Combined Measurement of the Higgs Boson Mass in *pp* Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments

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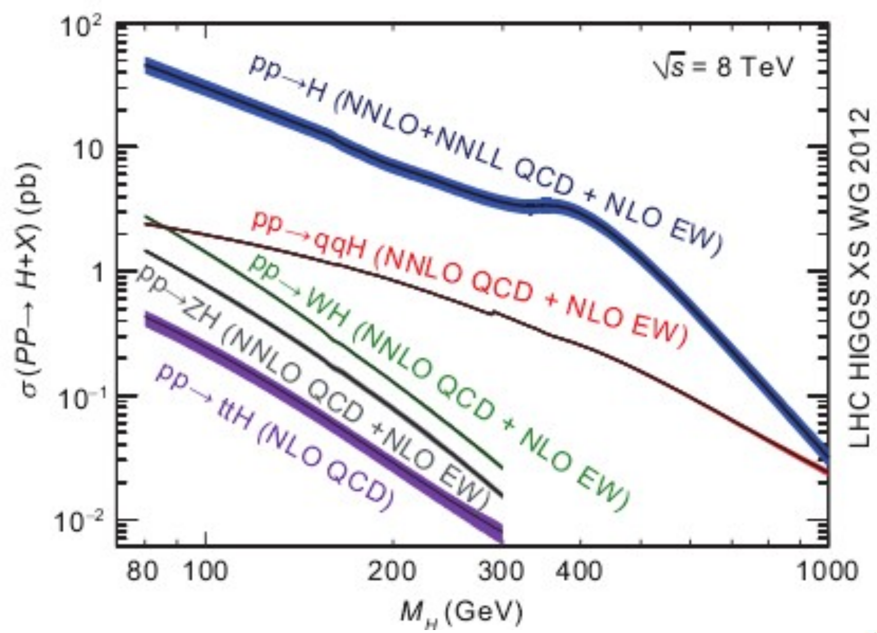
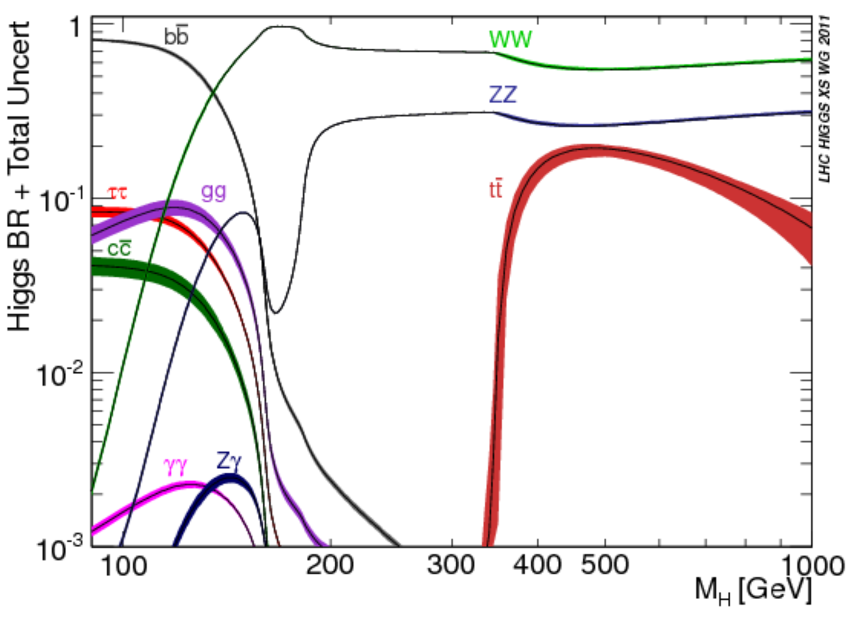
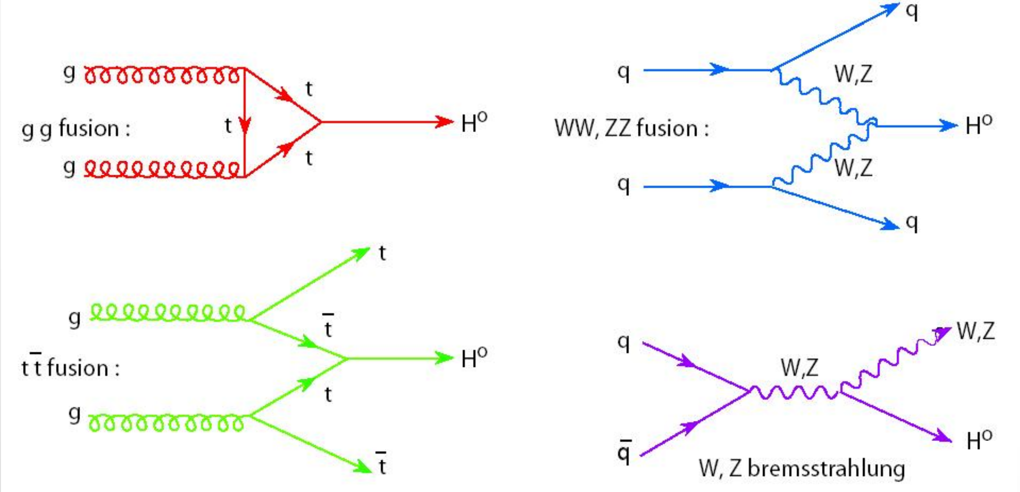
Outline

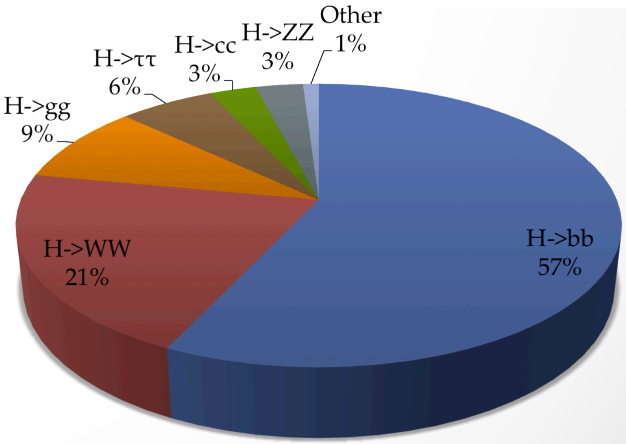
- The SM Higgs Boson: Production and Decay Modes
- The Measurement of the Higgs Boson Mass:
  - The H->$\gamma\gamma$ Decay Channel
  - The H->ZZ->4l Decay Channel
- The Combination:
  - Why Combining?
  - How to Combine
  - ATLAS and CMS Combined Mass Results

