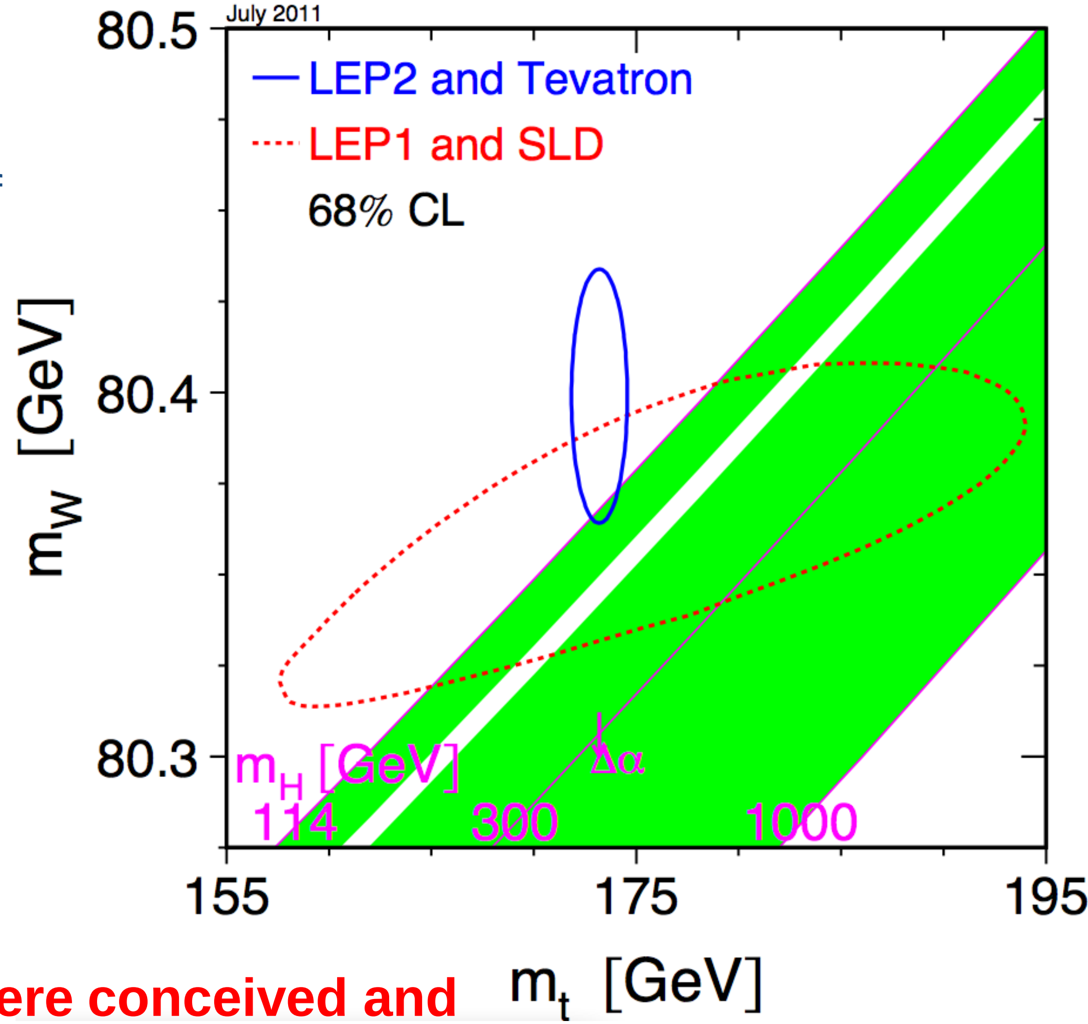
*g=0.6574; v=246GeV*

# 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 Higgs to the mass of the W and of the Top.

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

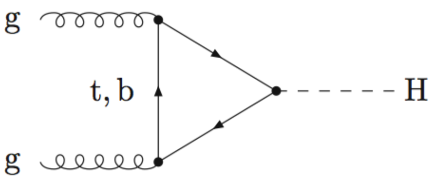
Before the LHC results the Higgs boson was allowed to sit anywhere between 114GeV/$c^2$ and ~1TeV/$c^2$ apart a narrow band between 158 and 175 GeV/$c^2$ directly excluded by the Tevatron Collider.

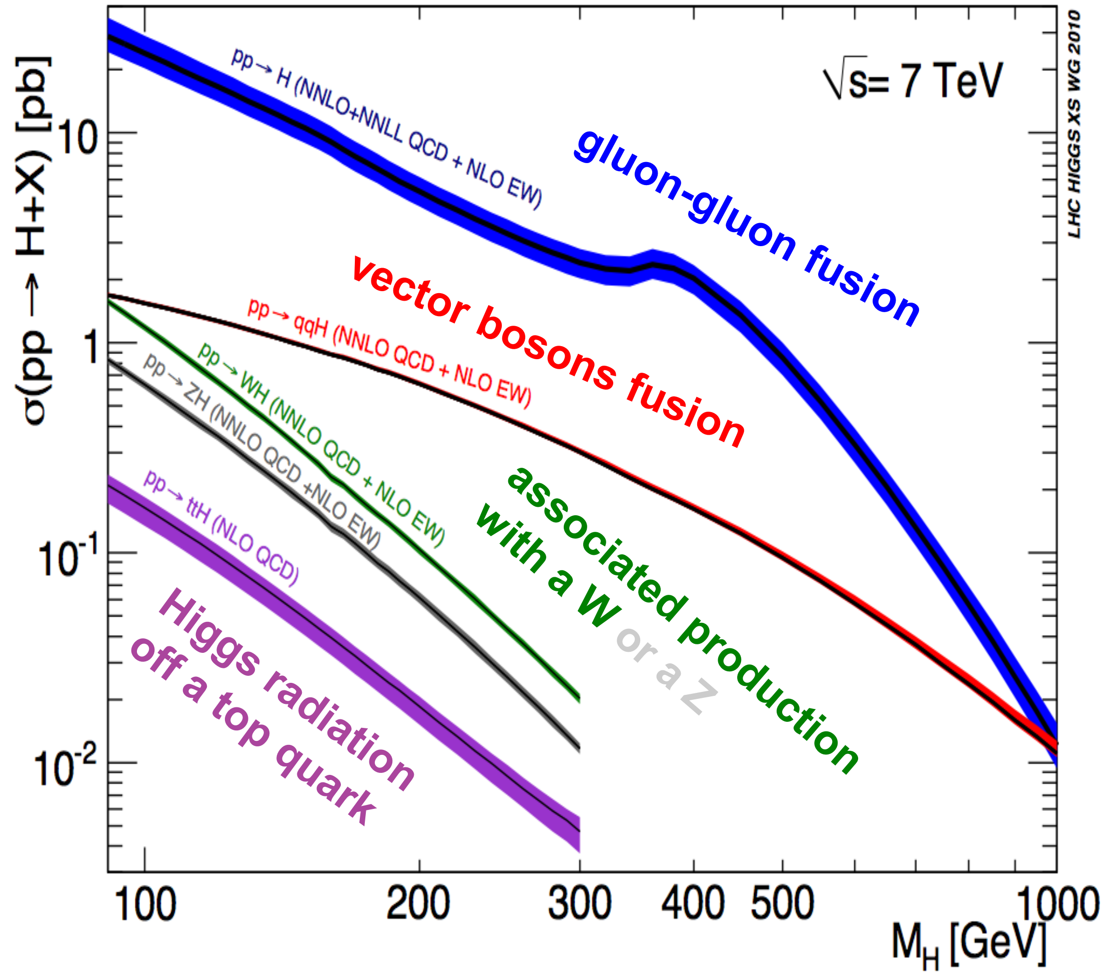



**The LHC and its major experiments were conceived and built to explore in depth the multi-TeV region and solve in a way or in another this major puzzle of particle physics.**

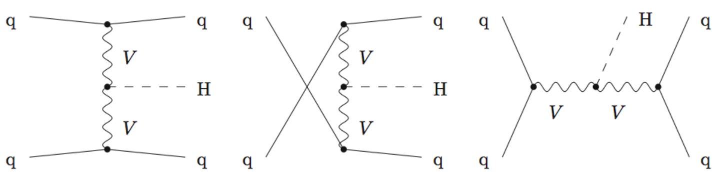
# Higgs boson production at LHC

## Gluon-gluon fusion

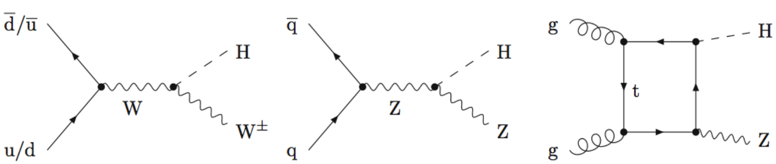


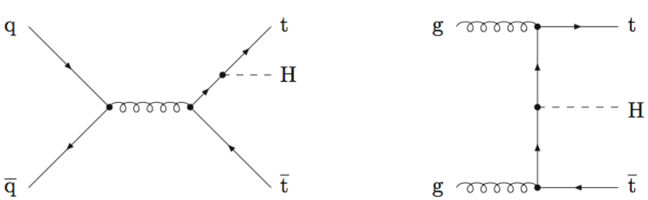

## Vector bosons fusion



## Associated production with W or Z



## Higgs radiation off a top quark



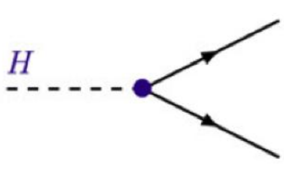
Typical size of the uncertainty (there is also a dependance on the mass)

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

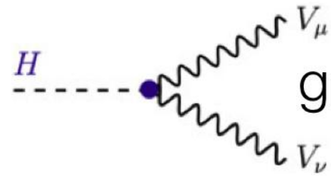
# SM Higgs decay modes vs mass

The SM Higgs boson couples directly only to massive particles and its couplings depend strongly on mass.

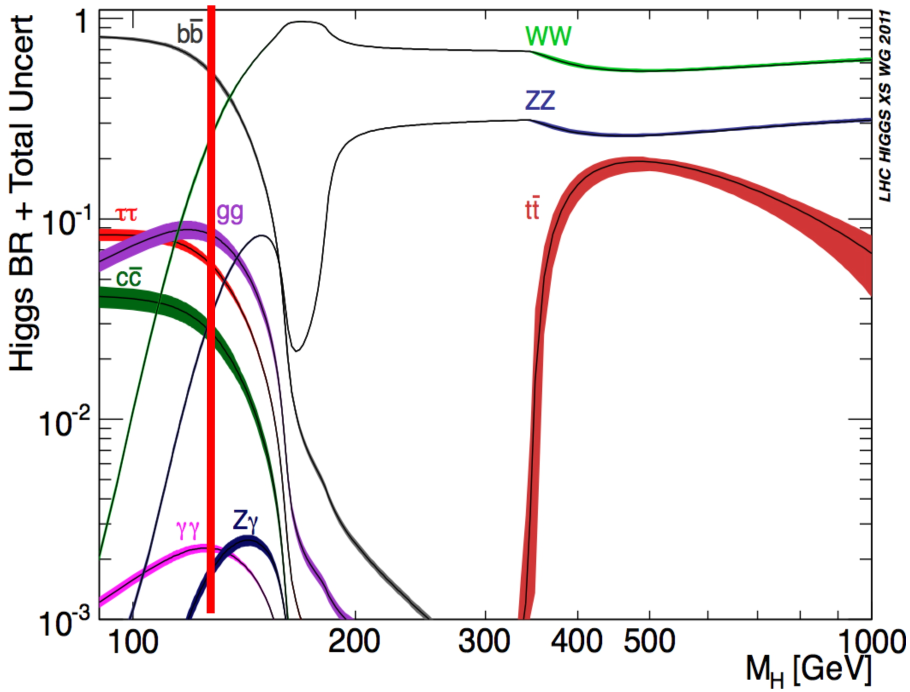
$\Gamma_{Hff} \sim m_f^2$
$\Gamma_{HVV} \sim m_V^4$




$g_{Hff} = m_f / \upsilon$




$g_{HVV} = 2m_V^2 / \upsilon$




In the low mass region there are many decay modes experimentally accessible.

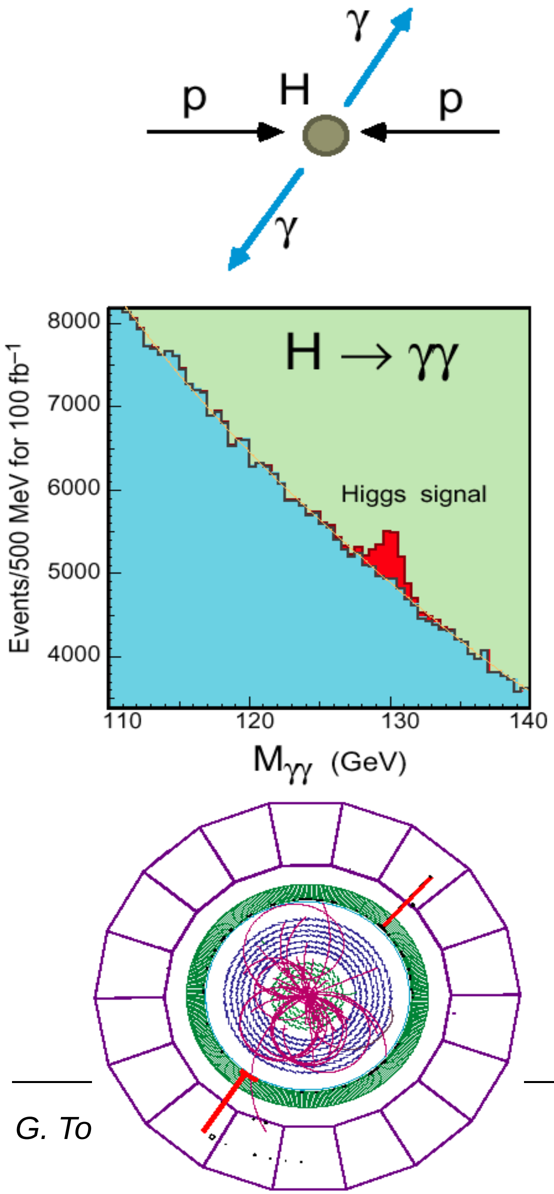
The 5 major ones @125.5GeV:

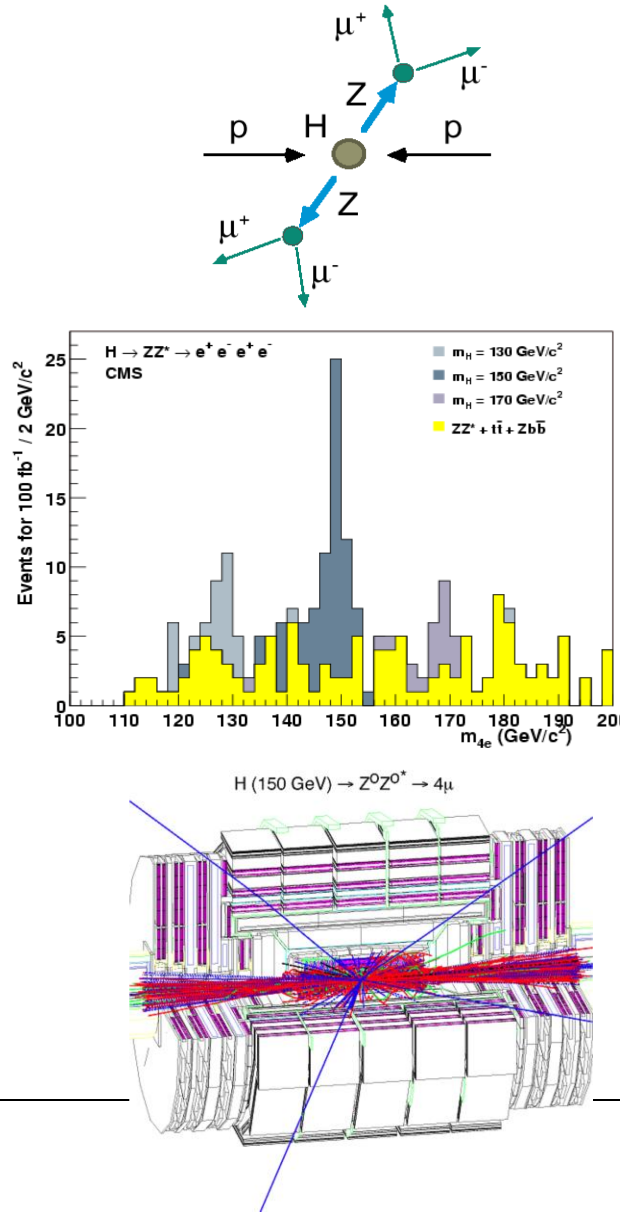
| | |
|---|---|
| H→bb | 57% |
| H→WW | 22% |
| H→ττ | 6.2% |
| H→ZZ→4l | 2.8% |
| H→γγ | 0.23% |

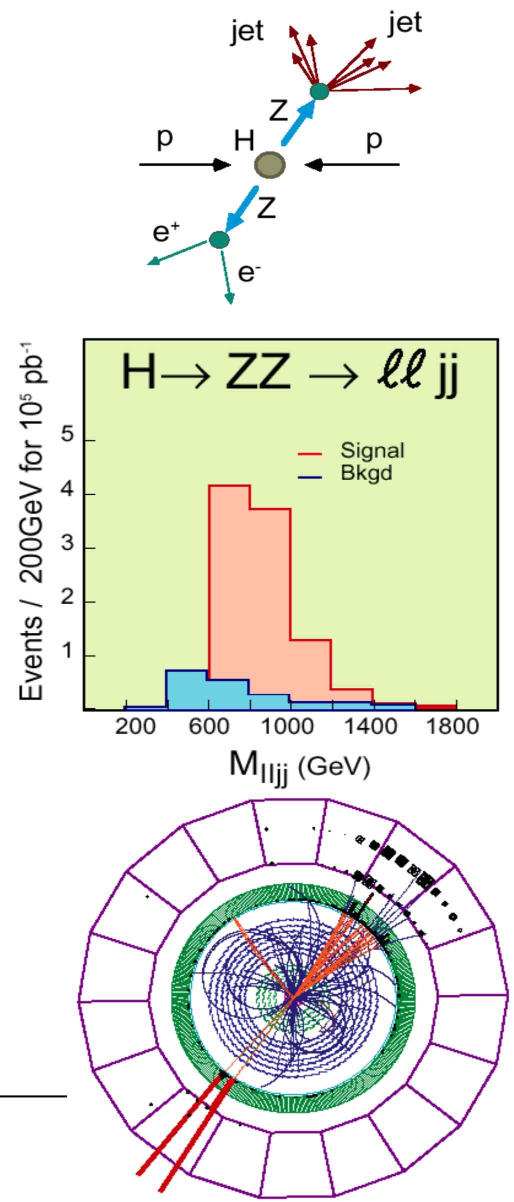
| | |
|---|---|
| H→Zγ | 0.16% |
| H→μμ | 0.02% |

# The old strategy

| Low $M_H$ < 140 GeV/c² | Medium 130<$M_H$<500 GeV/c² | High $M_H$ > ~500 GeV/c² |
|---|---|---|

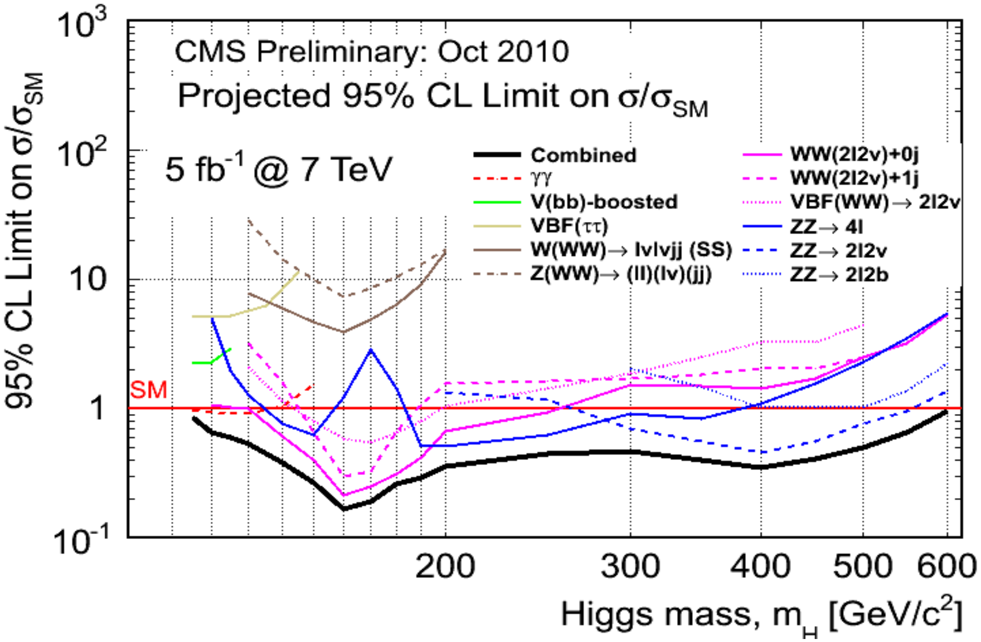


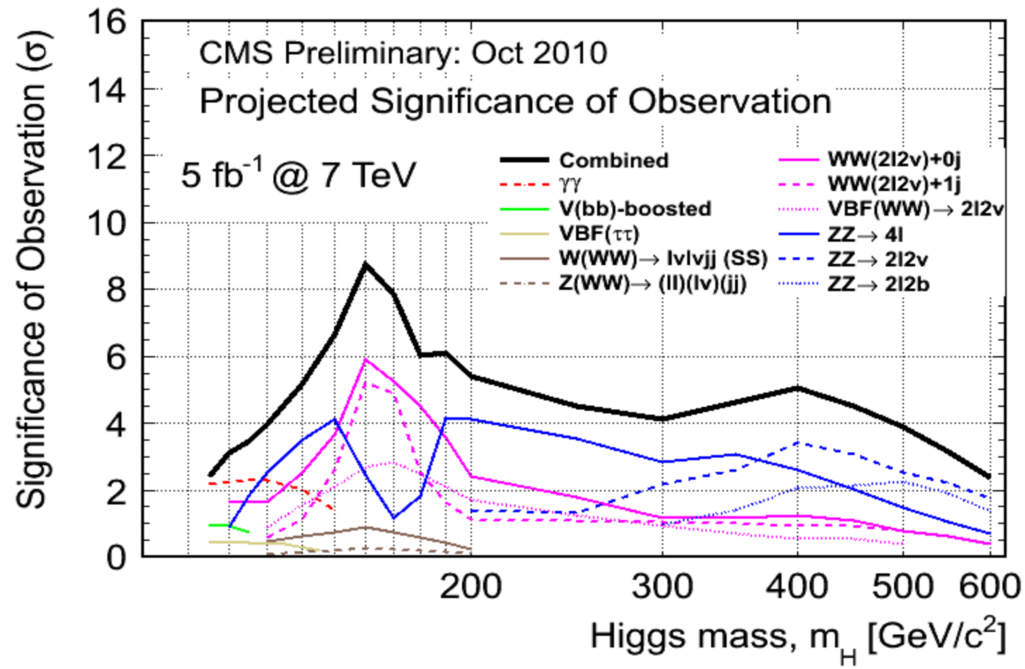



# The new strategy

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 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.**

# Goal: discover the Higgs boson at 7 TeV !

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

**"We'll discover the 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 long sought particle before the repair of the splices of LHC to **run at 13-14TeV**.

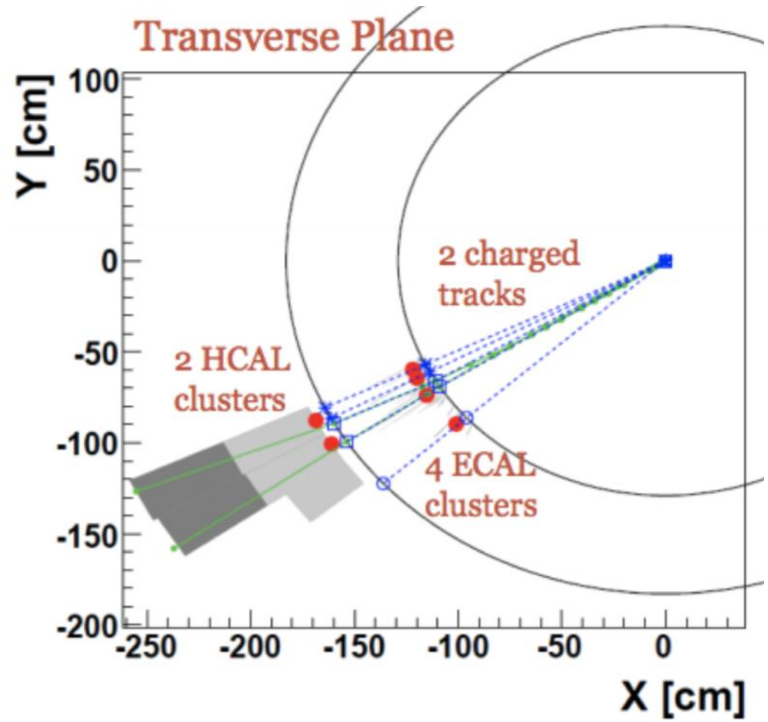
If we are here today it is just because, in the last three years, an incredible effort has been put together, basically, from scratch.

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

# Hunting the Higgs boson

The hunt for the Higgs boson requires a fine-tuning of all physics objects and a detailed understanding of all major SM processes.

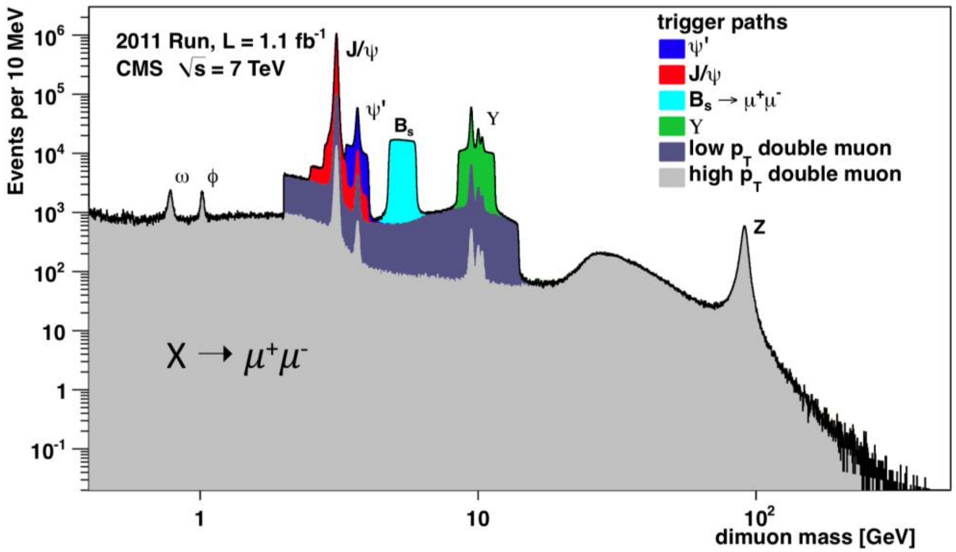
- high efficiency identification of leptons (e, μ, τ) and photons,
- very good momentum, energy, and angular resolution, of isolated particles and jets,
- efficient tagging of b-jets,
- good missing-energy (MET) resolution,
- robust against PU.

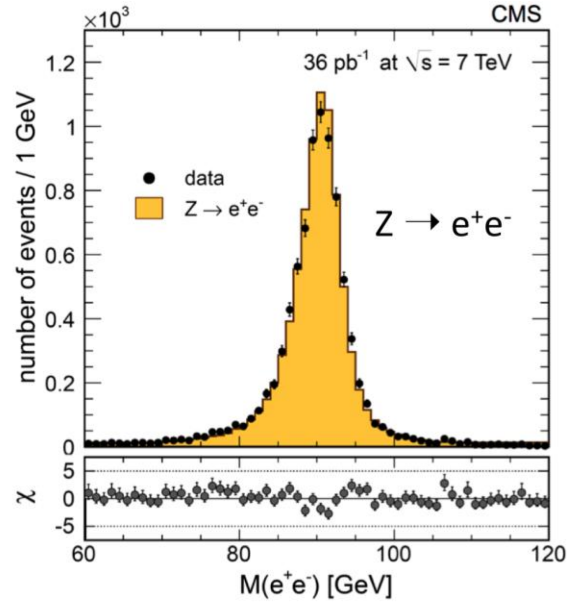


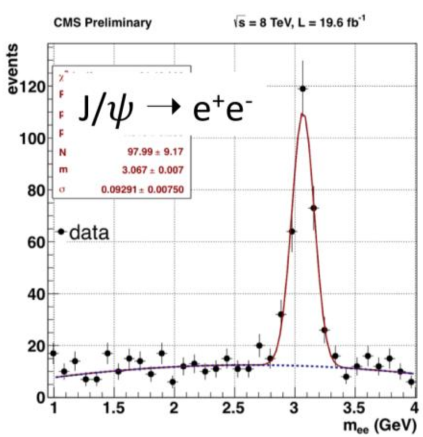

Efficiencies and resolutions determined from control data samples.

