A Standard and Model Higgs

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Outline

The Standard Model

- A working model based on Quantum Field Theory
- Describes elementary particles and their interactions
  Gravity not included
- 12 fermions - 6 quarks, 6 leptons
- γ, $W^{\pm}$, Z, g - gauge bosons mediate interactions

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  Gravity not included
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- γ, $W^{\pm}$, Z, g - gauge bosons mediate interactions
- Higgs (complex scalar) field generates mass of all particles
- H^0 $(J^P = 0^+)$ - one Higgs doublet and one physical Higgs boson
- except Higgs - all SM particles were discovered before LHC started

Higgs @ 2012

- Electroweak precision data from LEP, SLC, Tevatron, ...
  established SM as a valid model
- Prediction: $m_H \leq 152$ GeV at 95% CL; CERN-PH-EP-2010-095 (2010)
- LEP exclusion: $m_H \leq 114.4$ GeV at 95% CL; PLB 565 (2003) 61
- Tevatron exclusion: $162 \geq m_H \leq 166$ GeV at 95% CL; PRL 104 (2010) 061802
- CMS exclusion: $127 \geq m_H \leq 600$ GeV at 95% CL; Phys. Lett. B 710 (2012) 26
- ATLAS exclusion: 111.4 - 116.4, 119.4 - 122.1, and 129.2 - 541 GeV at 95% CL. Phys. Lett. B 716 (2012) 1

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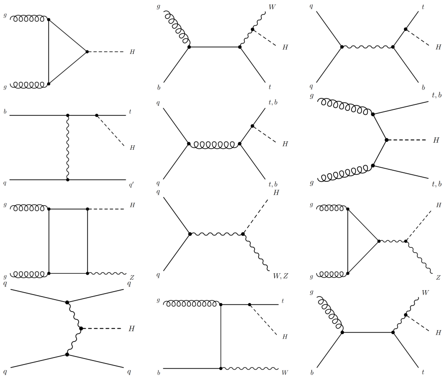
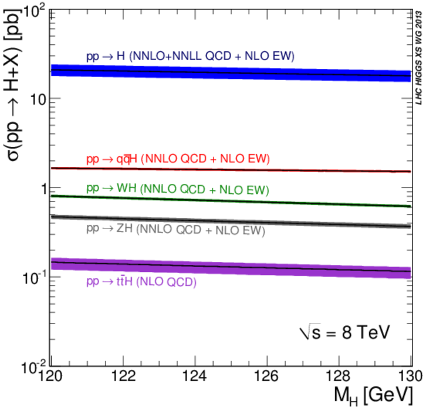
2012 - Very little space to hide for Higgs!

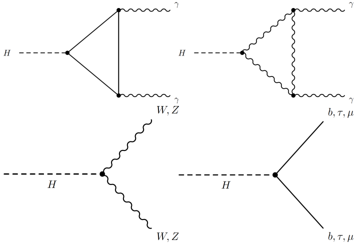
SM Higgs Production: Leading Order Diagrams

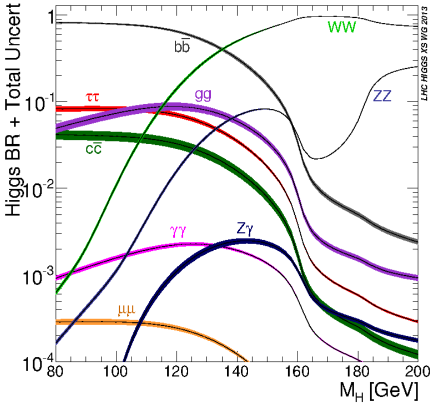




$gg \to H$ (ggF), $qq \to qqH$ (VBF), $qq \to VH$, $gg \to ZH$,
$qq,\ gg \to t\bar{t}H, b\bar{b}H$

SM Higgs Decay: Leading Order Diagrams





Decay modes of H:

$\gamma\gamma$, W^+W^-, ZZ, $q\bar{q}$, $\ell^+\ell^-$

Standard Model Higgs: Xsection & Decay BR

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Order of calculation
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) + APPROX. 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)
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)
bbH	0.156 $\pm$ 0.021	0.203 $\pm$ 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
Total	17.4 $\pm$ 1.6	22.3 $\pm$ 2.0	