The SM Higgs Boson: Production and Decay modes









Higgs decays at m_H=125 GeV

The Measurement of the Higgs Boson Mass

- The Higgs boson mass is a fundamental parameter:
  - not predicted by the theory
  - measured independently by ATLAS and CMS using a simultaneous likelihood-fit on the reconstructed invariant mass and then combined
  - data samples from pp collisions at $\sqrt{s} = 7$ and 8 TeV corresponding to 5 fb^{-1} and 20 fb^{-1} respectively [RUN 1]
  - only high mass resolution decay channels used for combination:
    - $H \rightarrow \gamma\gamma$
    - $H \rightarrow ZZ \rightarrow 4l$ (with $l = e, \mu$)

The H→γγ decay channel

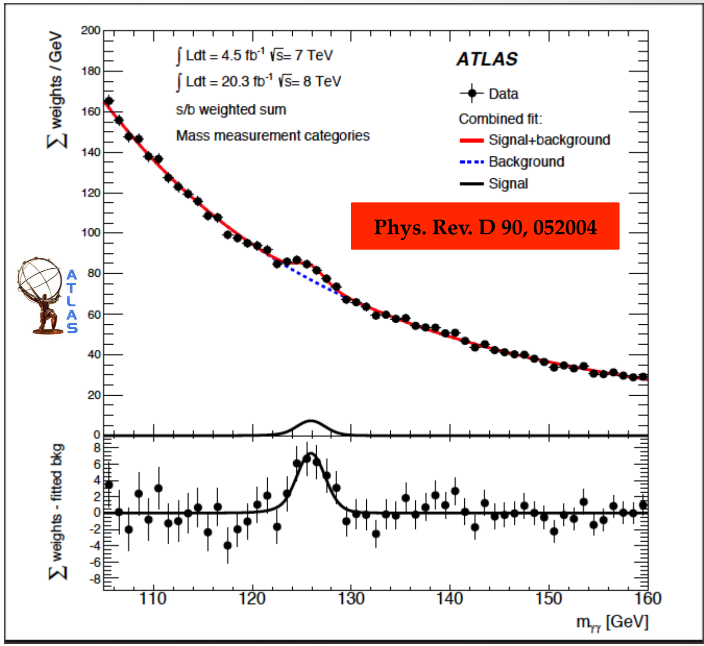
- Main features:
  - ○ Small B.R. (2.29E-03 at m_H=125 GeV) but clear signature with two isolated and high-pt photons, eccellent mass resolution 1-2 %
  - ○ A narrow resonant signal peak over a large smoothly falling continuum background:
    - Irreducible: prompt di-photon production, gg-> $\gamma\gamma$, qqbar, qg→ $\gamma\gamma$ from QCD
    - Riducibile: pp → γ+jets (1 prompt γ + 1 fake γ) pp → jets (2 fake), γ from $\pi^0 \to \gamma\gamma$

    Background obtained from a fit to the di-γ mass distribution
  - ○ **Selection Strategy**: events selected via di-photon trigger, categorized according to signal purity, to photon resolution and kinematic discriminants , very good photon reconstruction and Identification to improve sensitivity and bkg rejection, CUT-based selection and MVA to reconstruct the peak
  - ○ VBF and VH production modes used to improve sensitivity

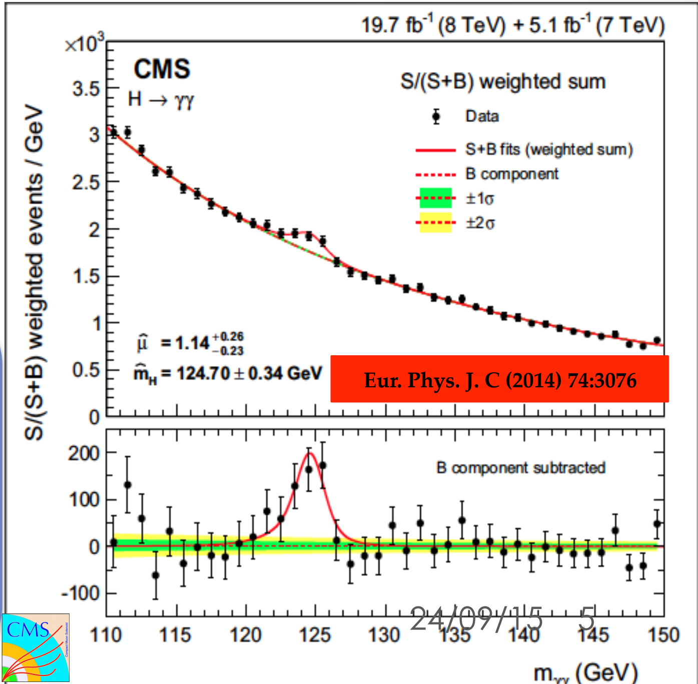
Mass Measurement

ATLAS : $m_H = 125.98 \pm 0.42\ (\text{stat}) \pm 0.28\ (\text{syst})$ GeV

CMS : $m_H = 124.70 \pm 0.31\ (\text{stat}) \pm 0.15\ (\text{syst})$ GeV



Phys. Rev. D 90, 052004



Eur. Phys. J. C (2014) 74:3076

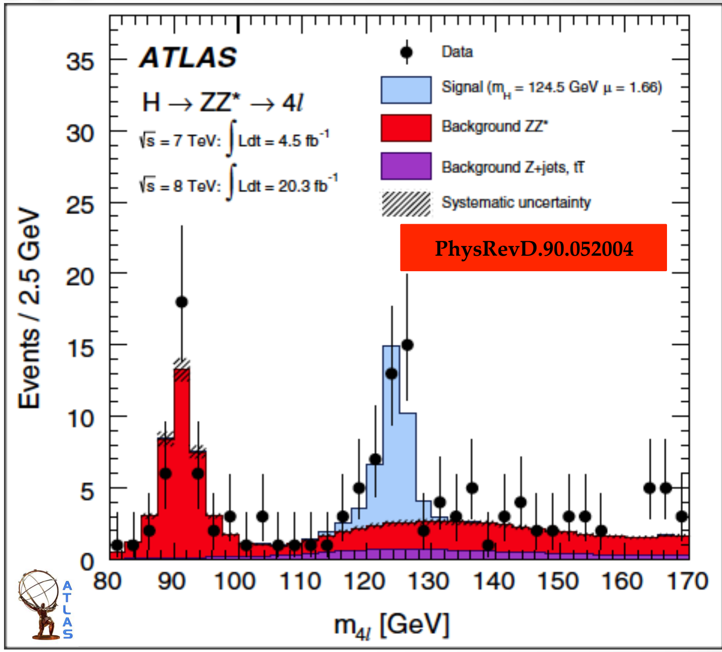
The H→ZZ→4l decay channel

- Main feature:
  - The Golden Channel: Small B.R. (2.66E-02 at m_H=125 GeV) but very clear signature with 4 well-isolated and high-pt leptons (e, μ)
  - A signal mass peak over a small continuum background:
    - Irreducible: ZZ, Zγ* from ggF and qqbar annihilation
    - Reducible: Z+*jets*, ttbar, Zγ+*jets*,WW+*jets*, WZ+*jets*
  - Excellent mass resolution: 1-2%
  - **Selection Strategy**: reconstruct a ZZ objects made of two di-lepton objects, same flavour and opposite sign. Kinematics discriminants, very good lepton reconstruction and Identification to improve sensitivity and bkg rejection

