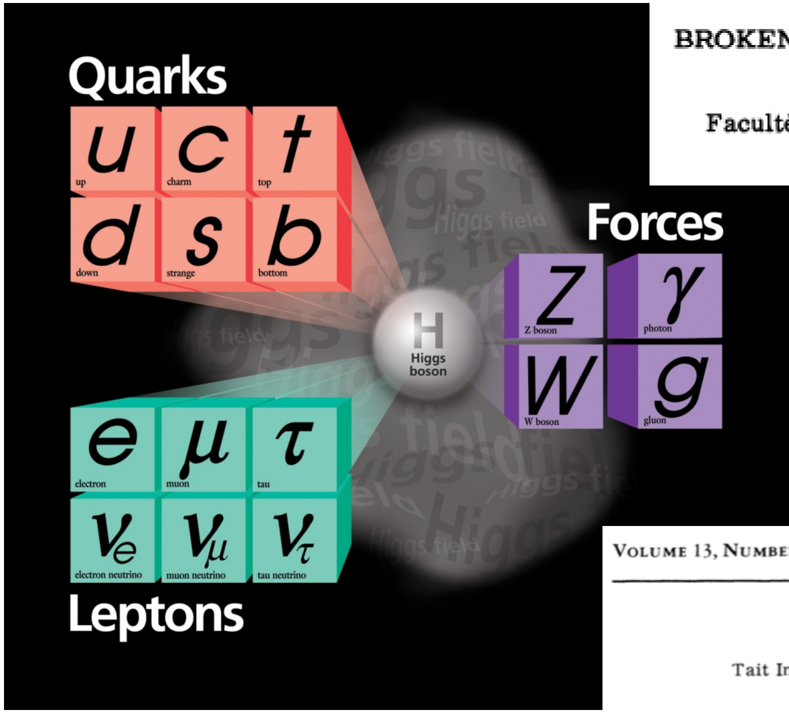
Eredità del run1 :
Il bosone di Higgs

Paolo Azzurri - *INFN sezione di Pisa*
per le collaborazioni ATLAS e CMS

101-esimo Congresso Nazionale SIF *Roma*, 24 Sett 2015

Il bosone di Higgs



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

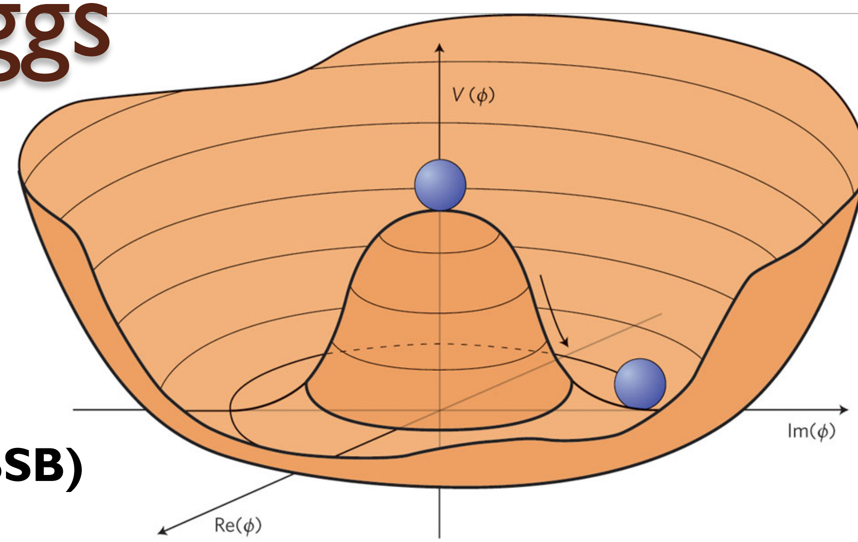
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

Il bosone di Higgs

$$\mathcal{L} = \partial_\mu \varphi^\dagger \partial^\mu \varphi - V(\varphi^\dagger \varphi)$$

$$V(\varphi^\dagger \varphi) = \frac{1}{2}(\lambda^2 |\varphi|^4 - \mu^2 |\varphi|^2)$$



Meccanismo di rottura
della simmetria SU(2)xU(1) (SSB)

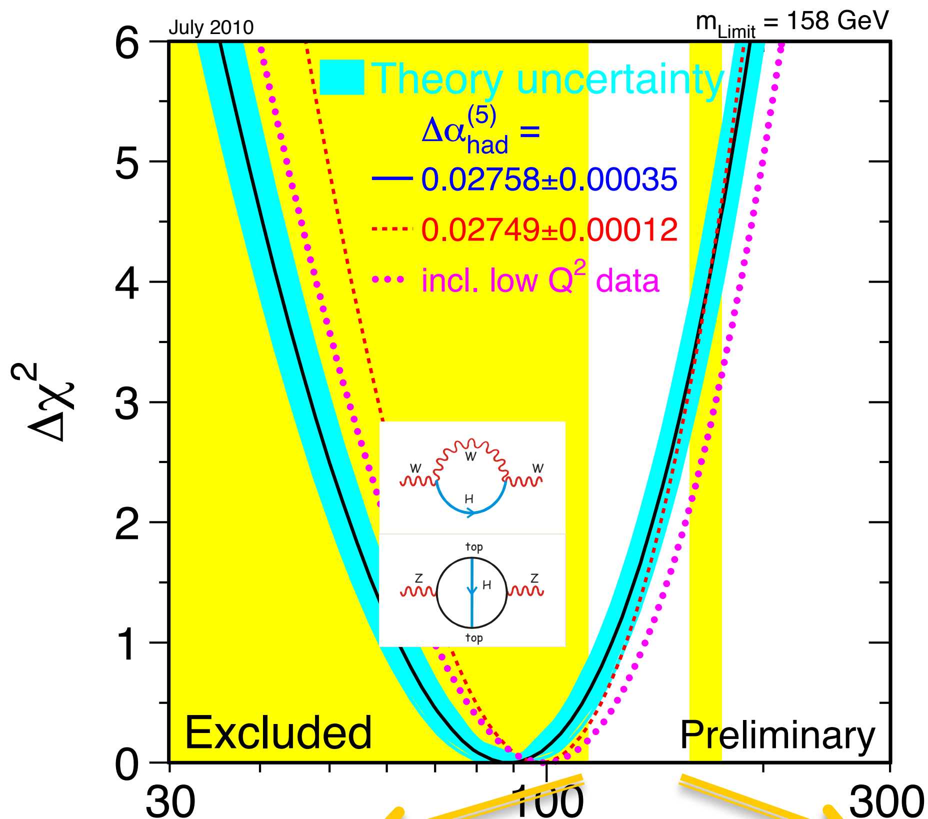
→ **bosoni vettori W,Z ricevono termini in massa da SSB**
→ **fermioni ricevono massa da accoppiamenti Yukawa**
→ **SSB lascia uno scalare massivo: il bosone di Higgs**

Permette di assegnare termini in massa alle particelle SM
Cancella le divergenze e la violazione di unitarietà in WW→WW,ZZ

