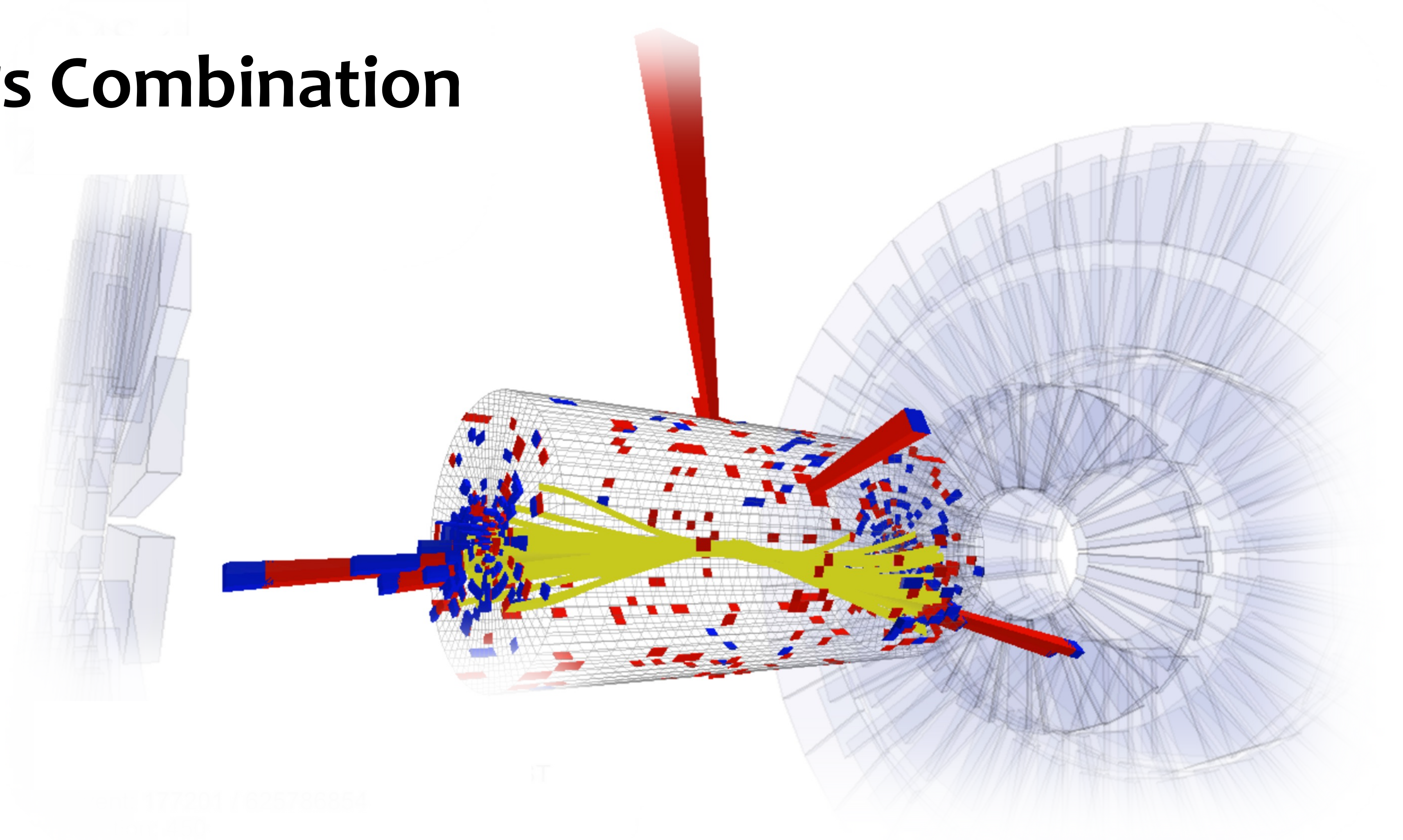
# ATLAS+CMS Higgs Combination Experience

Nicholas Wardle

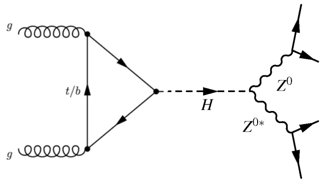


15 September 2024

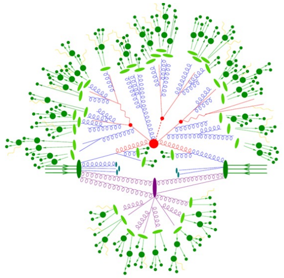
# Higgs measurements in one-slide

LHC data

Simulation of Higgs boson production

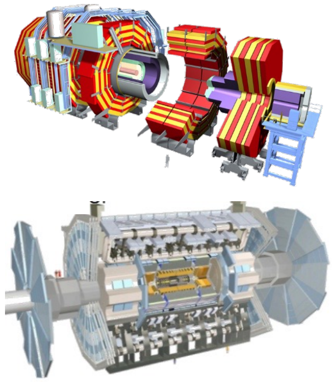



Simulation of "soft-physics" processes

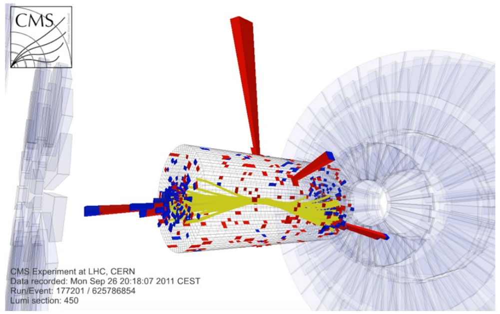


[Source: F. Krauss]

Simulation of ATLAS/CMS detector



Event reconstruction

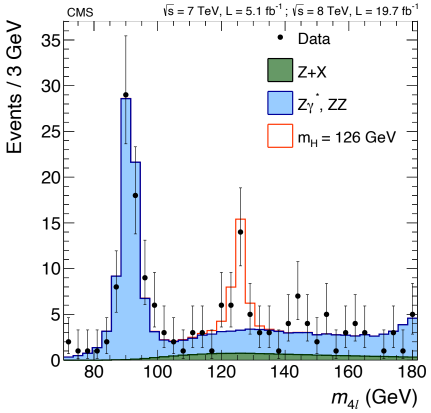



Analysis Selections

Combinations based on **multiple analyses** targeting different Higgs boson production and decay modes

Analyses all follow same basic workflow

$$p(\mathrm{data}|\mathrm{SM})$$




*Inspired from diagram by Wouter Verkerke*

# ATLAS+CMS Higgs combinations

So far, the ATLAS and CMS collaborations have published **3 combinations of Higgs boson measurements** using the LHC Run-1 & Run-2 pp collision data sets.

JHEP08(2016)045

Phys. Rev. Lett. 114, 191803 (2015)

Selected for a Viewpoint in *Physics*
PRL **114,** 191803 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

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

G. Aad *et al.*[*]

(ATLAS Collaboration)[†]
(CMS Collaboration)[‡]
(Received 25 March 2015; published 14 May 2015)

A measurement of the Higgs boson mass is presented based on the combined data samples of the ATLAS and CMS experiments at the CERN LHC in the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ decay channels. The results are obtained from a simultaneous fit to the reconstructed invariant mass peaks in the two channels and for the two experiments. The measured masses from the individual channels and the two experiments are found to be consistent among themselves. The combined measured mass of the Higgs boson is $m_H = 125.09 \pm 0.21$ (stat) $\pm$ 0.11 (syst) GeV.

DOI: 10.1103/PhysRevLett.114.191803 PACS numbers: 14.80.Bn, 13.85.Qk

JHEP Published for SISSA by Springer
Received: *June 8, 2016*
Accepted: *July 18, 2016*
Published: *August 5, 2016*

**Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC *pp* collision data at $\sqrt{s} = 7$ and 8 TeV**

**The ATLAS and CMS collaborations**
*E-mail:* atlas.publications@cern.ch, cms-publication-committee-chair@cern.ch

Abstract: Combined ATLAS and CMS measurements of the Higgs boson production and decay rates, as well as constraints on its couplings to vector bosons and fermions, are presented. The combination is based on the analysis of five production processes, namely gluon fusion, vector boson fusion, and associated production with a $W$ or a $Z$ boson or a pair of top quarks, and of the six decay modes $H \to ZZ, WW, \gamma\gamma, \tau\tau, bb$, and $\mu\mu$. All results are reported assuming a value of 125.09 GeV for the Higgs boson mass, the result of the combined measurement by the ATLAS and CMS experiments. The analysis uses the CERN LHC proton-proton collision data recorded by the ATLAS and CMS experiments in 2011 and 2012, corresponding to integrated luminosities per experiment of approximately 5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 20 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. The Higgs boson production and decay rates measured by the two experiments are combined within the context of three generic parameterisations: two based on cross sections and branching fractions, and one on ratios of coupling modifiers. Several interpretations of the measurements with more model-dependent parameterisations are also given. The combined signal yield relative to the Standard Model prediction is measured to be $1.09 \pm 0.11$. The combined measurements lead to observed significances for the vector boson fusion production process and for the $H \to \tau\tau$ decay of 5.4 and 5.5 standard deviations, respectively. The data are consistent with the Standard Model predictions for all parameterisations considered.

Keywords: Hadron-Hadron scattering (experiments), Higgs physics

ArXiv ePrint: 1606.02266

Phys. Rev. Lett. 132 (2024) 021803

PHYSICAL REVIEW LETTERS **132,** 021803 (2024)
Editors' Suggestion Featured in Physics

**Evidence for the Higgs Boson Decay to a *Z* Boson and a Photon at the LHC**

G. Aad *et al.*[*]
(ATLAS and CMS Collaborations)

(Received 8 September 2023; accepted 27 November 2023; published 11 January 2024)

The first evidence for the Higgs boson decay to a $Z$ boson and a photon is presented, with a statistical significance of 3.4 standard deviations. The result is derived from a combined analysis of the searches performed by the ATLAS and CMS Collaborations with proton-proton collision datasets collected at the CERN Large Hadron Collider (LHC) from 2015 to 2018. These correspond to integrated luminosities of around 140 fb$^{-1}$ for each experiment, at a center-of-mass energy of 13 TeV. The measured signal yield is $2.2 \pm 0.7$ times the standard model prediction, and agrees with the theoretical expectation within 1.9 standard deviations.