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

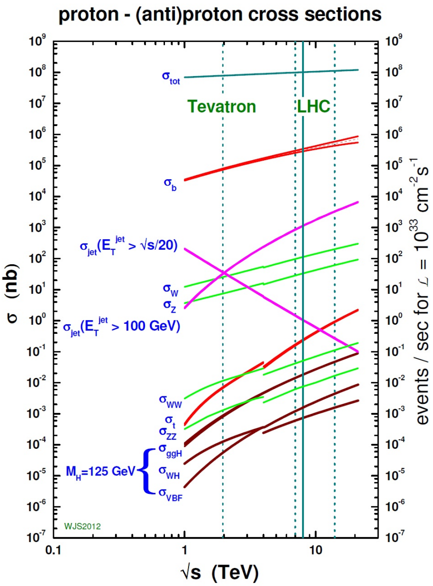
arXiv:1307.1347

The Dirty Picture

- Multiple production processes for Higgs.
- Multiple decay processes for Higgs.
- Multiple final states for decay products $W^{\pm}$, Z, τ, b, ...
- High luminosity for large data set -> Pile Up
  Multiple interactions in same BC, small interval between BC
- Limited detector aeecptance, resolution, efficiency -
  poor in the forward region
  - particle identification, 4-momenta measurement
  - reconstruction of Higgs, mass measurement
  - overall efficiency of Higgs identification
  - classification of events
  - distributions (p_T, η), ...reconstruction of Higgs properties

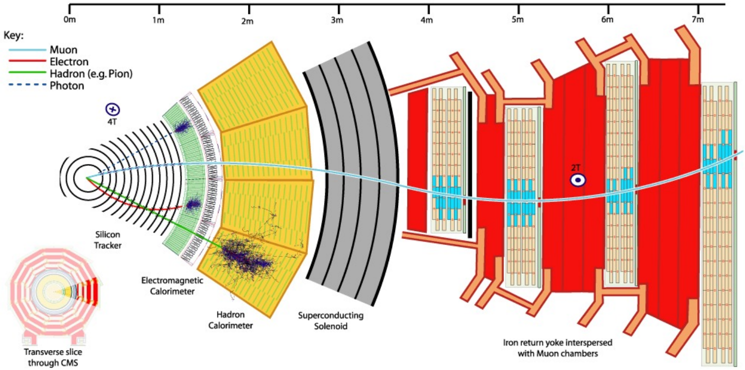
The Dirty Picture

- Signal size ($\sigma \times BR$) is very small compared to the possible background processes.
- Many searches have multiple final states for the signal. Reducible and irreducible) background processes for each final state, have to be understood and their contribution estimated.
- Multivariate Analysis (MVA) techniques are being used for better exploitation of the data - needs caution/understanding



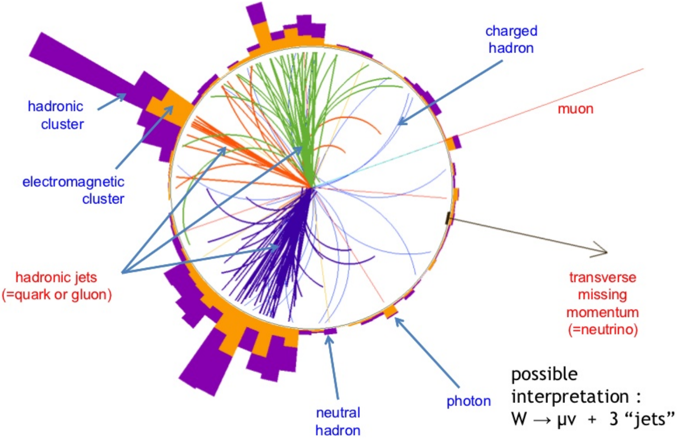
The Detectors

The particles produced in a collision pass through the detector - energy loss is converted into digital signals



A $r - \phi$ slice of the CMS detector in the central region.

The Detectors



$\mathcal{O}(10,000,000)$ pieces of information: energy deposits, positions

$\rightarrow$ few objects: γ, e, μ, τ, j, j_b, $\not{E}_T$, track, vertex

$\rightarrow$ higher level objects J/ψ, Υ, B_s, W, Z, H, t, ...