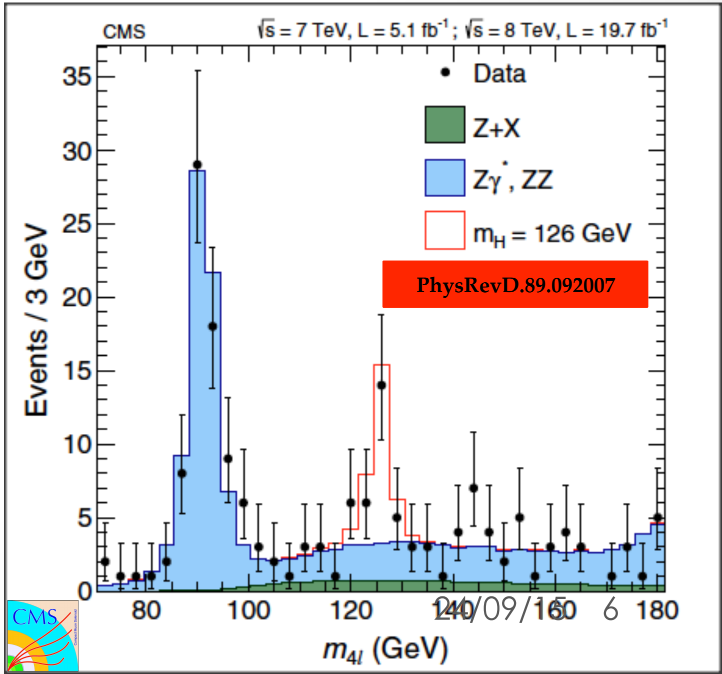
Mass Measurements

ATLAS (2D fit): $m_H = 124.51 \pm 0.52$ (stat) $\pm\, 0.06$ (syst) GeV

CMS (3D fit): $m_H = 125.59 \pm 0.42$ (stat) $\pm\, 0.17$ (syst) GeV



PhysRevD.90.052004



PhysRevD.89.092007

Why combining?

- Improved precision of m_H
  - In SM $m_{H,}$ m_W and m_t related through loop-induced effects:
    - Their comparison used to test the consistency of the SM (evidence of BSM Physics)
- More precise predictions of other Higgs properties
- Combination of other quantities, e.g. COUPLINGS (just completed)

How to combine

- Determination of the Higgs Mass best value and uncertainty maximizing the profile-likelihood ratio function:

Conditional maximum likelihood estimate for a given α

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$$

Unconditional maximum likelihood estimates for the best-fit value of α

L -> likelihood function
$\boldsymbol{\alpha}$ -> m_H
$\boldsymbol{\theta}$-> nuisance param:
  - systematics
  - fitted bkg params
  - unconstrained signal model params

$$\textbf{statistics} \left\{ \begin{array}{l} \text{fitted bkg params} \\ \text{unconstrained signal model params} \end{array} \right.$$

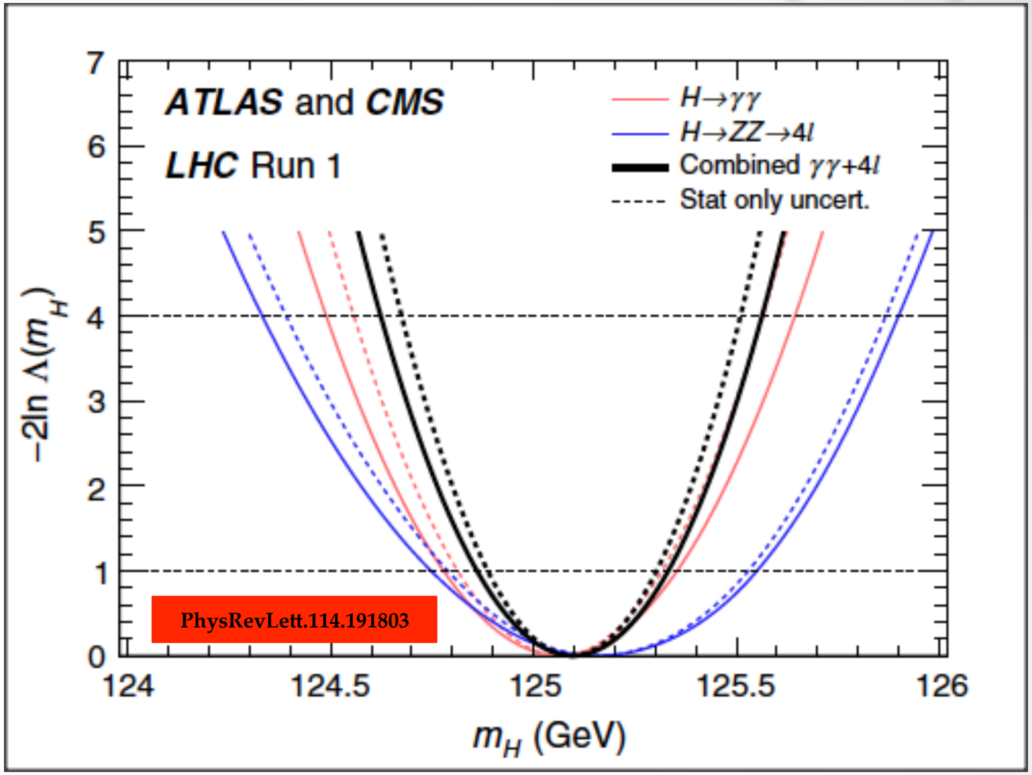
- Likelihood functions obtained using signal and bkg PDFs depending on the main discriminating variables:
  - Di-photon mass for H-> γ γ
  - Invariant 4l-mass distribution and KD for HZZ4l (also uncertainty for CMS)
- The parametrization used is approximately the same of the one used by the individual experiment

ATLAS and CMS Combined Mass Results [1/ 2]

Signal Strenght: $\mu = \dfrac{\sigma_{\exp} \times BF_{\exp}}{\sigma_{SM} \times BF_{SM}}$

To be more SM independent 3 signal strenght factors defined (same for ATLAS and CMS):

- $\mu^{\gamma\gamma}_{ggF+t\bar{t}H}$
- $\mu^{\gamma\gamma}_{VBF+VH}$
- μ^{4l}



PhysRevLett.114.191803

The corresponding profile-likelihood ratio is:

$$\Lambda(m_H) = \frac{L(m_H, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+t\bar{t}H}(m_H), \hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}(m_H), \hat{\hat{\mu}}^{4l}(m_H), \hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+t\bar{t}H}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}^{4l}, \hat{\theta})}$$

Combining ATLAS and CMS data using the above procedure:

Combined Mass Measurement

$\mathbf{m_H} = 125.09 \pm 0.24$ GeV
$= 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV

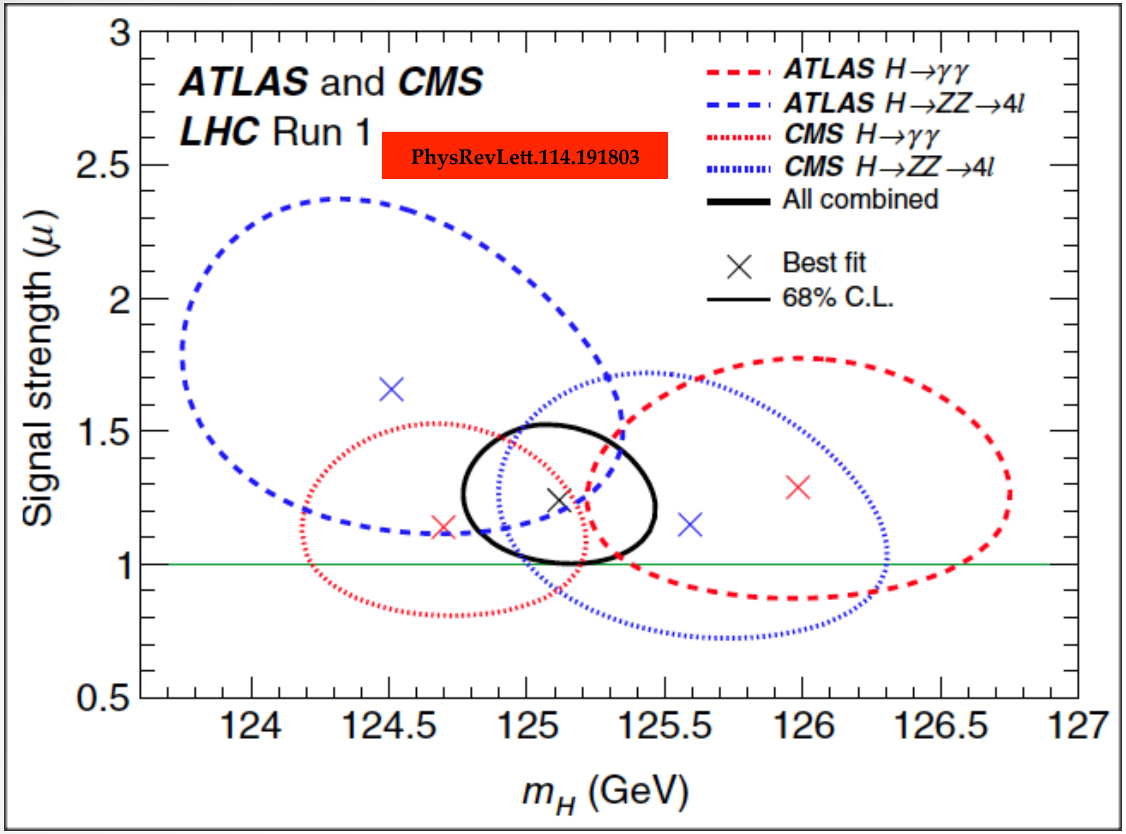
- Compatibility of the combined ATLAS and CMS mass measurement in H→ γ γ and in H→ZZ→4l is

$$\Delta m_{\gamma z} = m_H^{\gamma\gamma} - m_H^{4l} = -0.1 \pm 0.5\ GeV$$

- Compatibility of the ATLAS comb mass meas in the two channels with the CMS one is

$$\Delta m_H^{\exp} = m_H^{ATLAS} - m_H^{CMS} = 0.4 \pm 0.5\ GeV$$

ATLAS and CMS Combined Mass Results [2/2]



The signal strenghts at the measured value of m_H are:

- $\mu^{\gamma\gamma}_{ggF+t\bar{t}H} = 1.15^{+0.28}_{-0.25}$
- $\mu^{\gamma\gamma}_{VBF+VH} = 1.17^{+0.58}_{-0.53}$
- $\mu^{4l} = 1.40^{+0.30}_{-0.25}$

$$\mu_{comb} = 1.24^{+0.18}_{-0.16}$$

The compatibility among signal strenghts from ATLAS and CMS evaluated by:

$\lambda = \dfrac{\mu^{ATLAS}}{\mu^{CMS}}$ for all signal strenghts used (ggF+ttbar, VBF+VH and 4l) .

It has been calculated to be $\lambda = 1.21^{+0.30}_{-0..24}$.
All the values are consistent with unity whithin 1 σ .

Conclusions

- A combined measurement of the Higgs boson mass has been performed using pp collisions at $\sqrt{s} = 7$ and 8 TeV corresponding to 5 fb^{-1} and 20 fb^{-1} with ATLAS and CMS experiment at LHC
- A maximization of the profile-likelihood ratio $\Lambda(m_H)$ has been performed to determine the best value of m_H and its uncertainty
- The combined measure of the Higgs boson mass has been calculated to be 125.09 ± 0.21 (stat.) ± 0.11 (syst.) GeV
- The compatibility of the ATLAS combined mass measurement in the two channels with that of CMS has been evaluated to be 0.4 ± 0.5 GeV, definitely compatible with zero within 1 σ
- The combined signal strenght factor has been evaluated to be $\mu_{comb} = 1.24^{+0.18}_{-0.16}$ and the compatibility among signal strenghts from ATLAS and CMS has been calculated to be $\lambda = 1.21^{+0.30}_{-0..24}$, attesting the consistency of the measurements with the Standard Model assumptions

References

- **ATLAS and CMS Collaborations**, “Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments”, PhysRevLett.114.191803 (2015)

- **ATLAS Collaboration**, “Measurement of the Higgs boson mass from the H → $\gamma\gamma$ and H → ZZ → **4**l channels in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector, Phys. Rev. D 90, 052004 (2014).

- **CMS Collaboration**, “Observation of the diphoton decay of the 125 GeV Higgs boson and measurement of its properties”, Eur. Phys. J. C 74, 3076 (2014).