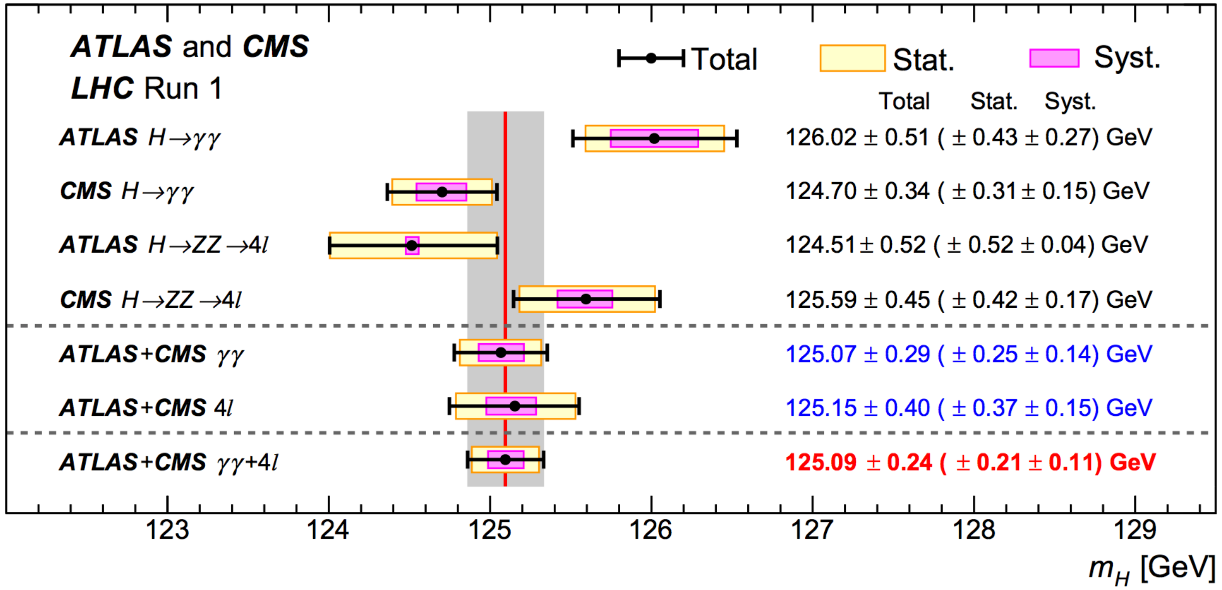
DOI: 10.1103/PhysRevLett.132.021803

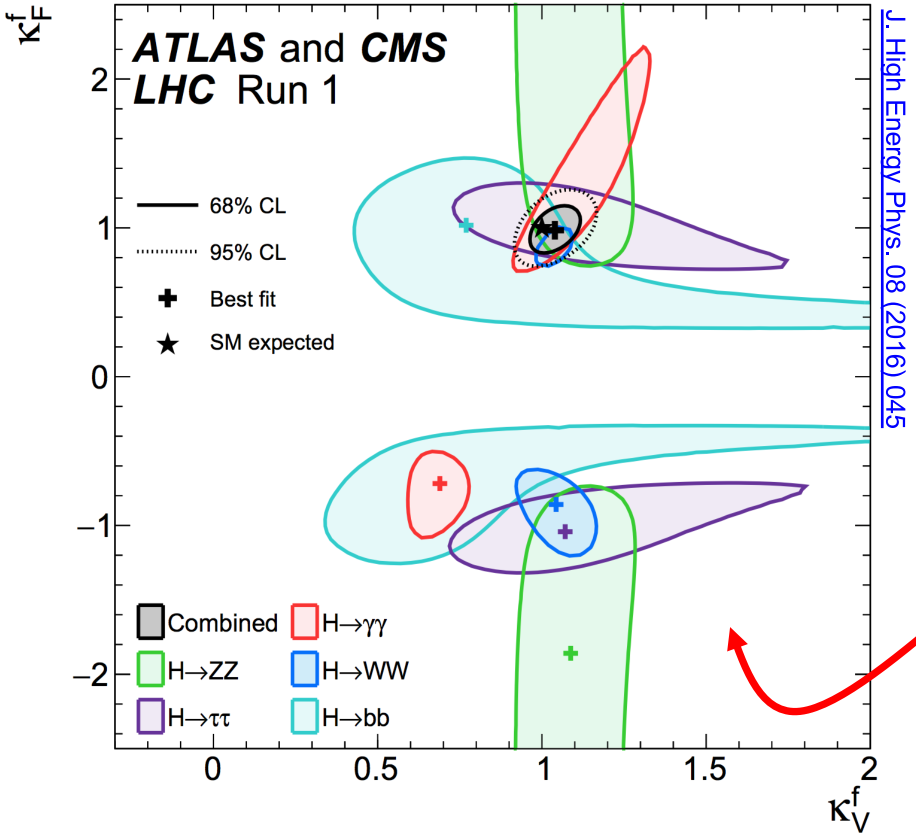
Additional combinations in Top-quark and B-physics measurements have also been performed but used different approaches to the one described here so I will not discuss them.

# Higgs combinations in LHC Run-1

Remarkable precision on **Higgs boson mass measurement** achieved through ATLAS+CMS combination

Phys. Rev. Lett. 114 (2015) 191803




Characterization of the **Higgs boson properties** through its couplings to SM particles

Not only reduced uncertainties but also lifted degeneracies through combination of multiple channels

# How these combinations were performed

In 2011 (before the Higgs discovery), ATLAS+CMS produced a detailed note laying out plans for future combinations;

- Limit setting procedure (that was used pre-discovery) & Look-elsewhere effects for discovery
- Systematic uncertainties pdfs (lnN vs Gaussian etc)
- Correlation schemes
  - Cross-section/acceptance
  - Underlying event and Parton shower
  - Proton pdf uncertainties
- Naming conventions for nuisance parameters

**PDF+$\alpha_s$ uncertainties**

| nuisance | groups of physics processes |
|---|---|
| **pdf_gg** | $gg \to H$, $t\bar{t}H$, $VQQ$, $t\bar{t}$, $tW$, $tb$ ($s$-channel), $gg \to VV$ |
| **pdf_qqbar** | VBF $H$, $VH$, $V$, $VV$, $\gamma\gamma$ |
| **pdf_qg** | $tbq$ ($t$-channel), $\gamma$+jets |

**QCD scale uncertainties**

| nuisance | groups of physics processes |
|---|---|
| **QCDscale_ggH** | total inclusive $gg \to H$ |
| **QCDscale_ggH1in** | inclusive $gg/qg \to H+ \geq 1$ jets |
| **QCDscale_ggH2in** | inclusive $gg/qg \to H+ \geq 2$ jets |
| **QCDscale_qqH** | VBF $H$ |
| **QCDscale_VH** | associate $VH$ |
| **QCDscale_ttH** | $t\bar{t}H$ |
| **QCDscale_V** | W and Z |
| **QCDscale_VV** | WW, WZ, and ZZ up to NLO |
| **QCDscale_ggVV** | $gg \to WW$ and $gg \to ZZ$ |
| **QCDscale_ZQQ** | Z with heavy flavor $q\bar{q}$-pair |
| **QCDscale_WQQ** | W with heavy flavor $q\bar{q}$-pair |
| **QCDscale_ttbar** | $t\bar{t}$, single top productions are lumped here for simplicity |

- Presentation of results and other technical details

ATL-PHYS-PUB-2011-11

CMS NOTE-2011/005

## Procedure for the LHC Higgs boson search combination in Summer 2011

The ATLAS Collaboration
The CMS Collaboration
The LHC Higgs Combination Group

August 18, 2011

**Abstract**

In this note, we report the results of the technical combination exercises conducted by the group during Winter-Spring 2011 and summarize the decisions taken in preparation for the statistical combination of the Standard Model Higgs boson searches at the LHC. The procedure to be used for the combination in Summer 2011 is explicitly detailed to avoid potential biases from decisions taken after the data have been collected.

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- Presentation of results and other technical details

ATL-PHYS-PUB-2011-11

CMS NOTE-2011/005

## Procedure for the LHC Higgs boson search combination in Summer 2011

The ATLAS C

The CMS

The LHC H

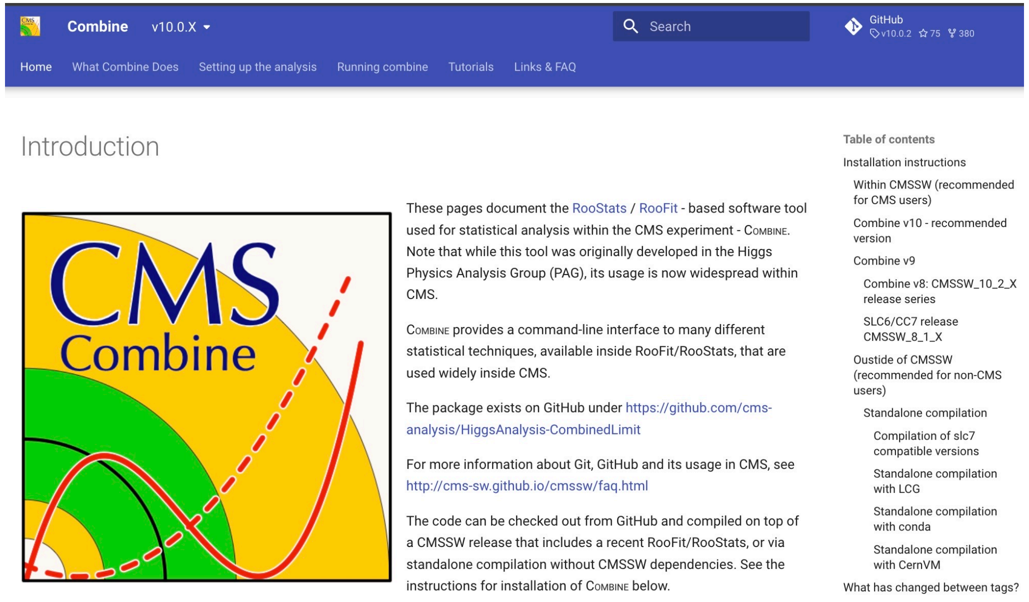
In this note ... of the technical combination exercises conducted by the gro... Spring 2011 and summarize the decisions taken in preparation for ... combination of the Standard Model Higgs boson searches at the LHC. ... procedure to be used for the combination in Summer 2011 is explicitly detailed to avoid potential biases from decisions taken after the data have been collected.

Served us as a good guide rather than an unbreakable rule book

# How these combinations were performed

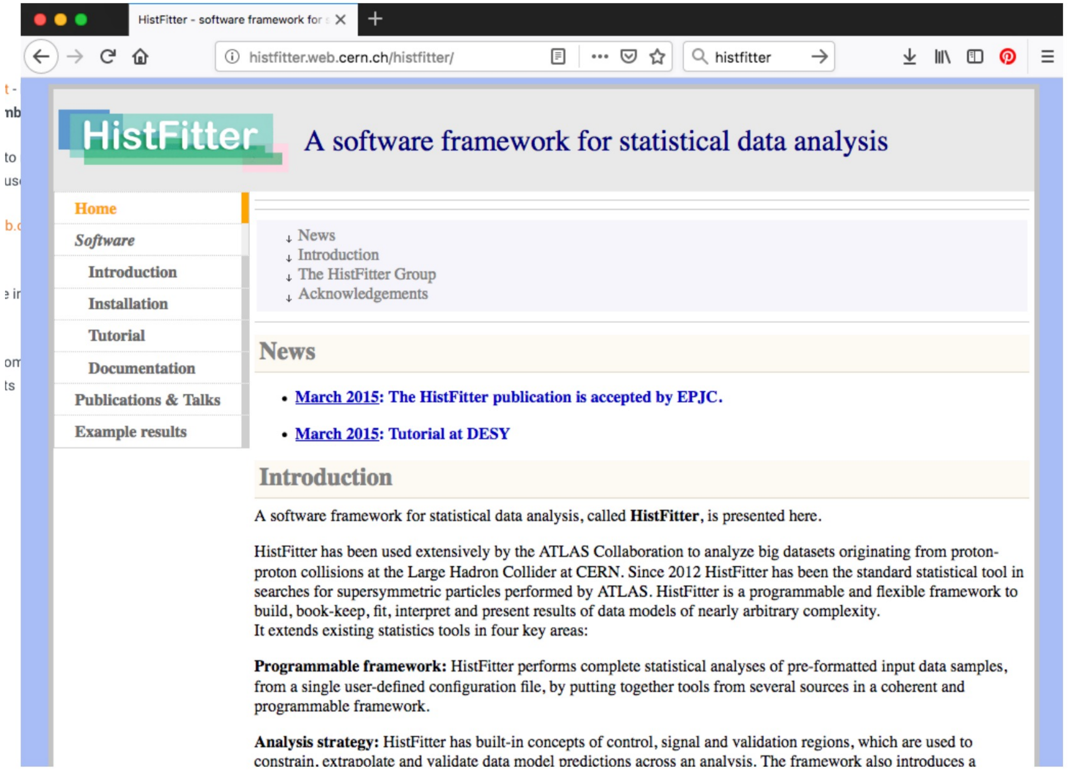
ATLAS and CMS use independent frameworks (software) to perform their own Higgs boson measurements however, **both of them being based on ROOT** makes exchange of data & statistical models much more straightforward → Recently both ATLAS and CMS have started making **statistical models public!**