Standard (Model independent) Declarations

Unless specifically mentioned

- for any process the charge conjugate process is also implied
- τ_h denotes the visible/reconstructed part of a τ lepton that has decayed into hadron(s) and a ν_τ
- ℓ represents either of $e,\ \mu$
- j and j_b represent an ordinary jet (quark or gluon) and a b-tagged jet respectively
- V represents either of Z and W

The Detectors

Mis-identification and mis-measurement are serious problems:

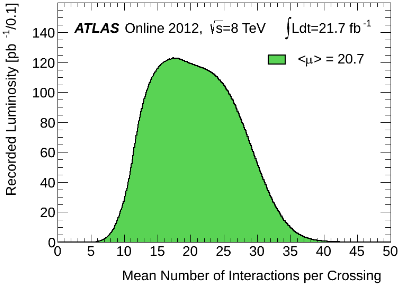
Object	Source of fake	
e	j	bremstrahlung in the tracker
γ	j	conversion in the tracker
τ	e, μ, j	missing νs
j_b	j	purity, efficiency
$\not{E}_T$	mismeasurement of jets	$\not{E}_T$ resolution

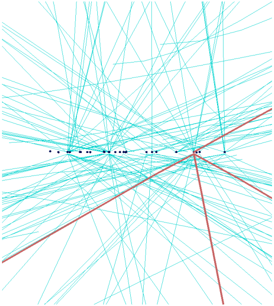
QCD events are background to almost all analyses due to mis-identification.

Various techniques to estimate background using data - reduce MC dependence - control systematic error

High Luminosity - Pile UP

Pile Up observed by ATLAS in 2012, 8TeV data.

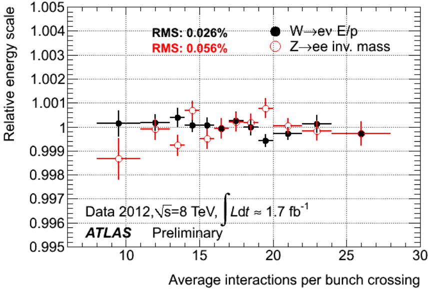


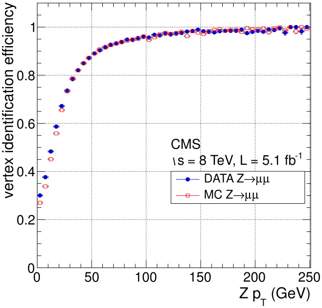


CMS $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ event with 24 reconstructed vertices.

Detector Performance

ATLAS electron detection efficiency.

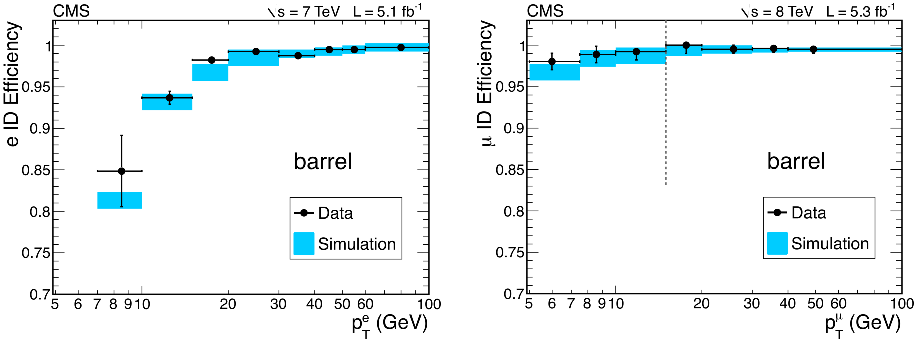




CMS vertex detection efficiency.

Detector Performance

Lepton identification efficiency using a tag-and-probe technique
Z and J/ψ dilepton events.



Electron (7 TeV, left) and muon (8 TeV, right)

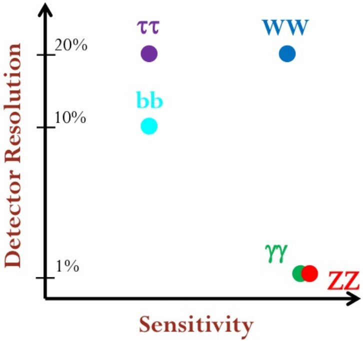
Monte Carlo Simulation

- Generation of signal and background events -
  understand event characteristics - kinematic distributions
- Fast detector simulation - parametric smearing of four-momenta, tracks
  fast generation of simulated events
- Complete detector simulation - Geant based - detailed simulation of detector response, detector noise, electronic noise and digitization
  understanding detector response, data

Important for estimating feasibility of an analysis, expected result, fine-tuning analysis strategy, selection cuts, ...