# SM "standard candles"

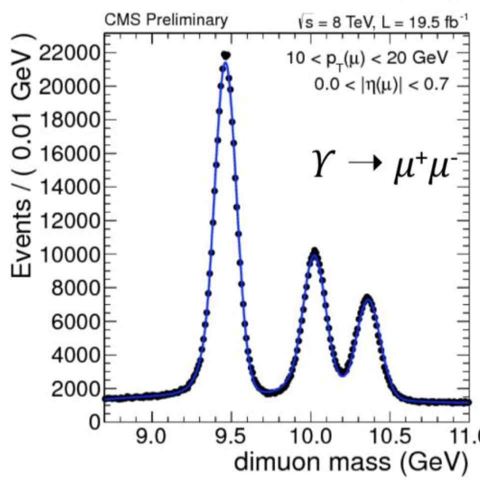
## Some examples

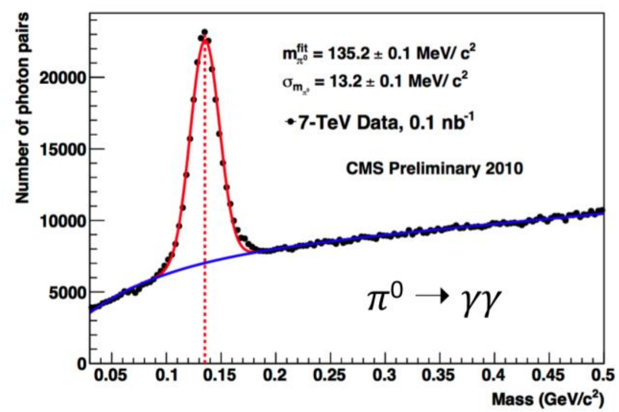



di-electron mass

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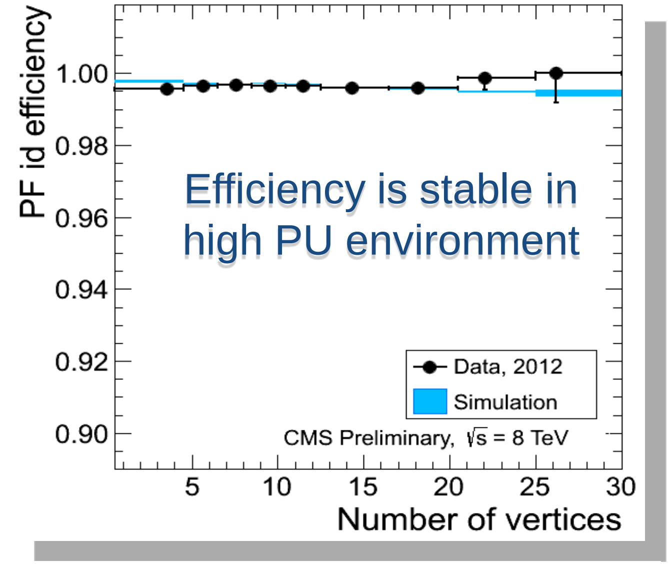
# Muon reconstruction and identification

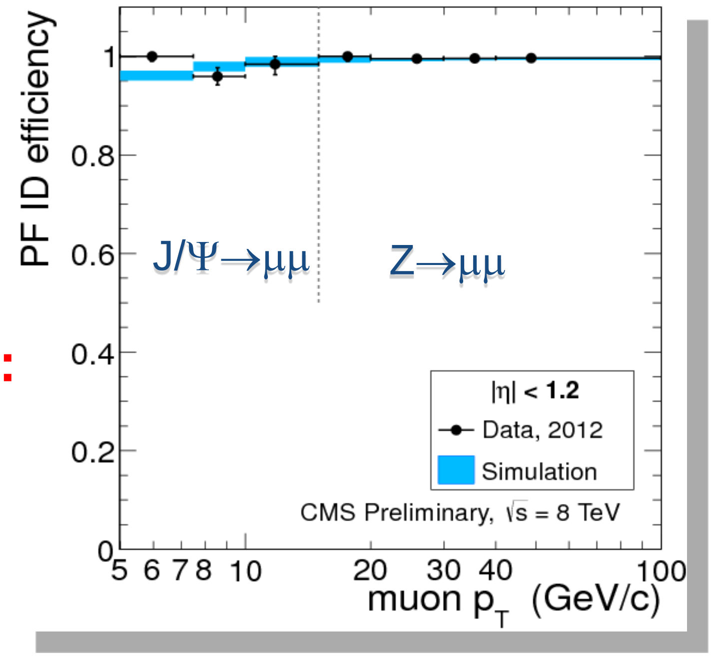
- PF Muon Identification in 2012
  - Exploit information from all subdetectors
- **Muon ID efficiency >96% for $p_T$=5 GeV; >99% for $p_T$=10 GeV;**
  - Exploit also tracker-based muon ID
  - Important for H->ZZ->4l
  - Efficiency controlled in data with J/Ψ and Z T&P

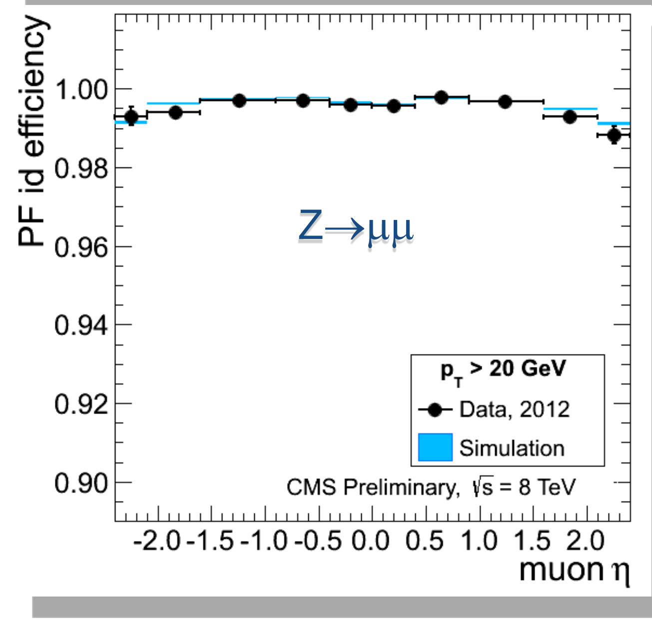



**Muon momentum resolution:**
**1% for $p_T$ < 100 GeV,**
**7-8% at 1 TeV.**

**pions mis-ID as muons:**
**<0.5% for $p_T$ > 2 GeV.**

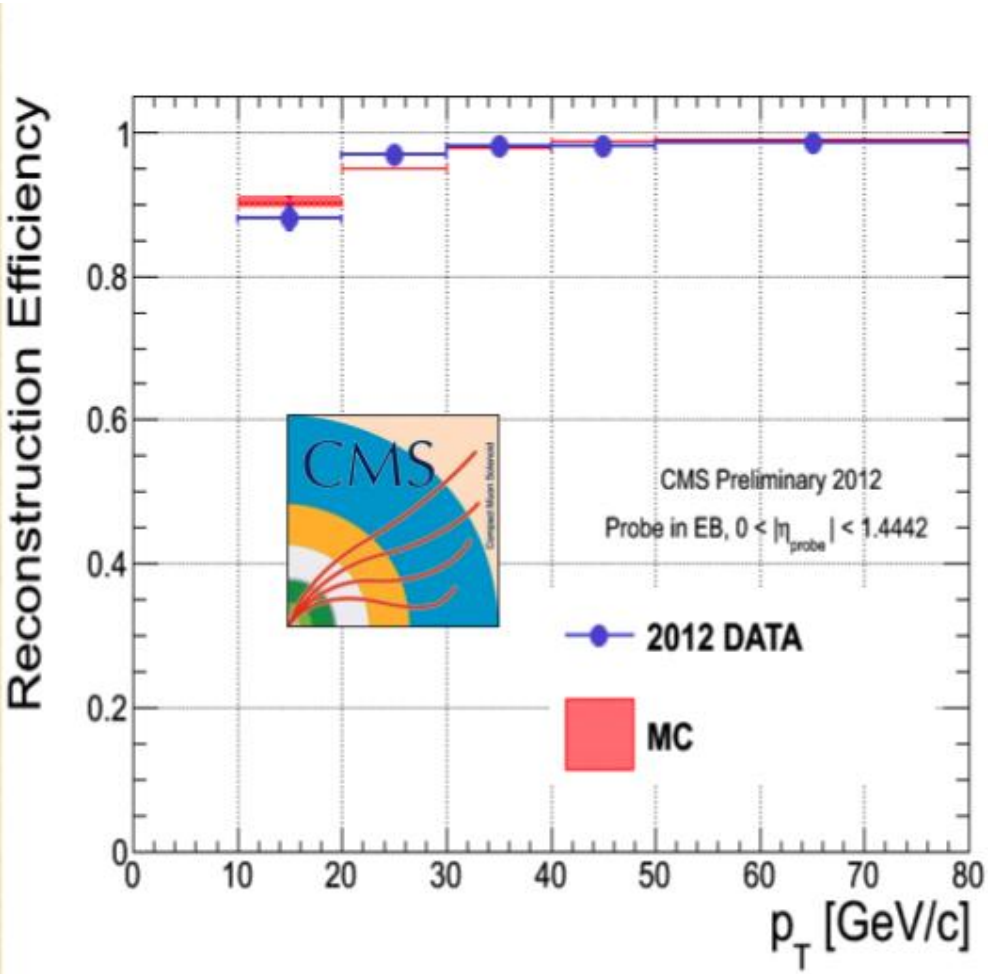
**Absolute scale known at 0.2%.**

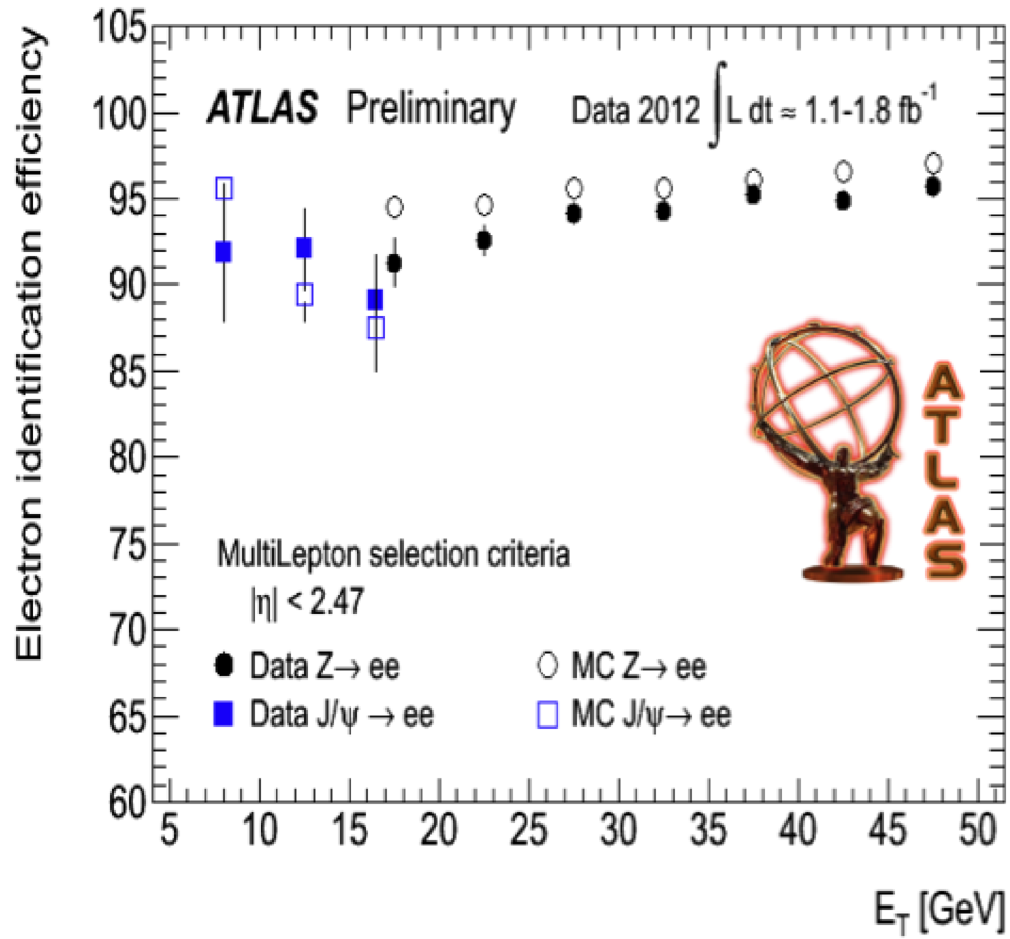


# Electron efficiency

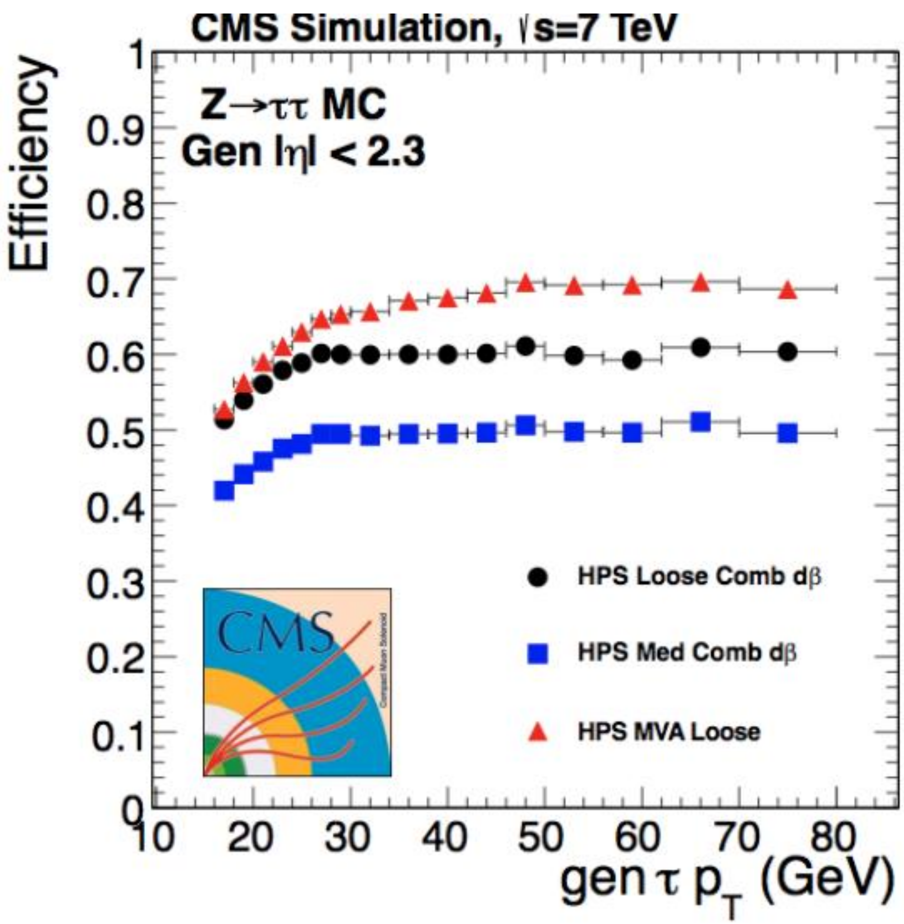
## >90% for $p_T$>15GeV

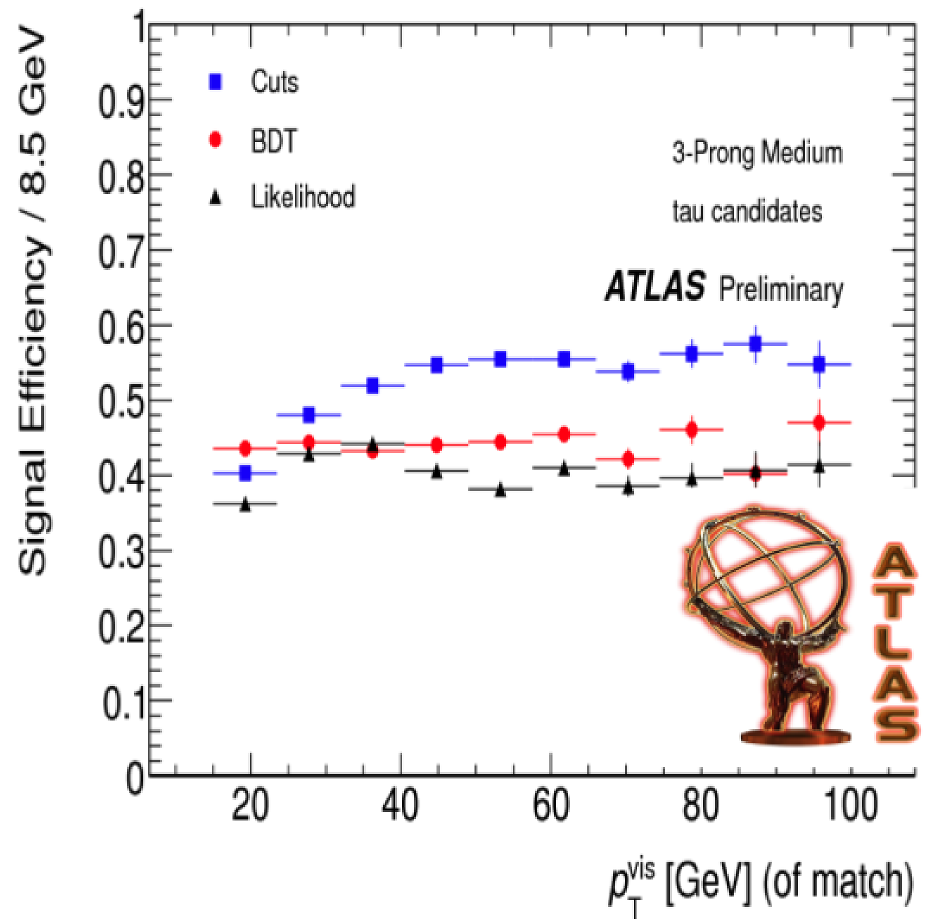


# $\tau_h$ reconstruction efficiency

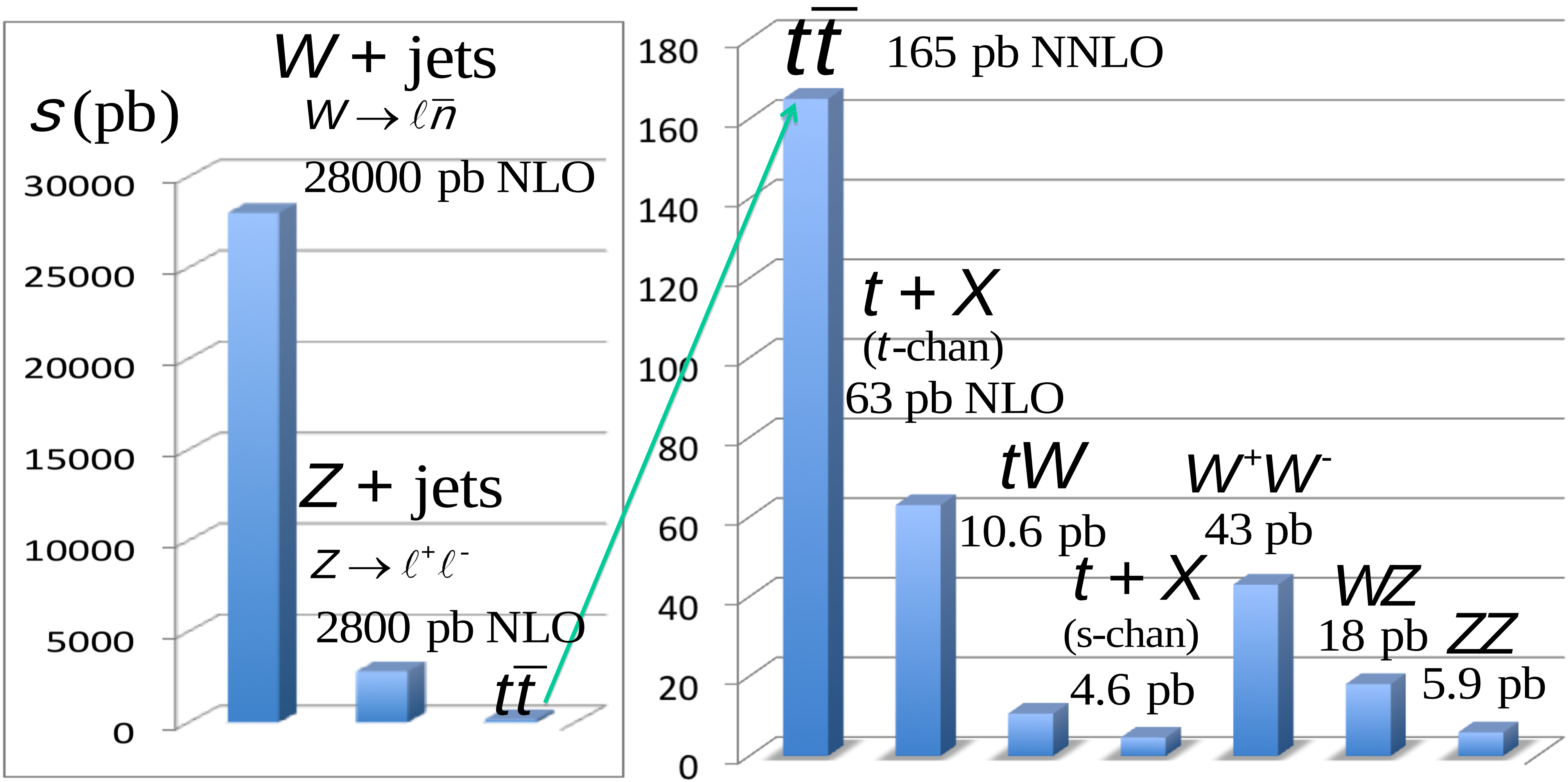
- $\tau_h$ reco. efficiency >60% (CMS) 50% (ATLAS)
- fraction of jets faking $\tau_h$ 3% (CMS) 1% (ATLAS).



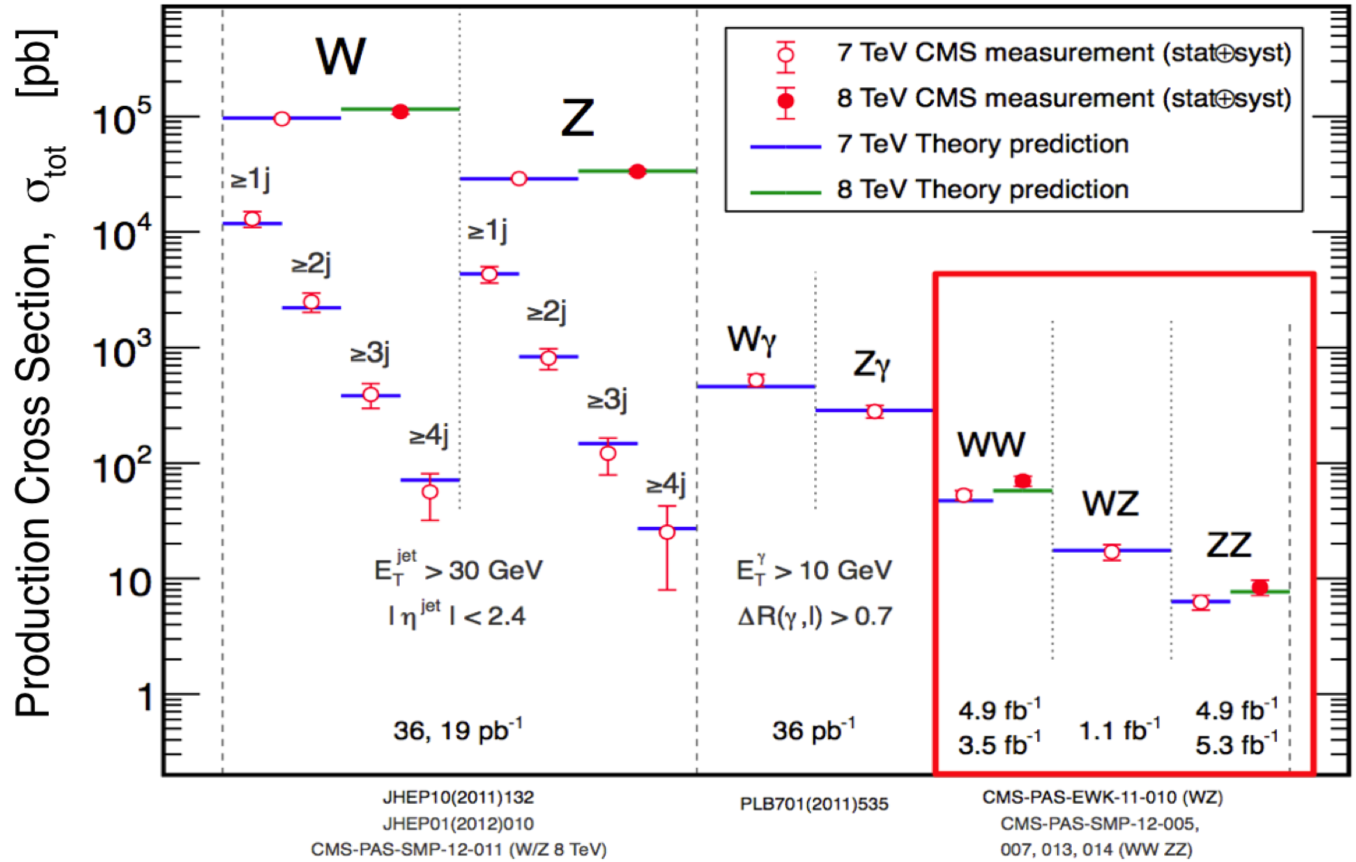



# Key SM Background Processes

$\sqrt{s} = 7$ TeV



# EWK measurements are SM Higgs background



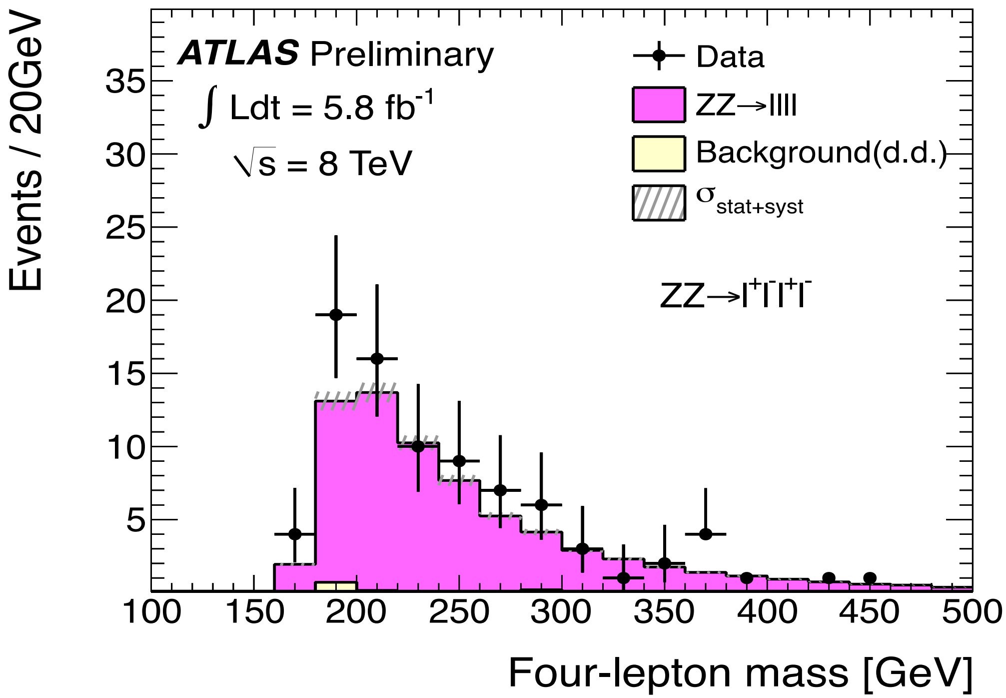

**$\sigma(pp) \rightarrow H$ (with $m_H$=125GeV) =17.5pb**

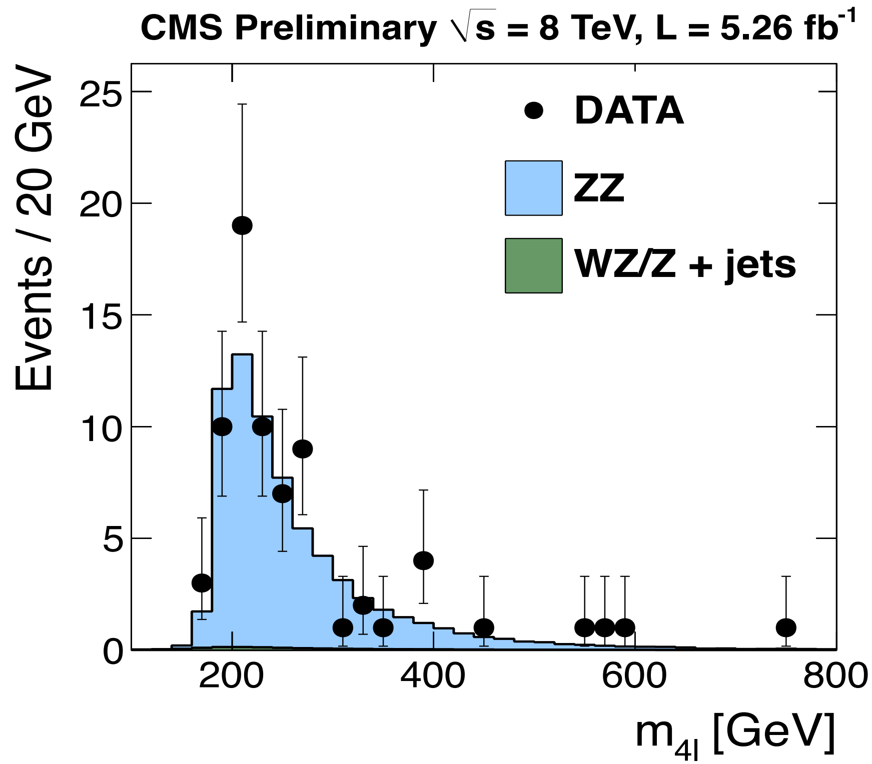
Same order of manitude of the diboson (WW,WZ,ZZ production).