**CMS framework**




http://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/

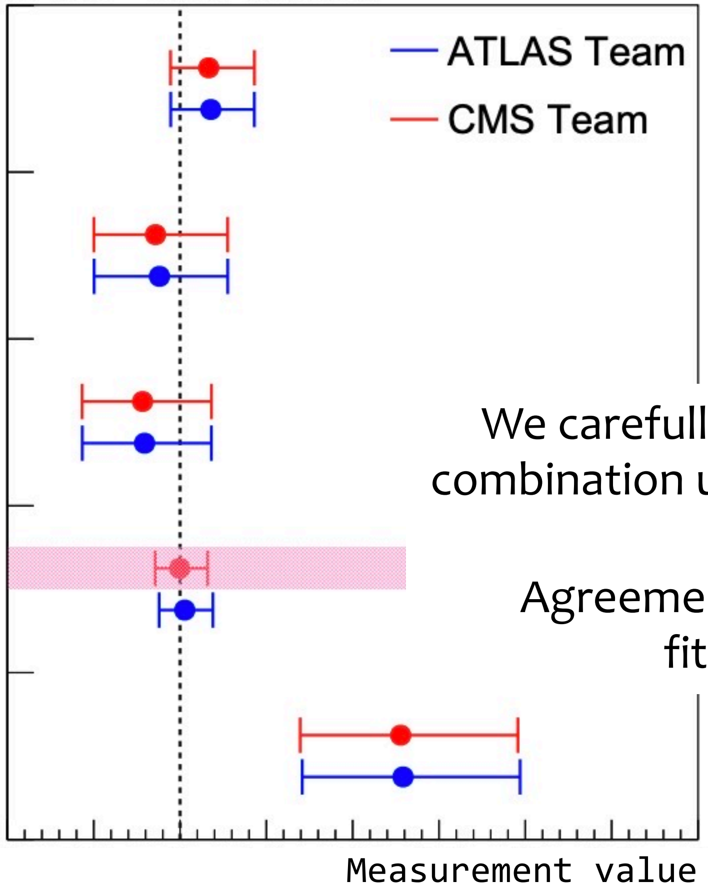
http://histfitter.web.cern.ch/histfitter/



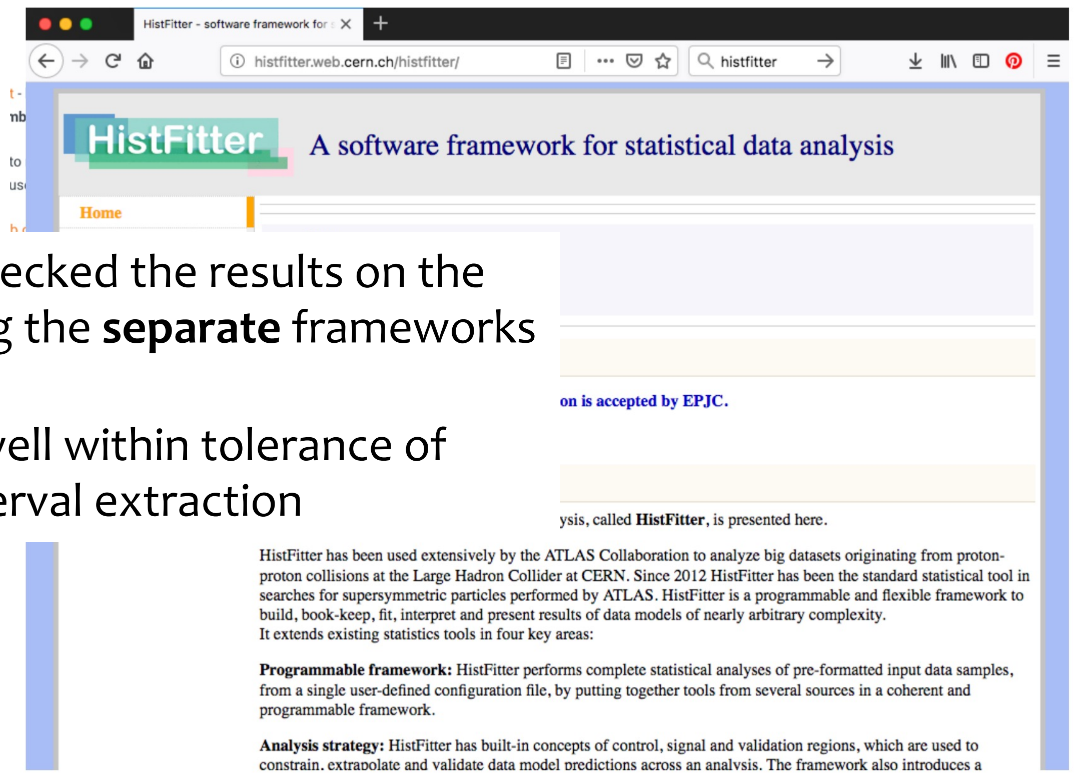

**ATLAS framework**

# How these combinations were performed

ATLAS and … to perform their own Higgs boson measurements however, b… ange of data & statistical models much more straightforw… arted making **statistical models public!**


http://histfitter.web.cern.ch/histfitter/




We carefully checked the results on the combination using the **separate** frameworks

Agreement well within tolerance of fit/interval extraction

**ATLAS framework**

# Building the likelihood function

Expectations under SM

External "constraints"

$$L(\vec{\mu},\vec{\nu}) = \prod_{n} p\left( x_n ; \sum_{i,f} \mu_i \mu^f S^f_{i,n}(\vec{\nu}) + \sum_k B_k(\vec{\nu}) \right) \cdot \prod_i p(y_i;\nu_i)$$

# Building the likelihood function

Expectations under SM

External "constraints"

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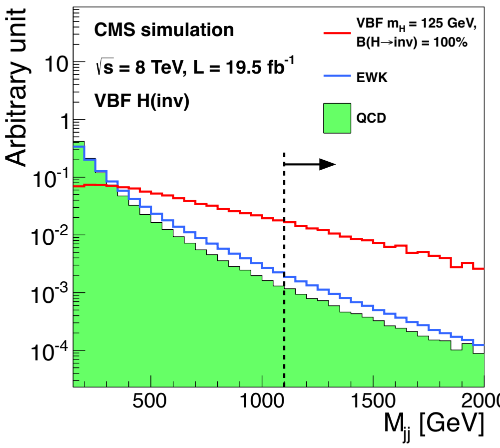
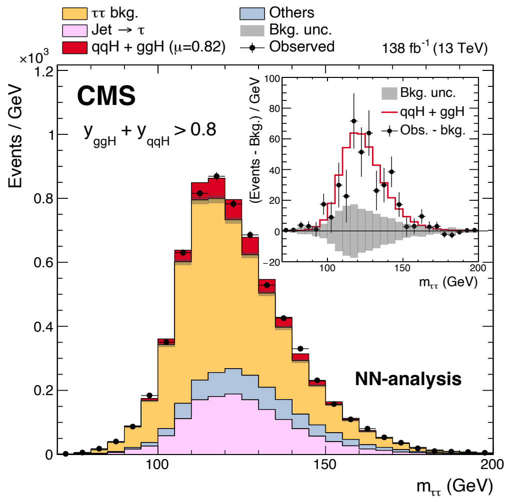
The "**data**" in each channel can be …

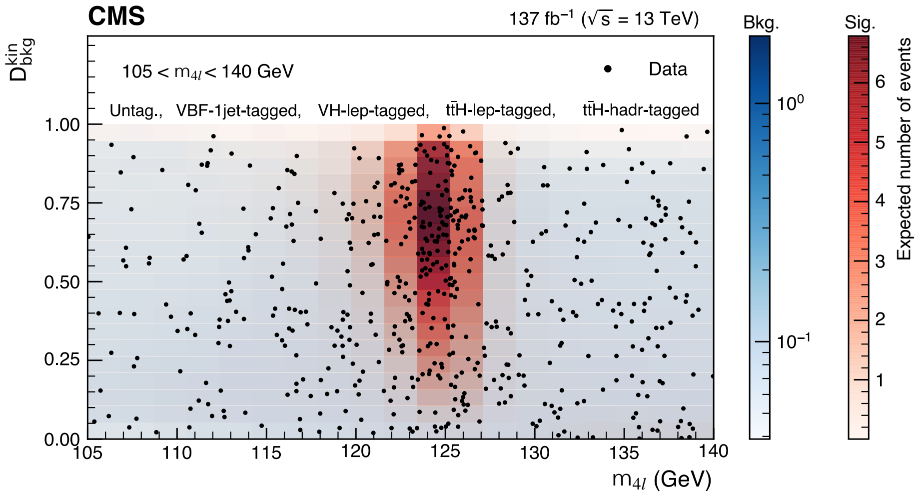
Event count(s) after some selection




Number of events in a given bin of some distribution

Multidimensional observable used to separate signal and background



# How these combinations were performed

We use the **Likelihood** to interpret the combined datasets from all channels / experiments …

$$L_{LHC} = L_{ATLAS} \cdot L_{CMS}$$

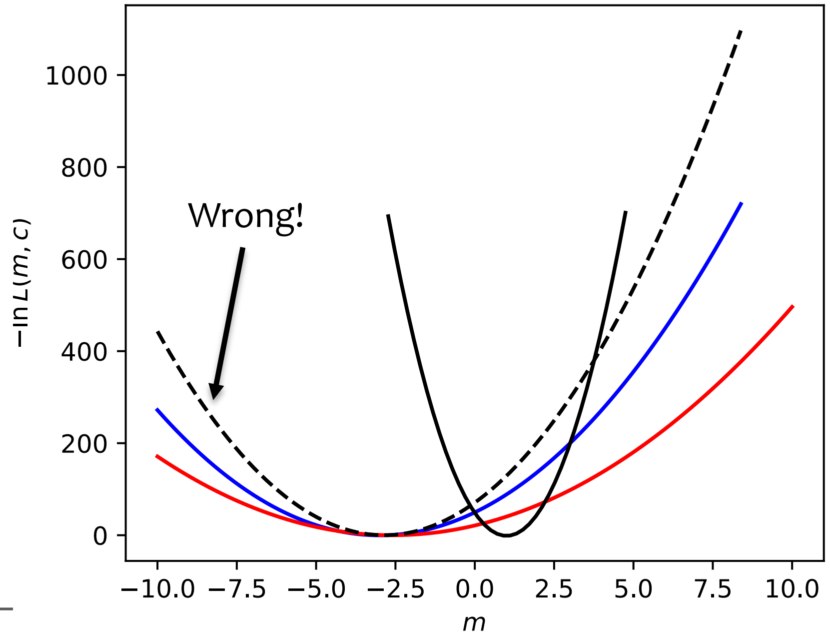
# How these combinations were performed

We use the **Likelihood** to interpret the combined datasets from all channels / experiments …

$$L_{LHC} = L_{ATLAS} \cdot L_{CMS}$$

We ***don't use*** weighted averages (or any variant thereof) in Higgs studies at the LHC.