Analysis Strategy

- Branching ratios
- Irreducible background processes
- the detectors' capabilities



Three classes of SM Higgs analyses

- High sensitivity, good m_H resolution
  $H \to \gamma\gamma$, $ZZ^*(\ell^+\ell^-\ell^+\ell^-, \ell^+\ell^-\tau_h^+\tau_h^-)$
- High sensitivity, poor m_H resolution
  $H \to W^+W^-$
- Low sensitivity, poor m_H resolution
  $H \to b\bar{b}$, $\tau_h^+\tau_h^-$

Analysis Strategy

- reduce the background (b) as much as possible
- model/estimate b: MC, Data Driven Method
- get the data, estimate errors - statistical, systematic (theory, experiment)
- Compare the data with background/model predictions

For a specific production process and a decay mode, $i \to H \to f$, we define the signal strengths:

production $\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$

decay $\mu^f = \frac{B^f}{(B^f)_{SM}}$

combined for production & decay $\mu_i^f = \mu_i.\mu^f = \frac{\sigma_i.B^f}{(\sigma_i)_{SM}.(B^f)_{SM}}$

Analysis Strategy

Expected significance is computed for the hypothesis background + SM signal with $\mu = 1$.

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

$b,\ s$ - expectations for background, signal - SM
μ - signal strength compared to the SM: $\mu = 0$ means no signal
θ - represents the nuisance paramaters (syatematic uncertainties)

p_0 - local p-value - probability to obtain a value q_0 at least as large as the one observed in data, q_0^{obs}, under b-only hypothesis:

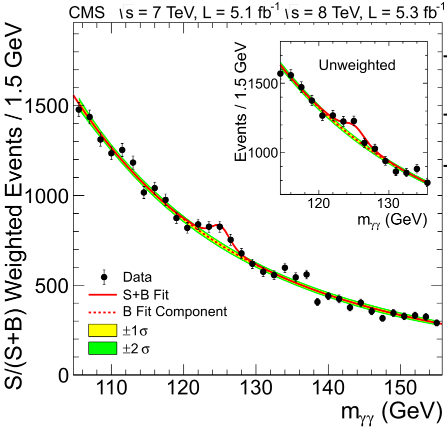
$$p_0 = P\left(q_0 \geq q_0^{obs} \mid b\right)$$

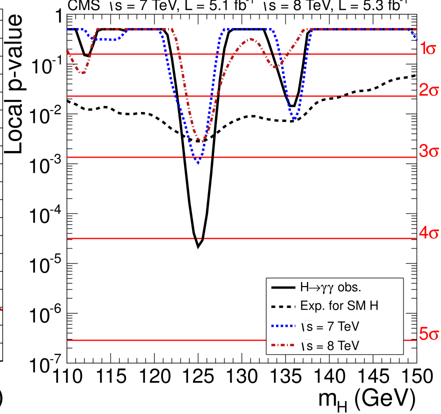
$H \to \gamma\gamma$

Identified as the best channel in early studies/TDR for low m_H

- Branching Ratio/Signal size is very small
- photon reconstruction/identification challenging
  - photon conversion before the ECAL
  - isolation - high PU
- Huge background - ISR/FSR, misidentification of jets
- excellent mass reconstruction: $\sigma(m_{\gamma\gamma}) \sim \mathcal{O}(GeV)$
- Multivariate Analysis (MVA) achieves better sensitivity than simple criteria based analysis.