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

# ZZ production at 8 TeV

ATLAS-CONF-2012-090; CMS-PAS-SMP-12-014




| | | |
|---|---|---|
| **ATLAS (5.8 fb$^{-1}$)** | $9.3^{+1.1}_{-1.0}(\text{stat})\pm^{+0.4}_{-0.3}(\text{syst})\pm 0.3(\text{lumi})$ pb | $7.4 \pm 0.4$ pb |
| **CMS (5.26 fb$^{-1}$) (include 2l2τ)** | $8.4 \pm 1.0(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})$ pb | $7.7 \pm 0.4$ pb |

# 3. Highlights of the discovery.

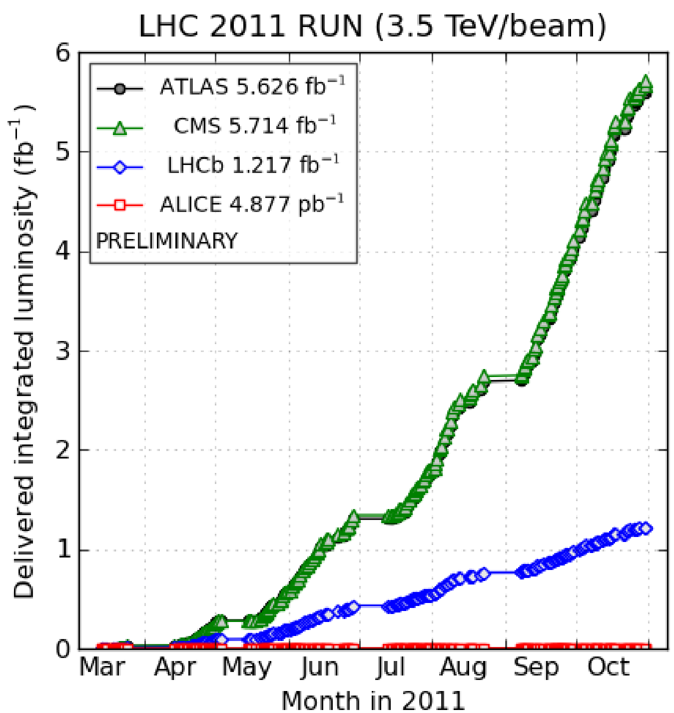
# The first breakthrough.

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

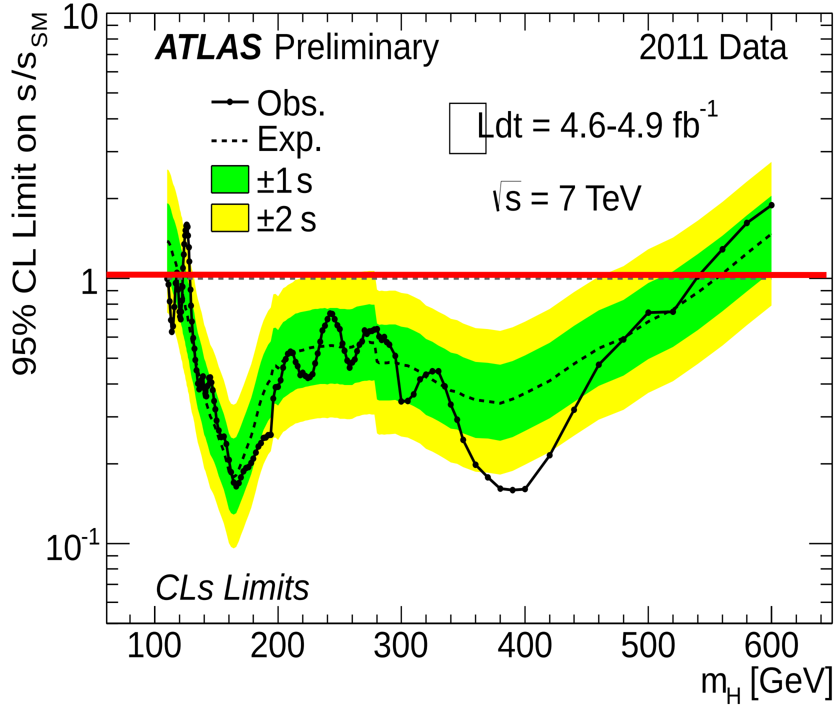
ATLAS and CMS detectors recorded typically **90-95%** of the delivered luminosity and about **85-90%** was good quality data for physics.

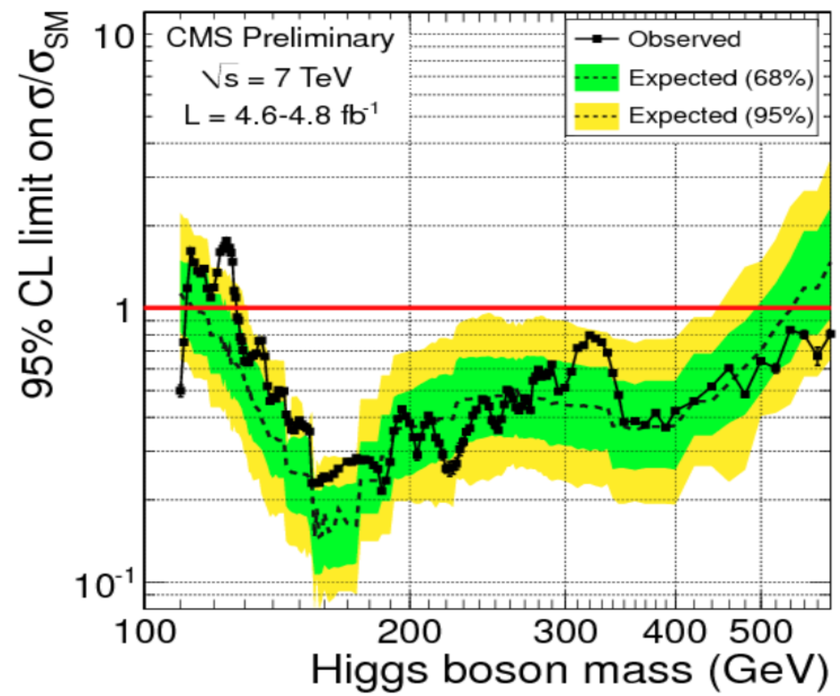
**Average fraction of operational channels per subsystem typically >98%.**

**For the first time the amount of data was large enough to allow experiments to say something significative on the SMS 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.**

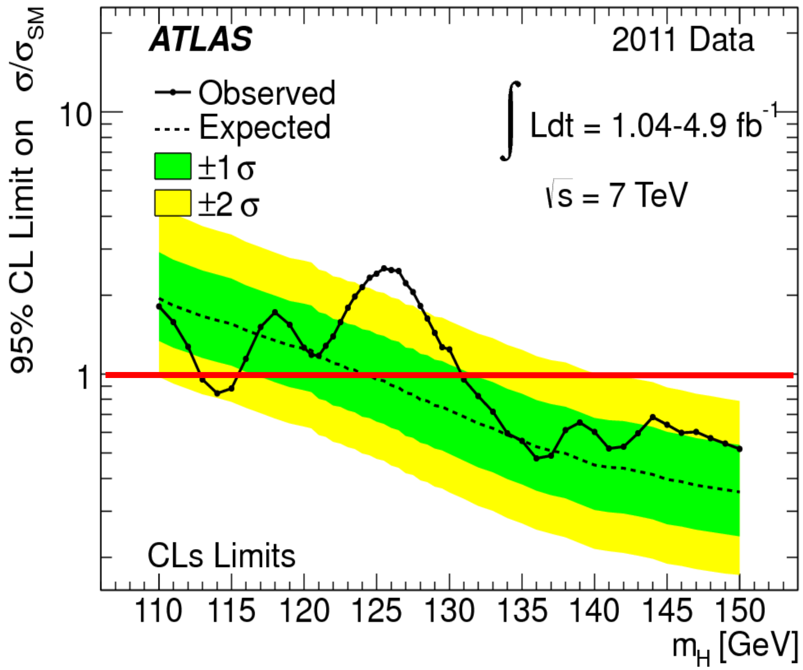
We have not been able to exclude the presence of the Higgs boson below **129GeV** due to the presence of **an excess of events** in the low mass region.

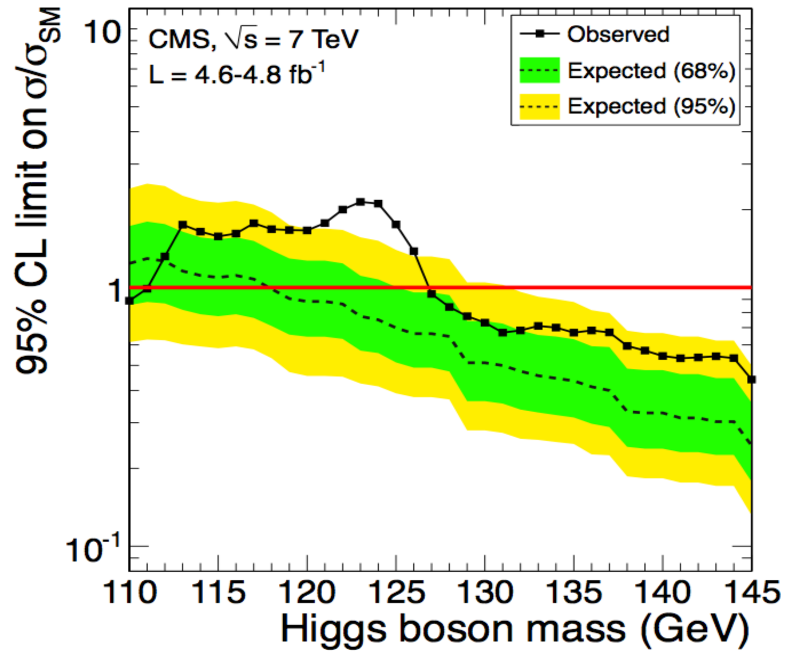
Expected exclusion 114.5 - 543 GeV

**Observed exclusion 127.5 - 600 GeV.**

We have not been able to exclude the presence of the 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** Higgs boson 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 Higgs boson 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.

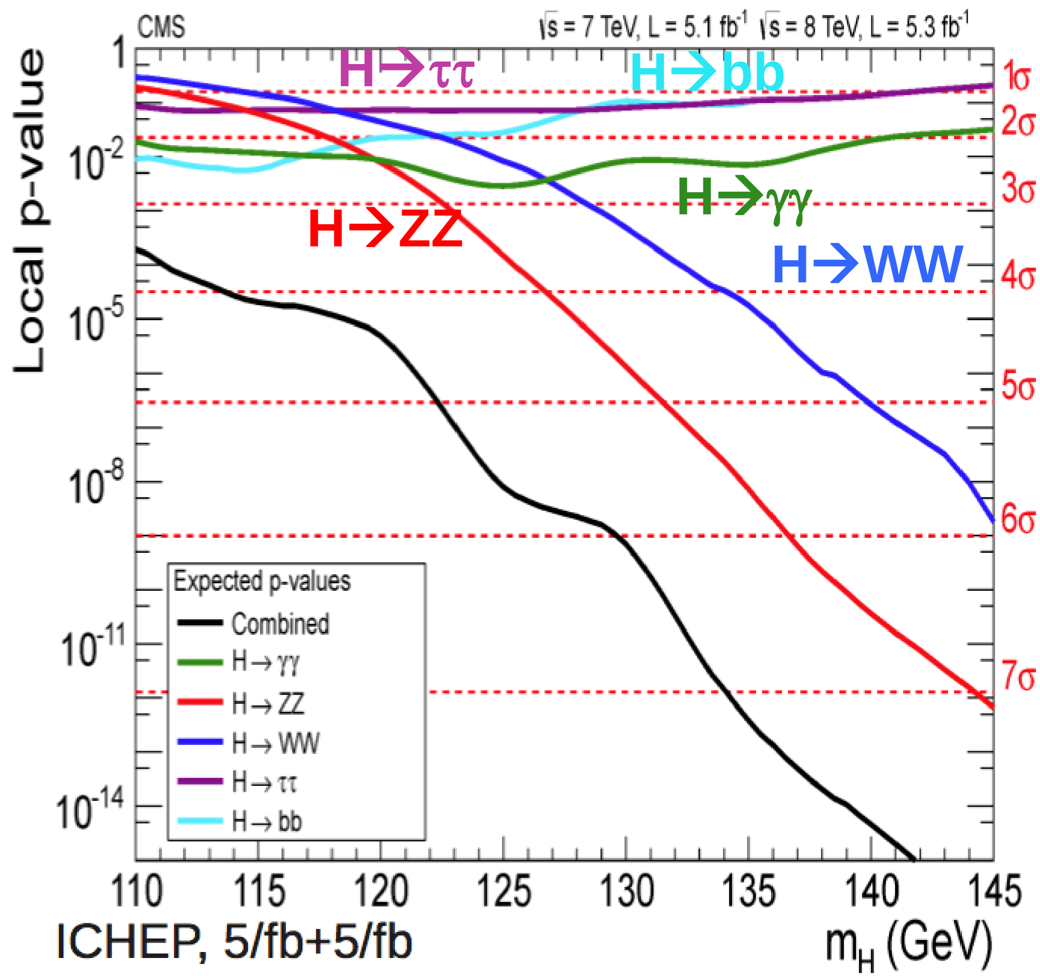
- A lot of improvements in the analyses
- Better understanding of the detector
- Optimal selection criteria to improve the sensitivity.

**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 around mid June as soon as the LHC delivered an additional 5fb$^{-1}$ of data at 8 TeV.**

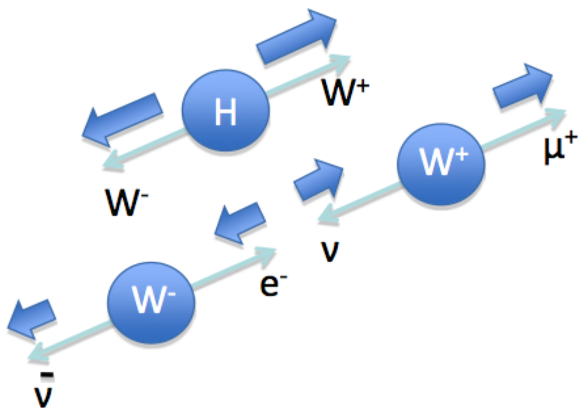
# Sensitivity in the low mass region

**The three bosonic channels have the highest sensitivity in the low mass region and indeed played a key role in the discovery.**

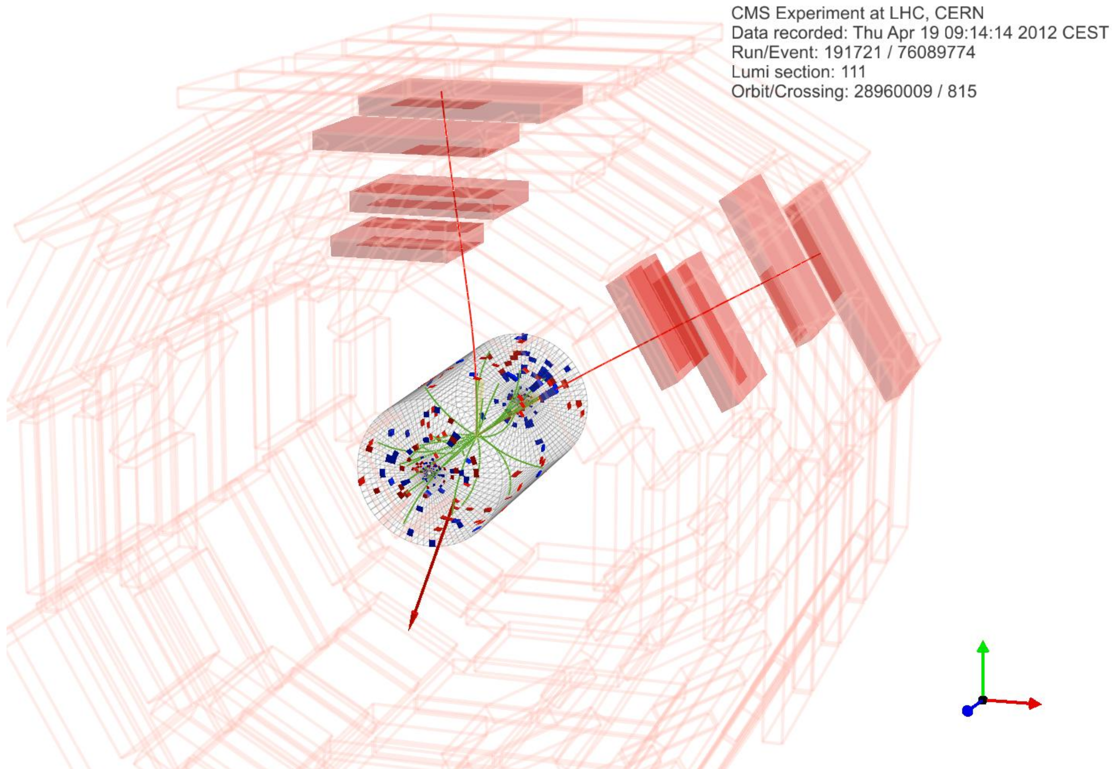


# H→ WW→2l2ν

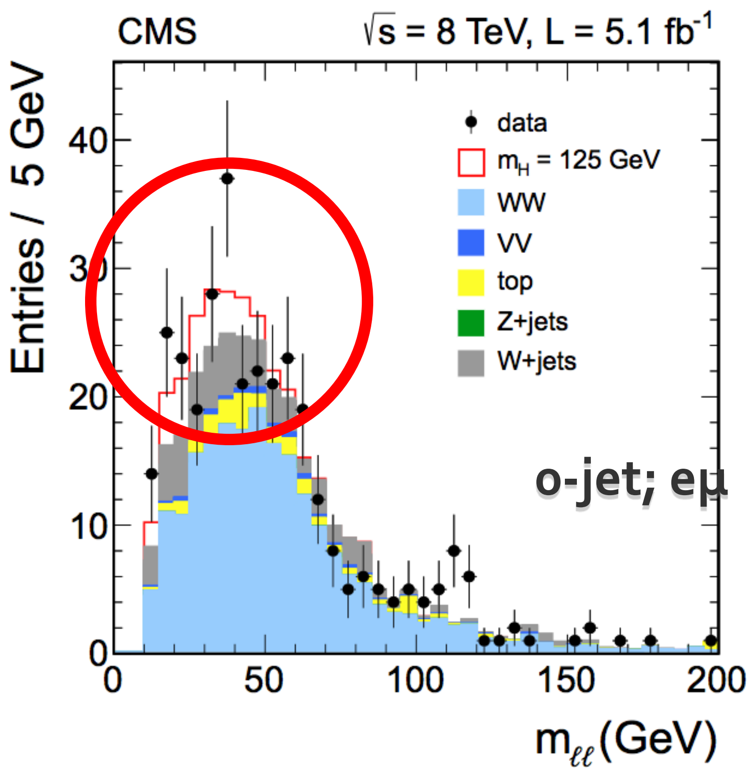
**Signal selection**: two hight $p_T$ leptons + missing $E_T$ ; low invariant mass distribution of the two leptons and low transverse mass distribution in the event (to discriminate against the dominant WW background). **High yield, coarse resolution (~20%) channel**. We cannot expect to see a narrow peak in the distributions for the presence of neutrinos (missing transverse energy) in the decay.

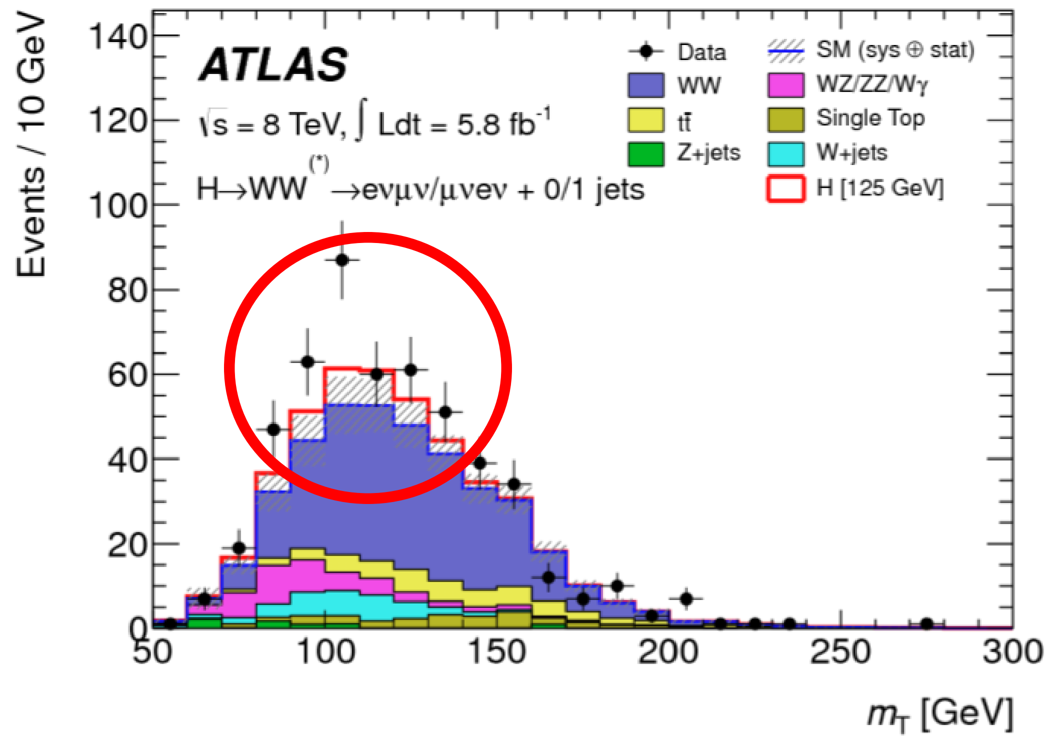



**The spin correlation leads to a smaller average opening angle between the two leptons**



# Results on H→ WW→2l2ν



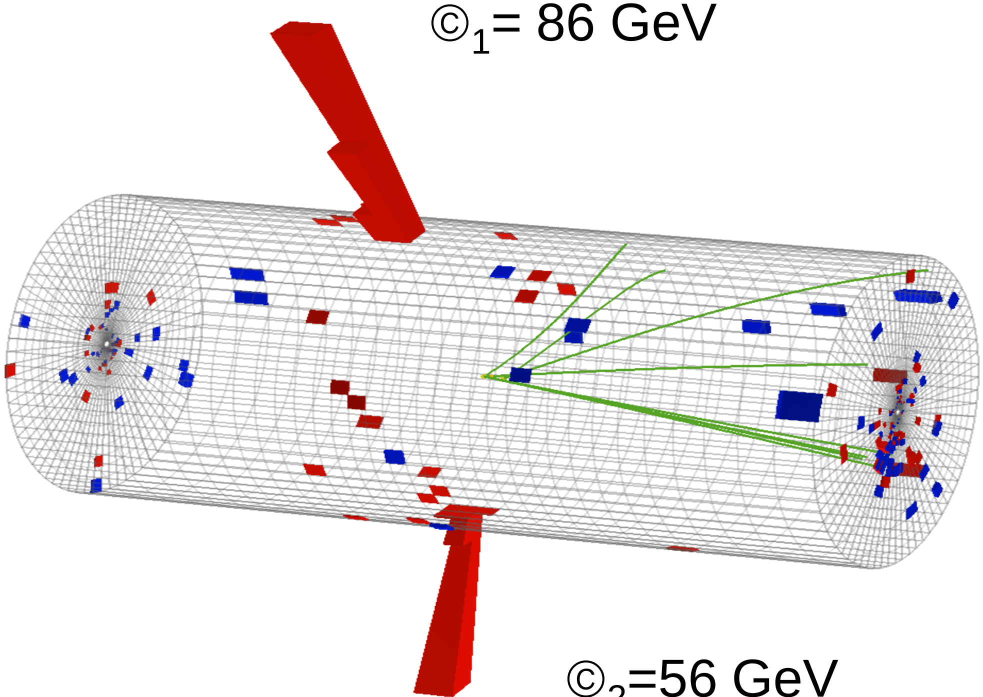

Search is done in 0-1and 2-jet categories in the ee, eμ, μμ channels. Most discriminating variables: the two-lepton invariant mass ($m_{ll}$) used by CMS and the two-lepton transverse mass distributions ($m_T$) used by ATLAS.

The presence of a SM Higgs boson at 125GeV would appear as a broad excess of events in the low mass end of the distributions.

# The specialist of the low mass: H→ γγ

**Signal: 2 energetic, isolated ©.**
**Search for a narrow mass excess over a smoothly falling background.**

©$_1$= 86 GeV

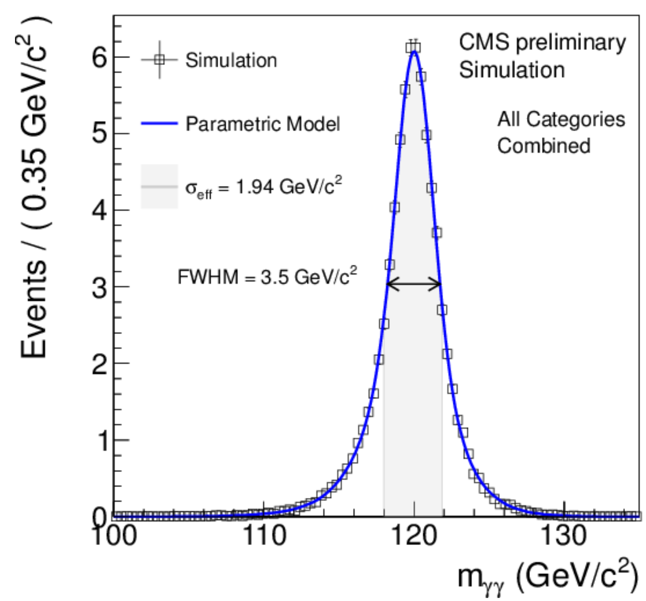


©$_2$=56 GeV

**Excellent resolution: 1-2%**
**Signal purity: ~3%-30%**

Challenges:

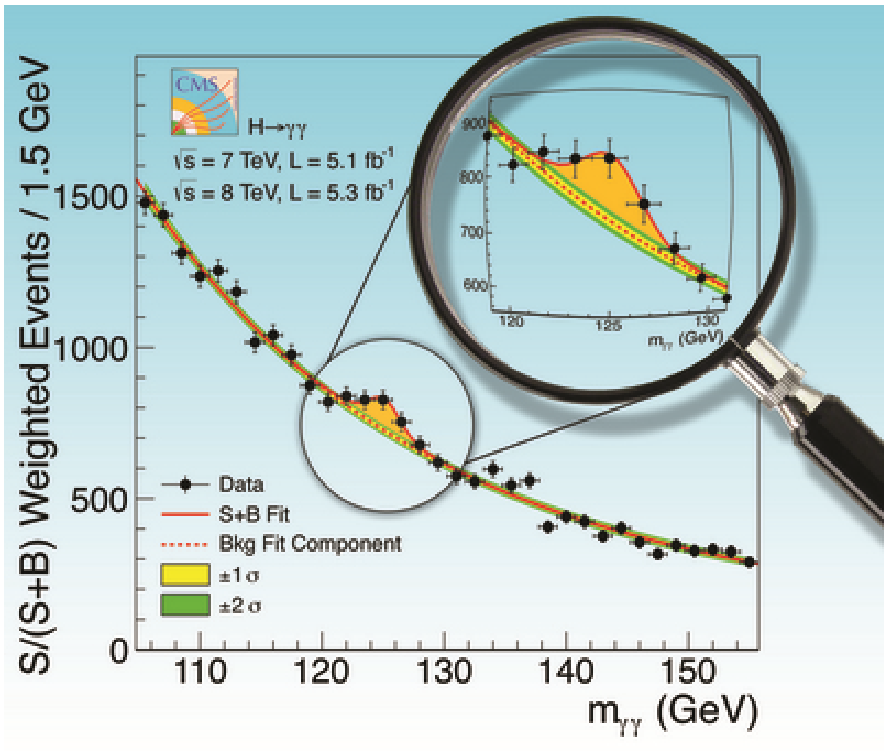
- Vertexing with high PU: photon pointing in ATLAS; dedicated MVA in CMS.
- Calibration of the electromagnetic calorimeters
- Photon identification.