- Allows us full access to knowledge of correlations between uncertainties
- Profiling is performed **after** likelihoods are combined → proper consideration of the various constraints from ATLAS and CMS data




(Note, CMS+ATLAS top-quark mass combination has used BLUE approach)

# Starting from the SM (same model)

To perform measurements and compared to the Standard Model, we **must start from the same definition of the Standard Model**

- *Inclusive* production cross-sections & decay rates, and uncertainties calculated by the LHC Higgs working group

✓

| Decay mode | Branching fraction [%] |
|---|---|
| $H \to bb$ | $57.5 \pm 1.9$ |
| $H \to WW$ | $21.6 \pm 0.9$ |
| $H \to gg$ | $8.56 \pm 0.86$ |
| $H \to \tau\tau$ | $6.30 \pm 0.36$ |
| $H \to cc$ | $2.90 \pm 0.35$ |
| $H \to ZZ$ | $2.67 \pm 0.11$ |
| $H \to \gamma\gamma$ | $0.228 \pm 0.011$ |
| $H \to Z\gamma$ | $0.155 \pm 0.014$ |
| $H \to \mu\mu$ | $0.022 \pm 0.001$ |

| Production process | Cross section [pb] | | Order of calculation |
|---|---|---|---|
| | $\sqrt{s}$ = 7 TeV | $\sqrt{s}$ = 8 TeV | |
| $ggF$ | $15.0 \pm 1.6$ | $19.2 \pm 2.0$ | NNLO(QCD)+NLO(EW) |
| $VBF$ | $1.22 \pm 0.03$ | $1.58 \pm 0.04$ | NLO(QCD+EW)+~NNLO(QCD) |
| $WH$ | $0.577 \pm 0.016$ | $0.703 \pm 0.018$ | NNLO(QCD)+NLO(EW) |
| $ZH$ | $0.334 \pm 0.013$ | $0.414 \pm 0.016$ | NNLO(QCD)+NLO(EW) |
| $[ggZH]$ | $0.023 \pm 0.007$ | $0.032 \pm 0.010$ | NLO(QCD) |
| $bbH$ | $0.156 \pm 0.021$ | $0.203 \pm 0.028$ | 5FS NNLO(QCD) + 4FS NLO(QCD) |
| $ttH$ | $0.086 \pm 0.009$ | $0.129 \pm 0.014$ | NLO(QCD) |
| $tH$ | $0.012 \pm 0.001$ | $0.018 \pm 0.001$ | NLO(QCD) |
| Total | $17.4 \pm 1.6$ | $22.3 \pm 2.0$ | |

LHC-HWG YR3: https://arxiv.org/abs/1307.1347

# Starting from the SM (same model)

To perform measurements and compared to the Standard Model, we **must start from the same definition of the Standard Model**

- *Inclusive* production cross-sections & decay rates, and uncertainties calculated by the LHC Higgs working group ✓
- *Acceptance* effects and observable distributions derived from simulated samples → not necessarily the same between ATLAS and CMS (preferences, time of analysis etc) ✗
- Need to introduce corrections to synchronize predictions for the signal (Higgs) production

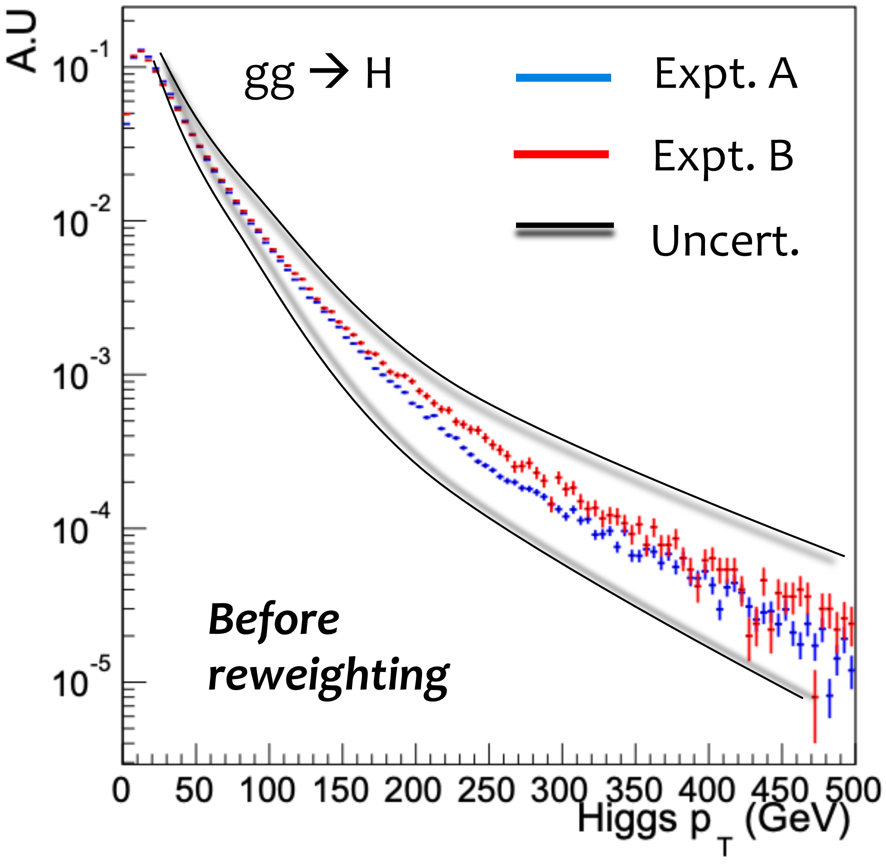
**SM Higgs MC to calculate acceptance in each channel (V-$p_T$, n-jets etc)**

| Production process | Event generator ATLAS | Event generator CMS |
|---|---|---|
| $ggF$ * | Powheg [30–34] | Powheg |
| VBF | Powheg | Powheg |
| $WH$ | Pythia8 [35] | Pythia6.4 [36] |
| $ZH$ ($qq \to ZH$ or $gg \to ZH$) | Pythia8 | Pythia6.4 |
| $ggZH$ ($gg \to ZH$) | Powheg | See text |
| $ttH$ | Powhel [44] | Pythia6.4 |
| $tHq$ ($qb \to tHq$) | MadGraph [46] | aMC@NLO [29] |
| $tHW$ ($gb \to tHW$) | aMC@NLO | aMC@NLO |
| $bbH$ | Pythia8 | Pythia6, aMC@NLO |

**Higgs $p_T$ distribution for ggF production with HRes2.1 (NNLO+NNLL QCD)*

# Starting from the SM (same model)

Better to decide on definition of "SM" before producing individual results but it's possible to account for differences after the fact




ATLAS and CMS use the "latest and greatest" calculation available but "latest" depends on **when** the publication is complete.

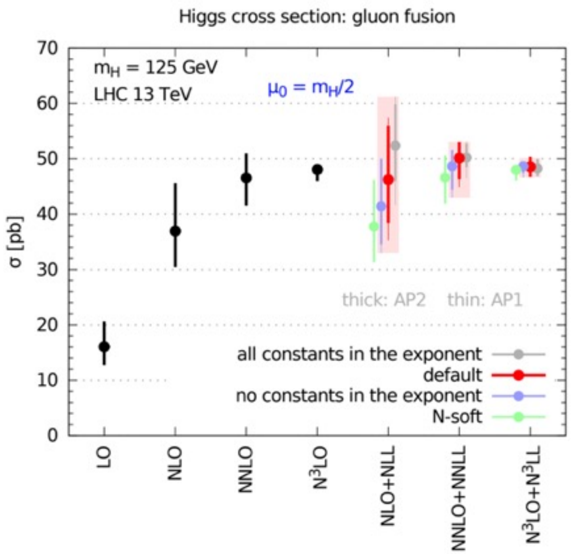
Typically differences between ATLAS and CMS signal predictions were << uncertainty on the prediction.

Reweight simulation to "best" prediction so that we start from the same inputs → uncertainties can be ***properly correlated***

***We probably spent longer deciding which experiment was A or B than necessary*** ☺

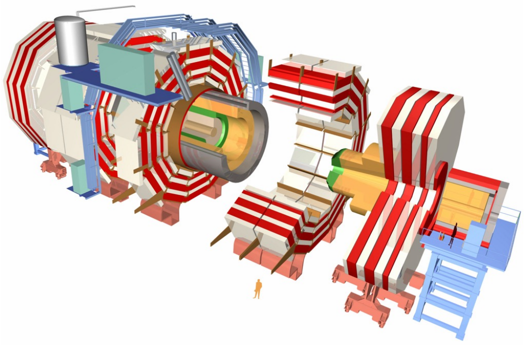
# Systematic uncertainties – (Couplings paper)

Combination consists of nearly 600 categories with a total of around **4200** nuisance parameters describing the composition of the different signal and backgrounds



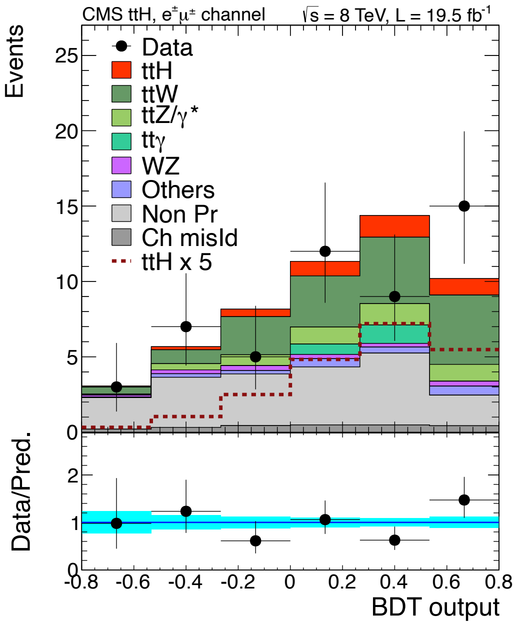

## Experimental/Detector systematics:

- Object efficiencies, energy scales, luminosity
- Largely uncorrelated between ATLAS and CMS*



## Signal theory uncertainties:

- Correlate inclusive x-section uncertainties, QCD scale, pdf, UEPS, Branching ratios, jet counting**
- De-correlate effects on object acceptance as these are often data-driven/estimation procedures generally differ




## Background theory uncertainties:

- Often rather different phase-spaces considered for two experiments or data-driven estimates
- Mostly uncorrelated with few exceptions (gg/qqZZ continuum, ttW, ttZ X-sections)

*Partial correlation of common luminosity measurement
** Follow the recommendations of the LHC-HXSWG

# Theoretical uncertainties

Correlating systematic uncertainties requires common strategy for modelling the effects of uncertainties

| Nuisance parameter name | Systematic uncertainty |
|---|---|
| QCDscale_ggH | QCD scale, ggH |
| QCDscale_ggH1in | QCD scale, ggH+≥1-jet (ST) |
| QCDscale_ggH2in | QCD scale, ggH+≥2-jets (ST) |
| QCDscale_ggH2in_vbf | QCD scale, ggH+≥2-jets, in VBF phase space (ST) |
| QCDscale_ggH2in_vh | QCD scale, ggH+≥2-jets, in VH phase space (ST) |
| QCDscale_ggH3in | QCD scale, ggH+≥3-jets (ST) |
| QCDscale_qqH | QCD scale, qqH |
| QCDscale_VH | QCD scale, WH and $qq \to ZH$ |
| QCDscale_ggZH | QCD scale, $gg \to ZH$ |
| QCDscale_ttH | QCD scale, ttH |
| QCDscale_WtH | QCD scale, tHW |
| QCDscale_tHjb | QCD scale, tHq |
| QCDscale_bbH | QCD scale, bbH |
| QCDscale_ttW | QCD scale, ttW |
| QCDscale_ttZ | QCD scale, ttZ |
| QCDscale_V | QCD scale, W/Z when from MC |
| QCDscale_VV | QCD scale, $(qq \to)VV$, mainly qqZZ in $H \to ZZ^* \to 4\ell$ |
| QCDscale_ggZZ | QCD scale, $gg \to ZZ$ |