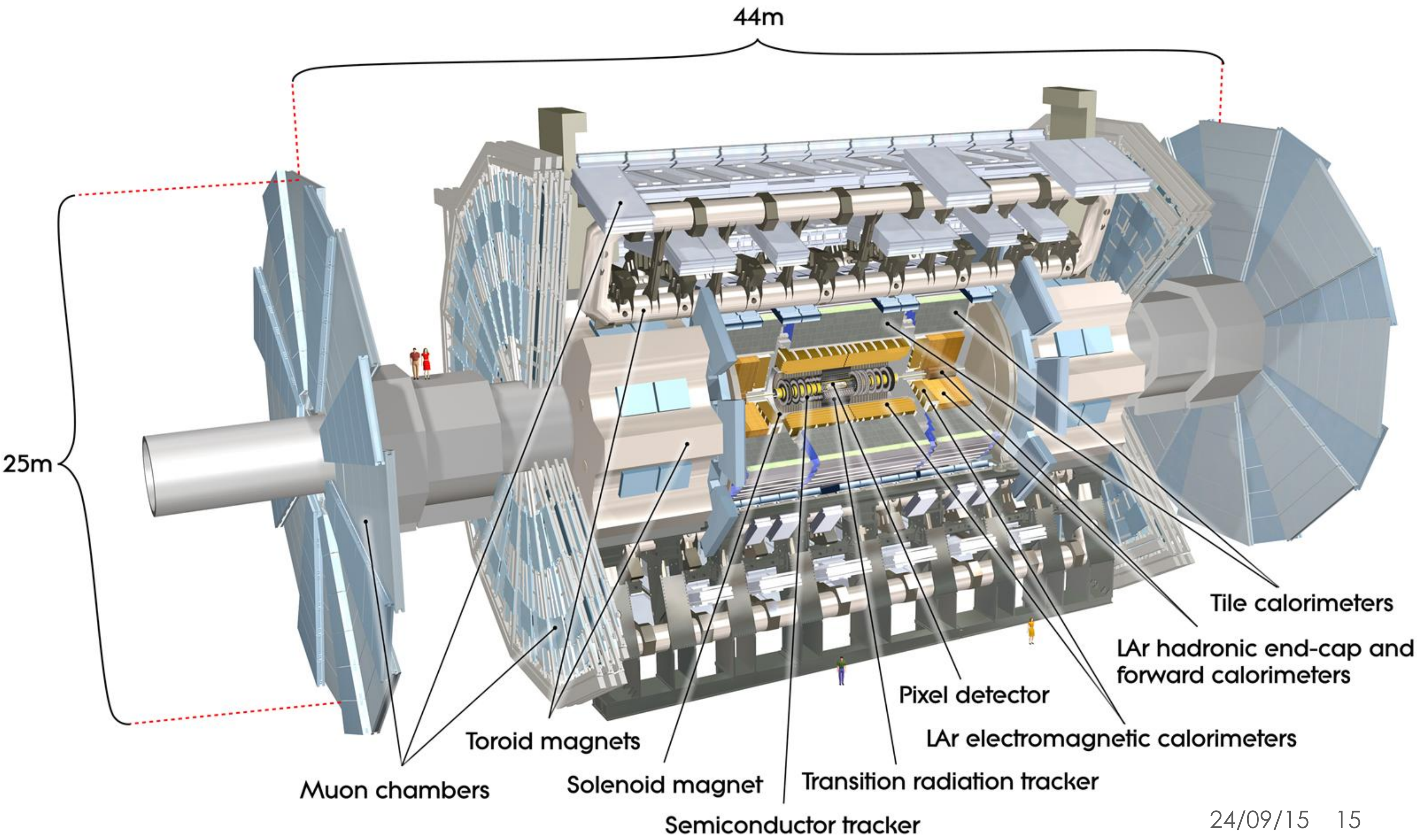
- **CMS Collaboration**, “Measurement of the properties of a Higgs boson in the four-lepton final state”, Phys. Rev. D 89, 092007 (2014).

Backup

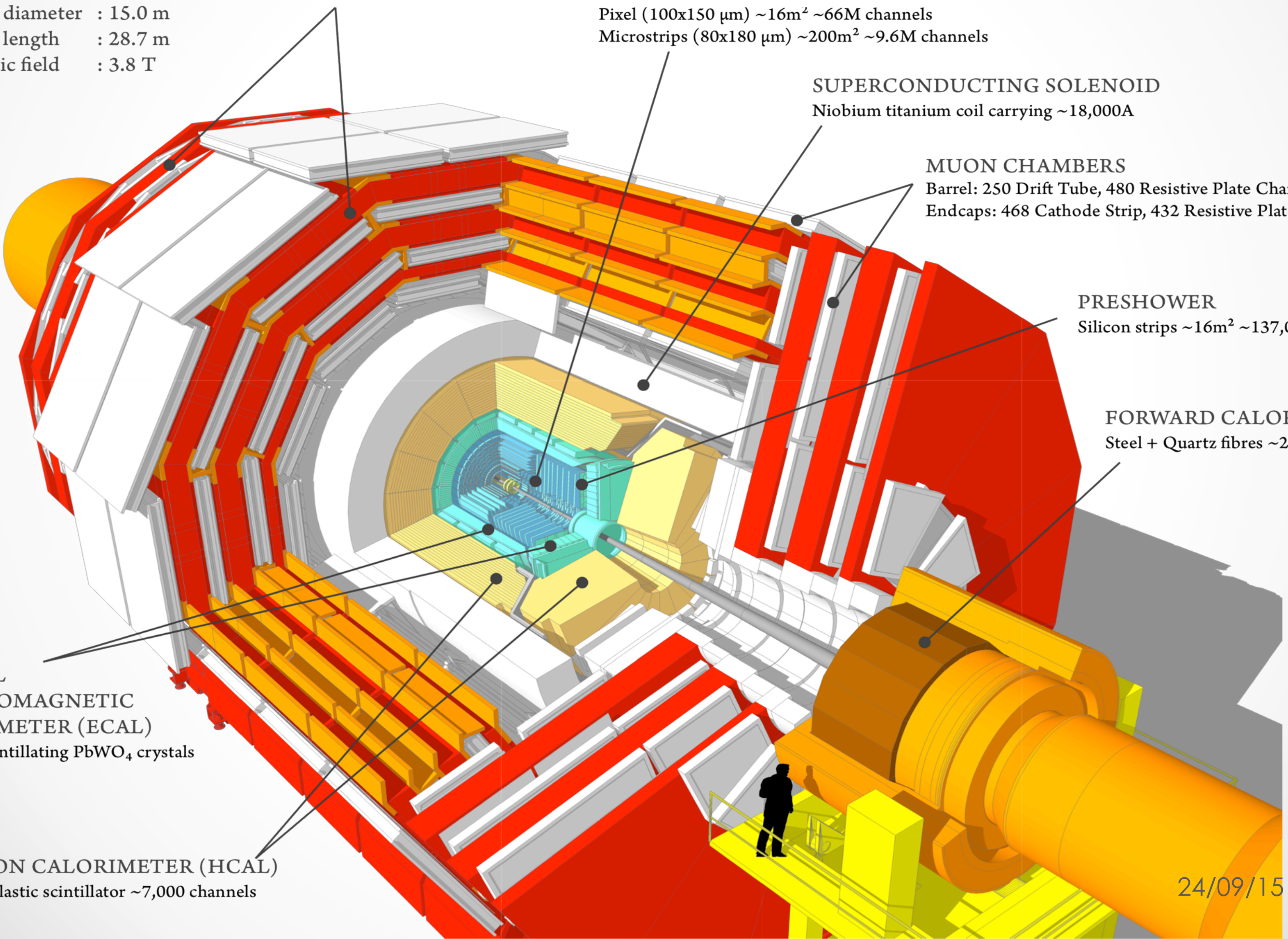
The Standard Model Higgs Boson at LHC

- The study of the electroweak simmetry breaking mechanism is one on the main goal of the LHC
- **2012**: **ATLAS** and **CMS** announced the discovery of a *new* boson with Higgs-boson-like properties with a mass ~125 GeV
- **2013**: more precise mesurements of its properties (mass, spin-parity, coupling strenghts to SM particles,…) brought to the Nobel prize assignment to Higgs and Englert for its discovery
- The discovery based primarly on mass peaks observed in decay channels H->$\gamma\gamma$ and H->ZZ->4*l*