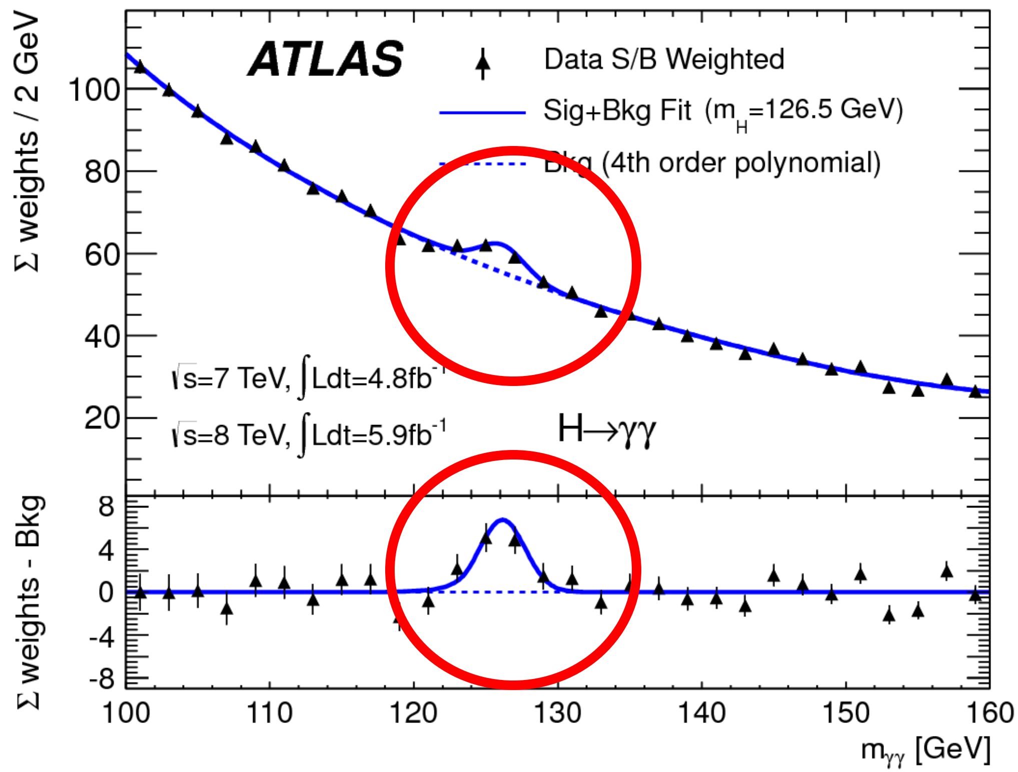



Background: Large and mostly irreducible QCD di-photons (+jet faking photons). Measured from M$_{©©}$ sidebands in data

# Results on H→γγ

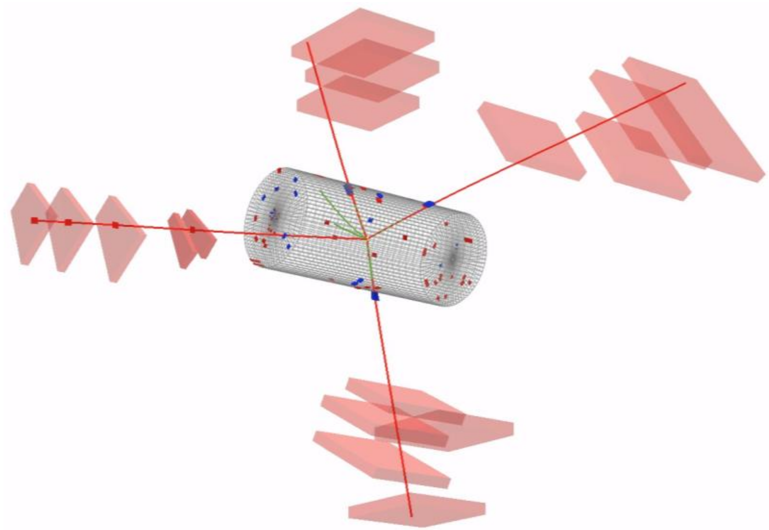
To increase the sensitivity the analysis is performed in categories: untagged, lepton tag (WH, ZH), MET tag (Z(νν)H), dijet tag (to enrich the VBF fraction)using MVA techniques. Cut-based analyses are often used as a cross check. Signal is enriched by the higher boost of the Higgs boson wrt to background.

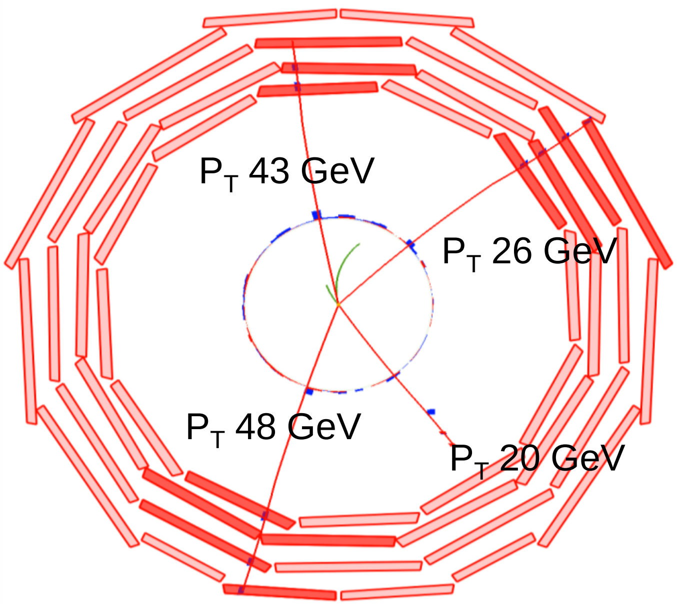



**Clear peaks visible corresponding to a > 4σ excess at ~125GeV**

# $H \rightarrow ZZ \rightarrow 4e, 4\mu, 2e2\mu$






**Signal**: two pairs of same flavor high $p_T$ oppositely charged isolated leptons. One or both pairs with invariant mass compatible with the Z.

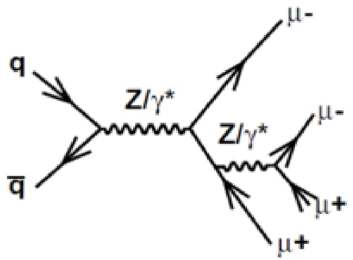
**Extremely clean (S/N:1), high resolution (1-2%) channel but very low rate (σ~2-5fb).**

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

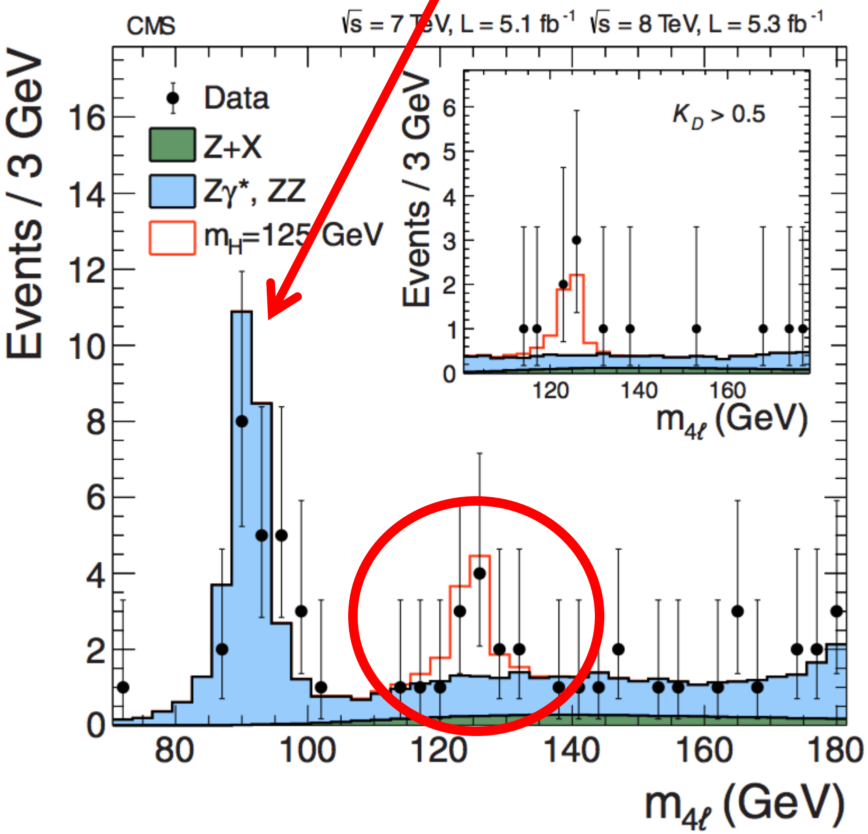
**Main backgrounds**: ZZ* (irreducible) for $m_H<2m_Z$, Zbb/cc, Z+jets, tt, WZ+jets

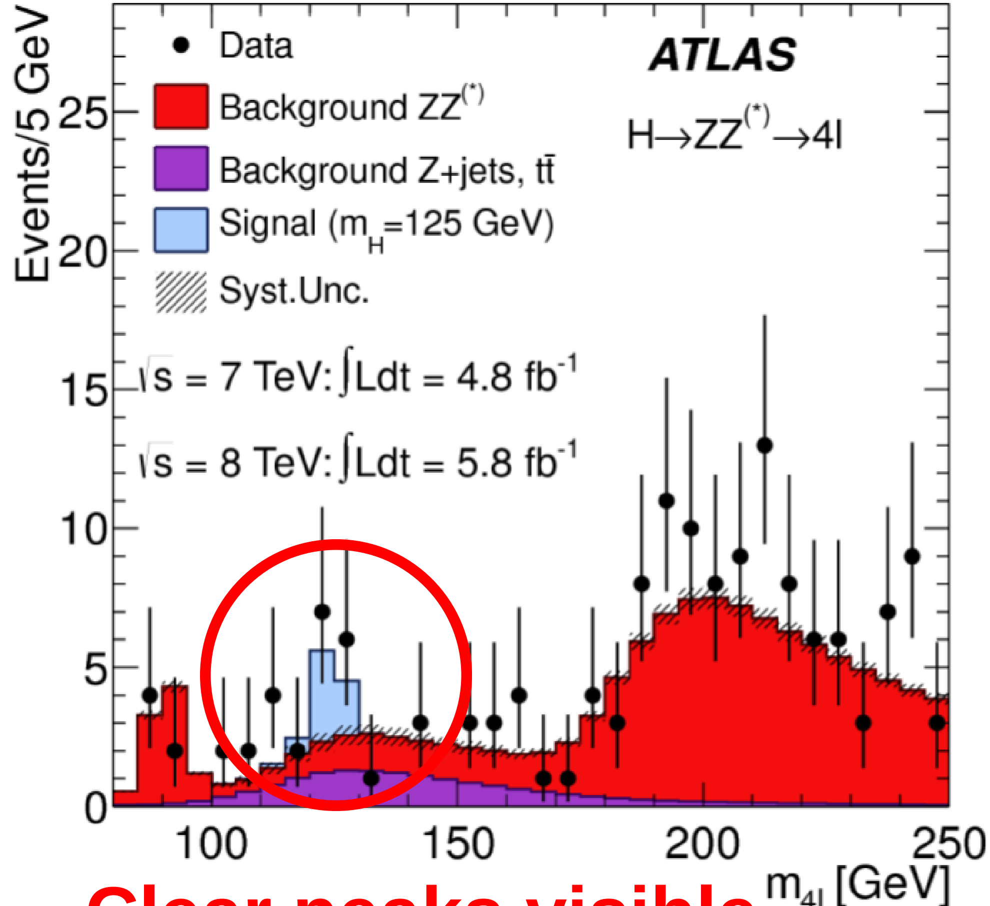
Suppress backgrounds with isolation and impact parameters cuts on two softest leptons.

# Results on H→ZZ→4 leptons




Very rare EWK process used for calibration purposes.

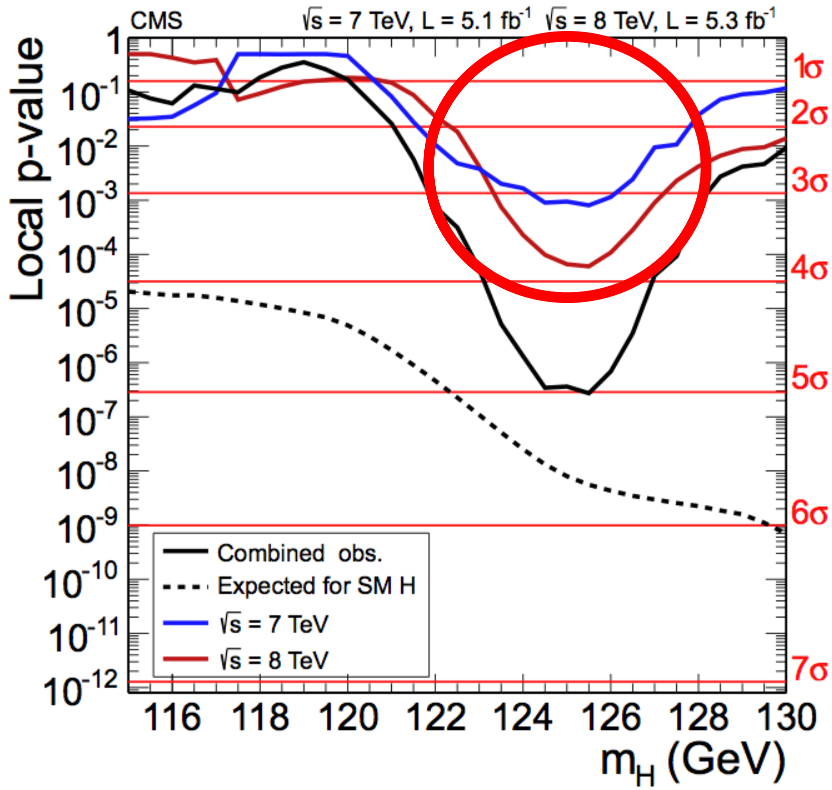


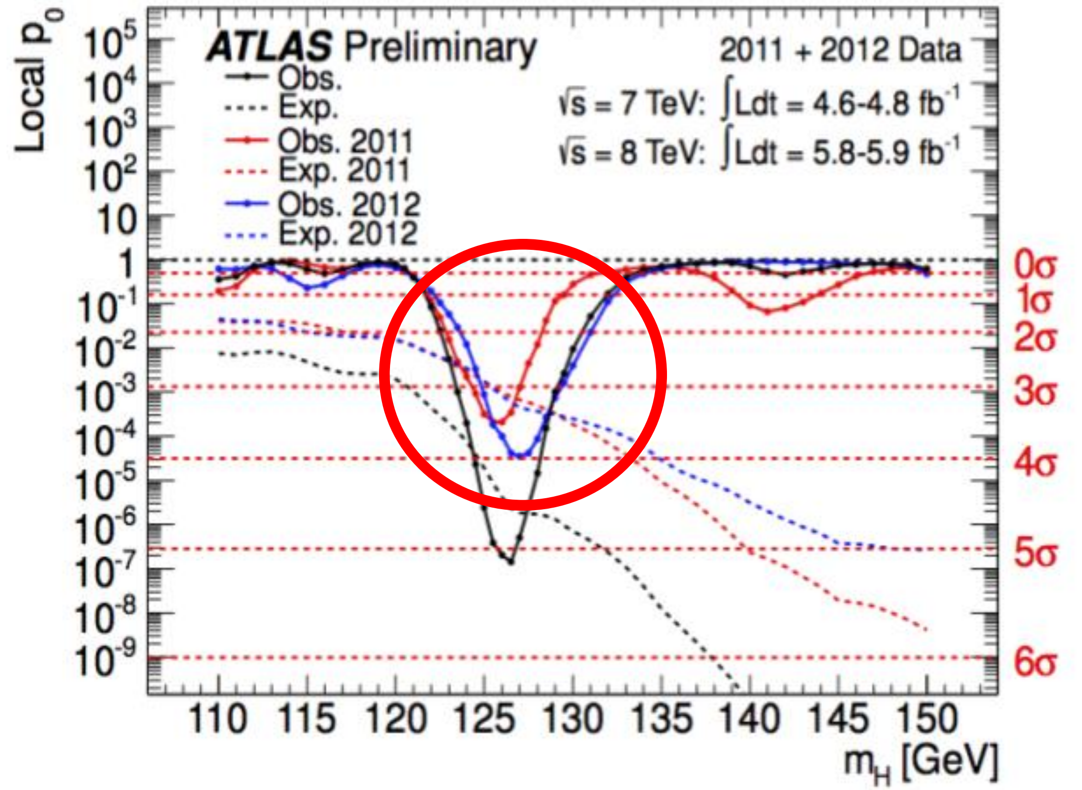




**Clear peaks visible corresponding to a > 3σ excess at 125.5GeV**

# Discovery of a Higgs-like boson.

**Combined significance 5.0 ʃ for CMS and 5.0σ for ATLAS**



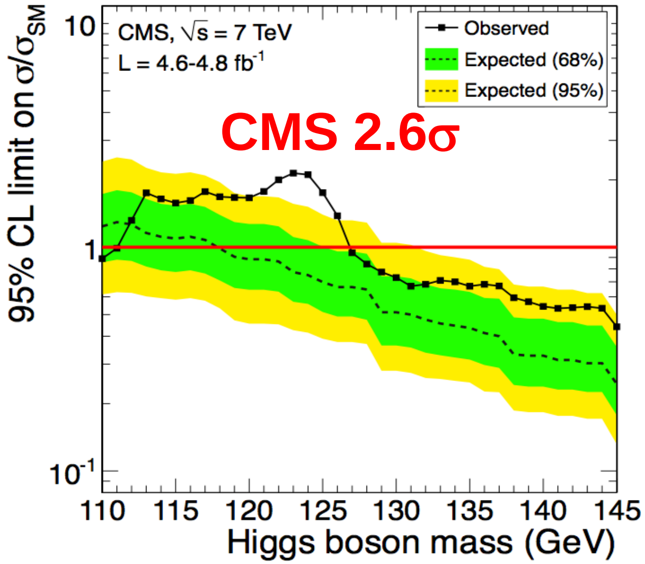



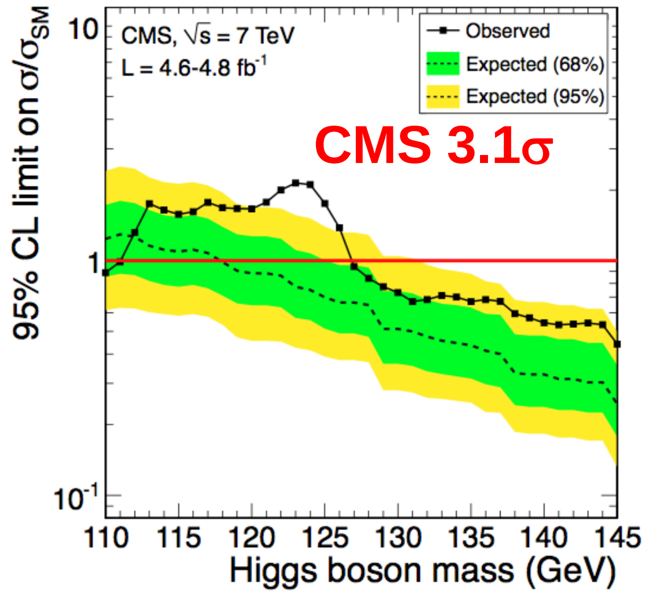

## 2nd Special Seminar at CERN, July 4th 2012.

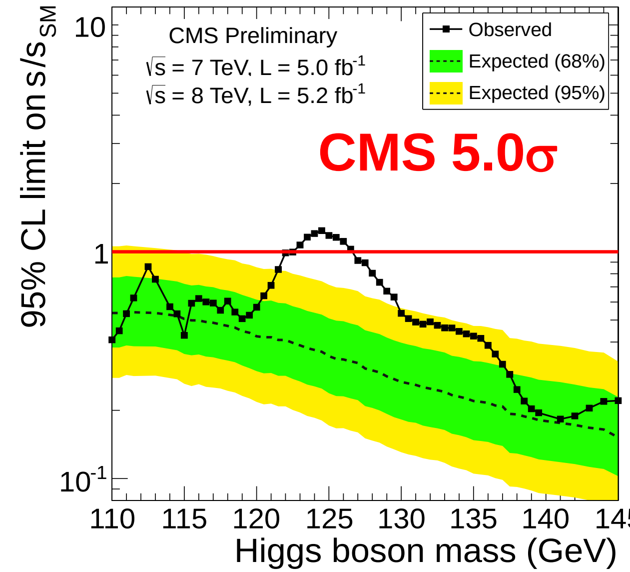
**Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC** arXiv: 1207.7214v1.

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

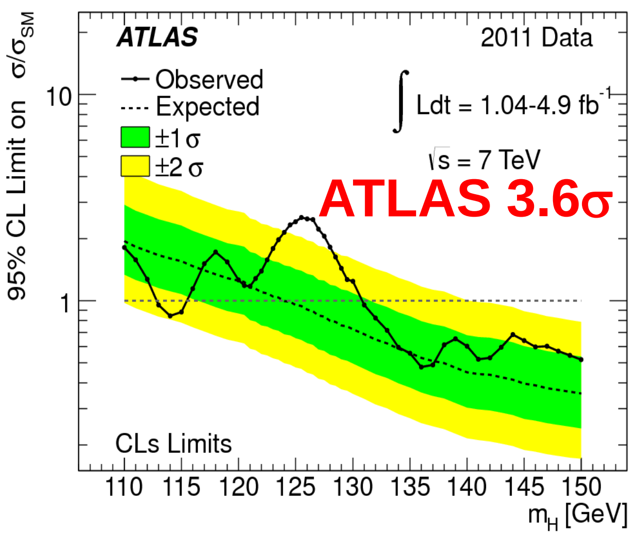
# The 7 months that changed physics

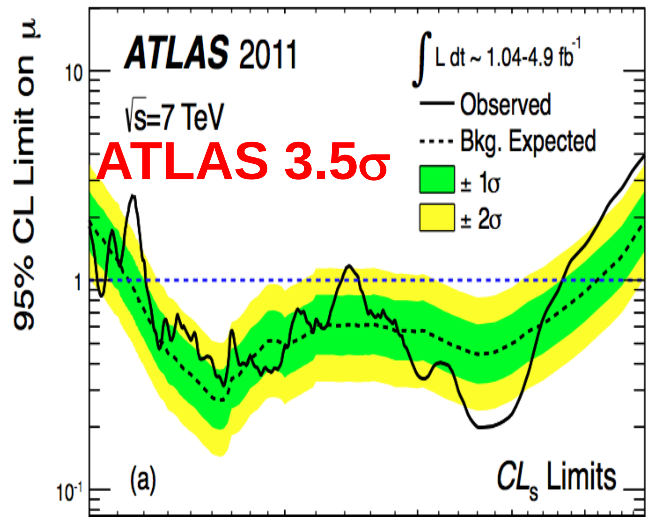


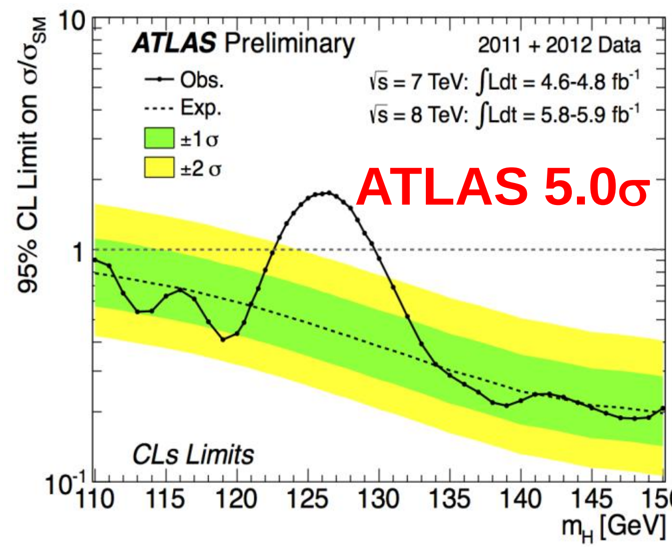




**13 Dec 2011 CERN Seminar** **7 Feb. 2012 arXiv:1202.1488v1/v3** **4 Lug 2012 CERN Seminar**

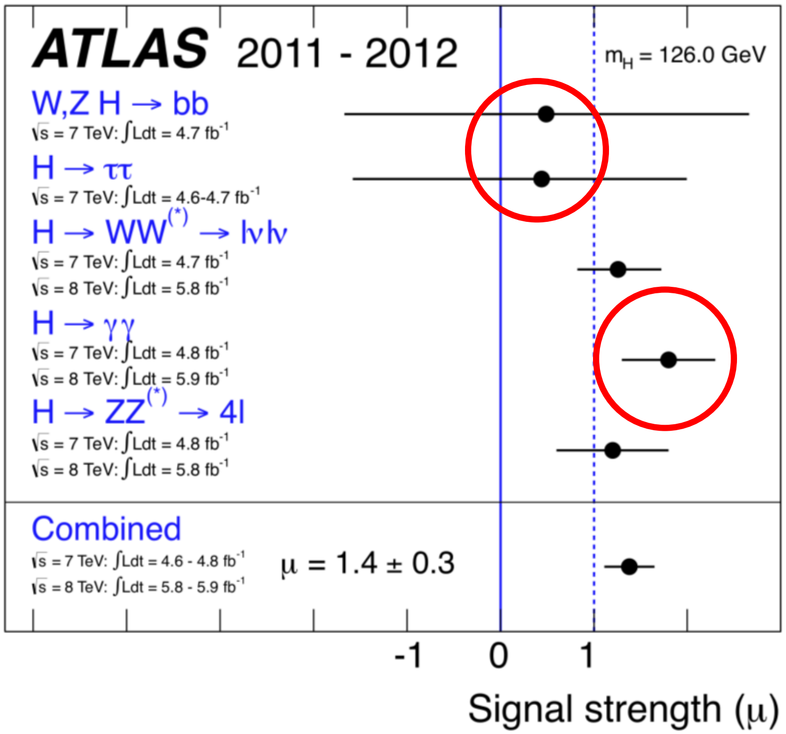


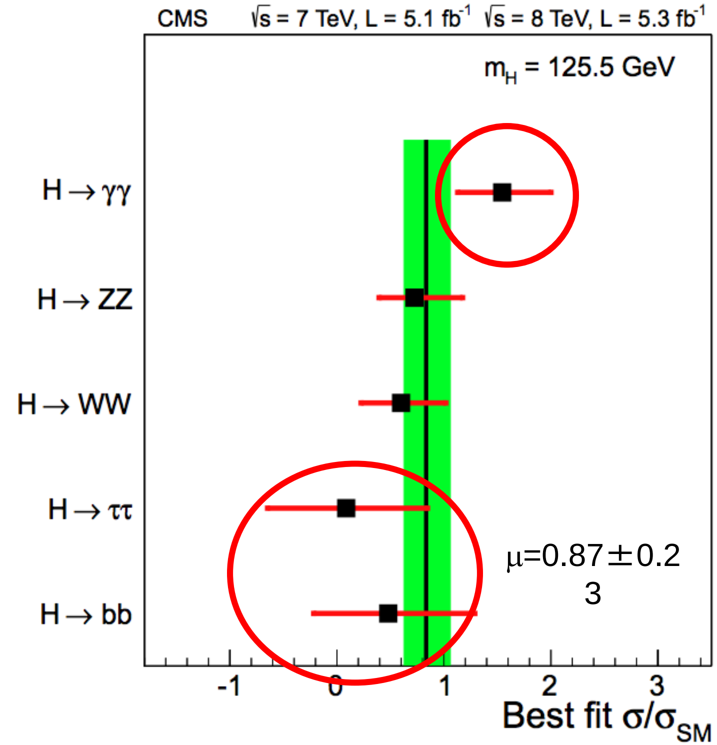



# Open issues at the time of the discovery

**1) Are we seeing the SMS? Is it a scalar? Is it preserving the custodial symmetry?**



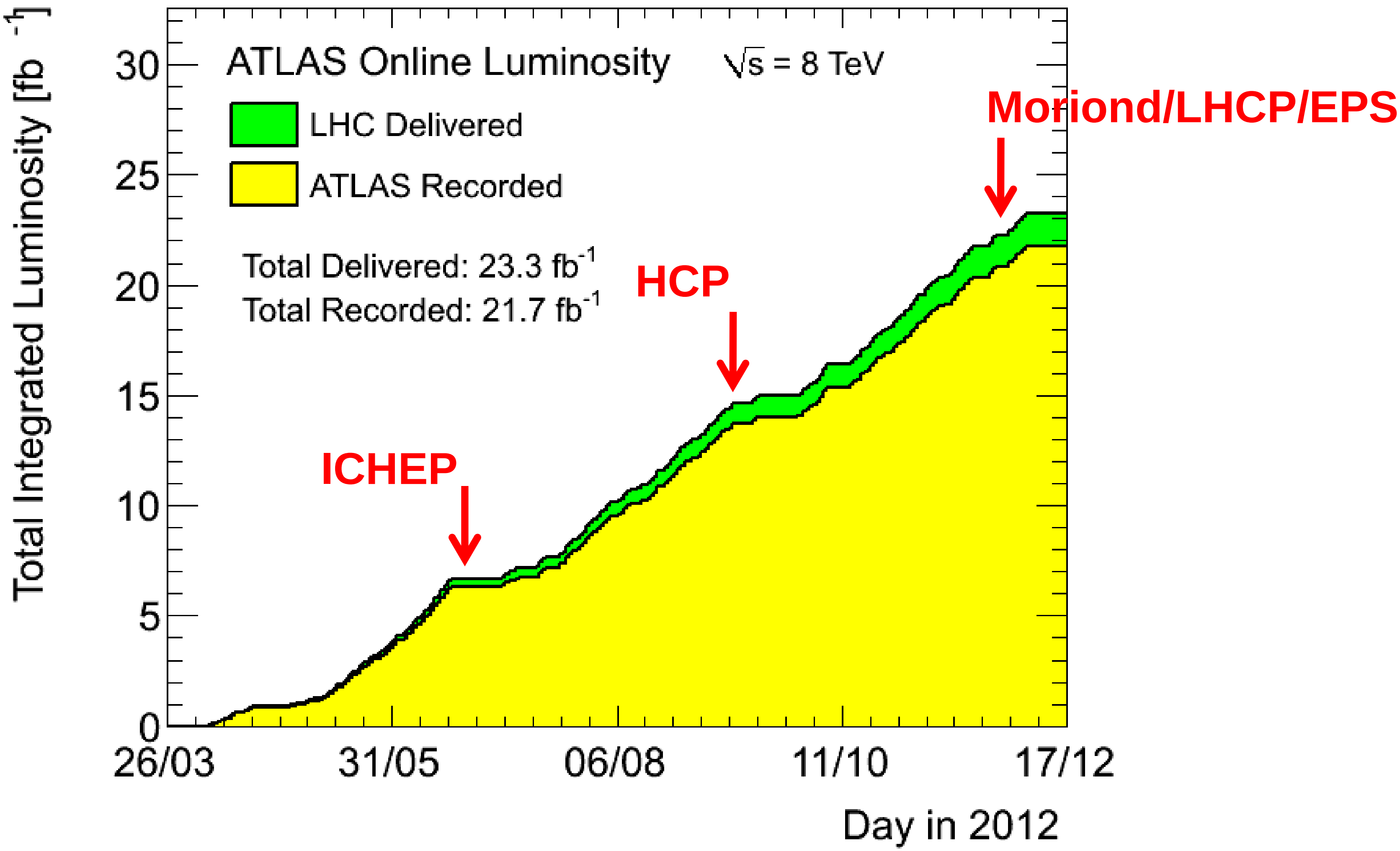

Signal strength $\sigma/\sigma_{SM}$ in different modes is consistent with the hypothesis that the new particle is the SMS boson, but…