Agreeing convention not only on how to model SM theoretical uncertainties involved long conversations between ATLAS & CMS analysts as well as experts from the theory community

# Relevance of (groups) of systematic uncertainties

Simplest model (discovery model) is one overall scaling parameter $\mu := \mu_i = \mu_f$

$\forall i, f \in \{ttH, qqH, H \rightarrow ZZ, ...\}$

| | Best-fit $\mu$ | Uncertainty | | | | |
|---|---|---|---|---|---|---|
| | | Total | Stat | Expt | Thbgd | Thsig |
| ATLAS and CMS (meas.) | 1.09 | $^{+0.11}_{-0.10}$ | $^{+0.07}_{-0.07}$ | $^{+0.04}_{-0.04}$ | $^{+0.03}_{-0.03}$ | $^{+0.07}_{-0.06}$ |
| ATLAS and CMS (exp.) | – | $^{+0.11}_{-0.10}$ | $^{+0.07}_{-0.07}$ | $^{+0.04}_{-0.04}$ | $^{+0.03}_{-0.03}$ | $^{+0.06}_{-0.06}$ |
| ATLAS (meas.) | 1.20 | $^{+0.15}_{-0.14}$ | $^{+0.10}_{-0.10}$ | $^{+0.06}_{-0.06}$ | $^{+0.04}_{-0.04}$ | $^{+0.08}_{-0.07}$ |
| CMS (meas.) | 0.98 | $^{+0.14}_{-0.13}$ | $^{+0.10}_{-0.09}$ | $^{+0.06}_{-0.05}$ | $^{+0.04}_{-0.04}$ | $^{+0.08}_{-0.07}$ |

*Theory uncert dominated by ggF incl. x-section*

# Combination timelines

All discussions happen(ed) in the **LHC Higgs Combination Group** (LHC-HCG)

"Open" forum with conveners from both ATLAS and CMS → answer to co-ordination **from both experiments**

- 05 Feb LHC-HCG Working Meeting (protected)

January 2015

- 23 Jan LHC-HCG Working Meeting (protected)
- 15 Jan LHC-HCG meeting (protected)

December 2014

- 11 Dec LHC-HCG meeting (protected)
- 04 Dec LHC-HCG meeting (protected)

November 2014

- 26 Nov LHC-HCG meeting (protected)
- 13 Nov LHC-HCG meeting (protected)

October 2014

- 29 Oct LHC-HCG meeting (protected)
- 16 Oct LHC-HCG meeting (protected)

September 2014

- 24 Sep LHC-HCG meeting (protected)
- 17 Sep LHC-HCG meeting (protected)
- 03 Sep LHC-HCG meeting (protected)

August 2014

- 27 Aug LHC-HCG meeting (protected)
- 20 Aug LHC-HCG meeting (protected)

e.g > 1 year of discussions for $m_H$ combination

## Charge

The working group has been charged to produce a combined Higgs result from LHC (ATLAS and CMS) Higgs analyses. The mandate of the group is as follows

- The implementation of Higgs boson theory aspects based on LHC Higgs XS WG recommendations will be discussed within the group. If needed, the group will request additional information from the LHC Higgs XS WG.
- Monte Carlo generators and systematic variations are to be compared and unified where profitable and consistent with the overall MC and systematic uncertainty strategy in the individual experiments. This could result in sharing MC samples between ATLAS and CMS.
- Technical aspects regarding the construction and usage of likelihood functions are to be discussed and solutions implemented as homogeneously as possible, including common naming conventions and tools. This includes efforts to construct simplified likelihood functions.

- 23 Apr LHC-HCG meeting (protected)
- 09 Apr LHC-HCG meeting (protected)
- 02 Apr LHC-HCG meeting (protected)

March 2014

- 12 Mar LHC-HCG meeting (protected)

February 2014

- 26 Feb LHC-HCG meeting (protected)

# Example timeline: $m_H$

Feb 2014 – Mar 2015

- 05 Feb LHC-HCG Working Meeting (protected)

January 2015

- 23 Jan LHC-HCG Working Meeting (protected)
- 15 Jan LHC-HCG meeting (protected)

December 2014

- 11 Dec LHC-HCG meeting (protected)
- 04 Dec LHC-HCG meeting (protected)

November 2014

- 26 Nov LHC-HCG meeting (protected)
- 13 Nov LHC-HCG meeting (protected)

October 2014

- 29 Oct LHC-HCG meeting (protected)
- 16 Oct LHC-HCG meeting (protected)

September 2014

- 24 Sep LHC-HCG meeting (protected)
- 17 Sep LHC-HCG meeting (protected)
- 03 Sep LHC-HCG meeting (protected)

August 2014

- 27 Aug LHC-HCG meeting (protected) — **First full combination (toy data)**
- 20 Aug LHC-HCG meeting (protected) — Parameterization for mH nominal fits
- 13 Aug LHC-HCG meeting (protected)
- 06 Aug LHC-HCG meeting (protected)

July 2014

- 30 Jul LHC-HCG meeting (protected) — First discussions on H→γγ nuisances and exchange of Hγγ workspaces (toy datasets)
- 16 Jul LHC-HCG meeting (protected)

June 2014

- 11 Jun LHC-HCG meeting (protected)

May 2014

- 28 May LHC-HCG meeting (protected) — Theory uncertainties discussions
- 14 May LHC-HCG meeting (protected)
- 07 May LHC-HCG meeting (protected)

April 2014

- 23 Apr LHC-HCG meeting (protected) — Discussions on nuisance parameters, + combination of H→4l toys
- 09 Apr LHC-HCG meeting (protected)
- 02 Apr LHC-HCG meeting (protected)

March 2014

- 12 Mar LHC-HCG meeting (protected) — Technical Discussions, first tests of exchanging H→ 4l inputs

February 2014

- 26 Feb LHC-HCG meeting (protected)

# Example timeline: $m_H$

CMS H→γγ paper

ATLAS combined mass paper

Feb 2014 – Mar 2015

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March 2014

- 12 Mar LHC-HCG meeting (protected)

February 2014

- 26 Feb LHC-HCG meeting (protected)

Detailed comparisons of scans from CMS and ATLAS ($10^{-6}$ precision on LH scans)

Full set of tests implemented

Compatibility tests proposed

**First full combination (toy data)**

Parameterization for mH nominal fits

First discussions on H→γγ nuisances and exchange of Hγγ workspaces (toy datasets)

Theory uncertainties discussions

Discussions on nuisance parameters, + combination of H→4l toys

Technical Discussions, first tests of exchanging H→ 4l inputs

# Example timeline:

## $m_H$

CMS combined properties paper

CMS H→γγ paper

ATLAS combined mass paper

**Feb 2014 – Mar 2015**

- 05 Feb LHC-HCG Working Meeting (protected)

January 2015

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March 2014

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February 2014

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LHC Combined mass **paper submitted 26th March 2015**

**Unblind Full Combination!**

Detailed comparisons of scans from CMS and ATLAS ($10^{-6}$ precision on LH scans)

Full set of tests implemented

Compatibility tests proposed

**First full combination (toy data)**

Parameterization for mH nominal fits

First discussions on H→γγ nuisances and exchange of Hγγ workspaces (toy datasets)

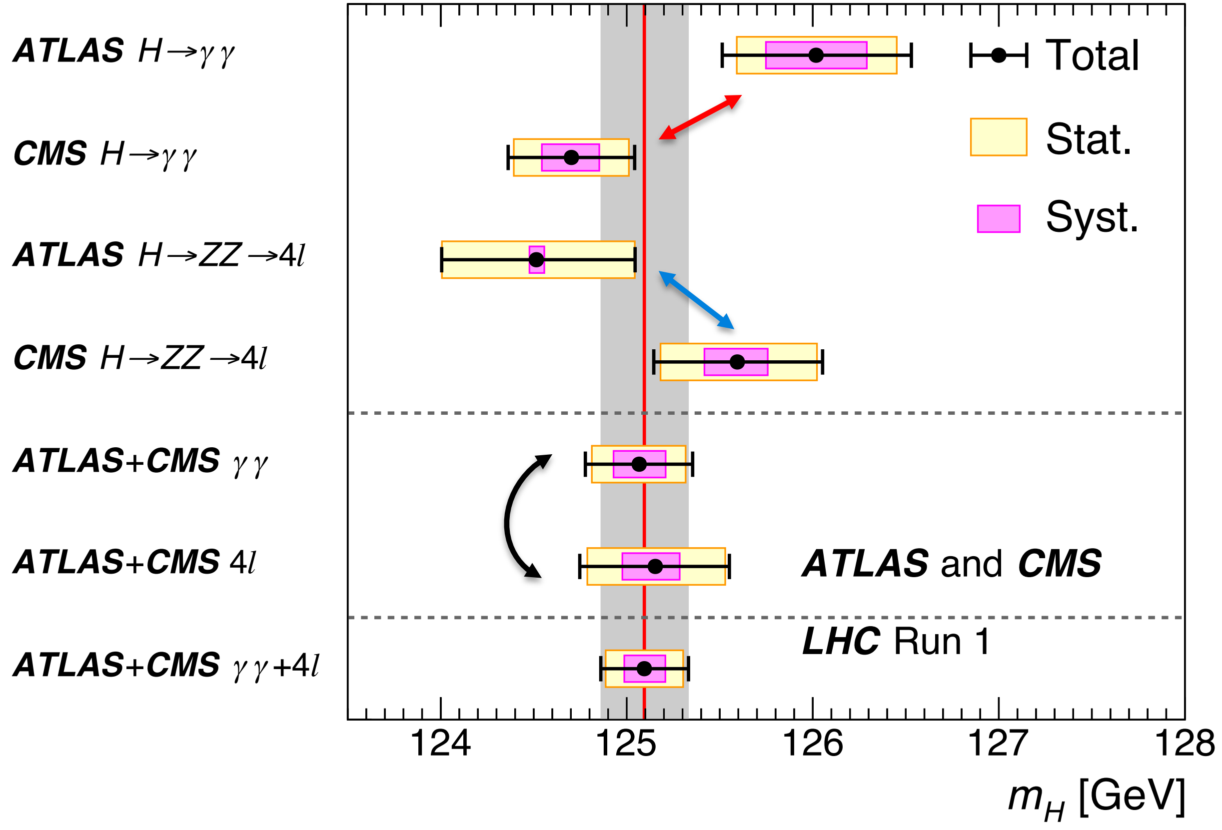
Theory uncertainties discussions

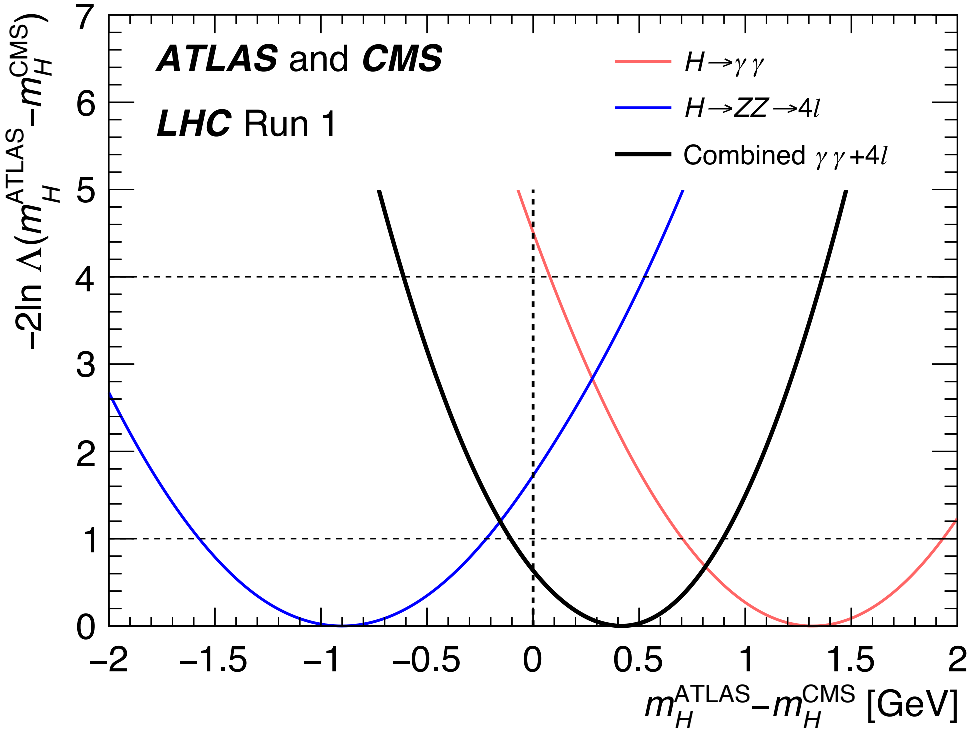
Discussions on nuisance parameters, + combination of H→4l toys