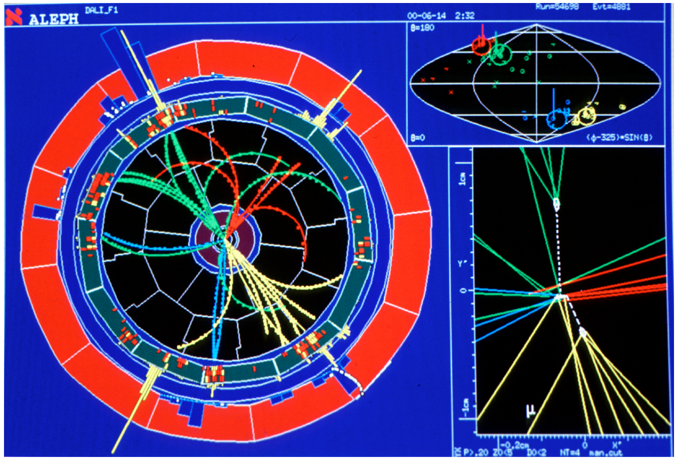
La conferma del meccanismo e l'osservazione del bosone di Higgs
è una **chiave di volta del modello standard**

… cercata per ~ 50 anni

Ricerche e indicazioni pre-LHC



114<m_H<162 GeV



Similitudini con le situazioni precedenti alle scoperte dei bosoni W,Z e del quark top

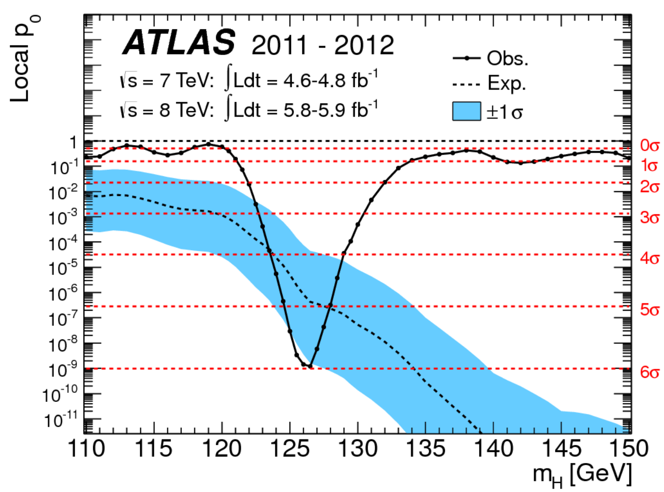
La scoperta

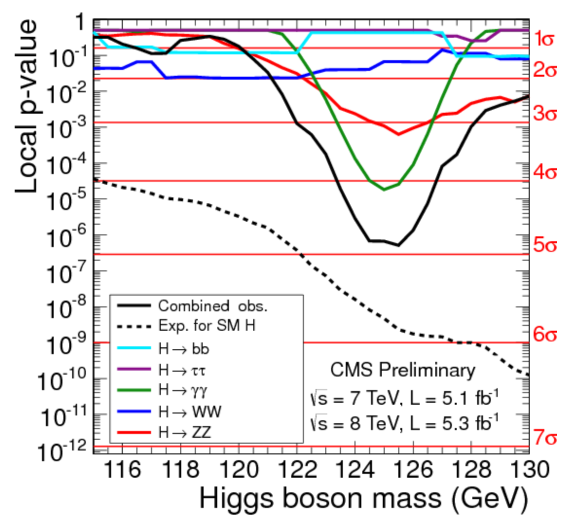
- 13 dicembre 2011 (5/fb @7TeV)
  eccesso di eventi nella regione m_H~125 GeV
  CMS:p≅5•10^{-3} =2.6 σ ATLAS:p≅2•10^{-4} 3.6 σ (exp 2.6 σ)

- 4 luglio 2012 (5/fb @7TeV + 5/fb @8TeV)

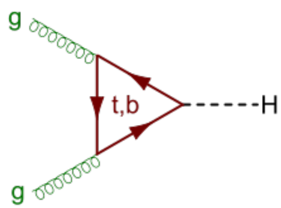
ATLAS  5 σ : p=2.85•10^{-7}
m_H = **126.5**±0.6 GeV

CMS  5 σ : p=2.85•10^{-7}
m_H = **125.3**±0.6 GeV

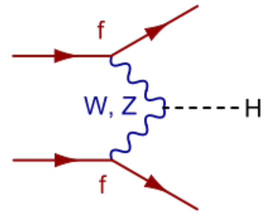




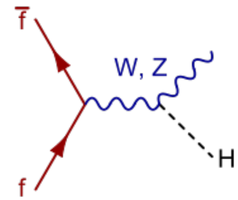
I canali di produzione ad LHC



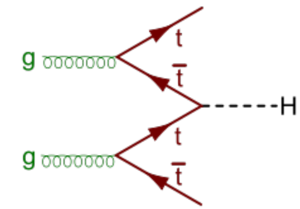
fusione di gluoni(GF)



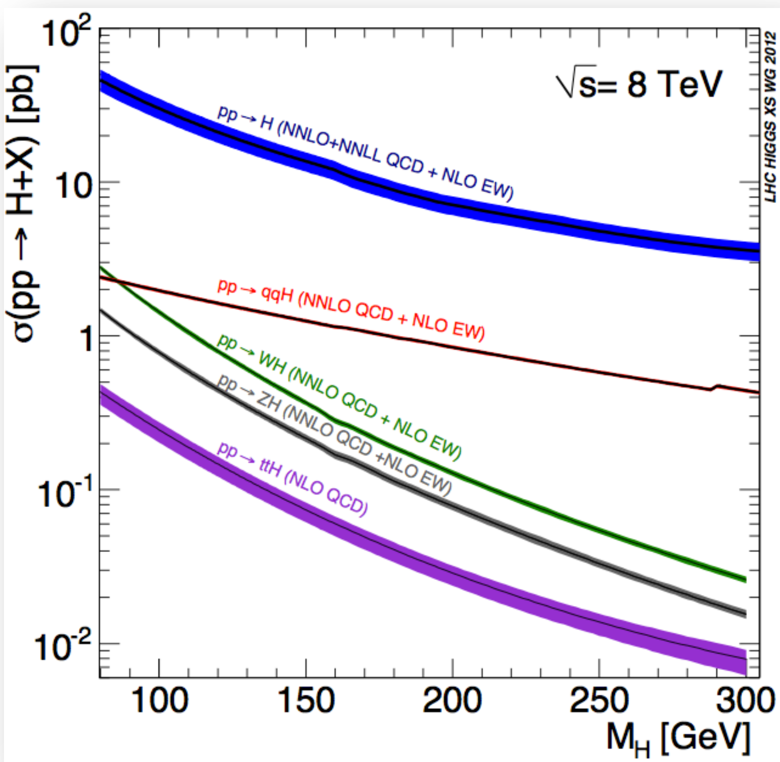
fusione di bosoni deboli(VBF)



Higgs-strahlung(VH)