**2) No signal in the fermionic modes ($\tau\tau$, bb): more data needed or first hint of a problem in the Yukawa coupling?**

**3) Hint of an excess in H→$\gamma\gamma$ in both experiments: statistics or new physics?**

# 4. Latest results

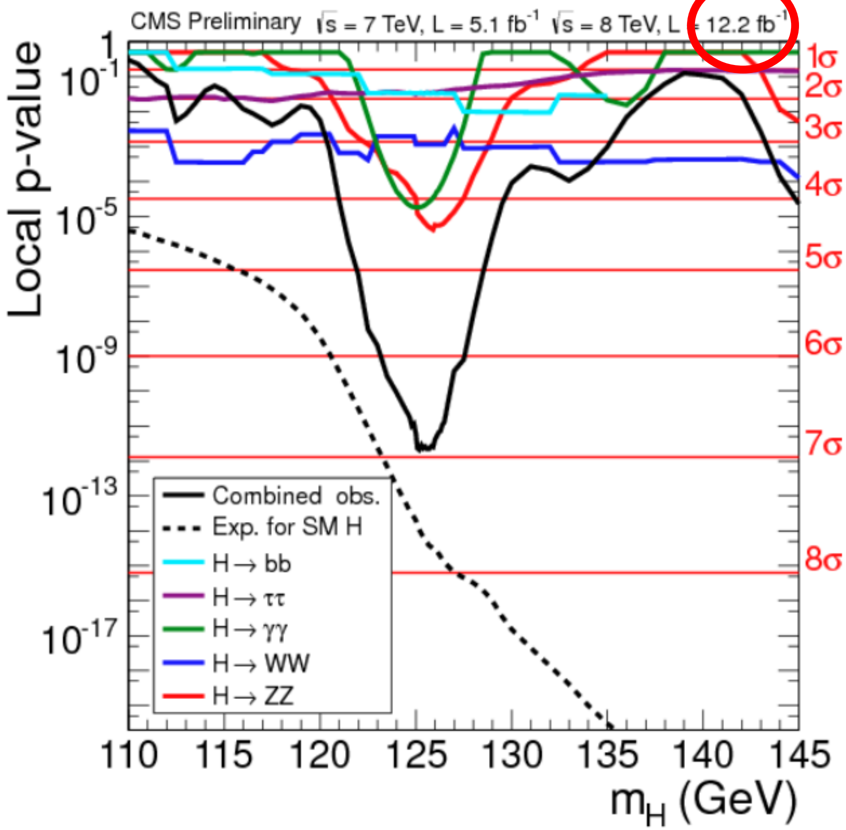
# New data collected since the discovery in 2012.



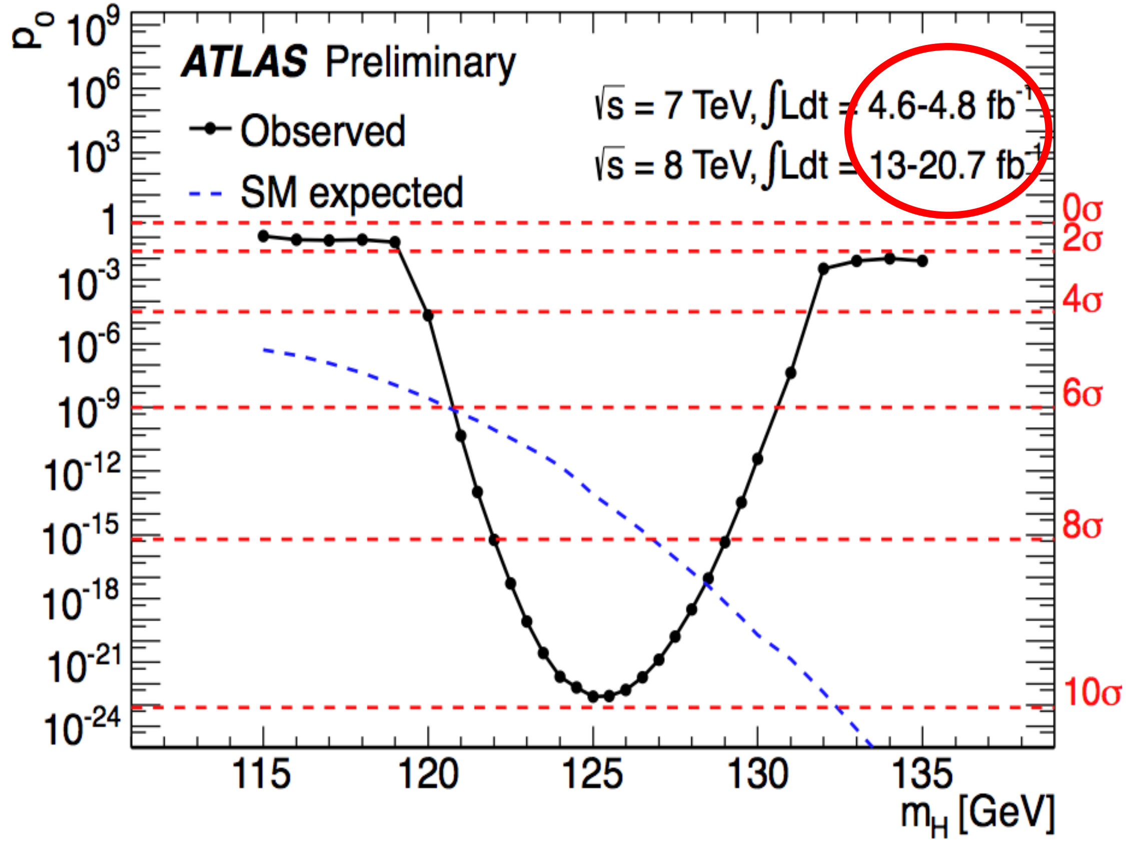

**Many results on the full data set (7+8 TeV) presented at HCP/Moriond/LHCP/EPS.**

# The signal is gaining further strength

New CMS combination shown at HCP in November 2012.




ATLAS combination shown at Moriond in March 2013 with full statistics in some channels.




**Higgs signal at 6.9σ**

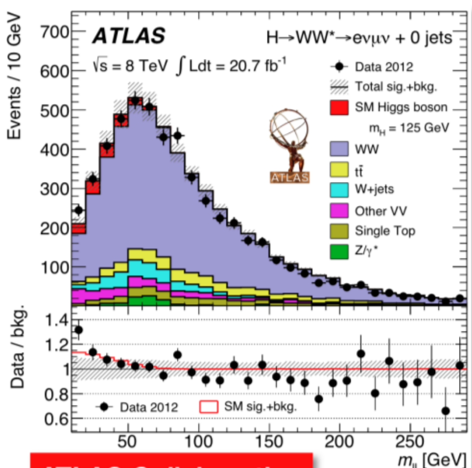
**Higgs signal at 10σ**

ATLAS-CONF-2013-034

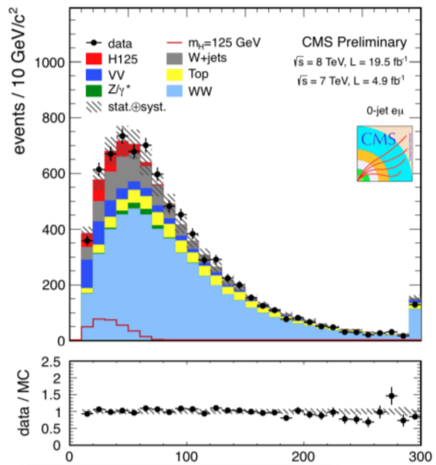
# New results on H→ WW→2l2ν

ATLAS fit to the $m_T$ distribution with full statistics. CMS: full statistics; 2D analysis using $m_{ll}$ vs $m_T$. $M_T$ for the eμ channel and cut-based analysis for the same-flavor channels (cross check in eμ)

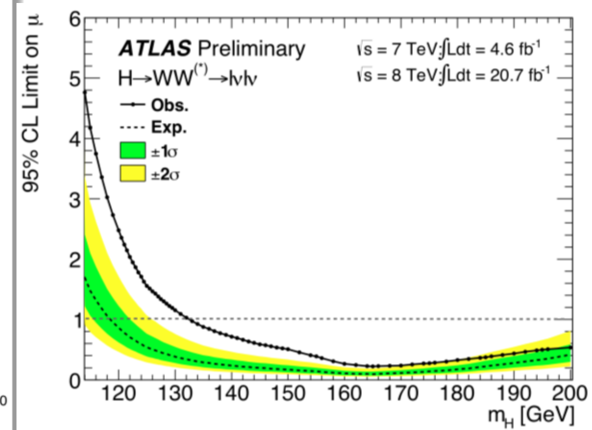
**A significant excess is observed.**




ATLAS Collaboration
arXiv:1307.1427

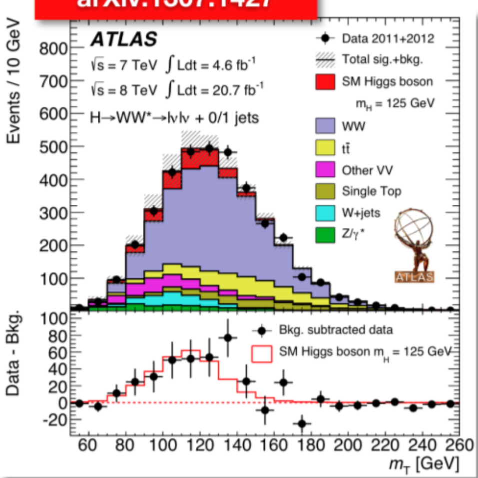


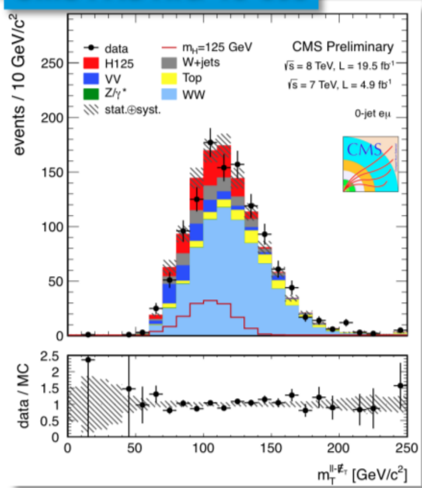

CMS PAS HIG-13-003

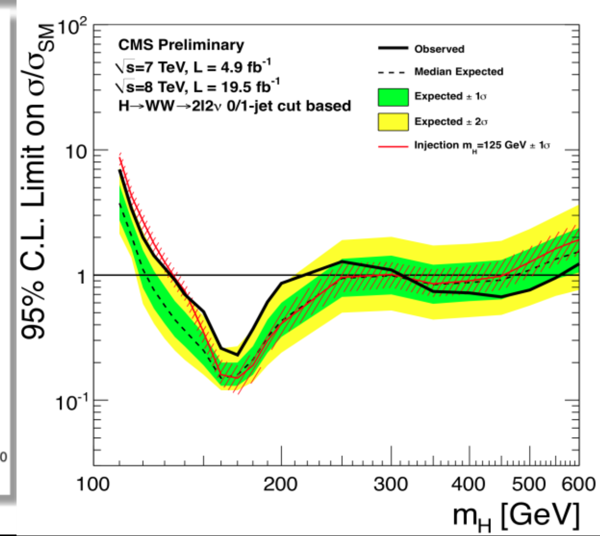



**ATLAS**
**3.8σ (3.8)**
**@ $m_H$=125.5GeV**
**μ=0.99+.31 -.28**

ATLAS-CONF-2013-030



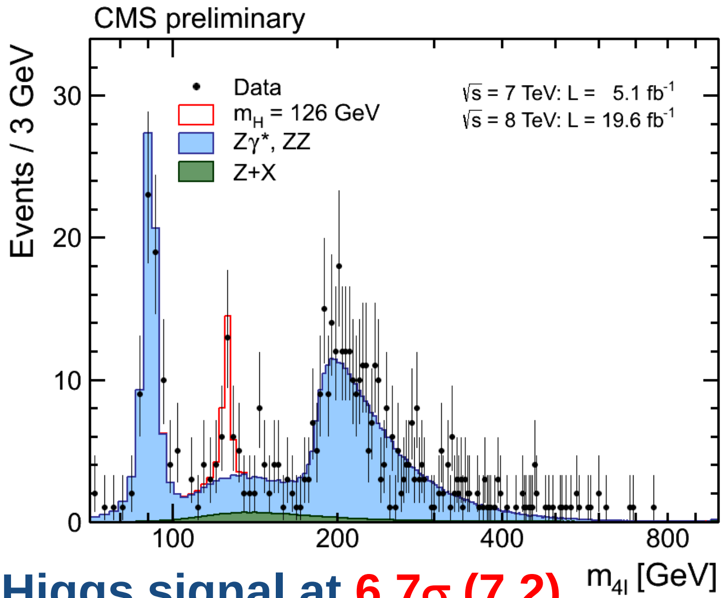

**CMS**
**4.0σ (5.1)**
**@ $m_H$=125GeV**
**μ=0.76±.21**

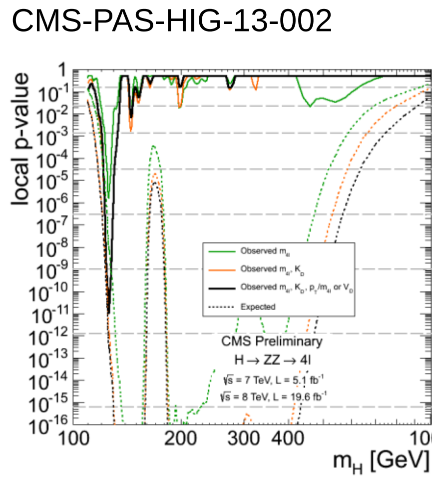
CMS-PAS-HIG-13-003

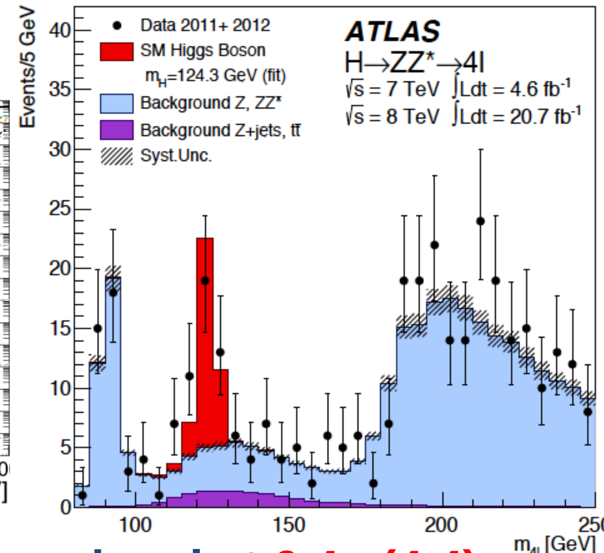
# New results on H→ZZ→4 leptons

ATLAS: cut in categories, FSR taken into account, untagged+VBF+VH

CMS: angular analysis, FSR corrections, untagged+VBF



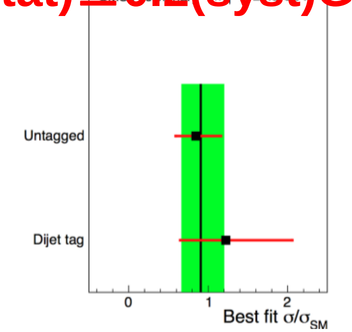




arXiv:1307.1427

**Higgs signal at 6.7σ (7.2)**

**μ=0.91+.30 -.24 @**

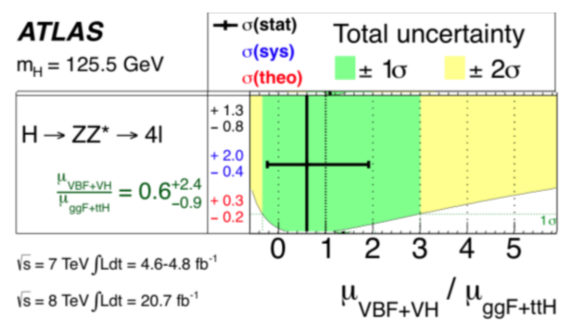
**$m_H$=125.8±0.5(stat)±0.2(syst)GeV**



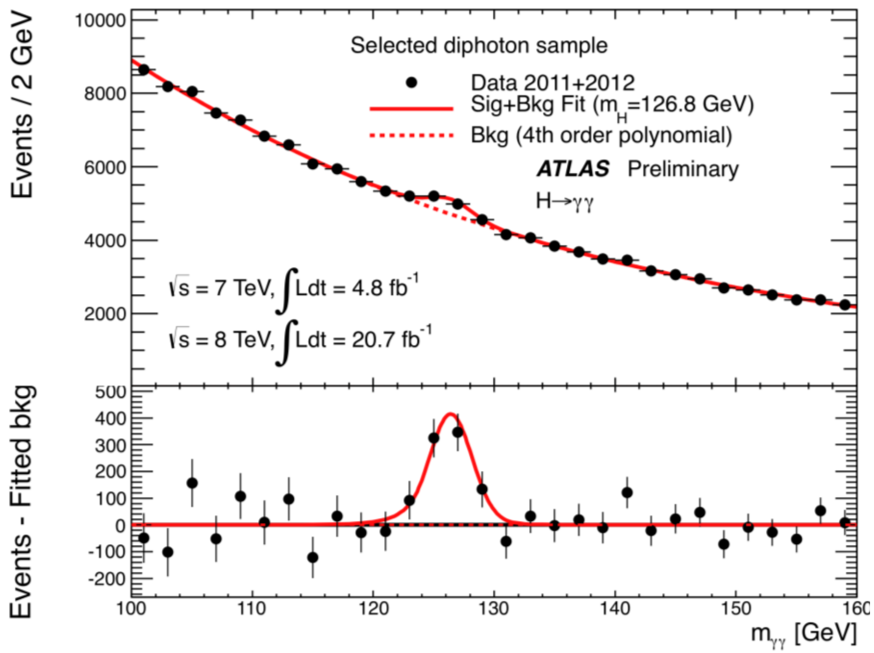

**Higgs signal at 6.4σ (4.4)**

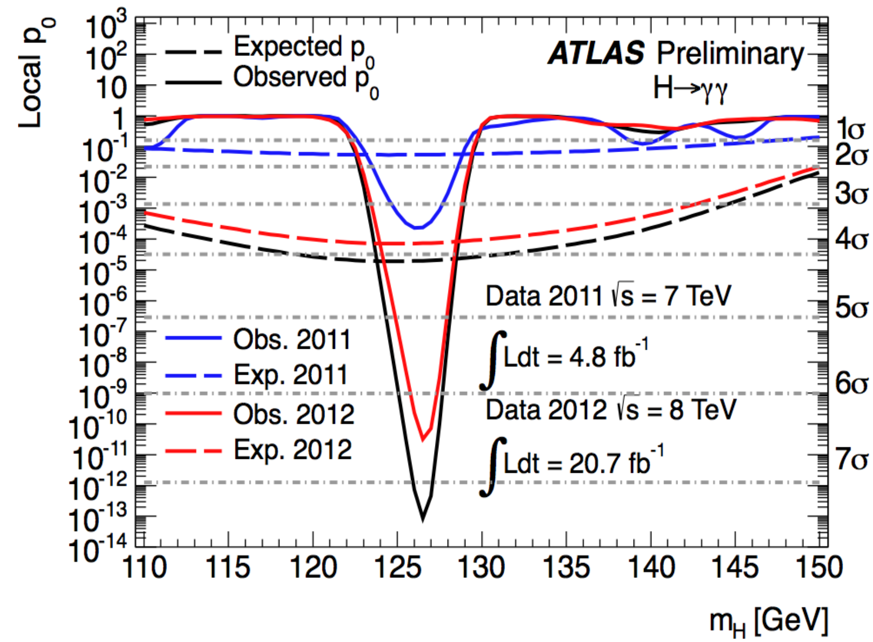
**μ=1.43+.40 -.35 @**

**$m_H$=124.3±0.5(stat)±0.4(syst)GeV**



# Updated results on H→γγ (ATLAS)

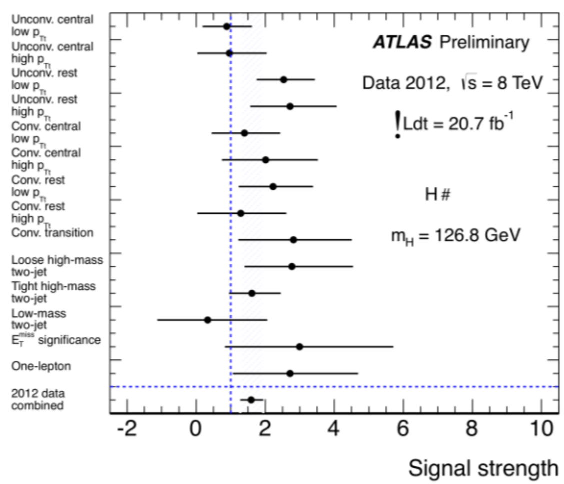


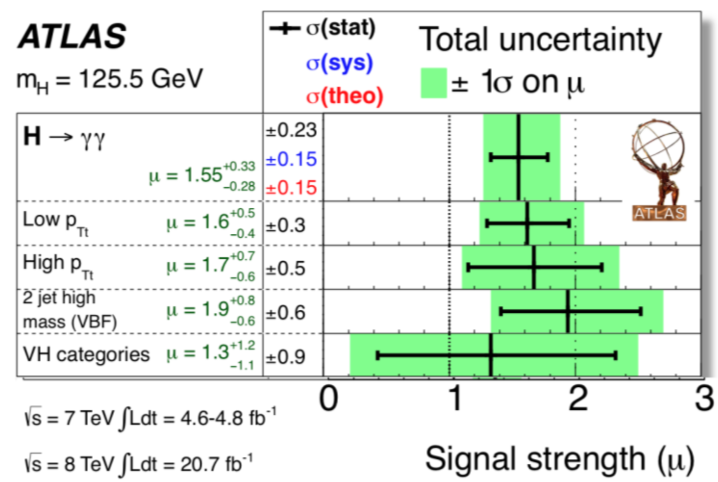




**Higgs signal at 7.4σ (4.1)**

**$\mu$=1.65±.24 +.25-.18**

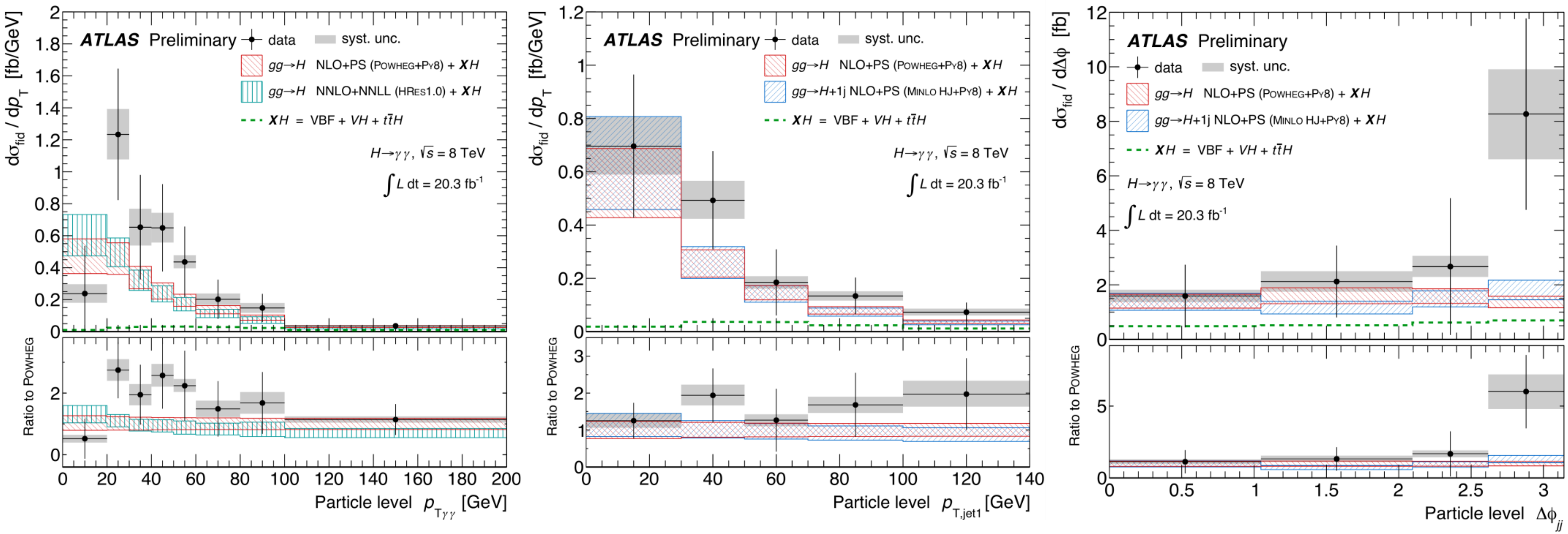
**@ $m_H$=126.8GeV**



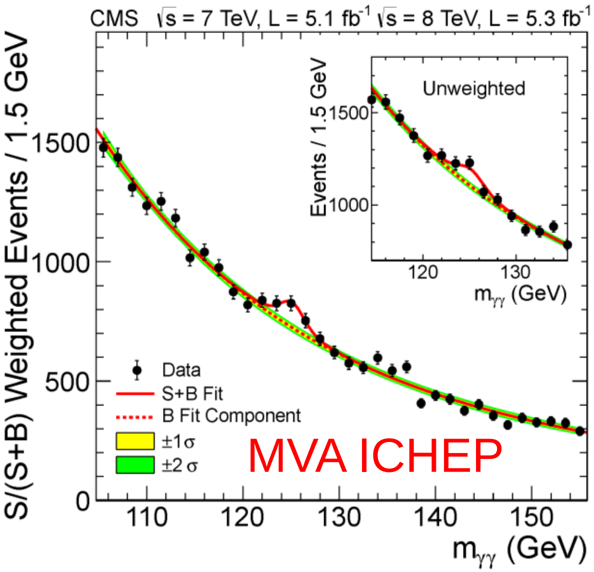
# Differential measurements in H→γγ (ATLAS)

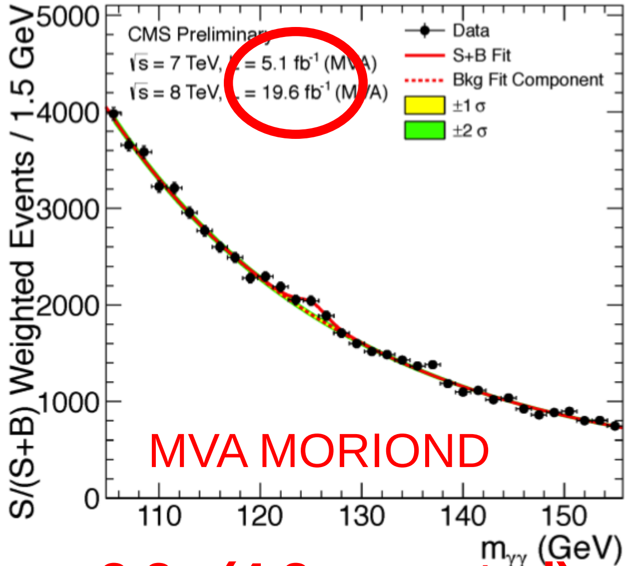
Differential cross sections of the Higgs bosons decaying into two isolated photons, for $p_T$, rapidity, |cos theta*|, and leading jet $p_T$.
Selections are similar to the ones used for the discovery + detector unfolding.