Technical Discussions, first tests of exchanging H→ 4l inputs

# Compatibility checks

Introduced new parameterizations (Δμ or Δm) to investigate compatibility between the measurements …



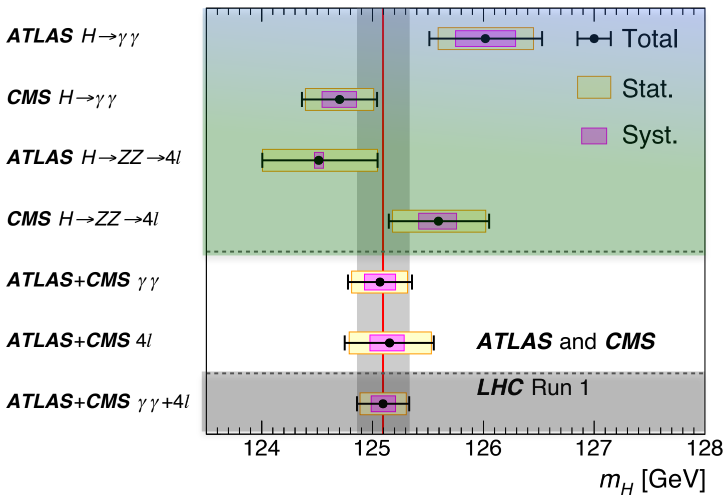




Calculate measure of compatibility using log-likelihood

$$\sqrt{-2\log\Lambda(\Delta m = 0)}$$

→ accounts for correlations between ATLAS & CMS

# Compatibility checks




More ways to check compatibility of the result …

What happens if the nominal model is used with 4 masses

3μ+4m
Four masses

10%

The combined value in the plot

3μ+1m
"Nominal"

24%

The actual compatibility between the combined value and the 4 measurements

The 4 measurements in the plot

6μ+4m
Both

7%

What we "see" when looking at the 4 measurements in the plot.

6μ+1m
Six signal modifiers

p-values

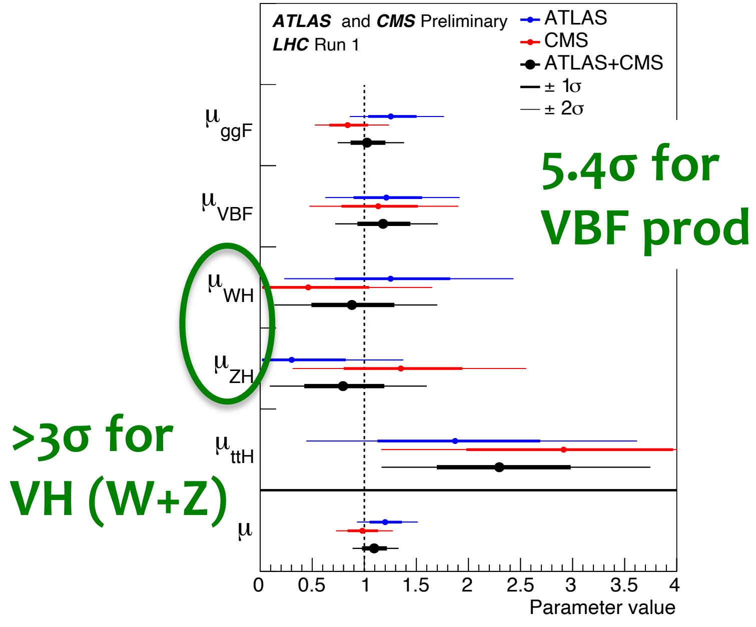
All results compatible within 2σ!

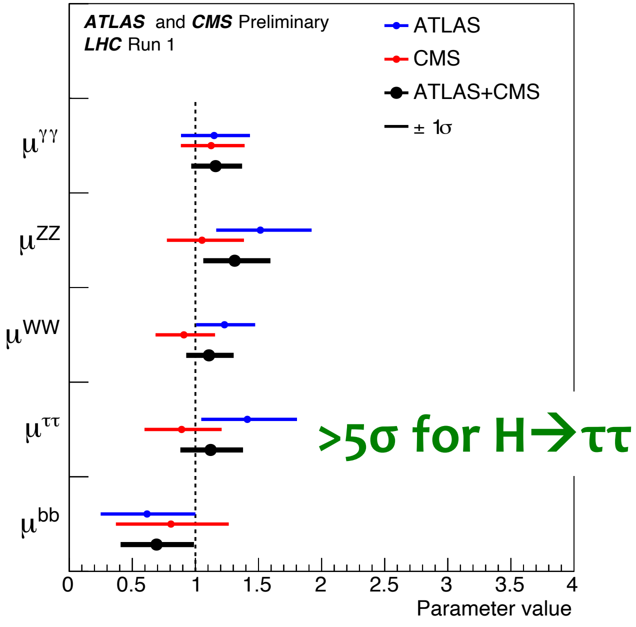
# Benefits of combinations

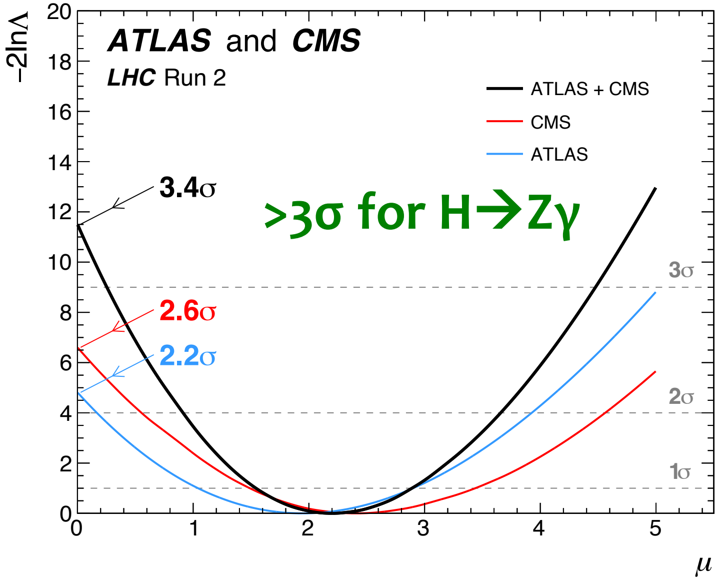
The combined measurements of the Higgs boson mass and its production/decay rates were published after the discovery and after each individual experiment completed their combinations

An improvement of $\sqrt{2}$ is the best one can expect (no correlations) on any individual measurement, however it is also possible that combination can lead to ***new statements*** about the physics

**Get the most out of the data!**



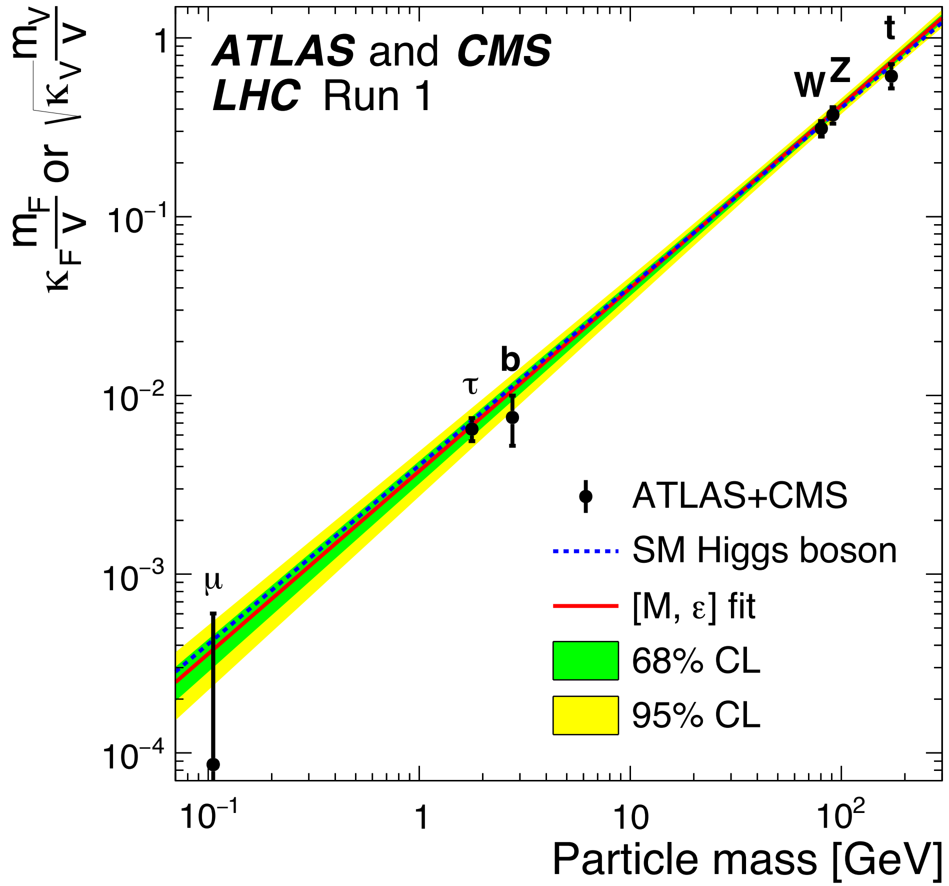
# Summary

**ATLAS + CMS performed successful Higgs Combinations in Run-1/2**

- Higgs boson mass, couplings and recent H→Zγ
- Combinations performed at the likelihood level → requires exchange of full statistical model and data sets
- Separate frameworks require common exchange format

**Sociological and scientific benefits**

- Some work needed to setup structures to allow combinations to take place (LHC-HWG, LHC-HCG)
- Followed a blind procedure towards final combined set of results
- Open attitude towards cross-checking each other's work and the final results → common goal of the best science in the end
- Combinations provide scientific results beyond sqrt(2) improvement in measurements