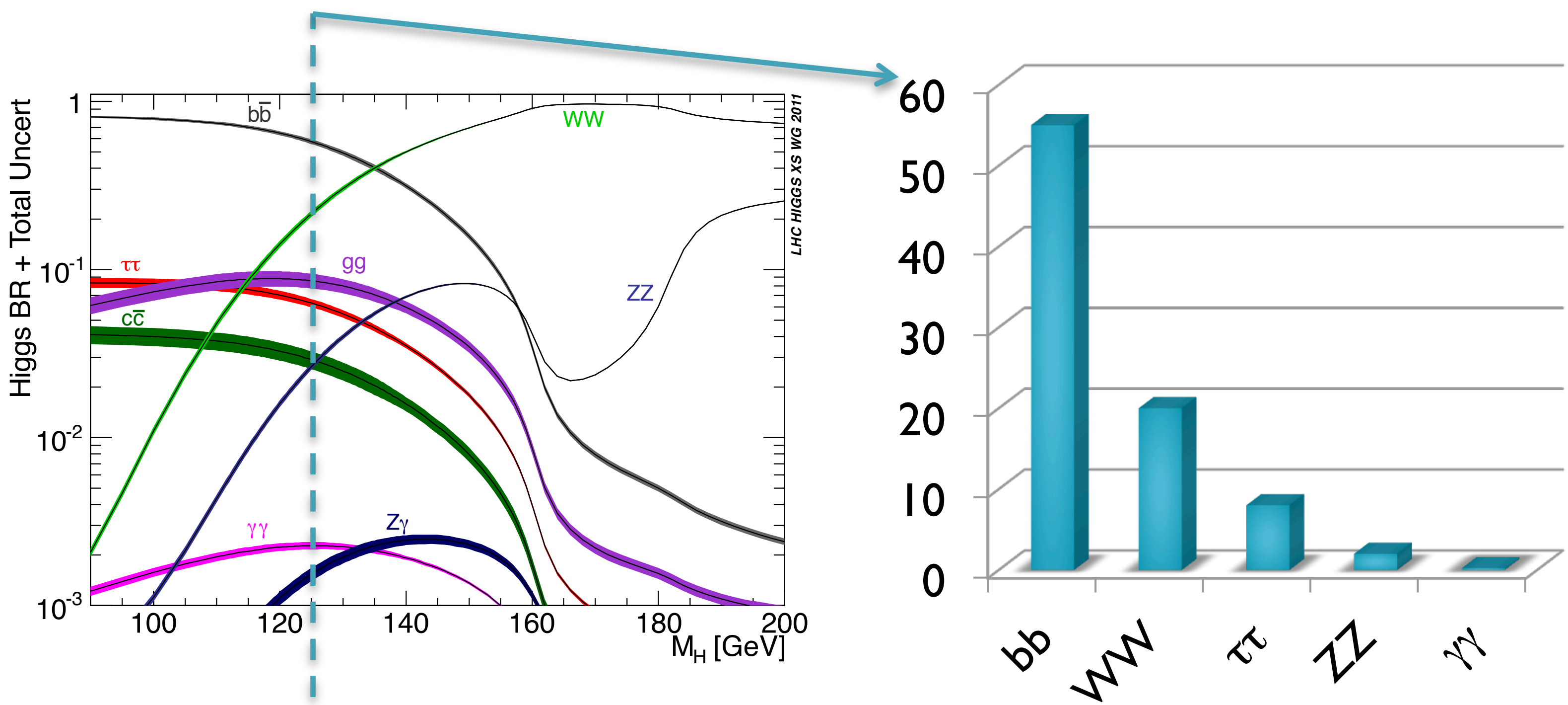
fusione di quark top (ttH)



A 8TeV di energia e alle luminosità di picco del 2012 ($7\ 10^{33}\ cm^{-2}\ s^{-1}$) LHC ha prodotto circa **500** bosoni di Higgs (SM da 125 GeV) all'ora

su 60 miliardi di collisioni totali all'ora

I canali di decadimento



con m_H= 125 GeV

… con m_H diverso sarebbe stato più difficile misurare accoppiamenti

- sezioni d'urto più alte (anche per il fondo)
- decadimenti fermionici (bb+ττ) accessibili
- larghezza naturale trascurabile: picco m_H ricostruibile con larghezza sperimentale

I canali di ricerca

Eventi prodotti in 5 fb^{-1}@7TeV +20 fb^{-1}@8TeV

$\Delta m_H / m_H$		GF	VBF	VH	ttH
~2%	$H \rightarrow ZZ^* \rightarrow 4l$	~120	~10	~3	~1
~1-2%	$H \rightarrow \gamma\gamma$	~1000	~90	~22	~7
~20%	$H \rightarrow WW^* \rightarrow ll\nu\nu$	~10 000	~900	~220	~70
~10%	$H \rightarrow \tau\tau$	~30 000	~2 400	~600	~180
~10%	$H \rightarrow bb$	~250 000	~22 000	~5 000	~1 700

(per VH solo con W,Z→leptoni)

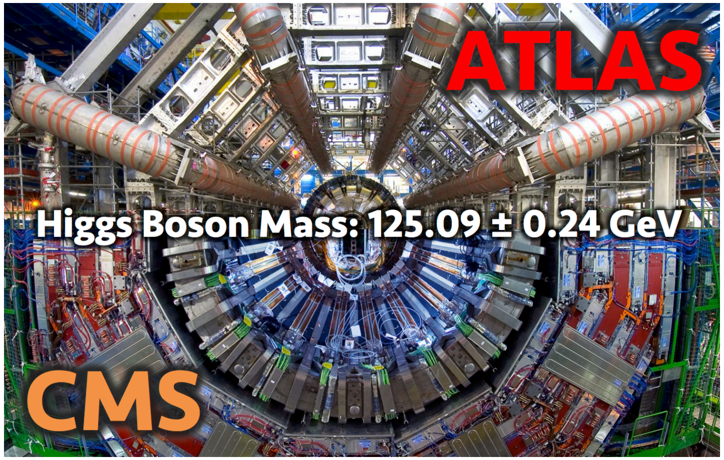
I canali di ricerca

Eventi prodotti in 5 fb^{-1} +20 fb^{-1}
➔ Selezionati **S/B** [basato su CMS]

	GF	VBF	VH	ttH
H➔ZZ*➔4l	~120 ➔ **20/10**	~10 ➔ **3/1**	~3	~1
H➔γγ	~1000 ➔ **500/10 000**	~90 ➔ **30/150**	~22 ➔ **7/25**	~7 ➔ **1/4**
H➔WW*➔llνν	~10 000 ➔ **250/1 500**	~900 ➔ **10/10**	~220 ➔ **10/100**	~70 ➔ **10/150**
H➔ττ	~30 000 ➔ **100/5 000**	~2 400 ➔ **20/50**	~600➔ **10/100**	~180 ➔ **1/100**
H➔bb	~250 000	~22 000 ➔ **50/2000**	~5 000 ➔ **20/200**	~1 700 ➔**10/500**