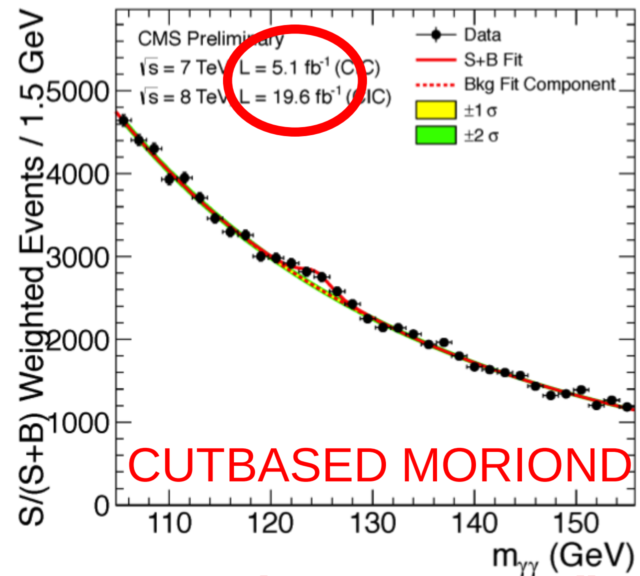



Observed a somewhat harder $p_T$ spectrum wrt the NLO predictions (POWHEG, MINLO) or NNLO (HRes). Slight excess in the back-to-back di-jets.

# The signal strenght in H→γγ in CMS.




**4.1σ (2.8 expected)** **3.2σ (4.2 expected)** **3.9σ (3.5 expected)**

Comparing to published result significance decreased, two effects contributing: re-analysis of 8 TeV data and addition of new data. Main analysis MVA, cut-in-categories (CiC) used as a cross-check.

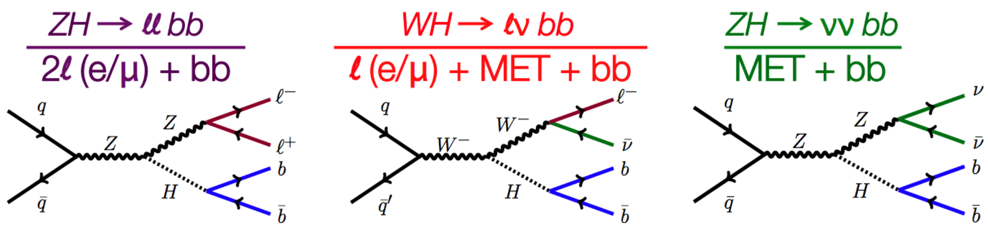
**Signal strength μ :**

CMS-HIG-13-001

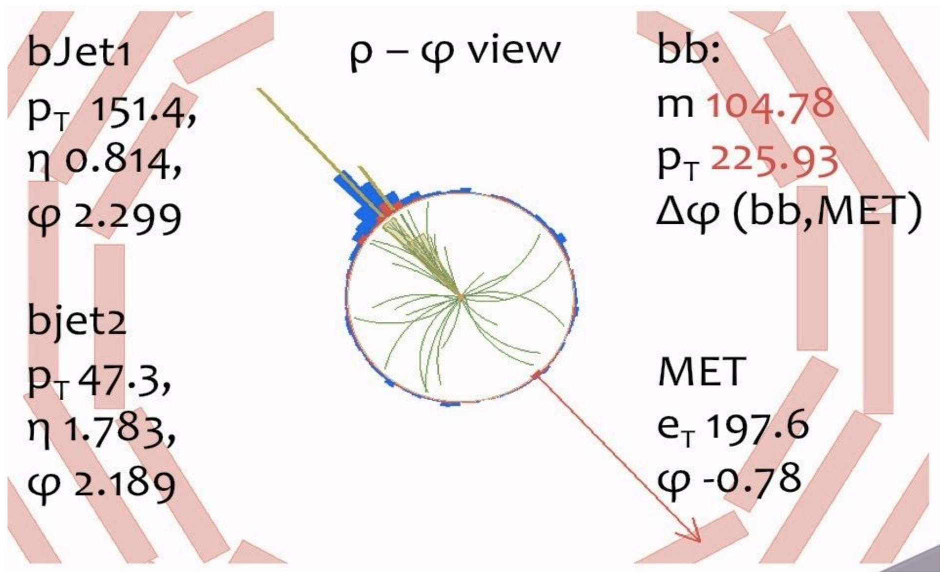
| | MVA analysis (at $m_H$=125 GeV) | cut-based analysis (at $m_H$=124.5 GeV) |
|---|---|---|
| 7 TeV | $1.69^{+0.65}_{-0.59}$ | $2.27^{+0.80}_{-0.74}$ |
| 8 TeV | $0.55^{+0.29}_{-0.27}$ | $0.93^{+0.34}_{-0.32}$ |
| 7 + 8 TeV | $0.78^{+0.28}_{-0.26}$ | $1.11^{+0.32}_{-0.30}$ |

# Coupling to fermions: H→bb

- The H→bb is the dominant BR in the low mass region (~60%) but the enormous QCD di-jet background makes this channel very challenging at LHC.
- **The best option: associated production: qq→VH; H→ bb; final states with leptons, missing $E_T$ and b-jets. Signal purity (S/N): ~1%-10%**
- **Several sub channels (W→lν incl. τ; Z→ee, μμ, νν)**




qq→ ZH; Z→νν, H → bb

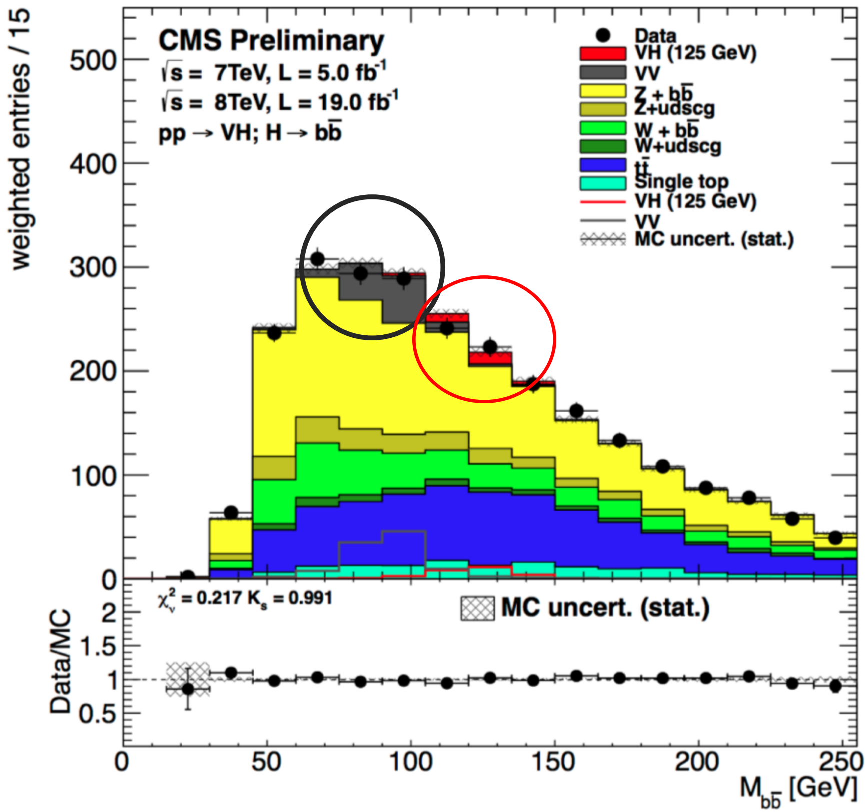


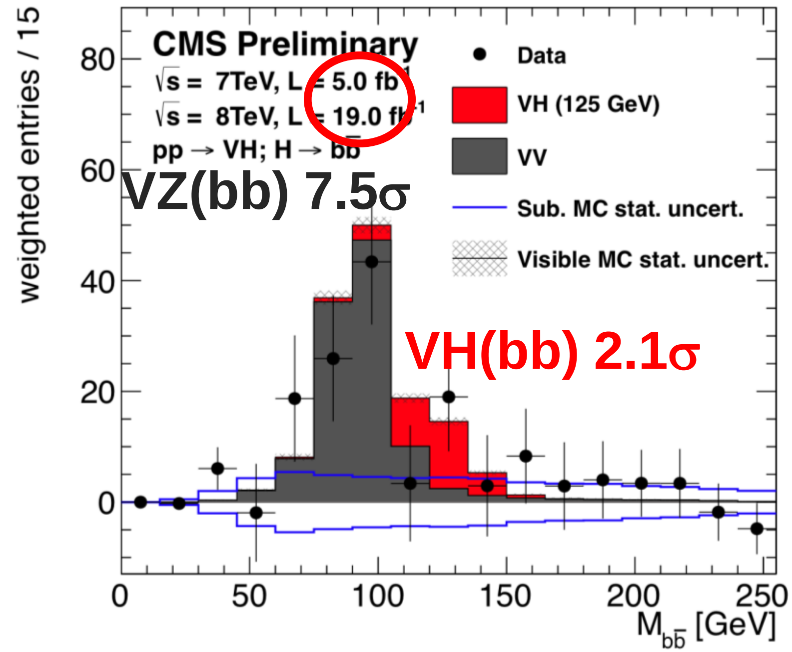

## Key selection criteria

- **VH topology : ΔΦ(V,H)**
- **$P_T$(V)> 100-160 GeV (boosted W/Z)**
- **Two b-tagged jets**
- Major backgrounds (V+jets, ttbar from data)
- Shape analysis on signal discriminator

# Coupling to fermions: H→bb (CMS)

**Mass resolution ~10%** we don't expect to see much more than a broad excess

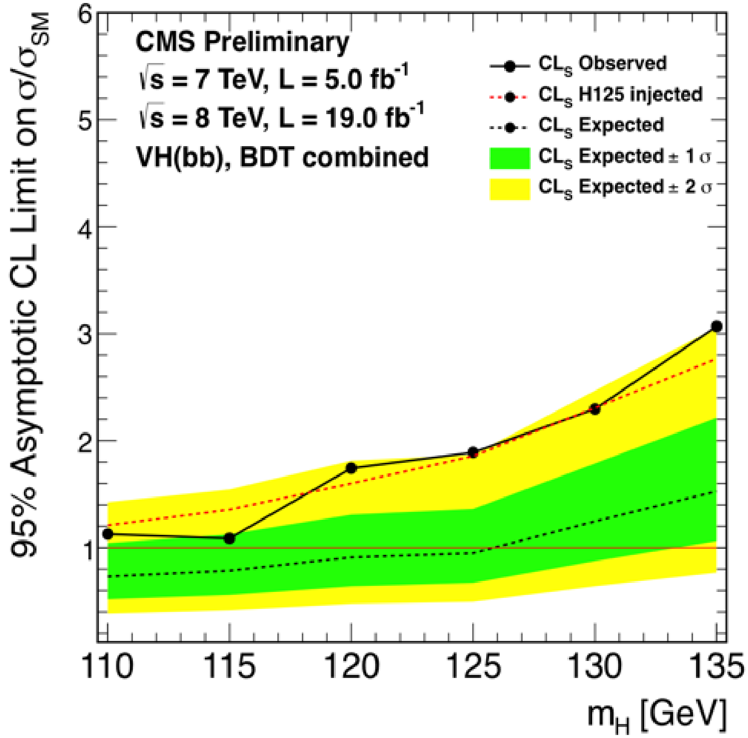


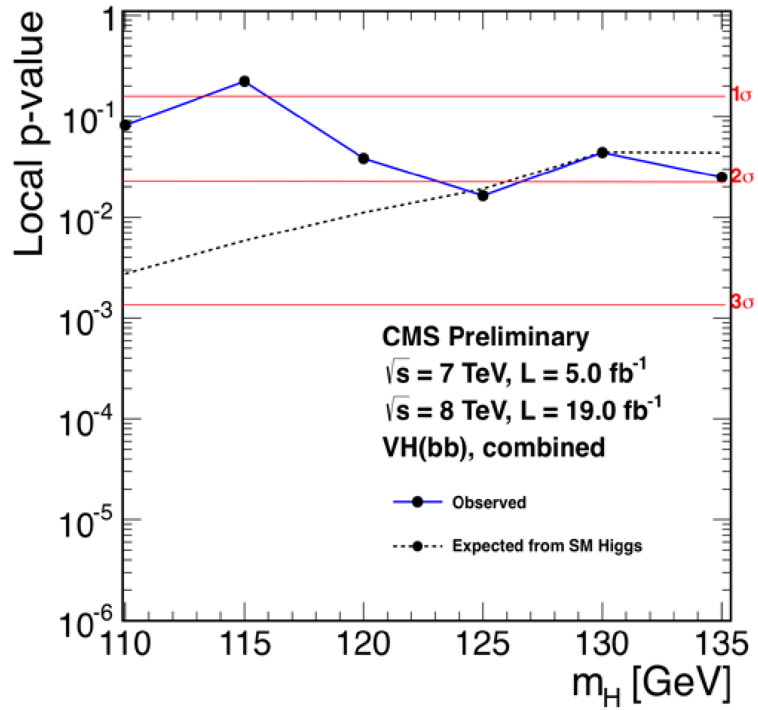



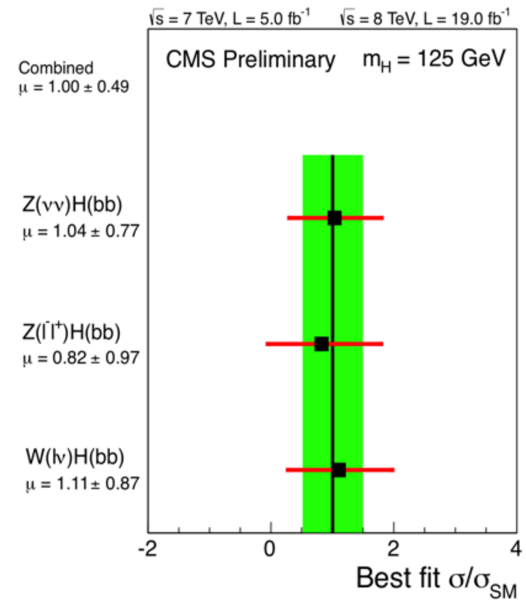

CMS-HIG-13-012

**Over 7σ significance for the VZ(bb) signal.** As a validation of the multi-variate technique, BDT discriminants are trained using the diboson sample as signal, and all other processes, including VH production, as background. **First hints of a broad excess compatible with a Higgs boson signal in the low mass region.**

# VH→bb (CMS)



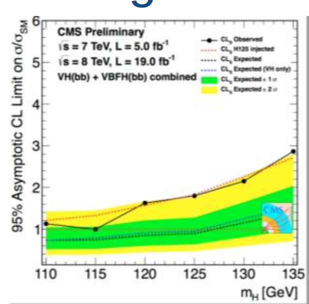



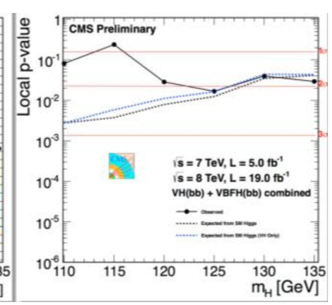

CMS-HIG-13-012

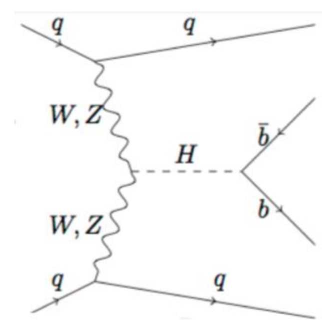
**Local significance at 125GeV 2.1σ (2.1σ). Best-fit μ=1.0±0.49. All modes compatible.**

New analysis in CMS on VBF H(bb): promising results.

CMS-HIG-13-011

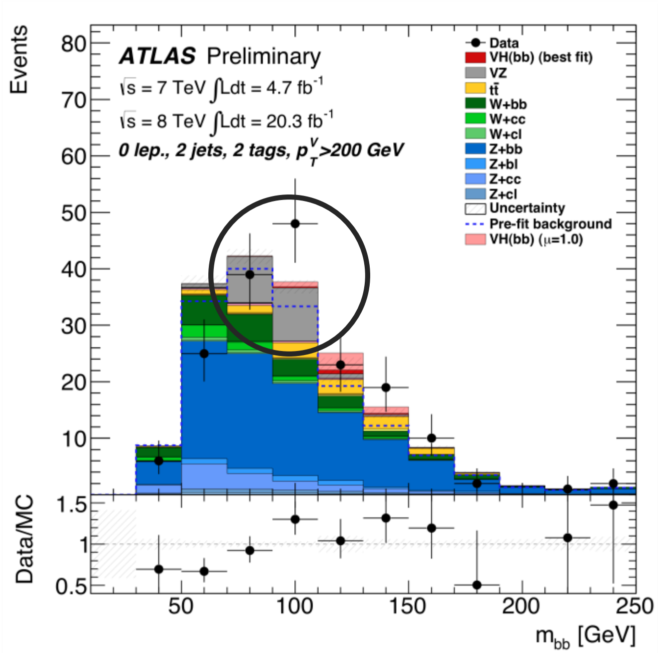


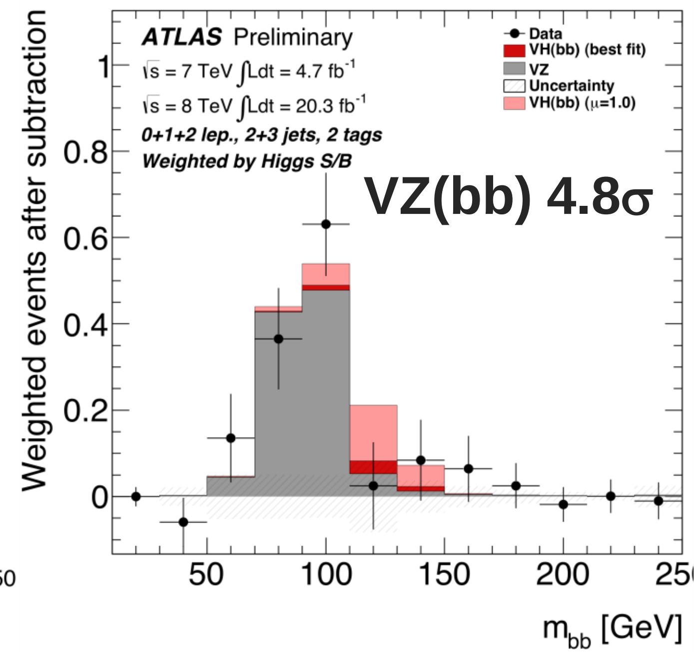



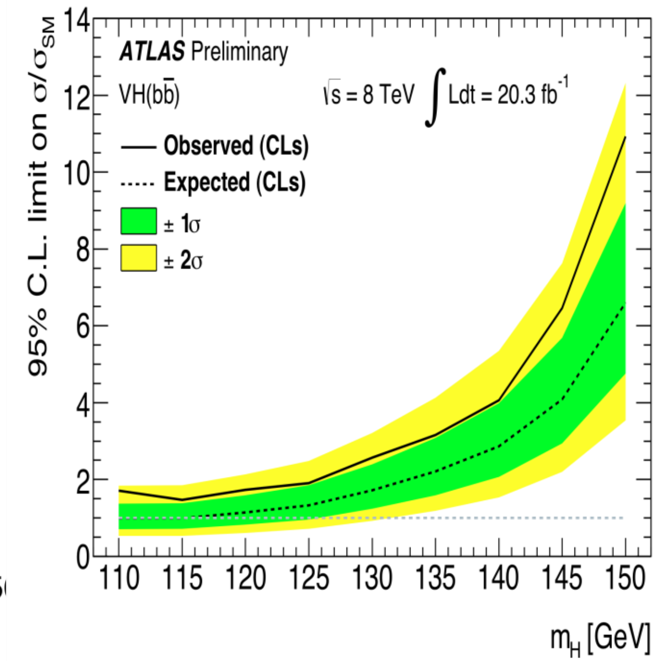



# VH→bb in ATLAS

Search done in 0, 1, 2 lepton categories. Additional split using $p_T$ (V) >200GeV



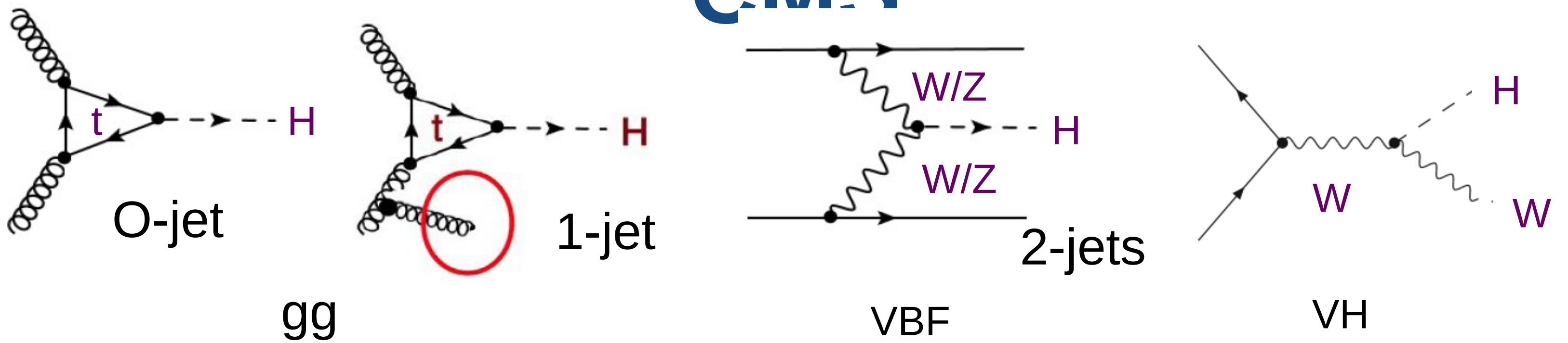



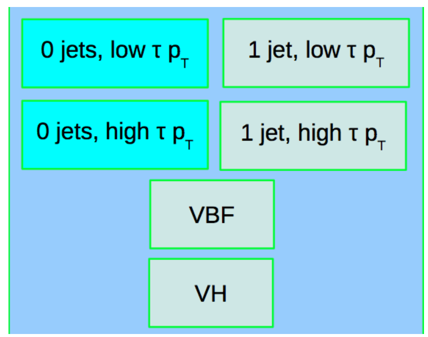

ATLAS-CONF--2013-080

**No signal (yet); limit $\mu$< 1.4 (1.3) @ 125GeV. $\mu$=.2+.7-.6.**

# Coupling to fermions: H→ | | in CMS

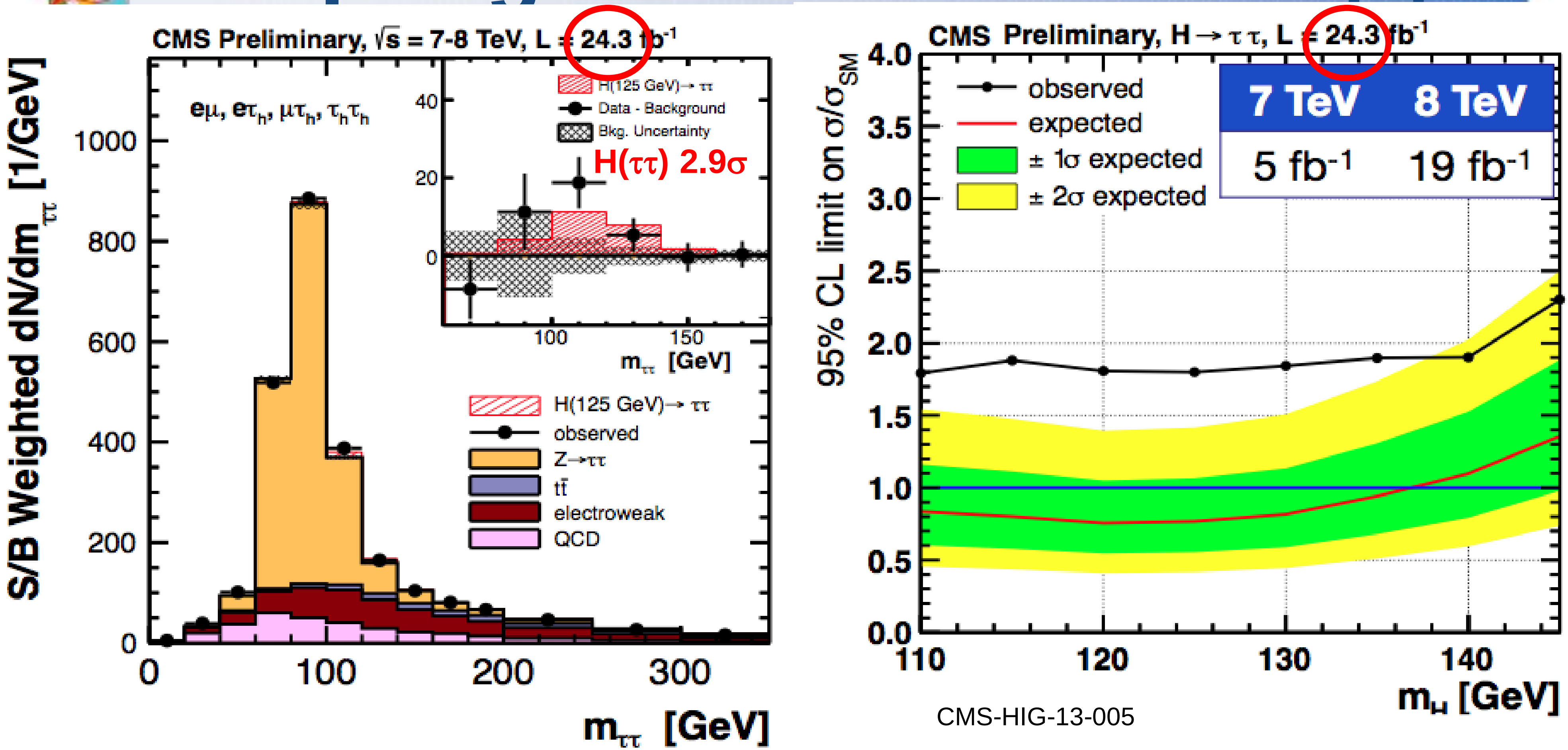



The H → | | analysis searches for a broad excess in the reconstructed di-tau invariant-mass distribution. Events are classified according to **several independent production channels and final states (e |$_h$ , μ |$_h$ , eμ, and μμ). Signal purity (S/N): 0.3-30%.**




The invariant mass $m_{\tau\tau}$ is reconstructed using algorithms combining the visible | decay products and the missing transverse energy. **Optimized mass resolution of about 15-20% at 125GeV**. Main irreducible background Z→ττ production. VBF most sensitive channel.