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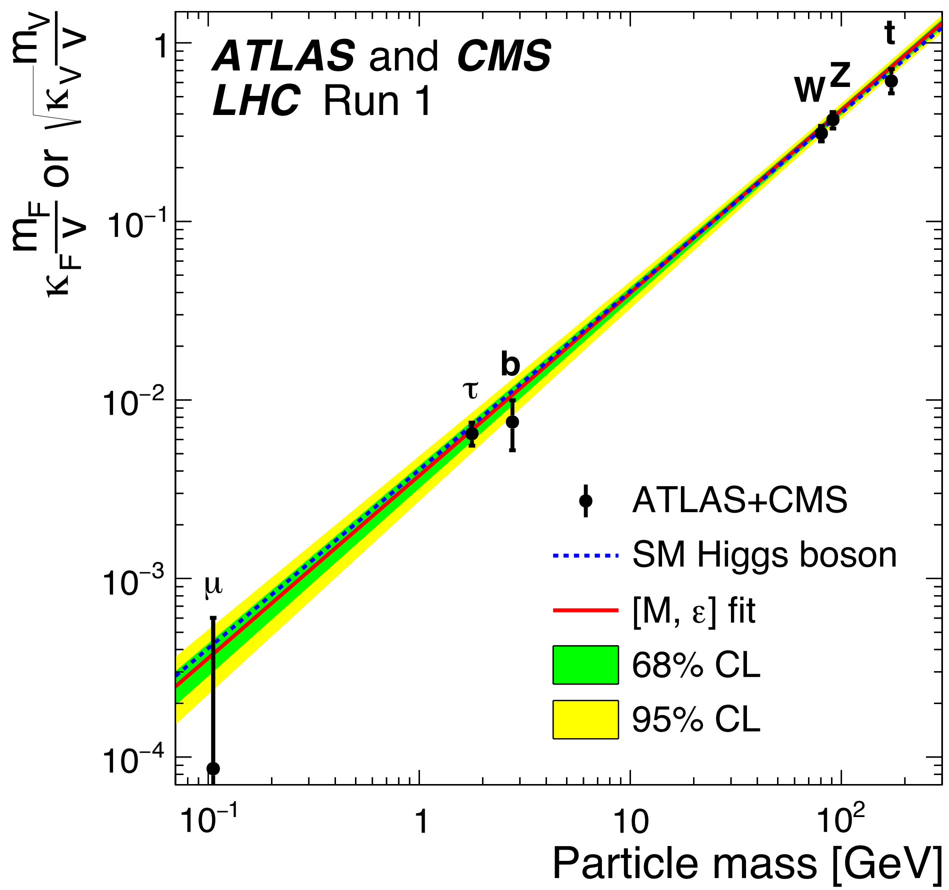
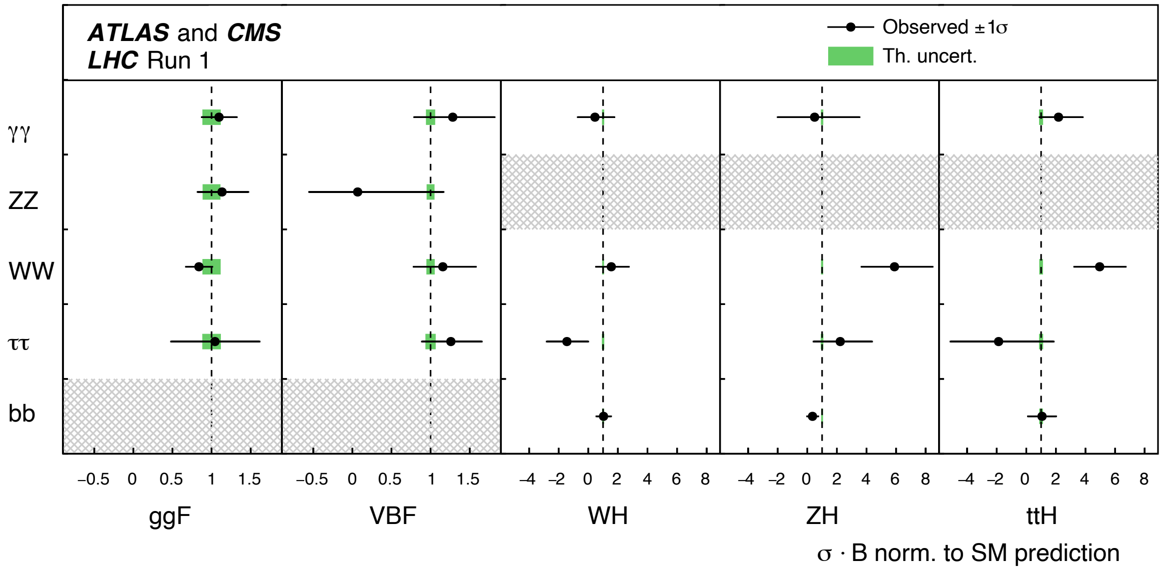



**Thanks!**

# Backup

# Inputs to the Higgs combination




Inputs for the production/decay and couplings combination

| | Untagged | VBF | VH | ttH(+tH) |
|---|---|---|---|---|
| H→γγ | ✓ | ✓ | ✓ | ✓ |
| H→ZZ→4l | ✓ | ✓ | ✓ | ✓ |
| H→WW→2l2ν | ✓ | ✓ | ✓ | ✓ |
| H→ττ | ✓ | ✓ | ✓ | ✓ |
| H→bb | ✗ | ✗ | ✓ | ✓ |
| H→μμ | ✓ | ✓ | ✗ | ✗ |

# Other LHC Combinations

PHYSICAL REVIEW LETTERS **132,** 261902 (2024)

Editors' Suggestion | Featured in Physics

## Combination of Measurements of the Top Quark Mass from Data Collected by the ATLAS and CMS Experiments at $\sqrt{s} = 7$ and 8 TeV

A. Hayrapetyan *et al.*[*]

(CMS Collaboration)[†]
(ATLAS Collaboration)[‡]

(Received 13 February 2024; accepted 1 April 2024; published 27 June 2024; corrected 12 August 2024)

A combination of fifteen top quark mass measurements performed by the ATLAS and CMS experiments at the LHC is presented. The datasets used correspond to an integrated luminosity of up to 5 and 20 fb$^{-1}$ of proton-proton collisions at center-of-mass energies of 7 and 8 TeV, respectively. The combination includes measurements in top quark pair events that exploit both the semileptonic and hadronic decays of the top quark, and a measurement using events enriched in single top quark production via the electroweak $t$ channel. The combination accounts for the correlations between measurements and achieves an improvement in the total uncertainty of 31% relative to the most precise input measurement. The result is $m_t = 172.52 \pm 0.14(\text{stat}) \pm 0.30(\text{syst})$ GeV, with a total uncertainty of 0.33 GeV.

DOI: 10.1103/PhysRevLett.132.261902

Available on the CERN CDS information server

**CMS PAS BPH-20-003**
**LHCb-CONF-2020-002**
**ATLAS-CONF-2020-049**

## CMS Physics Analysis Summary

Contact: cms-pag-conveners-bphysics@cern.ch

2020/08/05

## Combination of the ATLAS, CMS and LHCb results on the $B^0_{(s)} \to \mu^+\mu^-$ decays

The ATLAS, CMS and LHCb Collaborations

### Abstract

A combination of results on the rare $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays from the ATLAS, CMS, and LHCb experiments using data collected at the Large Hadron Collider between 2011 and 2016, is presented. The $B^0_s \to \mu^+\mu^-$ branching fraction is obtained to be $(2.69\,^{+0.37}_{-0.35}) \times 10^{-9}$ and the effective lifetime of the $B^0_s \to \mu^+\mu^-$ decay is measured to be $\tau_{B^0_s \to \mu^+\mu^-} = 1.91^{+0.37}_{-0.35}$ ps. An upper limit on the $B^0 \to \mu^+\mu^-$ branching fraction is evaluated to be $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.6\ (1.9) \times 10^{-10}$ at 90% (95%) confidence level. An upper limit on the ratio of the $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$ branching fractions is obtained to be 0.052 (0.060) at 90% (95%) confidence level.

# (Obvious?) Warning about combining likelihoods

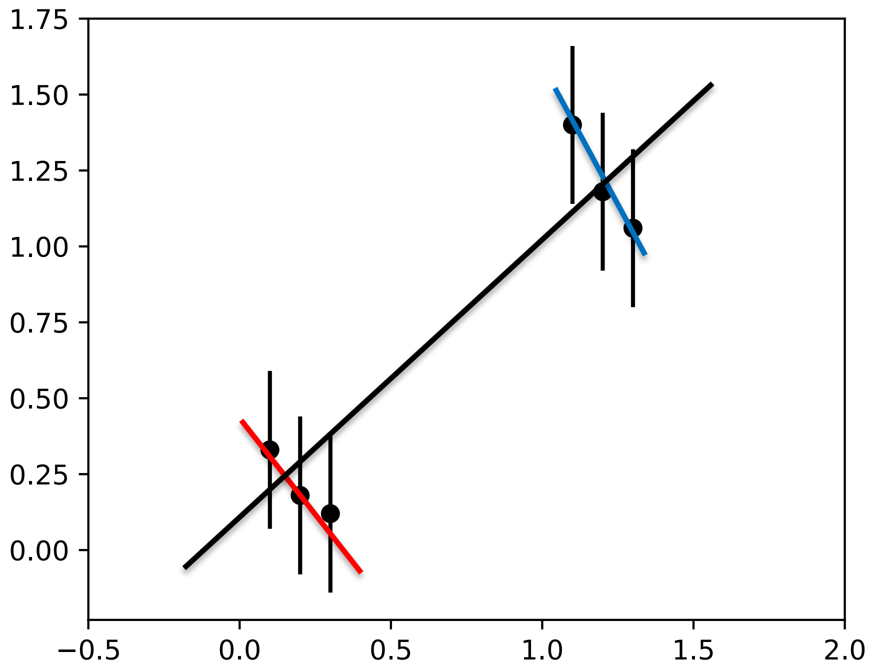
Cannot sum **profiled log-likelihoods**!

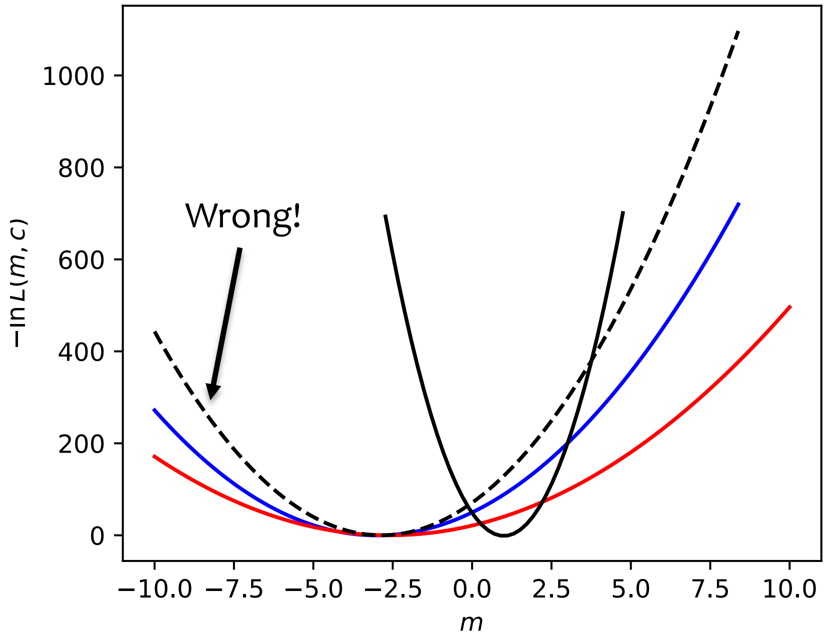
$$-\ln L_{\text{comb}}(\mu, \hat{\nu}(\mu)) \neq -\ln L_1(\mu, \hat{\nu}(\mu)) - \ln L_2(\mu, \hat{\nu}(\mu))$$