arbitrarietà nella scelta del livello di purezza indicato

La misura della massa



ATLAS m_H=125.36±0.37(stat)±0.18(syst) GeV

Phys. Rev. D 90 (2014) 052004

CMS $m_H = 125.02^{+0.26}_{-0.27}(\text{stat})^{+0.14}_{-0.15}(\text{syst})$ GeV

Eur.Phys.J.C 75 (2015) 212

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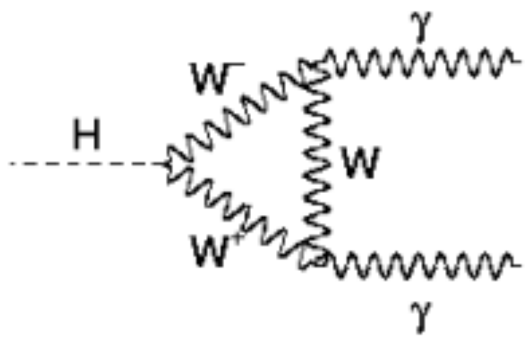
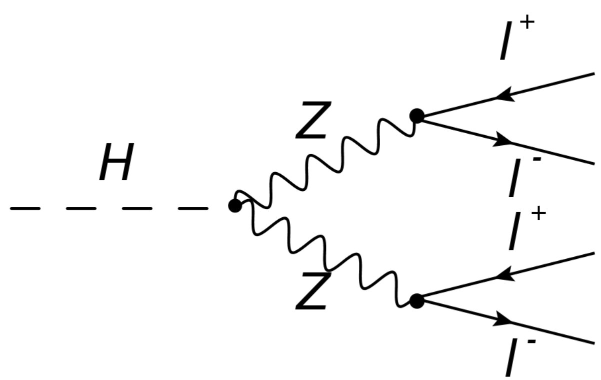
m_H=125.09±0.21(stat.)±0.11(syst.) GeV

Phys.Rev.Lett.114 (2015) 191803 (14 maggio 2015)

La misura della massa

m_H è un parametro libero del modello standard
➔ determina gli accoppiamenti
determina la forma e l'evoluzione del potenziale





misura di m_H nei canali
$H \rightarrow \gamma\ \gamma$ e $H \rightarrow 4l$
con statistica più significativa e migliore risoluzione (1-2%)

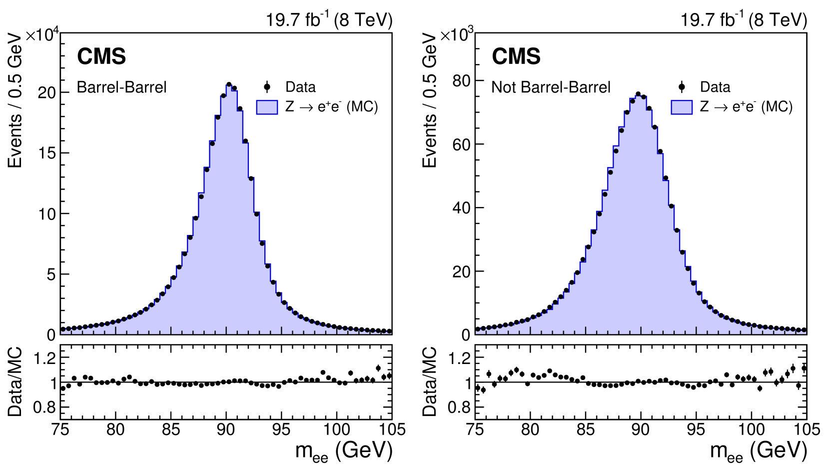
m_H da H→ γ γ

CMS: cristalli $PbWO_4$
alta granularità ($\delta\eta$, $\delta\phi$ ~ 0.02)

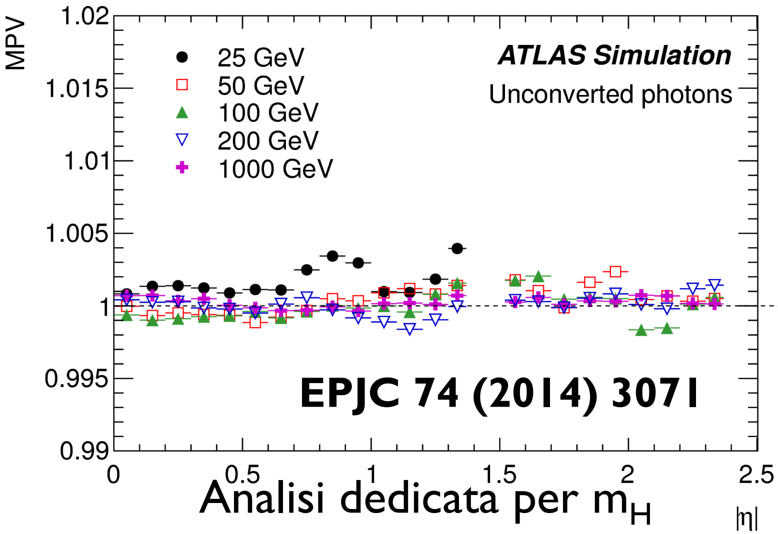
ATLAS: L Ar a campionamento
direzione sciame ricostruita

Energia stimata con tecniche di regressione MVA

J. INST 10 (2015) P08010



Z→ee con "e as γ"