# Coupling to fermions: H→ ττ



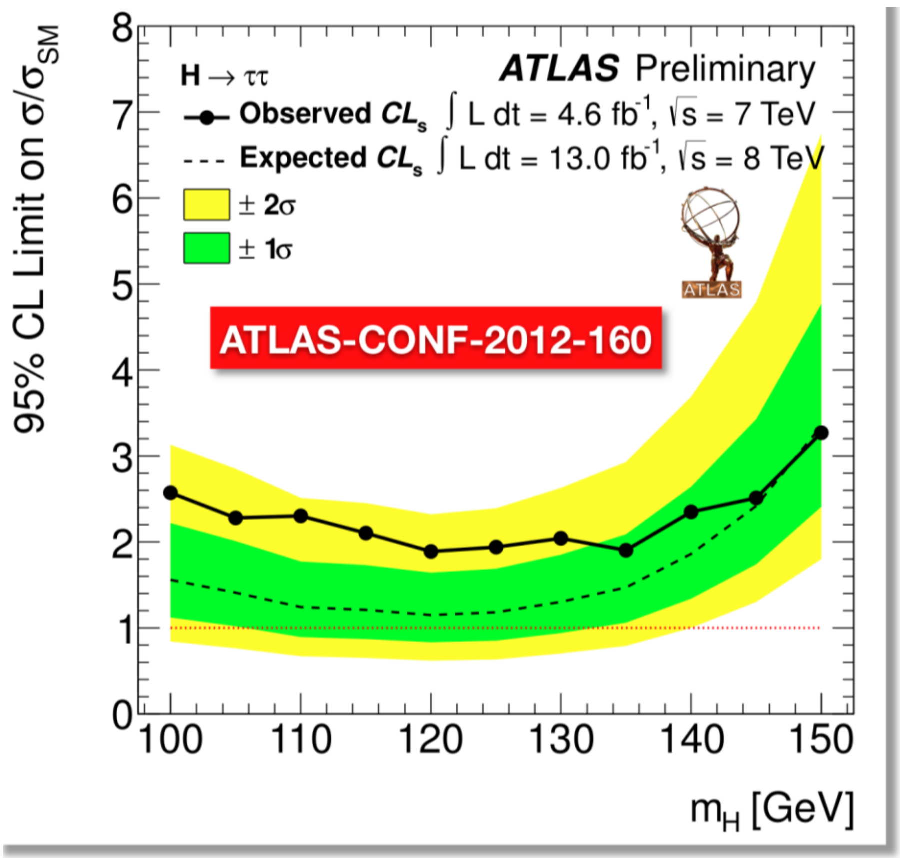

CMS-HIG-13-005

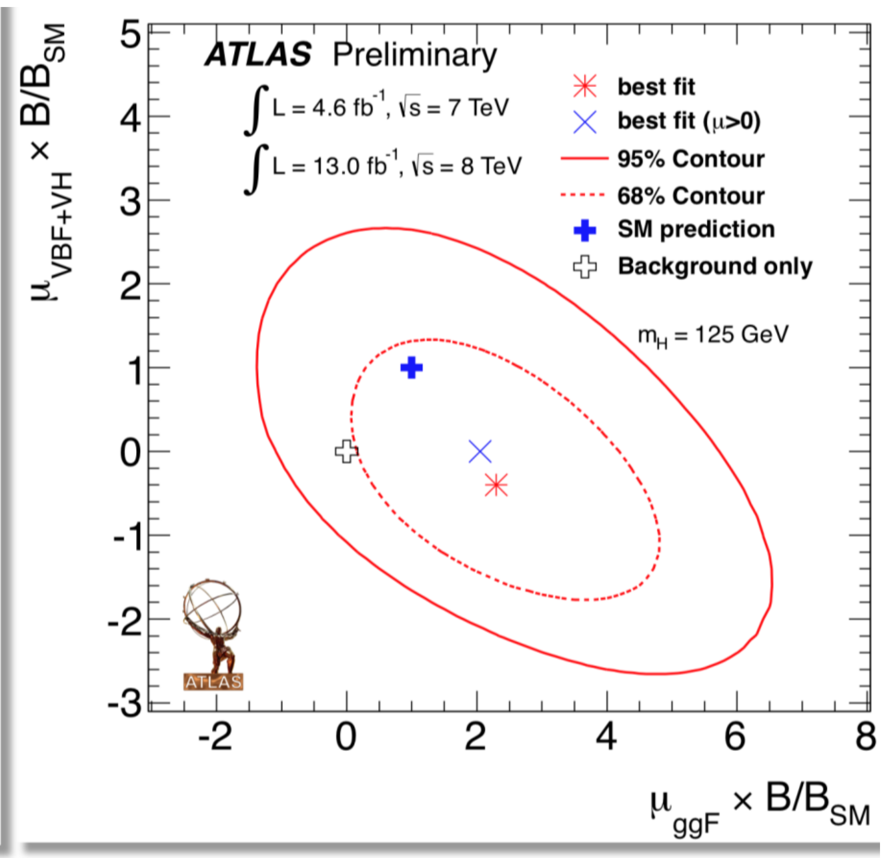
**Broad excess in the low mass region. Local significance @125GeV 2.9σ (2.6σ). Best-fit μ=1.1±0.4. Combining with VH→bb, CMS shows the first evidence, 3.4σ (3.4σ) that the new particle does couple directly to the 3rd gen. down-type fermions. First measurement of the mass $m_H$= 120+9-7GeV.**

# H→ | | in ATLAS

The H→ | | analysis in ATLAS uses similar techniques as the CMS analysis but it has not been updated yet with full statistics.

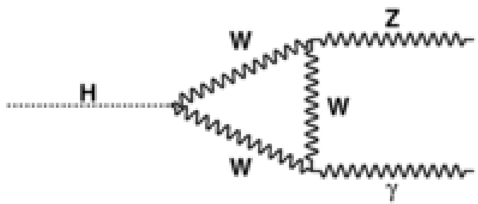
**Local significance at 125GeV 1.1σ (1.7σ). Best-fit μ=0.7±0.7.**

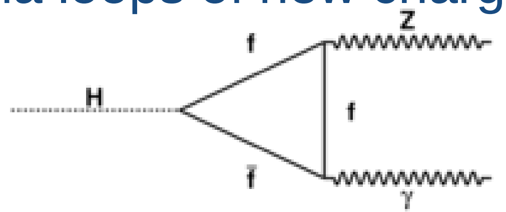


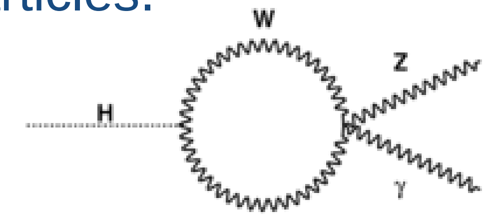



# H→Zγ results

Sensitive to new physics via loops of new charged particles.

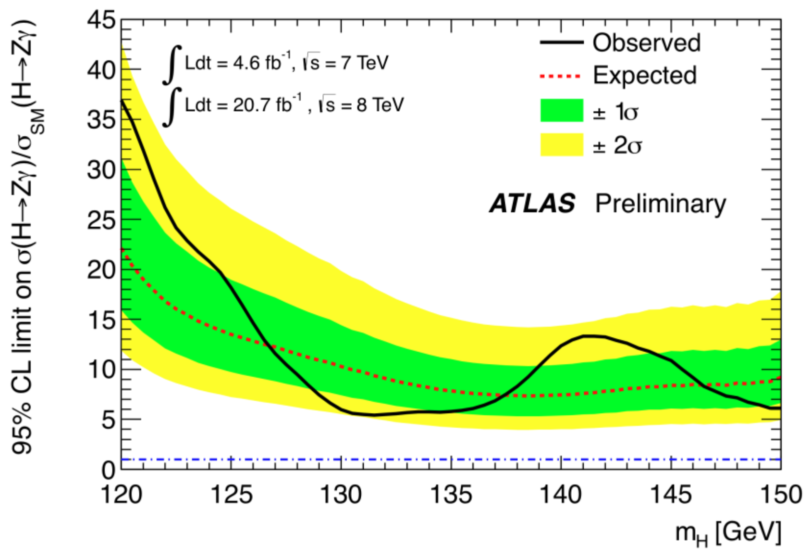


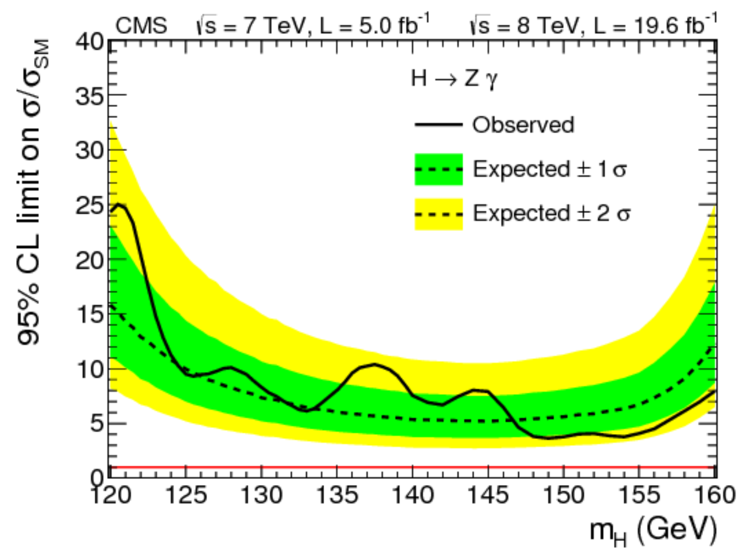




BR similar to H→γγ but decay further suppressed by the small BR of the Z leptonic decays.

ATLAS-CONF--2013-009




CMS: CERN-PH-EP-2013-113




Not sensitive (yet) to SM Higgs boson production. Ready to exclude large enhancements.

**Only limits for the μ<18.2 (13.5) ATLAS ; μ<5.4 (5.3) CMS @ 125GeV.**

# Search for ttH(H→bb, ττ, γγ)

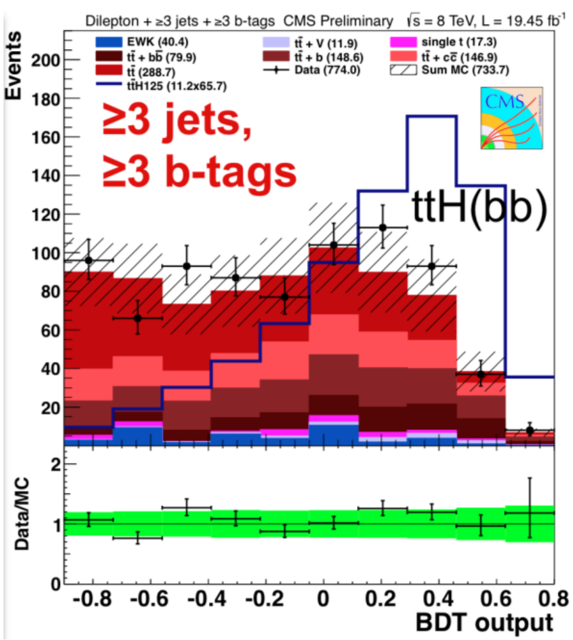
**Very important to check the direct coupling to the heaviest quark.**

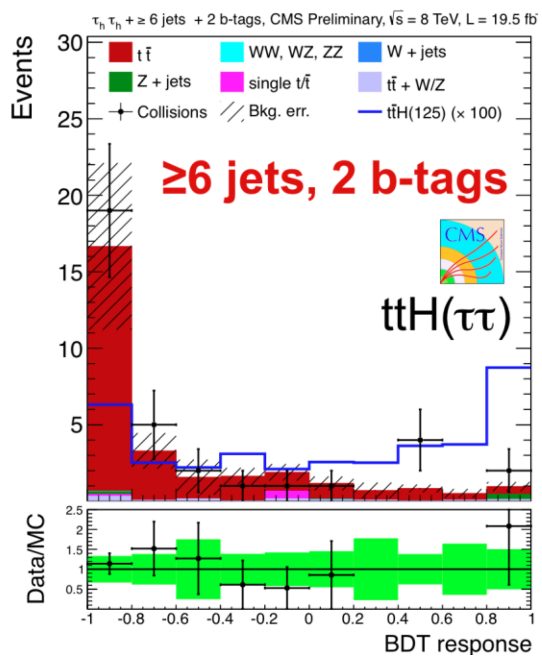
**H→bb**: tt-bar reconstructed in the lepton+jets and di-lepton channels. 2 or more b-tagged jets in the event.

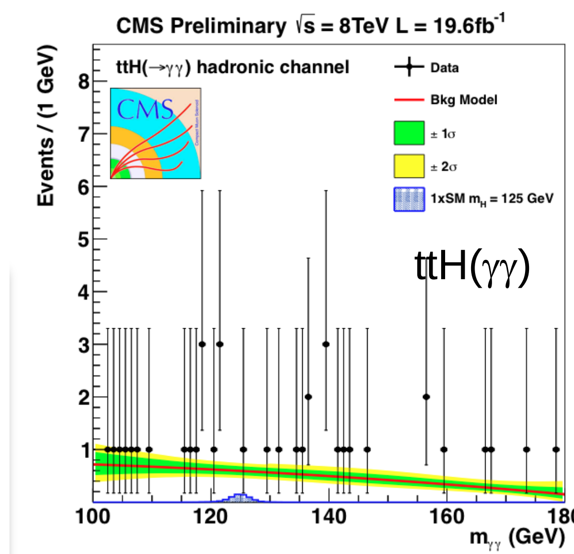
**H→ττ**: tt-bar pairs reconstructed in lepton+jets and 1 or 2 b-tagged jets + fully hadronic channels for both taus ($\tau_h+\tau_h$).

Signal extraction via BDT (separate BDts for each jet and b-tagged multiplicity).

**H→γγ**: tt-bar pairs reconstructed in lla hadronic and semileptonic modes with loose selections and at least 1 b-tag; di-photon analysis similar to the baseline for H→γγ.




CMS-PAG-HIG-13-019 CMS-PAG-HIG-13-015

# Results for ttH

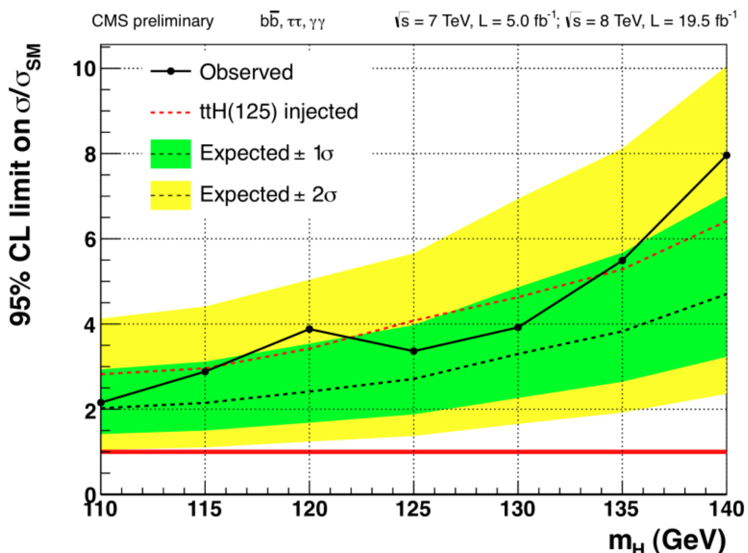
## Results for CMS

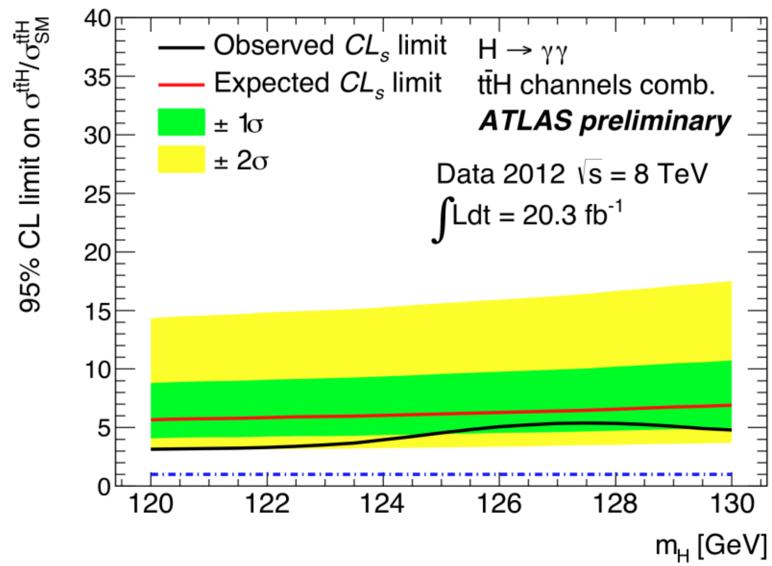
H→bb, ττ **μ<5.2 (4.1) @125GeV.** H→γγ **μ<5.4 (5.3)@ 125GeV.**

**Combined result for CMS: μ<3.4 (2.7) @125GeV.**

## Results for ATLAS

H→γγ **μ<5.3 (6.4)@ 125GeV.**




CMS-PAG-HIG-13-019

CMS-PAG-HIG-13-015 arXiv:1303.0763

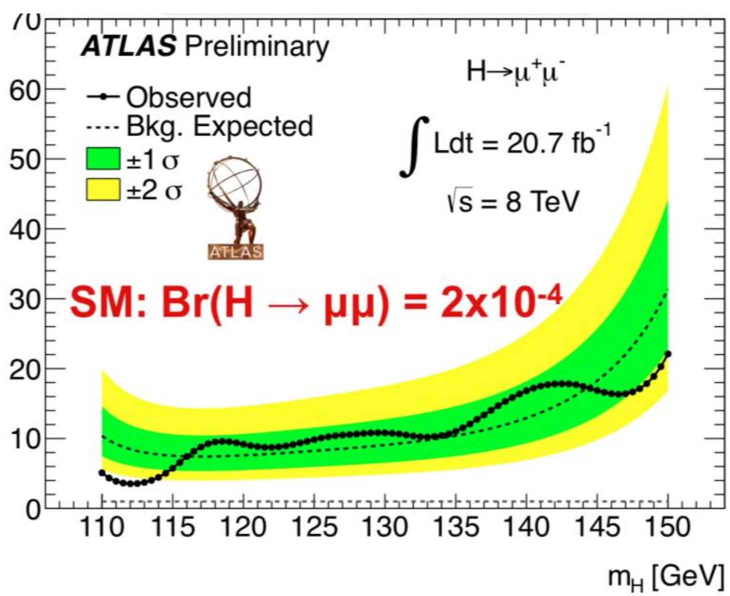
ATLAS-CONF-2013-080

# Very rare decays: H→μμ (ATLAS)

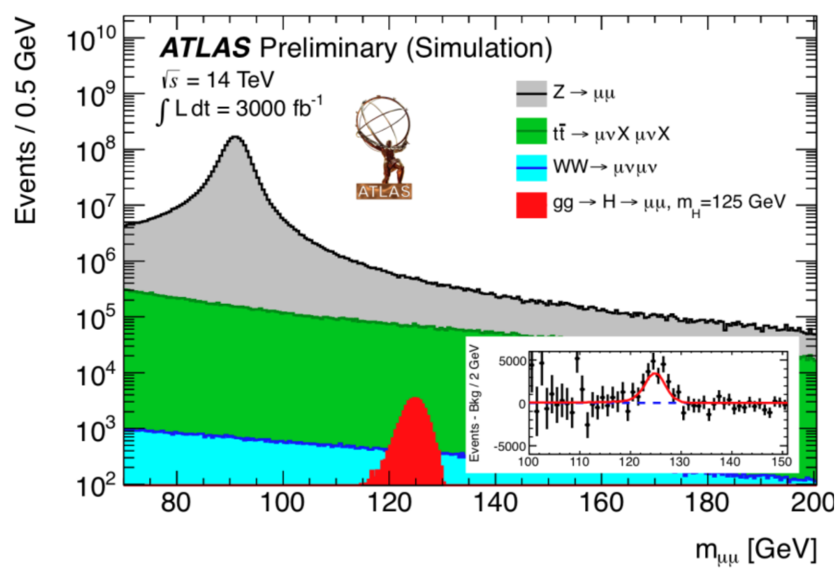
The observation of the H→μμ decay is mandatory to complete the probing of the Higgs coupling. It would require a huge statistics.
It is the typical benchmark for the HL-LHC.

The first search performed by ATLAS appears to be very promising:
Limits on the μ at the level of **μ<9.8 (8.2) @ 125GeV.**

ATLAS-CONF-2013-010




ATLAS-PHYS-PUB-2012-004



# Invisible Higgs decays.

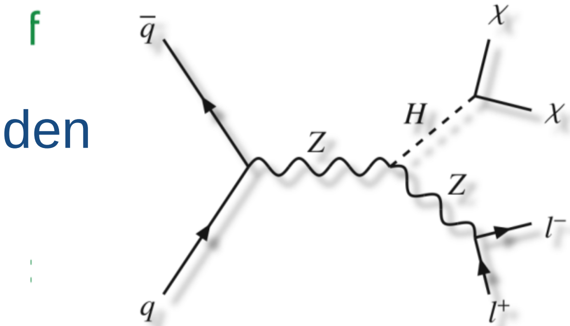
There is still a lot of room for decays of H into invisible particles (coupling to light dark matter, Hidden Valley models, RH neutrinos etc).

The search is done in looking for associated production of a Higgs boson with a Z decaying leptonically.

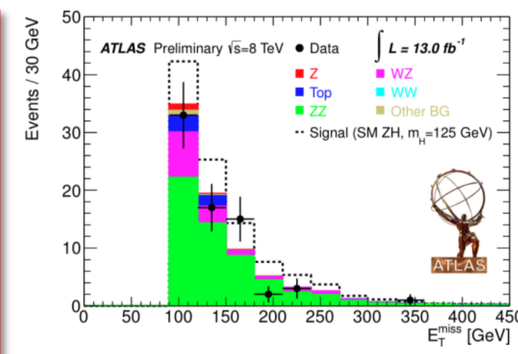
Discriminating variables: missing $E_T$ (ATLAS), $M_T$(CMS).

**ATLAS** (4.7+13fb$^{-1}$)
**BR(X)→χχ<65% (84%)  @ 125GeV.**

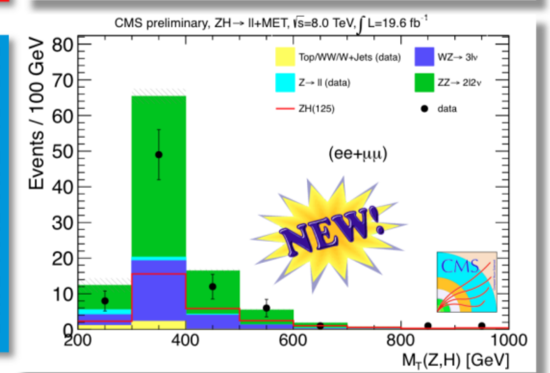
**CMS** (5+20fb$^{-1}$)
**BR(X)→χχ<75% (91%)  @ 125GeV.**




ATLAS-CONF-2013-011




CMS PAS HIG-13-018



# Have we observed a scalar?

**Spin/parity ⇆ angular distribution of final decay products**

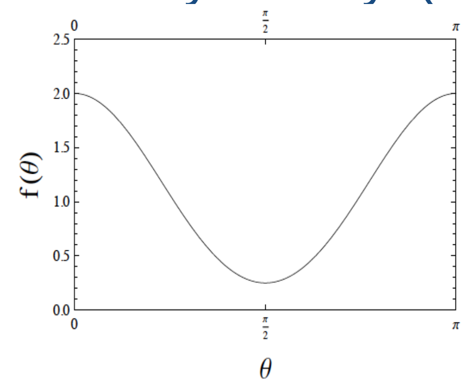
Since it decays to two photons: spin 1 is forbidden by Bose symmetry (Landau-Yang theorem).

1) gg →X→γγ qq →X→©© Gao et al. 2010

spin-0: flat in cosθ*

spin-2: quartic in cosθ*

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

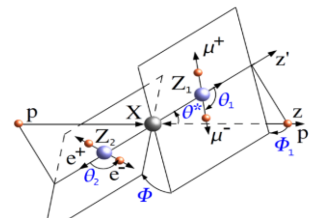



2) gg →X→ZZ*→4ℓ Choi et al. 2002, De Rujula et al 2010

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

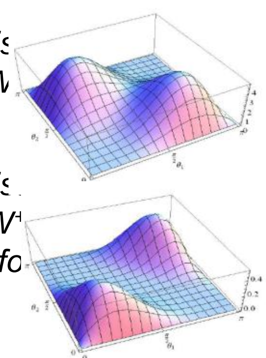
arXiv:1001.5300

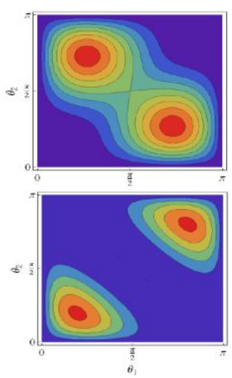
3) gg →X→W⁻W⁺ →ℓ⁻ℓ⁺{ { Ellis et al. 2012

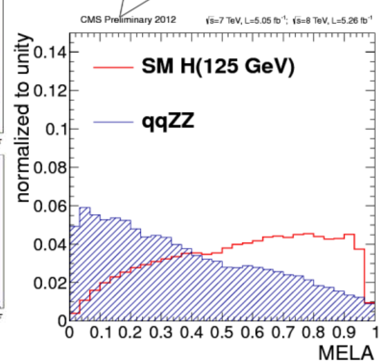


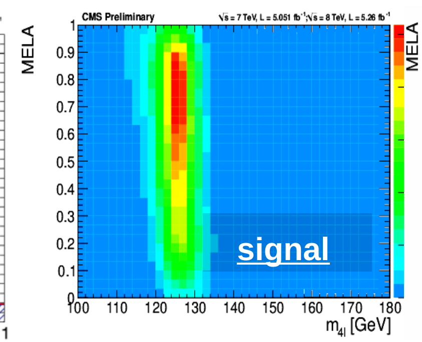

*Polar angle dis for $X_2$→W*

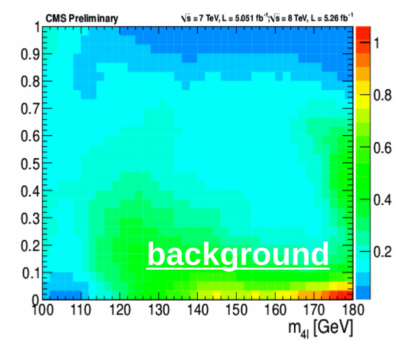
*Polar angle dis for $X_0$→W (fo*







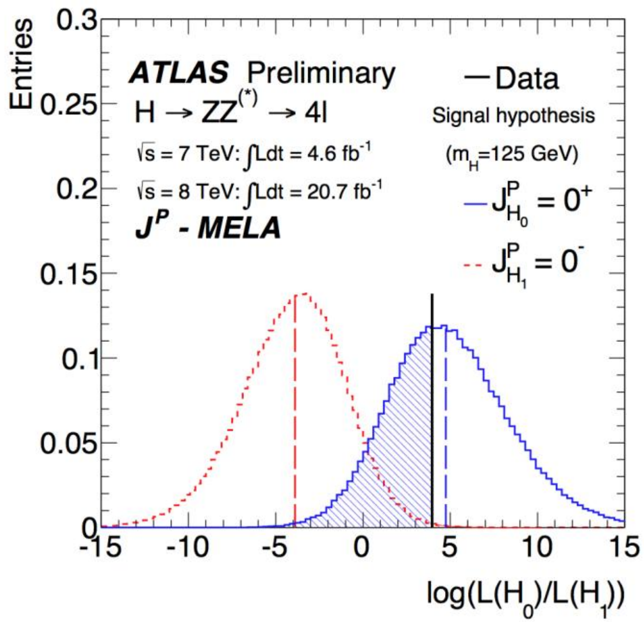
# 5. Preliminary results on the properties

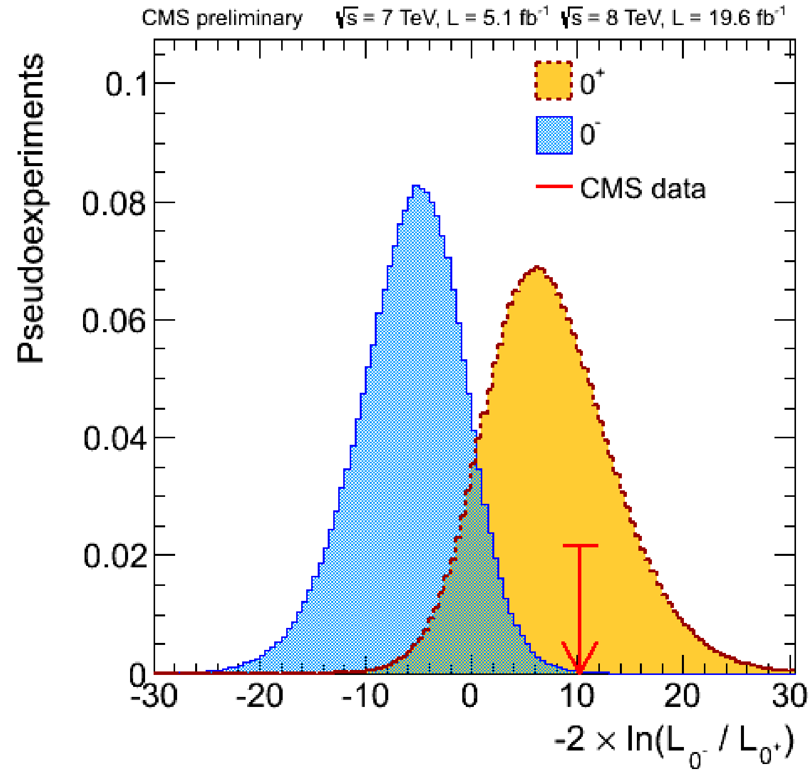
# Results on spin and parity

CMS-HIG-13-002

- Tests in ZZ→4l **disfavor $J^P = 0^-$** (pseudo-scalar) w.r.t. $J^P = 0^+$ (SM Higgs scalar boson), with **$1\text{-}CL_S^{obs.} = 99.84\%$ ($3.3\sigma$)**

**Very important test to check if the new particle can be a composite state.**

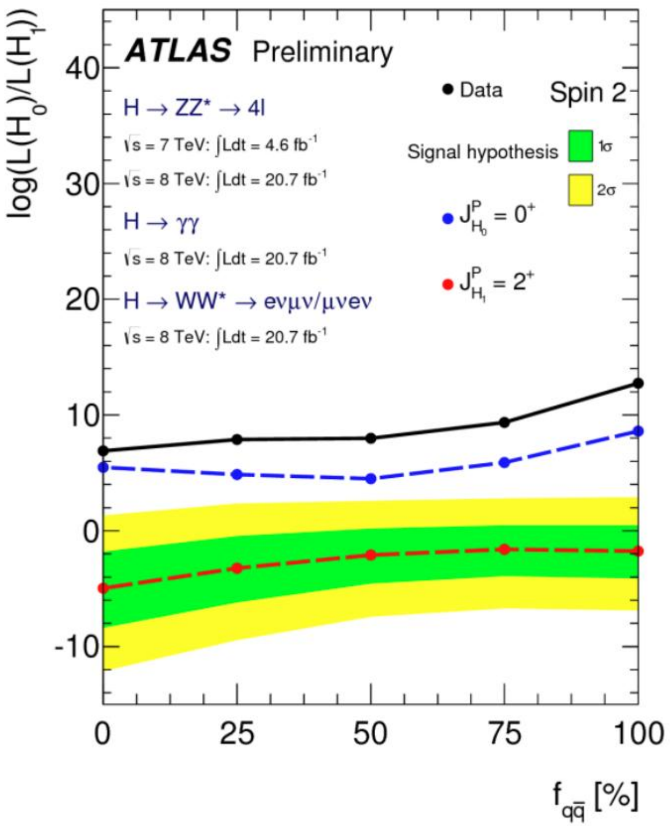


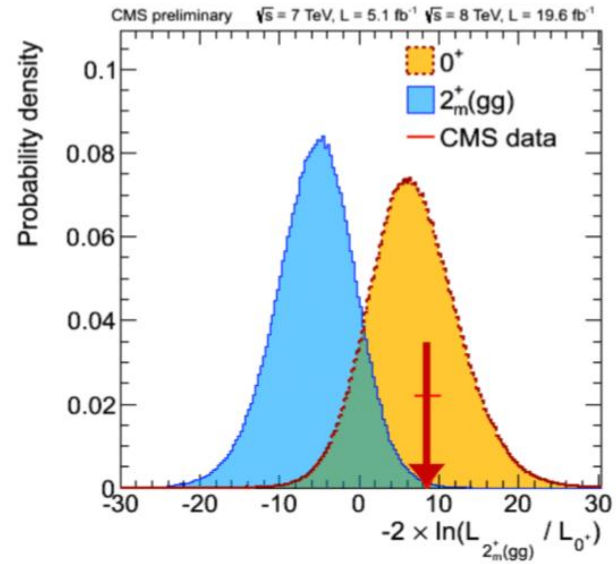




**Pseudo-scalar models are excluded at 99% CL or higher.**

Data consistent with the hypothesis that the new boson is indeed a scalar.