THE ATLAS DETECTOR



THE CMS DETECTOR



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE

12,500 tonnes

SILICON TRACKERS

Pixel (100x150 μm) ~$16m^2$ ~66M channels
Microstrips (80x180 μm) ~$200m^2$ ~9.6M channels

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying ~18,000A

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER

Silicon strips ~$16m^2$ ~137,000 channels

FORWARD CALORIMETER

Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)

~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)

Brass + Plastic scintillator ~7,000 channels

THE CONSTRUCTION OF THE TEST STATISTIC [1/3]

1.How to manage systematics (From bayesian to frequentist approach)

- Assigning a nuisance parameter θ_i for each independent source of systematic errors (both theoretical and experimental), $\tilde{\theta}_i$ is the best *a priori* estimate

- Bayes' Theorem:

$$\rho(\theta_i \,|\, \tilde{\theta}_i) \sim p(\tilde{\theta}_i \,|\, \theta_i) \cdot \pi_\theta(\theta_i)$$

It is related to the ***degree of belief*** about the real value of θ_i :

$\pi_\theta(\theta)$ → a priori probability function for $\tilde{\theta}_i$

If $\tilde{\theta}_i$ come from real or immaginary measurements and $\pi_\theta(\theta)$ is normally distributed (uniform prior)

→

$\rho(\theta_i \,|\, \tilde{\theta}_i)$ can be interpreted as an *a posteriori* probability

THE CONSTRUCTION OF THE TEST STATISTIC [2/3]

2. Choosing a pdf to describe θ_i

If θ_i is **normally** distibuted

The variation of θ_i propagates to the observable O in 2 ways:

- GAUSSIAN ERROR:

$$O = O_0(1+\sigma\cdot\theta) \quad (with\ O\ negative\ or\ positive\ )$$

- LOG-NORMAL ERROR

$$O = O_0\cdot\kappa^{\theta}\ (O\ only\ positive)$$

O_0 ➔observable with no error

σ,κ ➔contributions to uncertainties

THE CONSTRUCTION OF THE TEST STATISTIC [3/3]

3. Defining a *likelihood function*

$$\mathcal{L}(data\,|\,\mu,\theta) = Poisson(data\,|\,\mu\cdot s(\theta)+b(\theta))\cdot p(\tilde{\theta}\,|\,\theta)$$

$$\boxed{Poisson(data\,|\,\mu\cdot s(\theta)+b(\theta)):\ Poisson\ \ probability\ \ for\ \ data\ \ observation}$$

Product of the poissonian probabily for observing n$_i$ eventi in i bins

$$\prod_i \frac{(\mu\cdot s_i+b_i)^{n_i}}{n_i} e^{-\mu s_i - b_i}$$

Not binned likelihood on k events in data samples

$$k^{-1}\prod_i \frac{(\mu S f_s(x_i)+B f_b(x_i))}{n_i} e^{-(\mu S-B)}$$

$f_s(x)$ e $f_b(x)$ → p.d.f. for signal and bkg for observale x

S e B → total expected events rate for signal and bkg

$$\mu(\text{"}signal\ strenght\ modifier\text{"}) = \frac{\#\,observed\ \ events}{\#\,SM\,expected\ \ events}$$

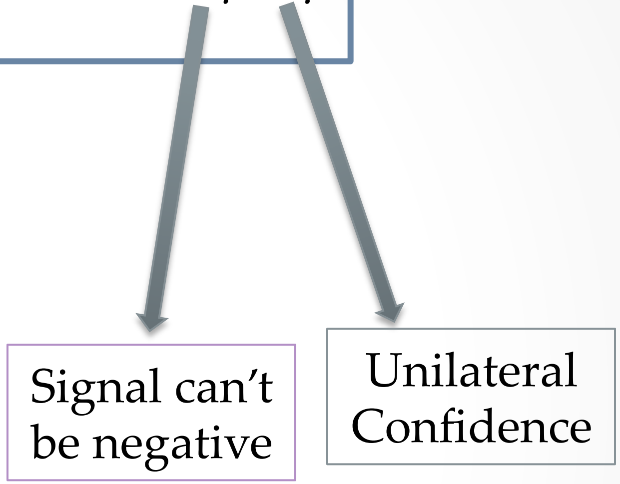
Definition of the Test Statistic

$$\boxed{q_\mu = -2\ln\frac{\mathcal{L}(data\,|\,\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\,|\,\hat{\mu},\hat{\theta})} \quad con\ \ 0 \le \hat{\mu} \le \mu}$$

$$\boxed{\begin{array}{l}\hat{\theta}_\mu,\ \hat{\mu},\ \hat{\theta} \rightarrow \text{ massimizzano num. e den.}\\ \mu \rightarrow \text{fissato}\end{array}}$$