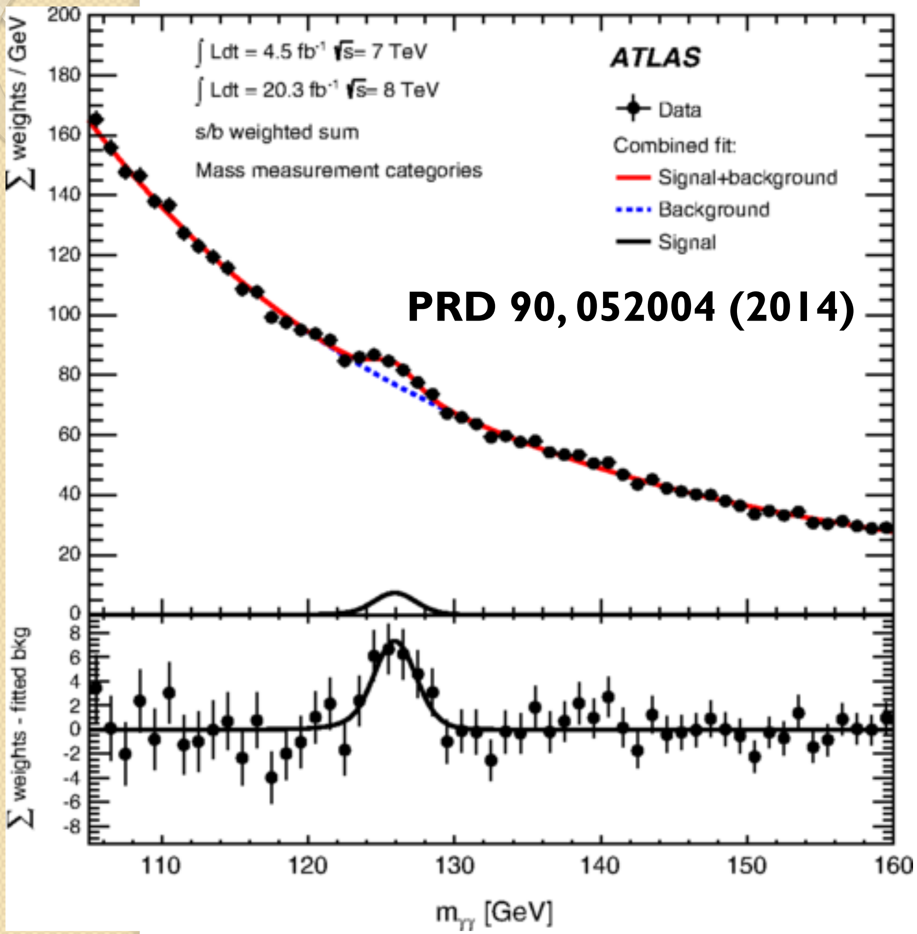


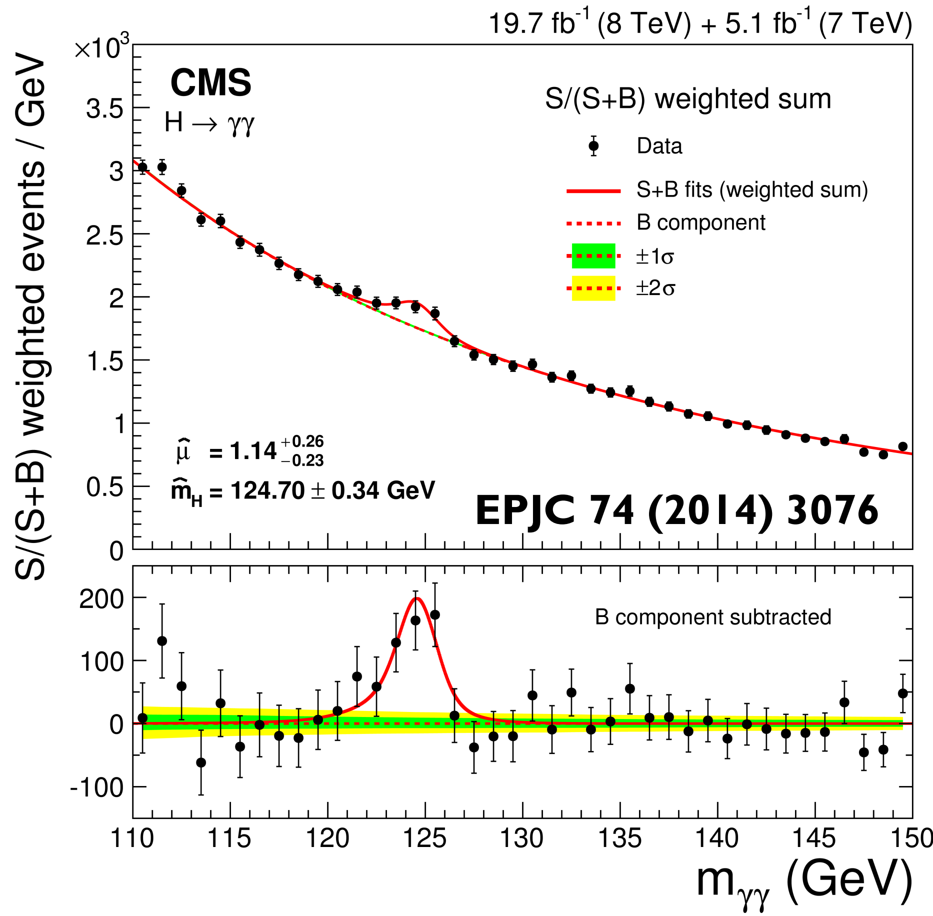
EPJC 74 (2014) 3071

Analisi dedicata per m_H

Eventi divisi in categorie a seconda delle proprietà cinematiche e qualità dei fotoni

m_H da $H \rightarrow \gamma\gamma$



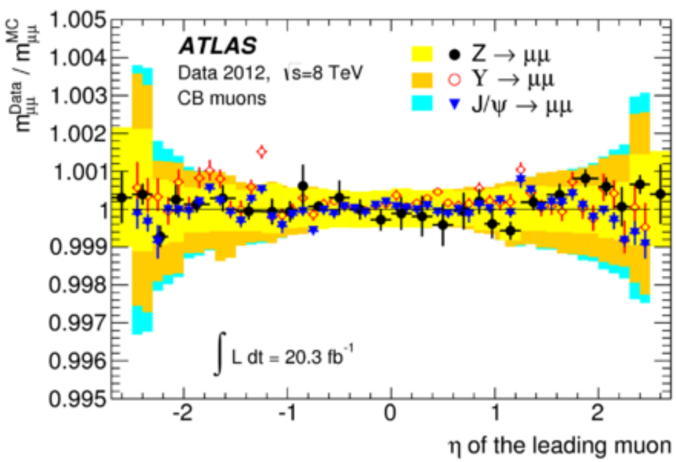


125.98±0.42(stat)±0.28(syst) GeV

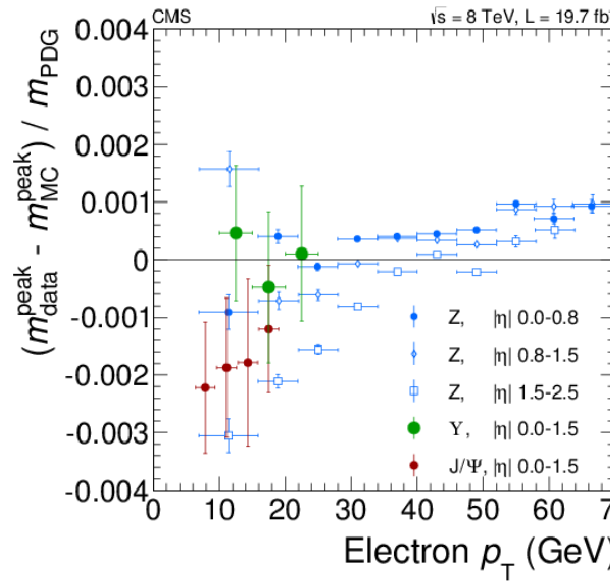
124.70±0.31(stat)±0.15(syst) GeV

m_H da H→4l(e, μ)