$H \to \gamma\gamma$





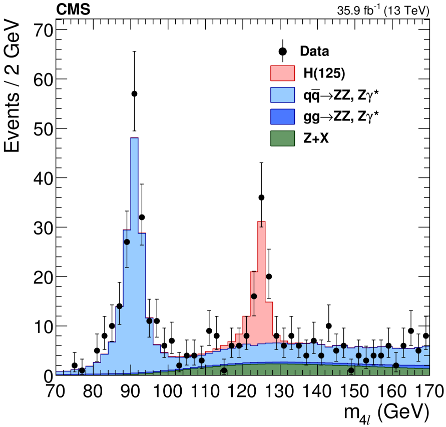
Observed (Expected) significance at 125GeV is $3.2\sigma(4.2\sigma)$

Best fit $\sigma_{exp}/\sigma_{SM} = 0.8 \pm 0.3$

$H \to ZZ^* \to 4l$

- $e, \ \mu$ are clean and well measured
- small background (B)- $ZZ, \ ZZb\bar{b}, \ t\bar{t}, \ WZ, \ Z + nj$
- Reco/ID problems - bremstrahlung in the tracker, high PU
- Reco/ID problems - final states with τ
- $\sigma(m_{4l}) \sim \mathcal{O}(1\%)$ for $\ell^+\ell^-\ell^+\ell^-$, small signal (S)

Higgs Mass: CMS : $H \to ZZ \to 4\ell$: $35.9 fb^{-1}$ at 13 TeV



$$m_H = 125.26 \pm 0.20(stat) \pm 0.08(syst) \text{ GeV}$$

$$\mu = 1.05^{+0.15}_{-0.14}(stat)^{+0.11}_{-0.09}(syst) = 1.05^{+0.19}_{-0.17} \ (m_H = 125.09 \text{ GeV})$$

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$H \to WW$

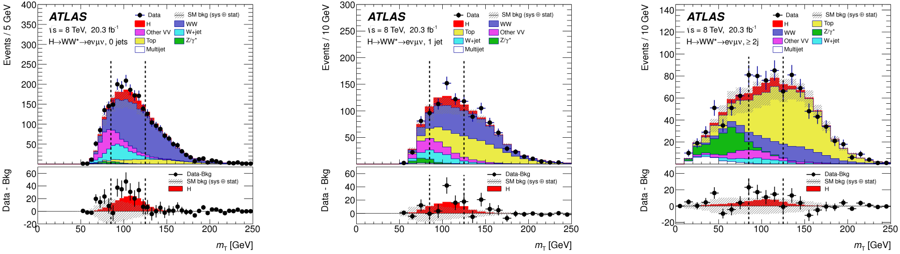
- large signal size
- measurement of HWW coupling
- clean signal - opposite sign dilepton, large $\not{E}_T$ $H \to WW^* \to \ell^+\ell^-\nu\bar{\nu}$
- invariant mass reconstrucion is not possible - instead use

$$m_T = \left[\left(E_T^{\ell^+\ell^-} + \not{E}_T\right)^2 + |\, \vec{p}_T^{\ell^+\ell^-} + \vec{\not{E}}_T \,|^2\right]^{1/2}$$

- no narrow mass peak - wide signal shape
- irreducible background $pp \to WW,\ ZZ,\ \ell^+\ell^-,\ t\bar{t}$

ATLAS - $H \to WW$

$20.3 fb^{-1}$ data at 8 TeV.



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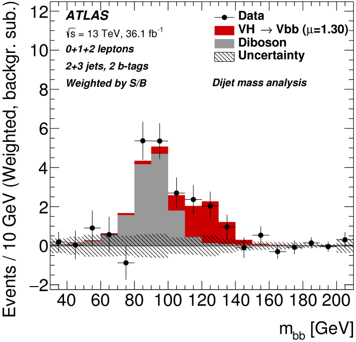
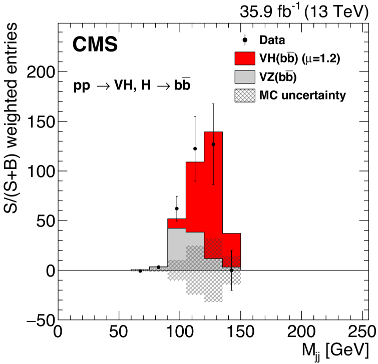
$H \to f\bar{f}$

- Investigating the properties of the scalar - couplings to the fermions
- $BR(H \to b\bar{b}) = 0.58$ is large, BUT
  - overwhelming background: $b\bar{b}$, $V + jets$, $t\bar{t}$, single-top, VV, QCD
  - fake b-tag
  - not so good resolution for $m_{j_b j_b}$
- $BR(H \to \tau^+\tau^-) = 0.064$ not too small, BUT
  - huge background: $W + jets$, $Z + jets$, VV, $t\bar{t}$ and even $H \to WW$
  - τ reconstruction-identification efficiency is moderate
  - fakes: huge QCD jet background contribute
  - poor resolution: $m_{\tau^+\tau^-}$

You can not argue with your Nature.