# Results on spin and parity




| | Expected | | Observed (μ from data) | | |
|---|---|---|---|---|---|
| | μ=1 | $\mu_{meas}$ | P(q > Obs \| Other) | P(q > Obs \| SM) | CLs [%] |
| $gg \to 0^-$ | 2.8σ | 2.6σ | 3.3 σ | -0.5 σ | 0.16 |
| $gg \to 0_h^+$ | 1.8 | 1.7 | 1.7 | +0.0 | 8.1 |
| $gg \to 2_m^+$ | 1.9 | 1.8 | 2.7 | -0.8 | 1.5 |
| $qq \to 2_m^+$ | 1.9 | 1.7 | 4.0 | -1.8 | < 0.1 |

CMS-HIG-13-002

**Pseudo-scalar and spin-2 models are excluded at 99% CL or higher.**

Everything consistent with the hypothesis that the new boson is indeed a scalar.

# Measurement of the mass in CMS

- Only **excellent-resolution channels** considered for **mass** measurement  CMS-HIG-13-001-2
- Mass is measured  **$m_X$ = 125.7 ± 0.3(stat.) ± 0.3(syst.) GeV** = **125.7 ± 0.4 GeV**

**H→ZZ→4l**

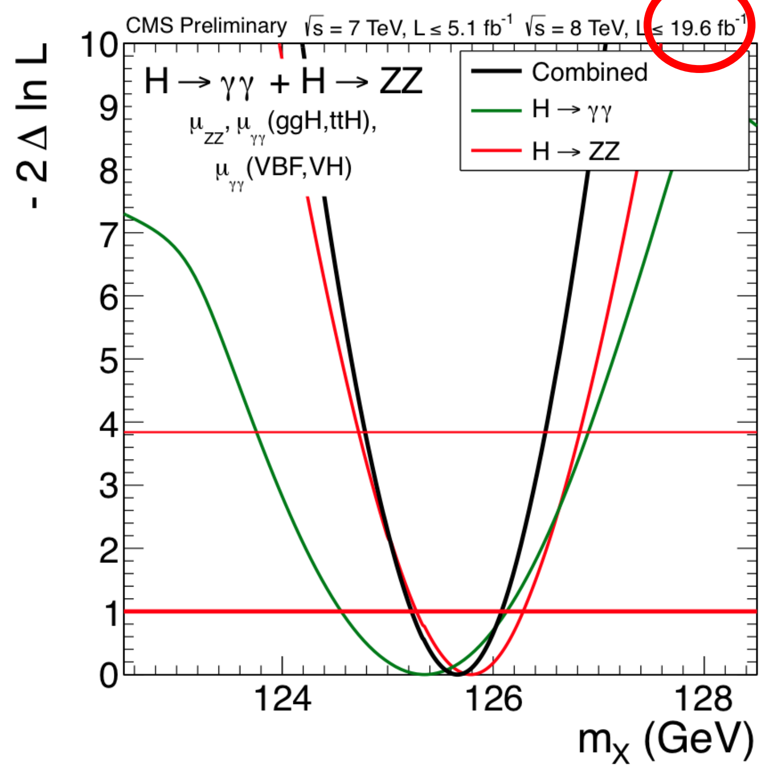
- 3D fit using $m_{4l}$, $\sigma(m_{4l})$, $K_D$
- very small syst. uncertainties thanks to good control of lepton momentum scale and resolution
- **$m_X$ = 125.8 ± 0.5(stat.) ± 0.2(syst.) GeV**

**H→γγ**

- systematics from Z→ee to H→γγ extrapolation (0.25% for e→γ and 0.40% for $H_T$ 90→125 GeV)
- **$m_X$ = 125.4 ± 0.5(stat.) ± 0.6(syst.) GeV**

Lepton momentum scale and resolution validated with Z, J/Psi, Y→ll; $m_{4l}$ uncertainties due to lepton scale 0.1% (4μ) and 0.3% (4e)

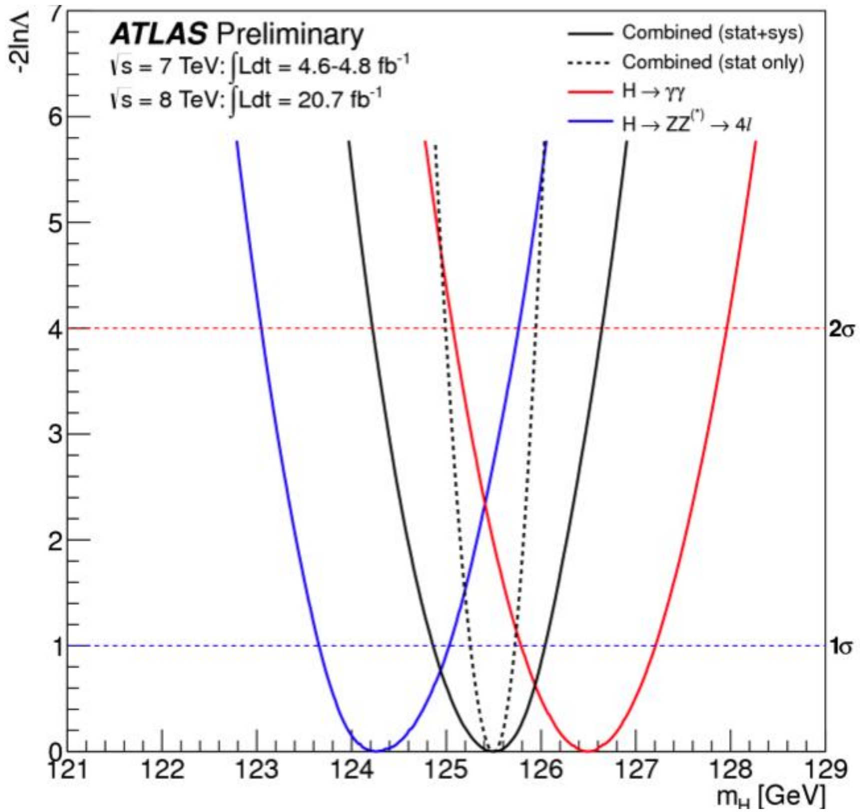
Overall photon energy scale 0.47% mostly dominated by the extrapolation Z→H and e→γ

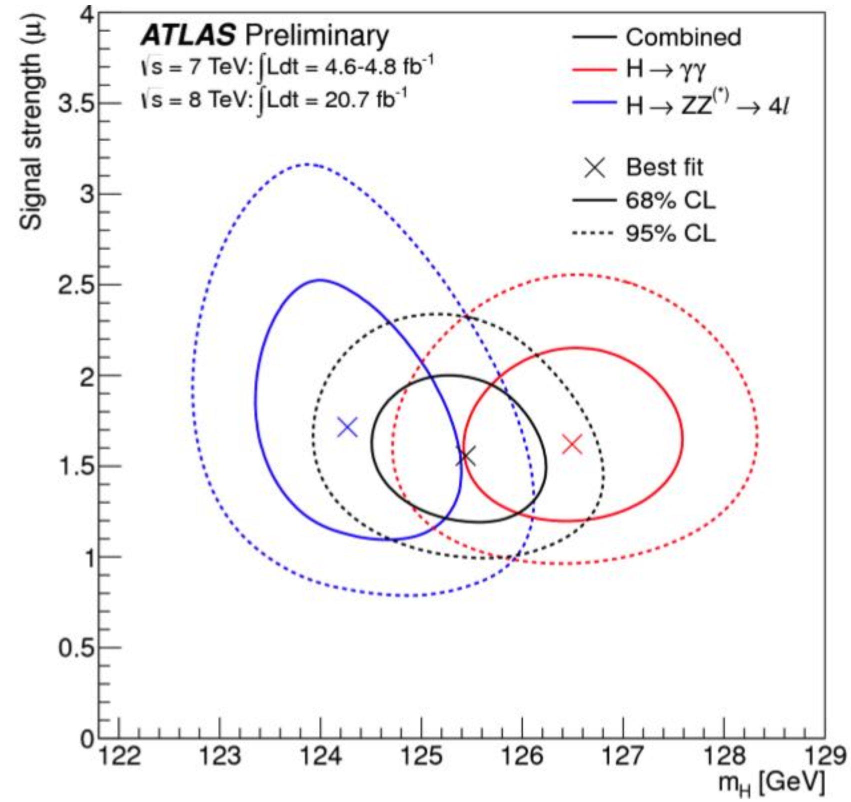



**model-independent extraction**

signal strength modifiers for ZZ, γγ(ggH+ttH) and γγ(VBF+VH) profiled as nuisances in the likelihood scan

# Measurement of the mass in ATLAS




$H \rightarrow \gamma\gamma$ $m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$GeV $H \rightarrow 4l$ $m_H = 124.3 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$GeV

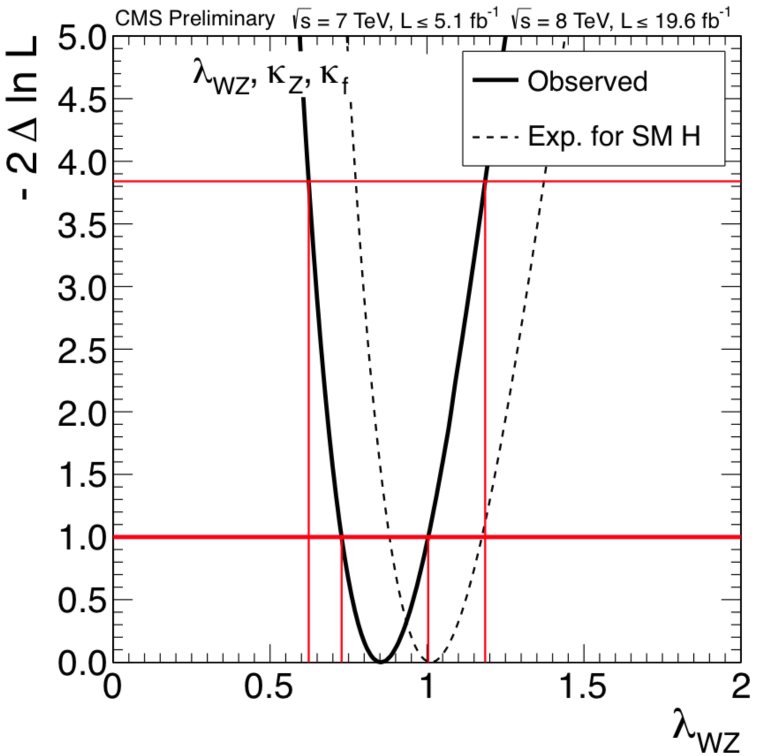
The two values are compatible within 2.4σ (p-value 1.5%);
using more conservative treatment of the systematics within 1.5σ (p-value 8%)

**Combining $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ $m_H = 125.5 \pm 0.2(\text{stat}) \pm 0.6(\text{syst})$GeV**

# Custodial symmetry

In the SM the ratio of the H couplings to W and Z bosons is protected from large radiative corrections by a global $SU(2)_L xSU(2)_R$ symmetry of the SMS sector.

- $\rho^{(0)} = M_W^2/M_Z^2\cos^2\vartheta_W = 1$ at tree level
- $\rho = 1 + \Delta\rho$ with radiative corrections, with $\Delta\rho$ small ($\Delta\rho = 0.005 \pm 0.001$ @ LEP)




combination of all channels

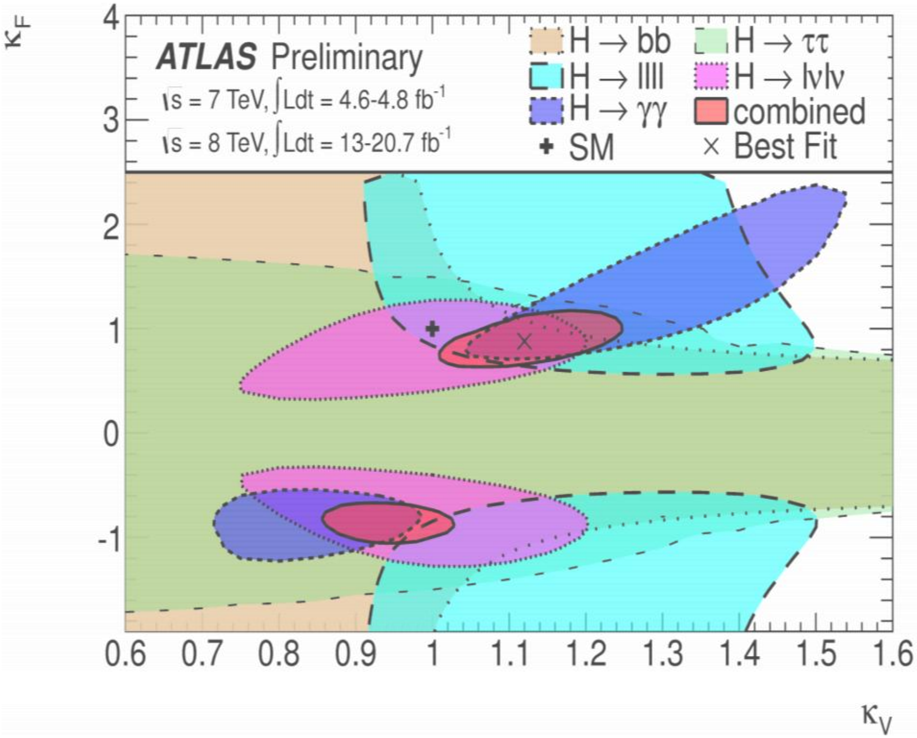
- 3 d.o.f.: $\lambda_{WZ}$, $\kappa_Z$ and $\kappa_f$
- $\Gamma_{BSM} = 0$, $\Gamma_{gg} \sim \kappa_f^2$, $\Gamma_{\gamma\gamma} \sim |\alpha\kappa_W + \beta\kappa_f|^2$
- $\kappa_W = \lambda_{WZ} \cdot \kappa_Z$ and $\alpha,\beta$ from SM
- $m_x = 125.7$ GeV

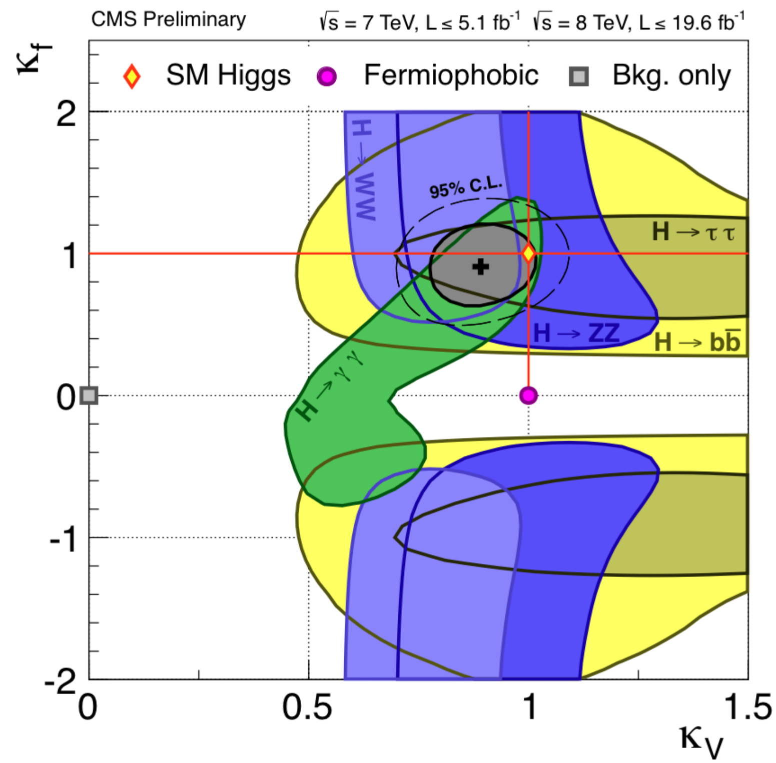
- $\lambda_{WZ} \in [0.62, 1.19]$ @ 95% C.L.

in the following, $\lambda_{WZ} = 1$ - use a common $\kappa_V$ for W

**Measured values of the the ratio $\lambda_{WZ}$ fully consistent with 1.**

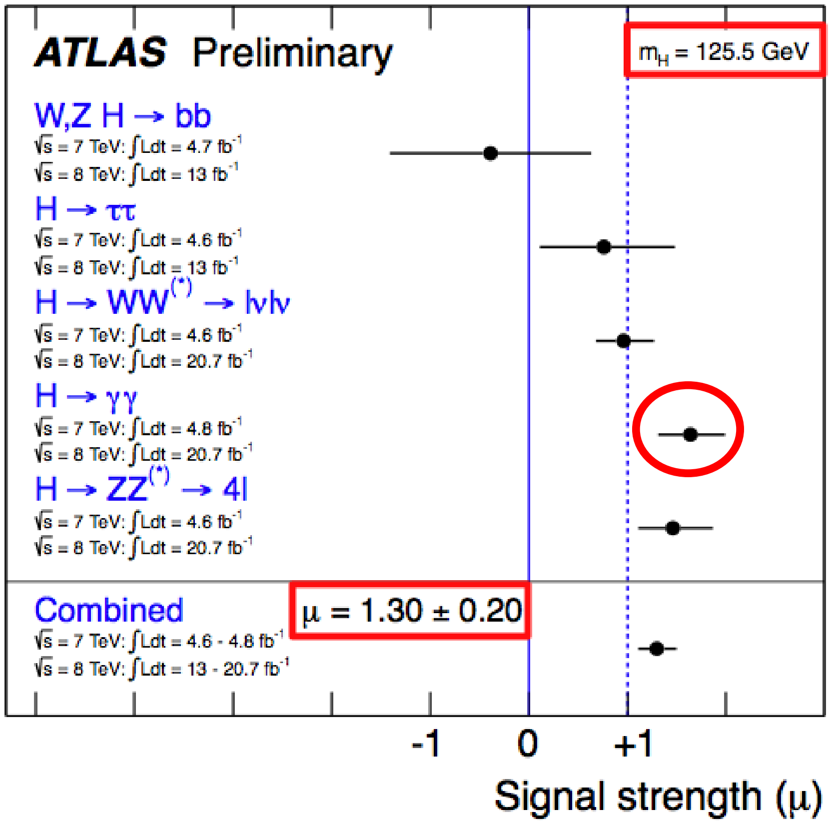
# "It continues to walk like a duck, and to quack like a duck…"

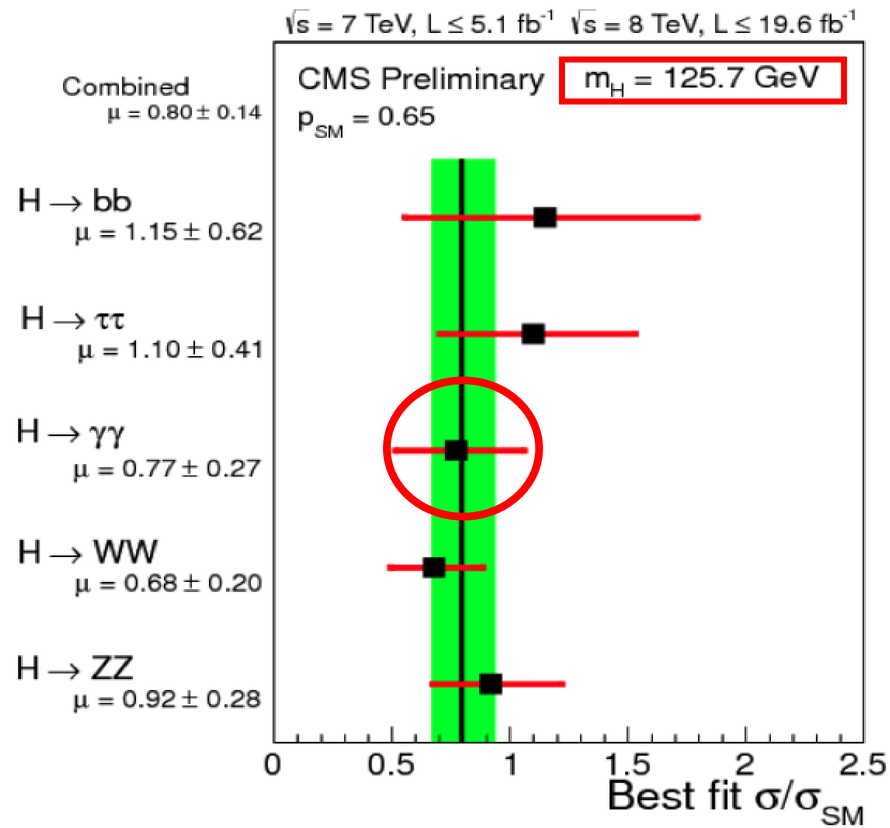



**Signal strengths $\sigma/\sigma_{SM}$ in different modes are consistent with the hypothesis that the new particle is definitely a (the) Higgs boson.**

# Results on the signal strenghts

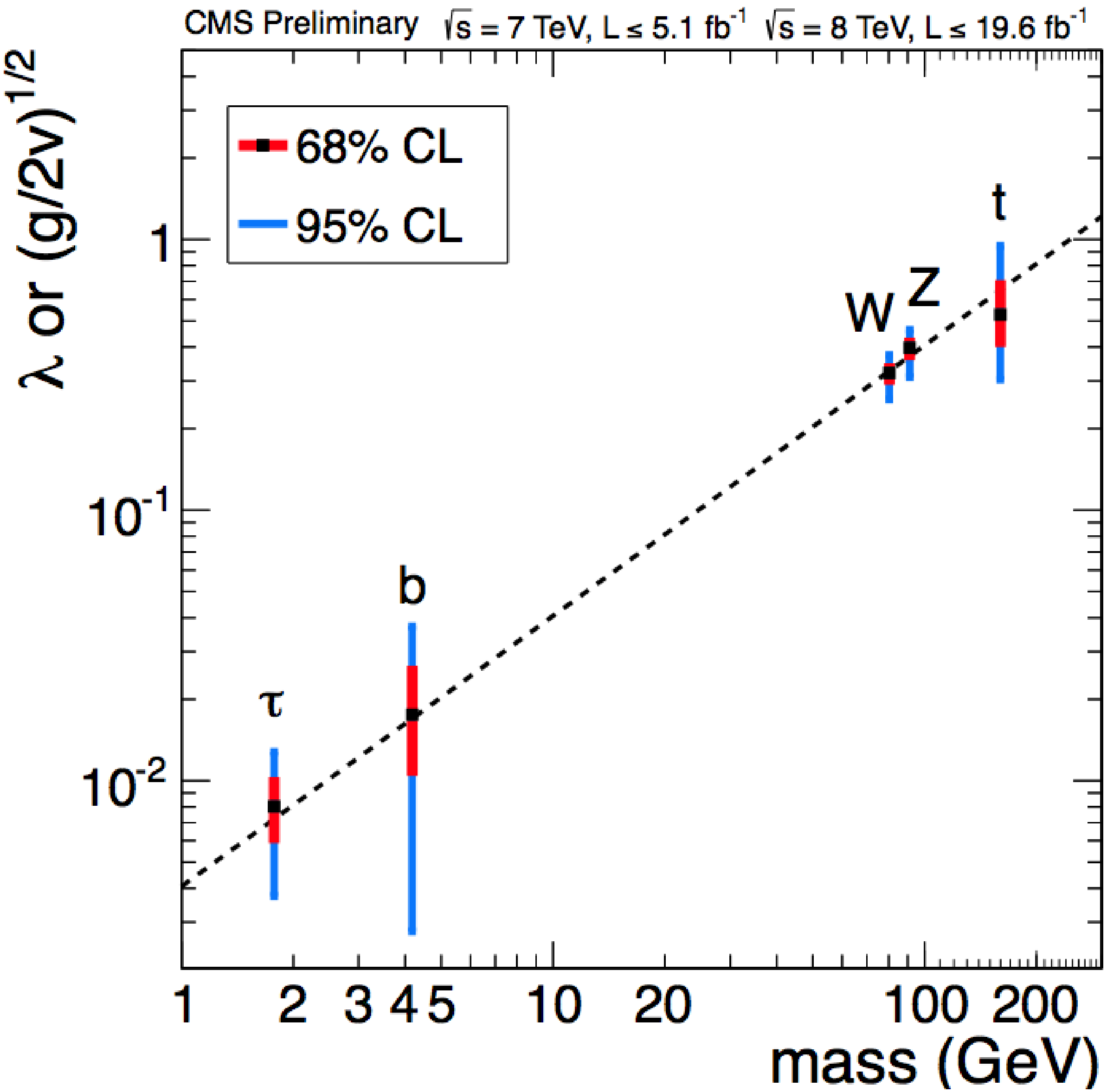



**ATLAS μ=1.30±0.20.** **CMS μ=0.80±0.14.**

You can guess yourself what could be the average μ of the two experiments.

# It does look like a (the) Higgs boson



# 6. Conclusion.

- By analysing the 2011 and 2012 data, we have discovered a new boson around a mass of 125GeV/$c^2$. **The result is consistent, within uncertainties, with expectations for a (the) Higgs boson.** The collection of further data will enable a more rigorous 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. The hunt for new physics beyond SM is still open.

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