Calibrazione energia e, μ con decadimenti da candele standard J/ψ , Υ e Z



Categorie 4e,2e2 μ ,4 μ

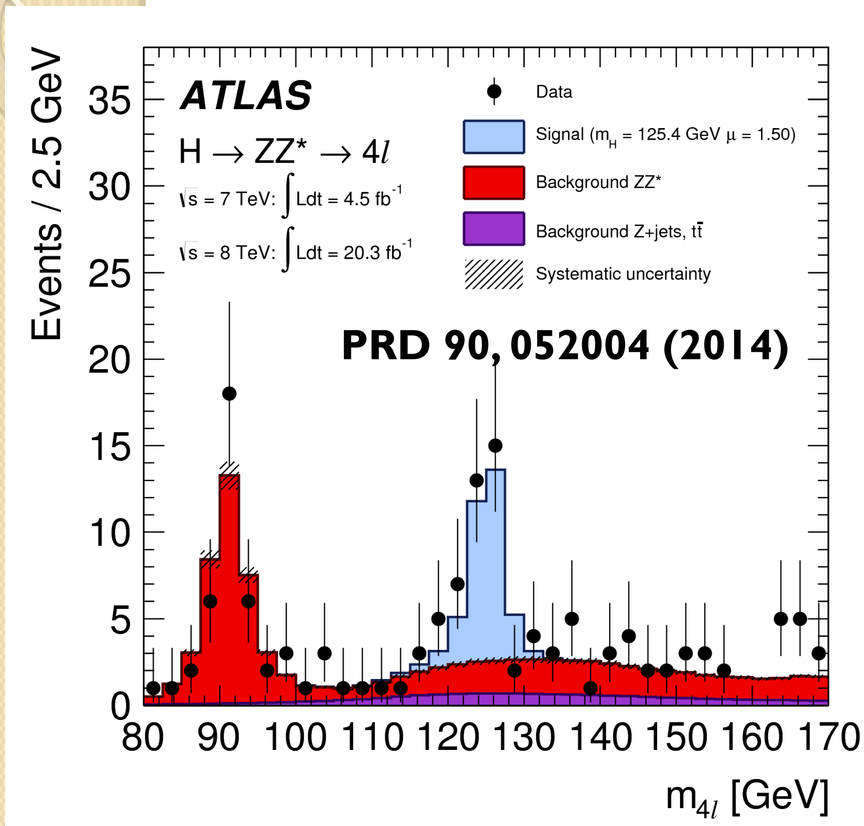


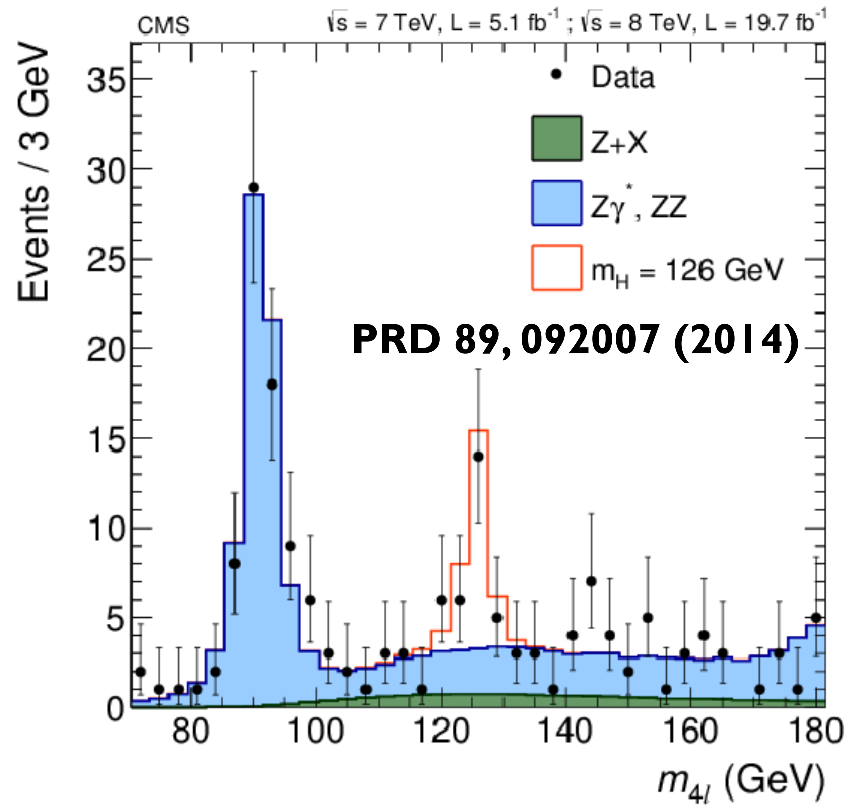
calibrazioni e/ μ di altissima precisione

Fit 2D a BDT,m(4l)

Fit 3D a m(4l),Db,Dm
Db(kin) basato su calcoli ME
uso di Dm= δ m_H/evento

m_H da $H \rightarrow 4l(e, \mu)$





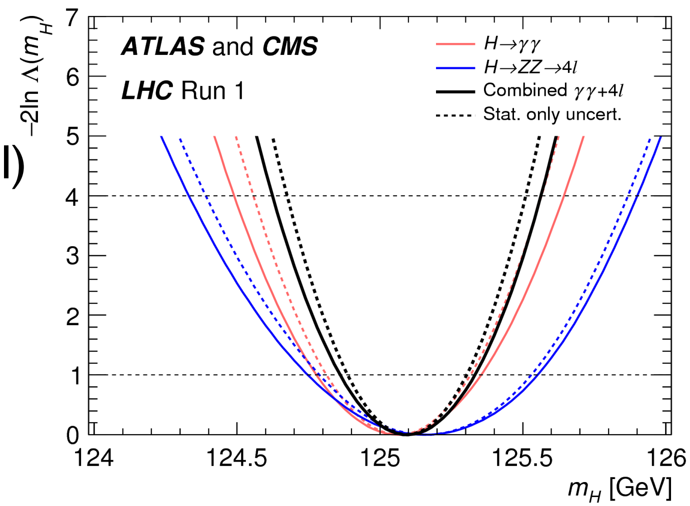
124.51±0.52(stat)±0.06(syst) GeV

125.59±0.42(stat)±0.17(syst) GeV

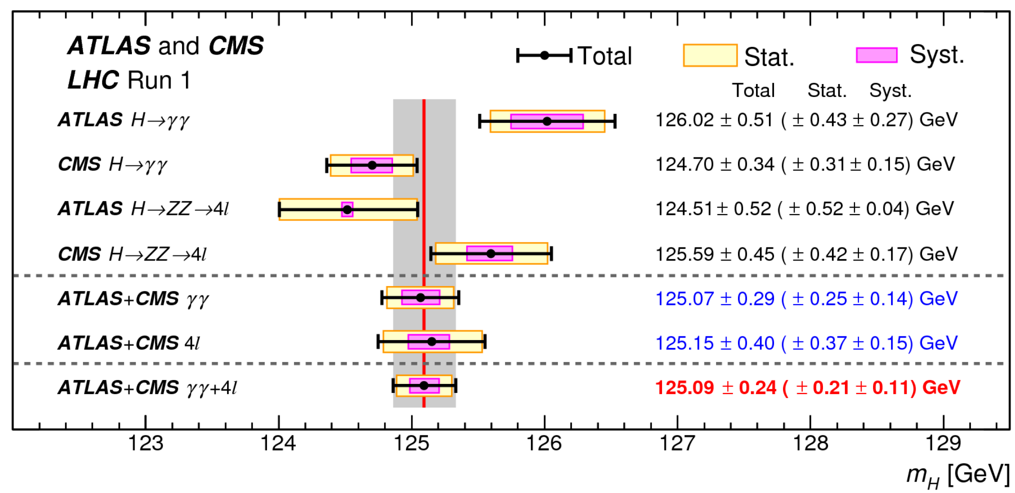
La misura combinata di m_H

massimizzazione di profile-likelihood ratio con 3 intensità di segnale: GF($\gamma\gamma$),VBF($\gamma\gamma$), GF(4l)