$WH,\ ZH \rightarrow b\bar{b}$





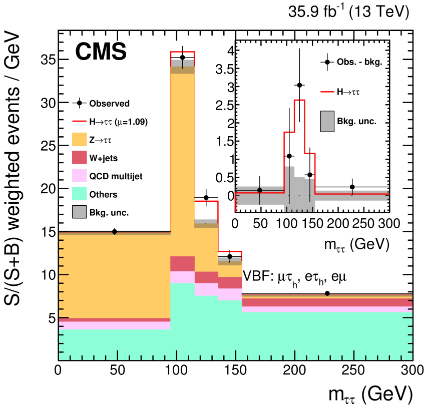
	ATLAS arXiv:1708.03299	CMS arXiv:1709.07497
	$36.1 fb^{-1}$, 13 TeV	$35.9 fb^{-1}$, 13 TeV
Signal significance	3.5σ	3.3σ
Signal strength μ	$0.9 \pm 0.18(stat)^{+21}_{-0.19}(syst)$	1.2 ± 0.4

CMS: $H \to \tau^+\tau^-$

$35.9 fb^{-1}$ data at 13 TeV.
Signal significance 4.7σ.

$$\frac{\sigma_i . B^f}{(\sigma_i)_{SM} . (B^f)_{SM}} = 1.09^{+0.27}_{-0.26}$$

arXiv:1708.00373



Definitions

production	$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$
decay	$\mu^f = \frac{B^f}{(B^f)_{SM}}$
combined for production & decay	$\mu_i^f = \mu_i.\mu^f = \frac{\sigma_i.B^f}{(\sigma_i)_{SM}.(B^f)_{SM}}$
coupling modifier	$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} = \frac{\Gamma_j}{\Gamma_j^{SM}}$
coupling modifier	$\kappa_H^2 = \Sigma_j \kappa_j^2.B_{SM}^j = \frac{\Gamma_H}{\Gamma_H^{SM}}, \ \frac{(1-B_{BSM}).\Gamma_H}{\Gamma_H^{SM}}$
$\sigma(VBF)$	$0.74.\kappa_W^2 + 0.26\kappa_Z^2$

Definitions

The signal yield in a category k,

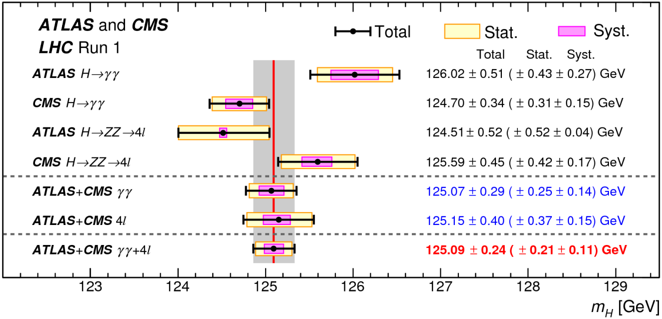
$$
\begin{aligned}
n_{signal}(k) &= \mathcal{L}(k).\Sigma_i\Sigma_j\left(\sigma_i.A_i^{f,SM}(k).\epsilon_i^f(k).B^f\right) \\
&= \mathcal{L}(k).\Sigma_i\Sigma_j\mu_i\mu^f\left(\sigma_i^{SM}.A_i^{f,SM}(k).\epsilon_i^f(k).B_{SM}^f\right)
\end{aligned}
$$

$\mathcal{L}(k)$: integrated luminosity used for category k
$A_i^{f,SM}(k)$: detector acceptance for SM Higgs production and decay
$\epsilon_i^f(k)$: overall selection efficiency for the signal category k

Higgs Mass

Combined CMS and ATLAS results:

$5fb^{-1}$ at $\sqrt{7}$ TeV, $20fb^{-1}$ at $\sqrt{s} = 8$ TeV



A lot of interest generated by the difference in masses in the early measurements!