Data can be

- *Real Data*
- *Pseudo-dati (toys)*



Signal can't be negative

Unilateral Confidence

Maximization of $\mathcal{L}$ ⟺ **Minimization of log** ⟺ q_μ distributed as χ^2

Summary of m_H measurements with uncertainties

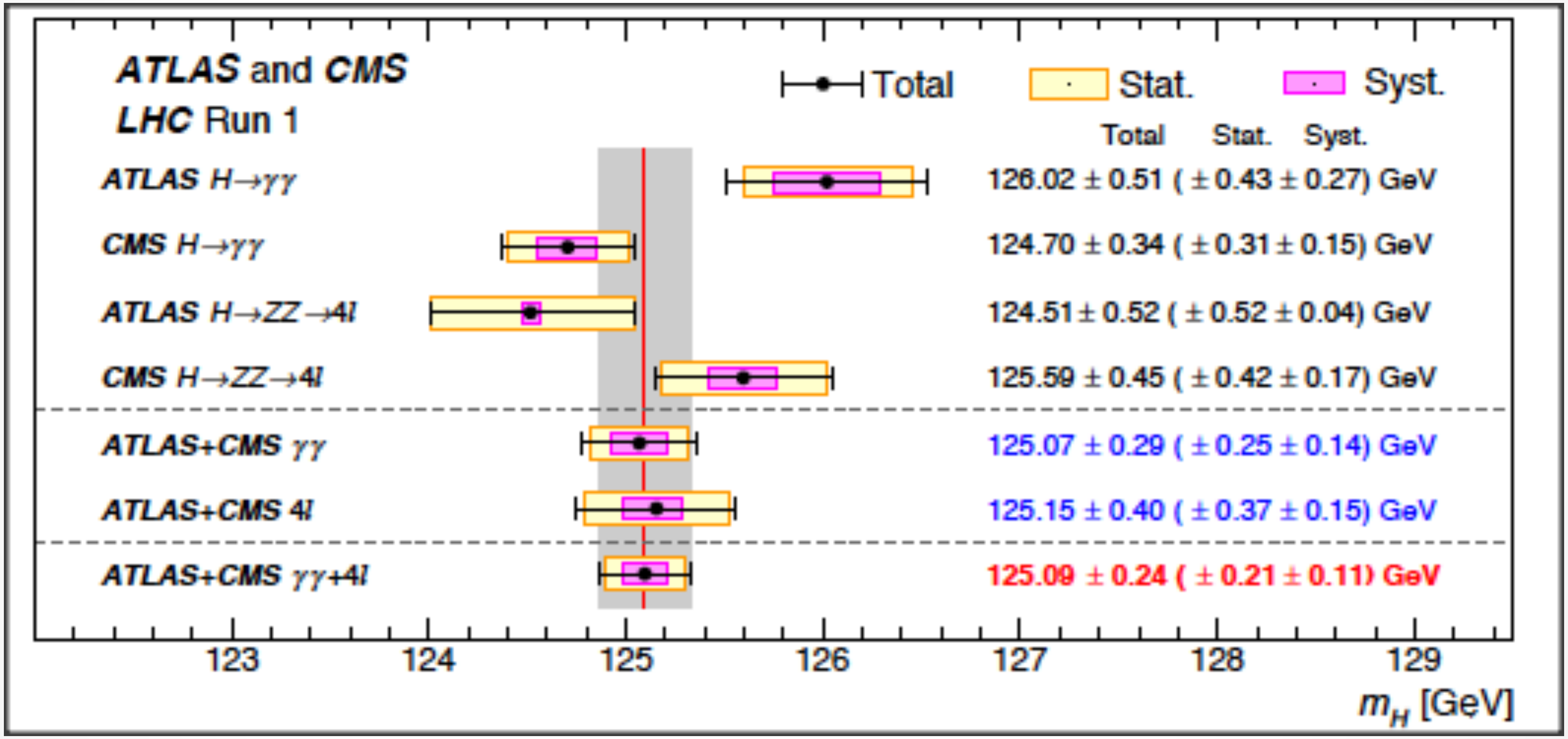
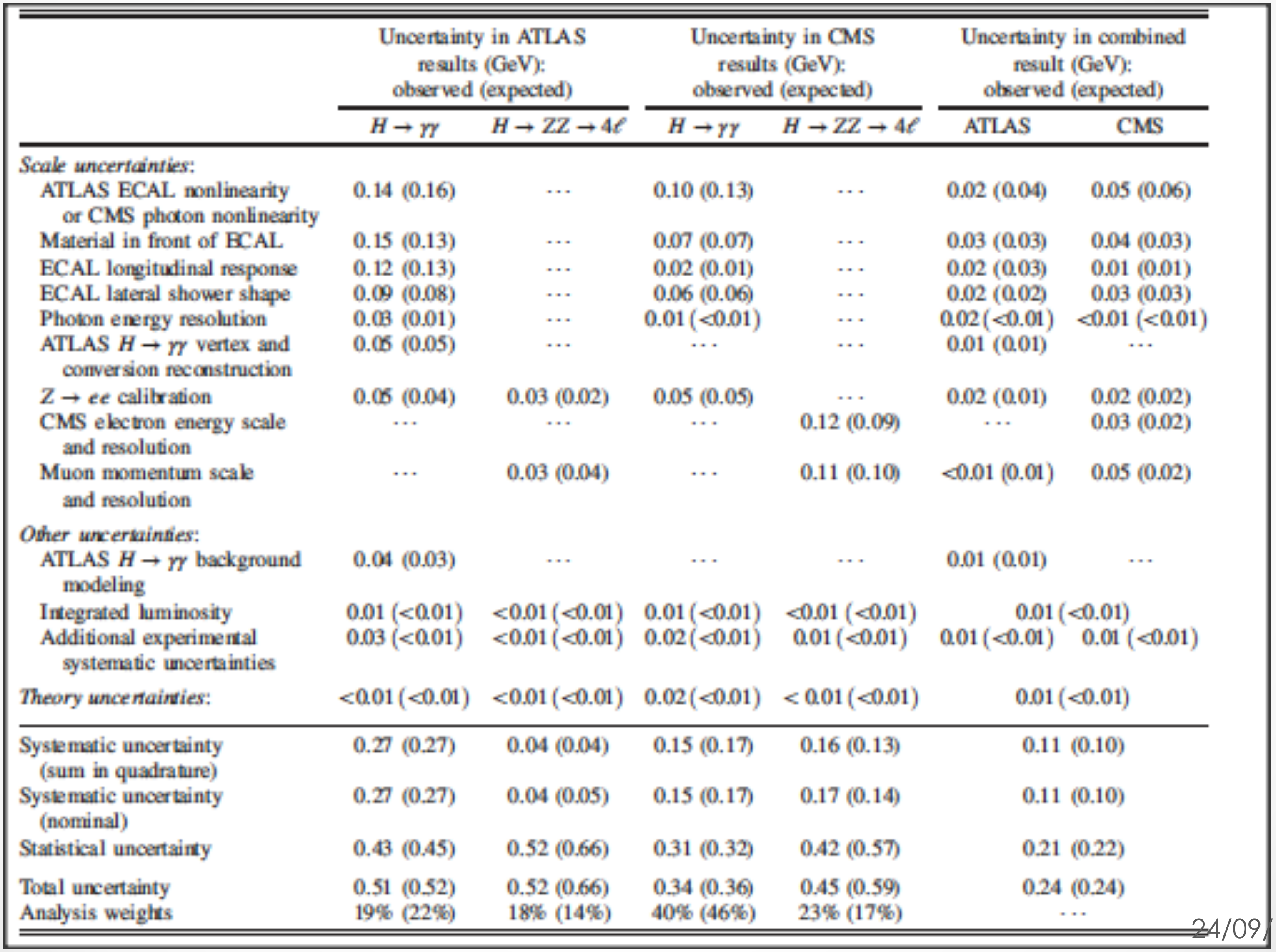