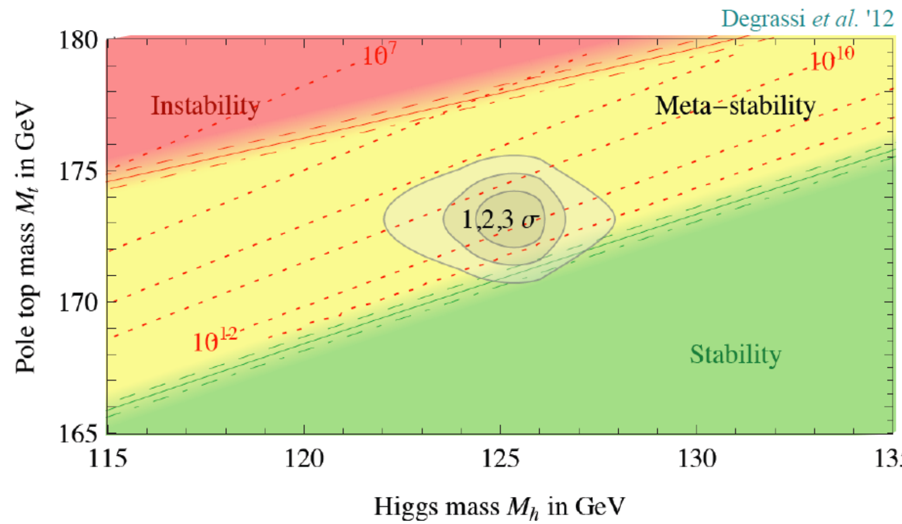
~300 effetti sistematici inclusi (nuisances)

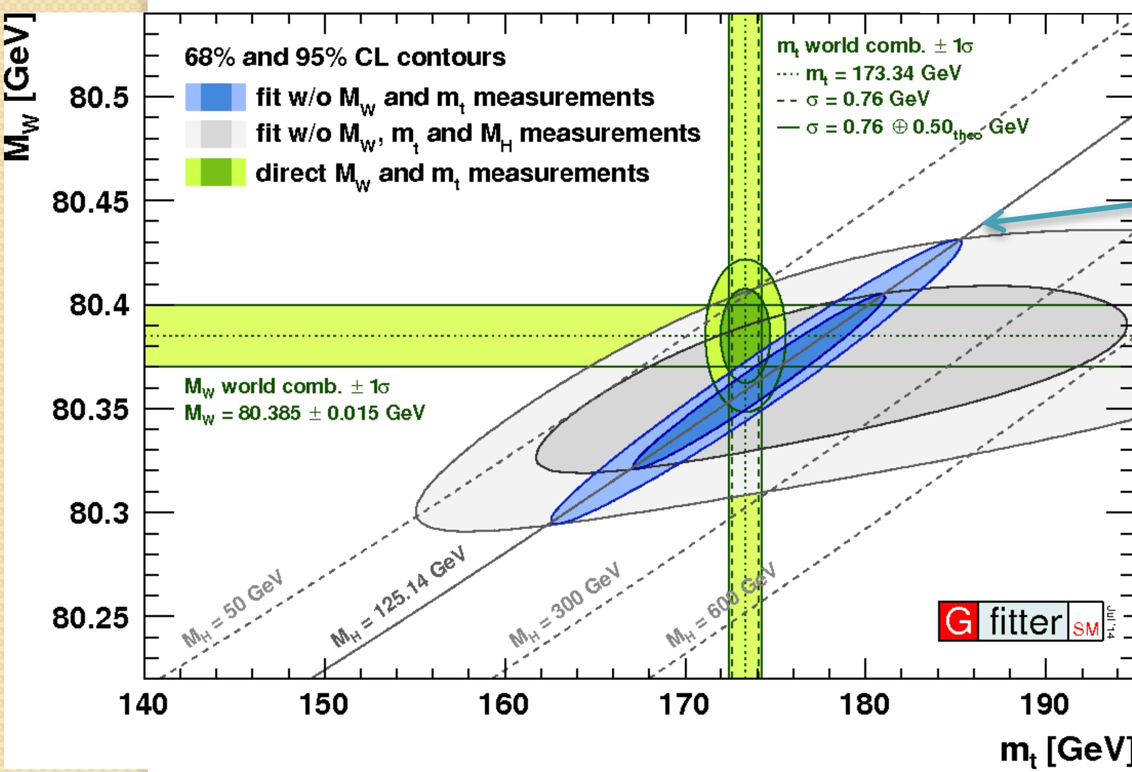


Compatibilità 4 misure: ~24% (χ^2-prob)



m_H nel SM





Misura allo 0.2% di m_H !

EPJC (2014) 74:3046

Accoppiamenti

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

15th September 2015

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

m_H=125.09 GeV

Seminario LHC lunedì 21/9 (W. Verkerke)

Accoppiamenti

input da **17** pubblicazioni

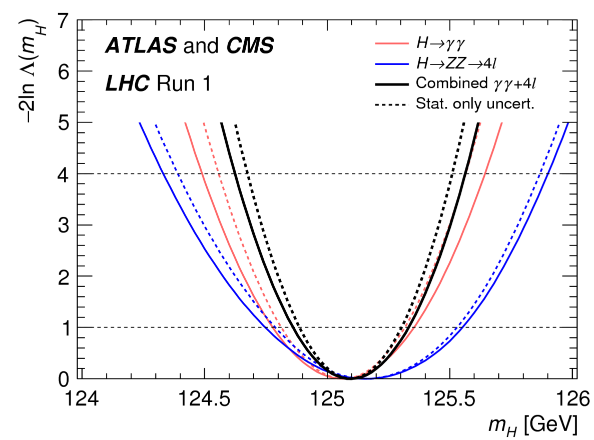
ATLAS **arXiv:1507.04548** CMS **Eur. Phys. J. C 75 (2015) 212**

Likelihood combinata con ~580 distribuzioni (regioni di segnale e fondo)
Cura nel trattamento delle accettanze incrociate
Cura nel trattamento delle correlazioni (~4200 sistematiche)

Intensità globale del segnale

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

	Best-fit μ	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	$^{+0.14}_{-0.13}$	$^{+0.10}_{-0.09}$	$^{+0.06}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$



$$\mu = \sigma / \sigma_{SM} = 1.09^{+0.11}_{-0.10}$$

Intensità produzione e decadimento

i→ H → f

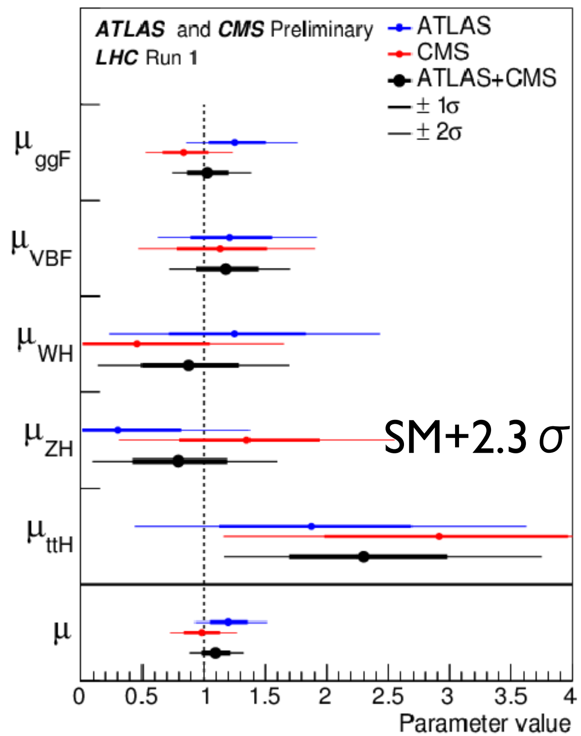
$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