Imaging fitting a straight line to the points

$$y = mx + c$$

The profiled likelihoods as a function of the slope **do not sum to give the correct combined profiled likelihood!**



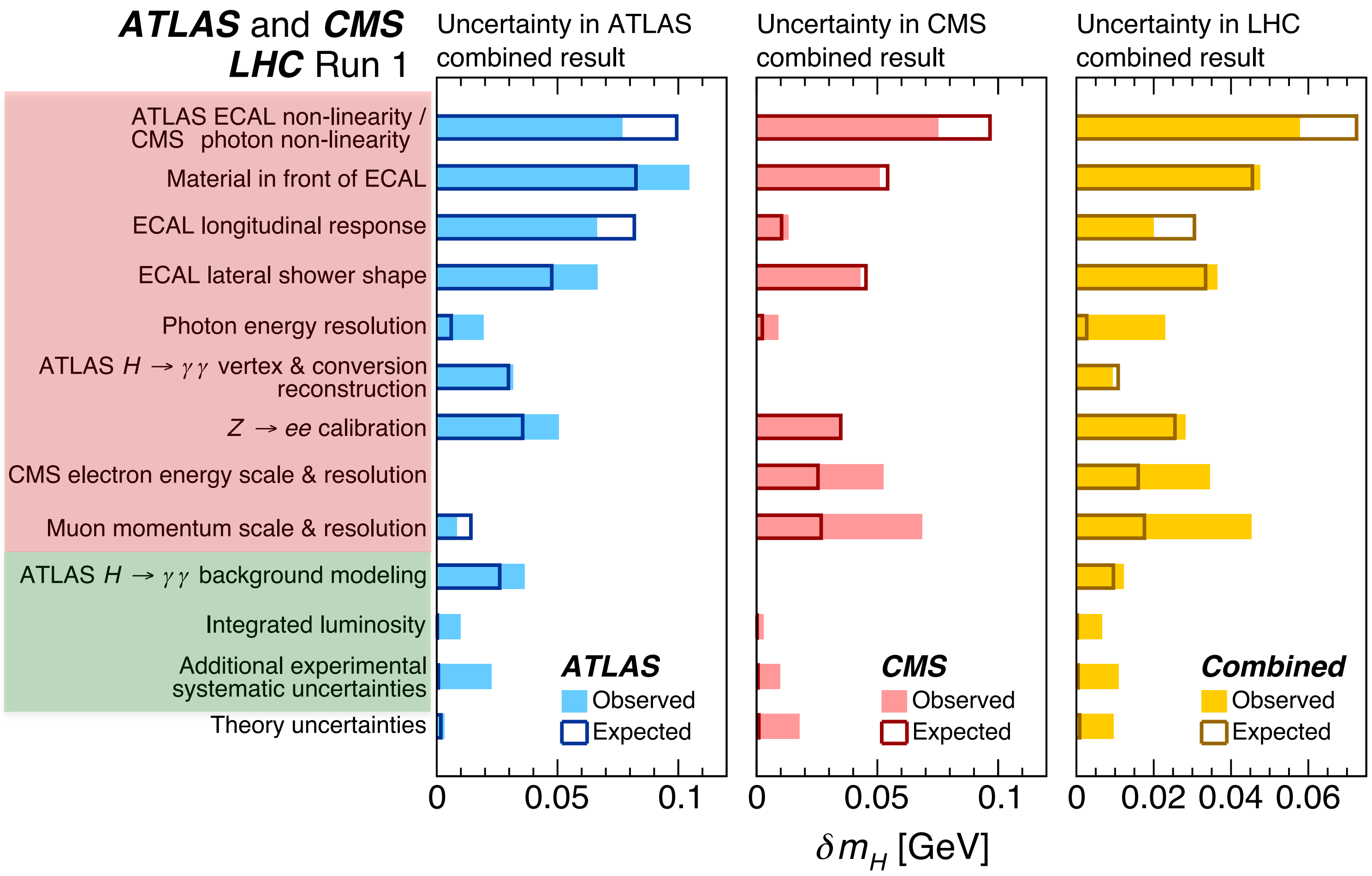
# Relevance of (groups) of systematic uncertainties $m_H$

Energy/momentum scale and resolution of μ, e and γ dominate systematic uncertainty for combined mass measurement

Other experimental uncertainties (eff, JES, luminosity… )

Carefully studied the relevance (impact) of various groups of systematic uncertainties.

Correlations between dominant sources should be studied in greater detail → for $m_H$, most experimental uncertainties kept uncorrelated, correlated (theory) parameters are sub-dominant in this case



# Nuisance parameters

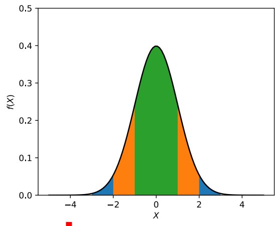
We model the effects of systematic uncertainties through the introduction of nuisance parameters into our model

$$p(X;\theta) \rightarrow p(X;\mu,\nu)$$

$\mu$ **Parameters of interest:** cross-section, Top mass, …

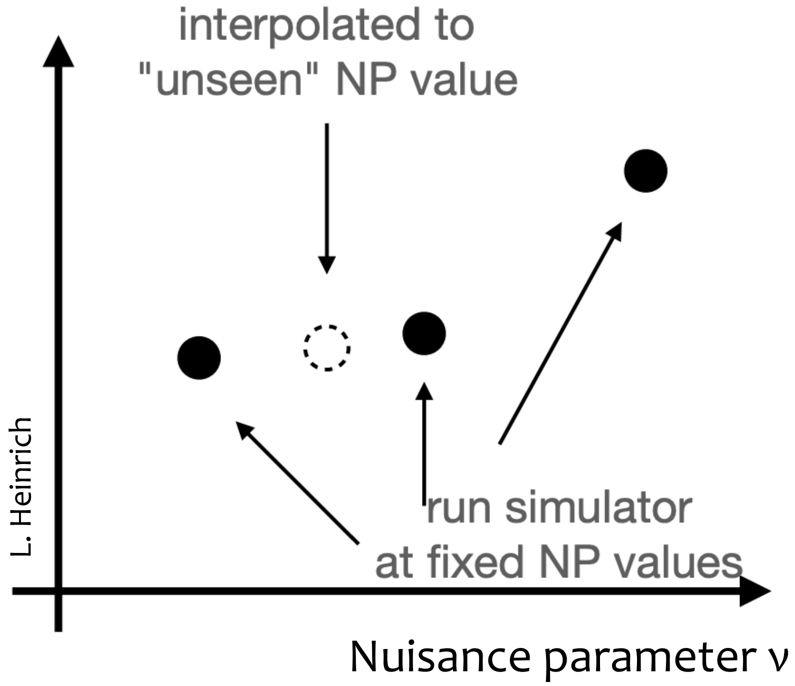
$\nu$ **Nuisance parameters:** Jet energy scale, Luminosity, …

We need to choose a parameterization for the effects of each of our nuisance parameters
e.g counting experiment – 30% lumi uncertainty



$$e^{-\lambda}\frac{\lambda^k}{k!} \rightarrow e^{-\lambda(r,\nu)}\frac{\lambda(r,\nu)^k}{k!}\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}\nu^2}$$

$$\lambda(r,\nu) = r\sigma L_0(1.3)^{\nu}A\epsilon$$



# Public Statistical Models

News › News › Topic: Experiments

*Voir en [français]*

## CMS releases Higgs boson discovery data to the public

**The collaboration has also made publicly available the software that it developed to search for the unique particle**

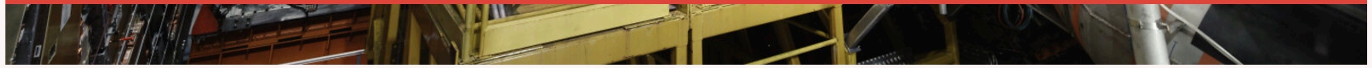
16 APRIL, 2024 | By CMS collaboration

CMS event display of a candidate Higgs boson decaying into two photons, one of the two decay channels that were key to the discovery of the particle. (Image: CERN)

https://home.cern/news/news/experiments/cms-releases-higgs-boson-discovery-data-public

https://www.symmetrymagazine.org/article/atlas-releases-full-orchestra-of-analysis-instruments?language_content_entity=und

symmetry topics follow +



Courtesy of CERN

## ATLAS releases 'full orchestra' of analysis instruments

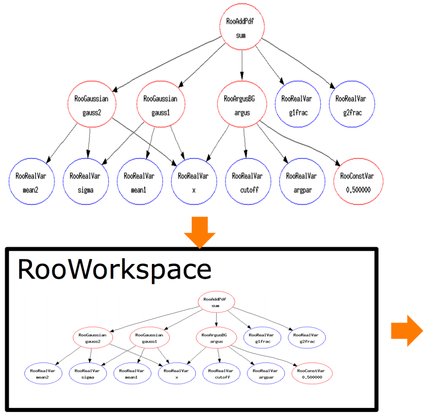
01/14/21 | By Stephanie Melchor

The ATLAS collaboration has begun to publish likelihood functions, information that will allow researchers to better understand and use their experiment's data in future analyses.

# RooFit/RooStats

ROOT based statistical modeling tool is the workhorse for many analyses at the LHC

Make persistent for collaborating



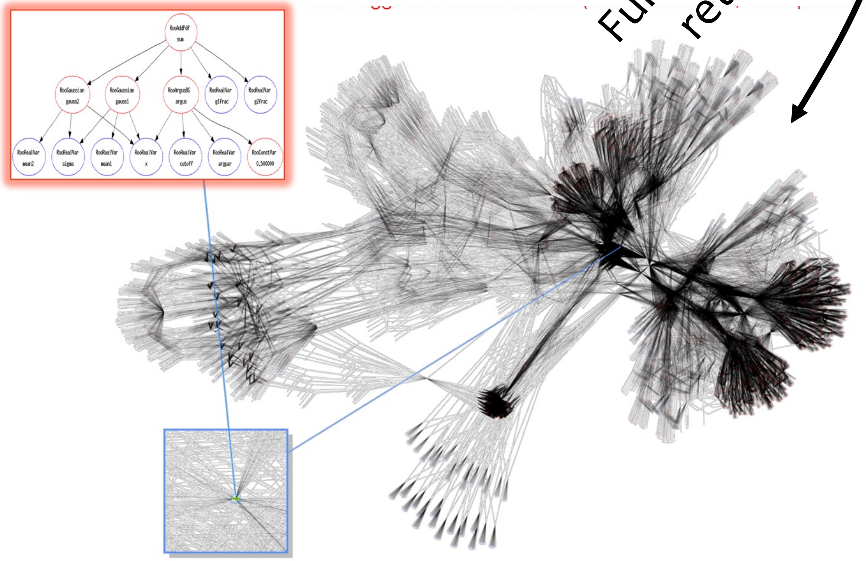

```
RooWorkspace w("w") ;
w.import(sum) ;
w.writeToFile("model.root") ;
```

model.root

Wouter Verkerke, NIKHEF

| Mathematical concept | | RooFit class |
|---|---|---|
| variable | $x$ | RooRealVar |
| function | $f(x)$ | RooAbsReal |
| PDF | $f(x)$ | RooAbsPdf |
| space point | $\vec{x}$ | RooArgSet |
| integral | $\int_{x_{min}}^{x_{max}} f(x)dx$ | RooRealIntegral |
| list of space points | | RooAbsData |

Full model easily retrievable



https://root.cern.ch/roofit