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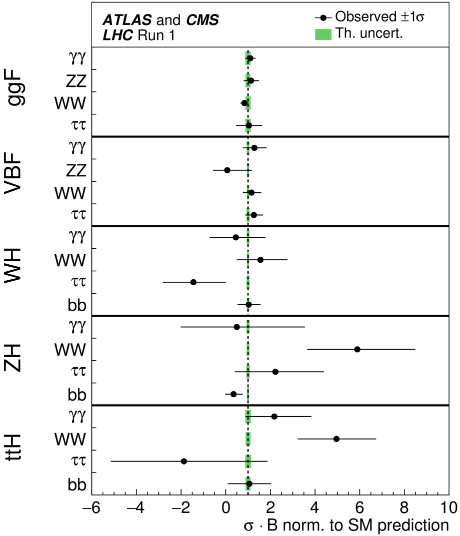
Definitions

σ and B ratio parameterisation	Coupling modifier ratio parameterisation
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\sigma_{\text{VBF}} / \sigma_{gg\text{F}}$	
$\sigma_{WH} / \sigma_{gg\text{F}}$	
$\sigma_{ZH} / \sigma_{gg\text{F}}$	$\lambda_{Zg} = \kappa_Z / \kappa_g$
$\sigma_{ttH} / \sigma_{gg\text{F}}$	$\lambda_{tg} = \kappa_t / \kappa_g$
$\text{B}^{WW} / \text{B}^{ZZ}$	$\lambda_{WZ} = \kappa_W / \kappa_Z$
$\text{B}^{\gamma\gamma} / \text{B}^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$
$\text{B}^{\tau\tau} / \text{B}^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$
$\text{B}^{bb} / \text{B}^{ZZ}$	$\lambda_{bZ} = \kappa_b / \kappa_Z$

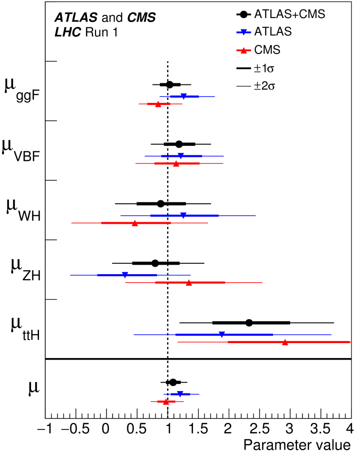
Results: Production & Decay

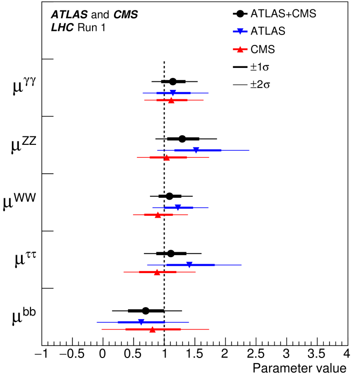
$5fb^{-1}$ at $\sqrt{7}$ TeV, $20fb^{-1}$ at $\sqrt{s} = 8$ TeV
Combined ATLAS and CMS measurement of $\sigma.BR$

for different processes normalized to their SM values (μ_i^f).



Results: Production & Decay

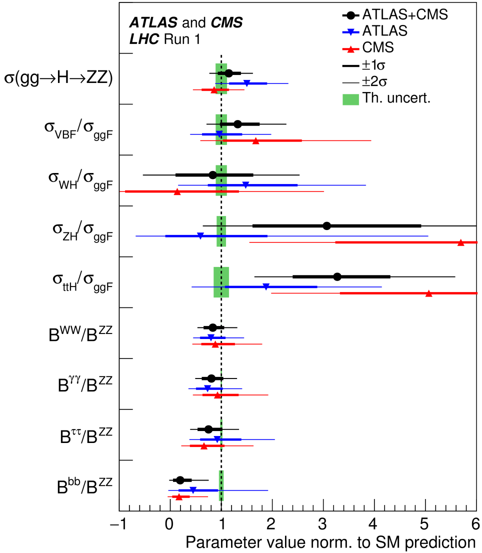




Global signal strength

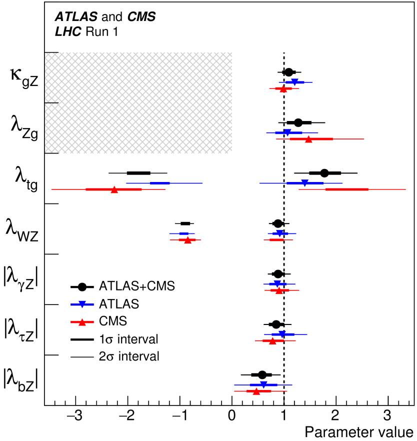
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}(stat)^{+0.04}_{-0.04}(expt)^{+0.04}_{-0.04}(thbgd)^{+0.07}_{-0.06}(expt)$$