Table of systematic uncertainties for ATLAS and CMS



	Uncertainty in ATLAS results (GeV): observed (expected)		Uncertainty in CMS results (GeV): observed (expected)		Uncertainty in combined result (GeV): observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL nonlinearity or CMS photon nonlinearity	0.14 (0.16)	···	0.10 (0.13)	···	0.02 (0.04)	0.05 (0.06)
Material in front of ECAL	0.15 (0.13)	···	0.07 (0.07)	···	0.03 (0.03)	0.04 (0.03)
ECAL longitudinal response	0.12 (0.13)	···	0.02 (0.01)	···	0.02 (0.03)	0.01 (0.01)
ECAL lateral shower shape	0.09 (0.08)	···	0.06 (0.06)	···	0.02 (0.02)	0.03 (0.03)
Photon energy resolution	0.03 (0.01)	···	0.01 (<0.01)	···	0.02 (<0.01)	<0.01 (<0.01)
ATLAS $H \to \gamma\gamma$ vertex and conversion reconstruction	0.05 (0.05)	···	···	···	0.01 (0.01)	···
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.02)	0.05 (0.05)	···	0.02 (0.01)	0.02 (0.02)
CMS electron energy scale and resolution	···	···	···	0.12 (0.09)	···	0.03 (0.02)
Muon momentum scale and resolution	···	0.03 (0.04)	···	0.11 (0.10)	<0.01 (0.01)	0.05 (0.02)
Other uncertainties:						
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	···	···	···	0.01 (0.01)	···
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Additional experimental systematic uncertainties	0.03 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties:	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	< 0.01 (<0.01)	0.01 (<0.01)	
Systematic uncertainty (sum in quadrature)	0.27 (0.27)	0.04 (0.04)	0.15 (0.17)	0.16 (0.13)	0.11 (0.10)	
Systematic uncertainty (nominal)	0.27 (0.27)	0.04 (0.05)	0.15 (0.17)	0.17 (0.14)	0.11 (0.10)	
Statistical uncertainty	0.43 (0.45)	0.52 (0.66)	0.31 (0.32)	0.42 (0.57)	0.21 (0.22)	
Total uncertainty	0.51 (0.52)	0.52 (0.66)	0.34 (0.36)	0.45 (0.59)	0.24 (0.24)	
Analysis weights	19% (22%)	18% (14%)	40% (46%)	23% (17%)	···	

Impacts of nuisance param group

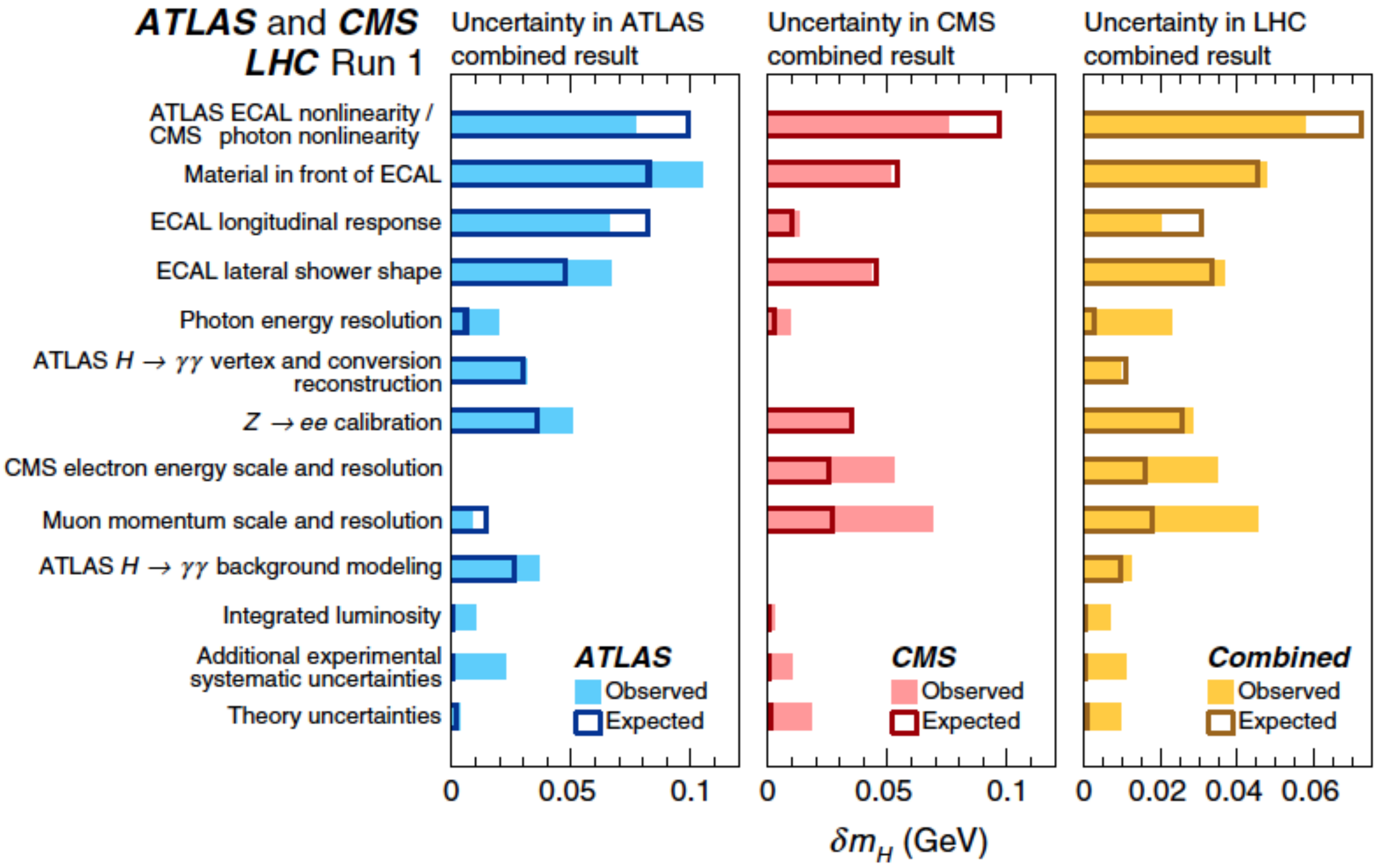


FIG. 3 (color online). The impacts δm_H (see text) of the nuisance parameter groups in Table I on the ATLAS (left), CMS (center), and combined (right) mass measurement uncertainty. The observed (expected) results are shown by the solid (empty) bars.

Asimov Data Sets

- Observed uncertainties in the combined measurement compared with the expected ones:
  - The expected calculated by generating 2 **ASIMOV datasets**:
    - An ASIMOV data : representative event sample that provides:
      - MEDIAN EXPECTATION
      - EXPECTED STATISTIC STATISTICAL VARIATION
    - The first ASIMOV DATA SET is a PRE-FIT sample

      (generated using m_H=125.0 GeV, SM couplings, θ fixed to nominal values)

    - The second ASIMOV DATA SET is a POST-FIT sample

      (m_H, $\mu^{\gamma\gamma}_{gFF+t\bar{t}H}$, $\mu^{\gamma\gamma}_{VBF+VH}$, μ^{4l} and all θ fixed to best-fit estimatesfrom data)
    - The expected uncertainties for mass combination are:

$$\delta m_{Hprefit} = \pm 0.24\ GeV = \pm 0.22(stat) \pm 0.10(syst)\ GeV$$

$$\delta m_{Hpostfit} = \pm 0.22\ GeV = \pm 0.19(stat) \pm 0.10(syst)\ GeV$$