Results: Ratios



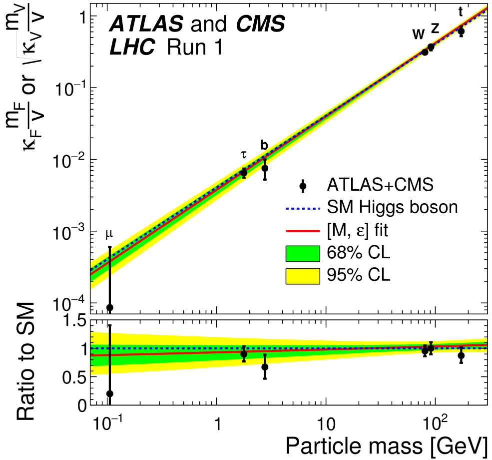
Results

Best fit values of ratios of Higgs boson coupling modifiers, for the combination of the ATLAS and CMS measurements.



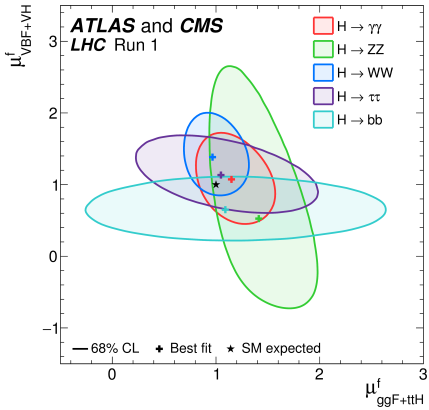
Higgs Couplings

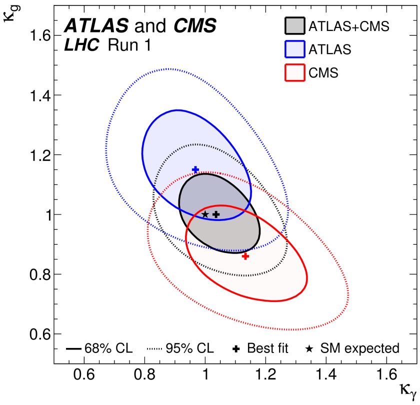
Higgs couplings are very standard!



Results: Compatibility

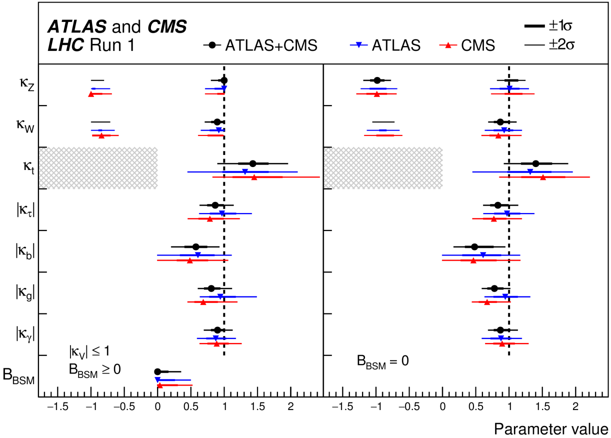
Compatibility of different measurements





Results: New Physics?

Fit results
allowing BSM loop couplings $B_{BSM} \geq 0, \ |\kappa_V| \leq 1$ (Left)
without BSM loop couplings $B_{BSM} = 0$ (Right)



Higgs Couplings

- A large number of measurements have been made in the Higgs sector
- Detailed study of Higgs properties from all possible angles
- **It is a very Standard and Model Higgs.** Very little clue for New Physics
- High luminosity : measurements will be more challenging
- High luminosity may bring out discripancies within the SM

We do not know yet if SUSY is the New Physics.

Fall of the Standard Model and
the advent of New Physics are equally inevitable.

Effective Coupling Modifiers

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2