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

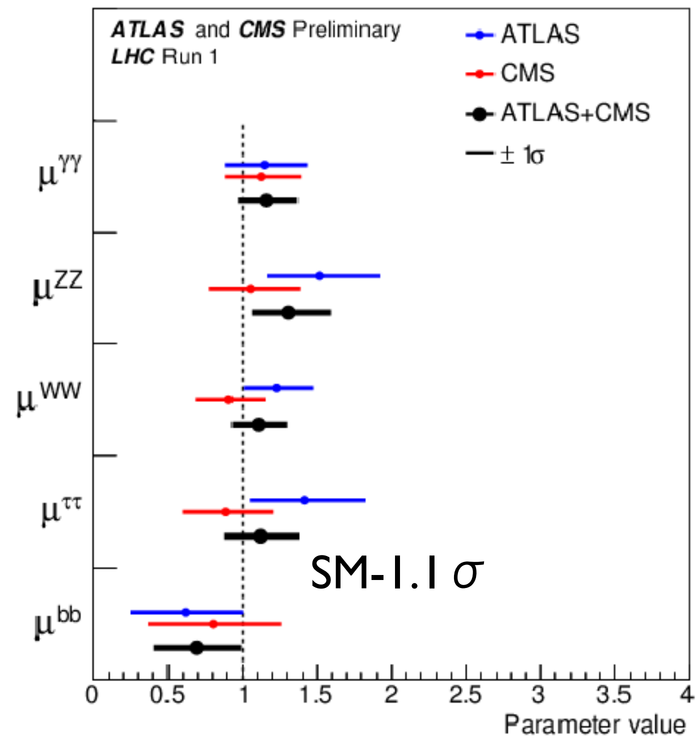
i = ggF, VBF, WH, ZH, ttH

$$\mu^f = \frac{\mathrm{BR}^f}{(\mathrm{BR}^f)_{\mathrm{SM}}}$$

f = γ γ , ZZ, WW, τ τ , bb



Prob(SM)=25%



Prob(SM)=60%

Significatività produzione e decadimento

i→ H → f

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

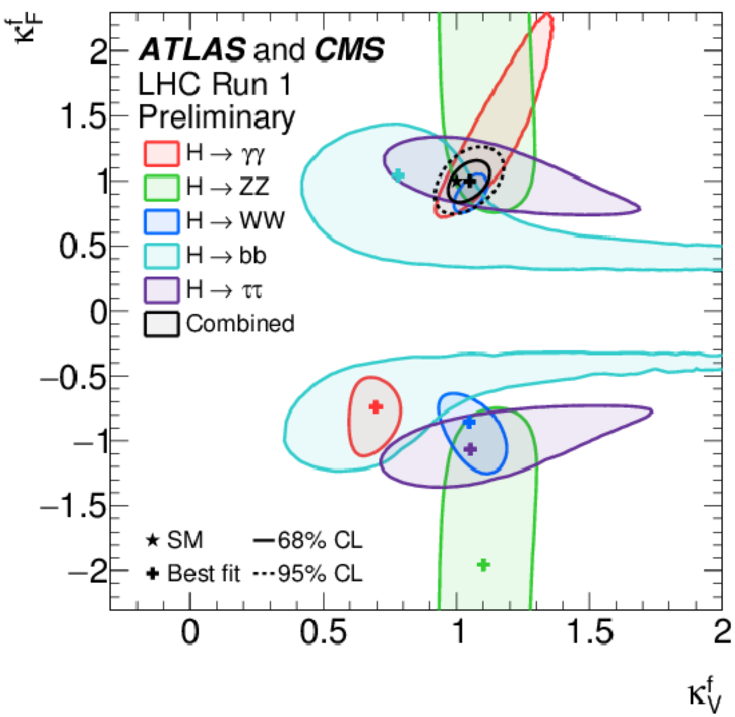
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

nel club delle 5σ (con i=GF, f=WW,ZZ, $\gamma\gamma$)

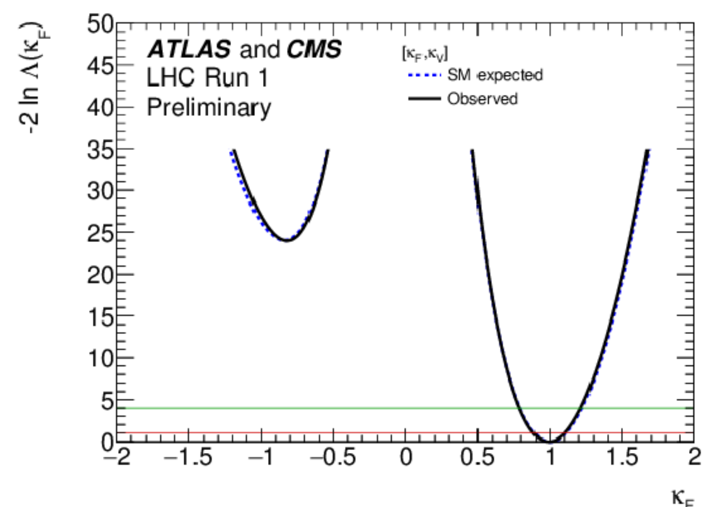
Accoppiamenti

schema dei "coupling modifiers" κ sviluppato nel LHC XS WG

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H} \qquad \kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \qquad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$



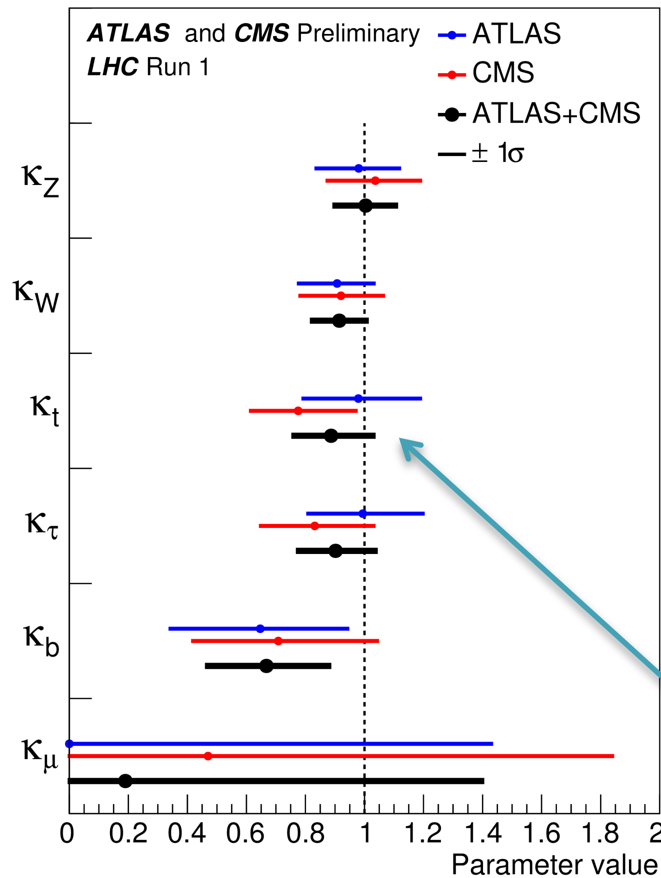
riscalamento universale di fermioni κ_F e bosoni κ_B

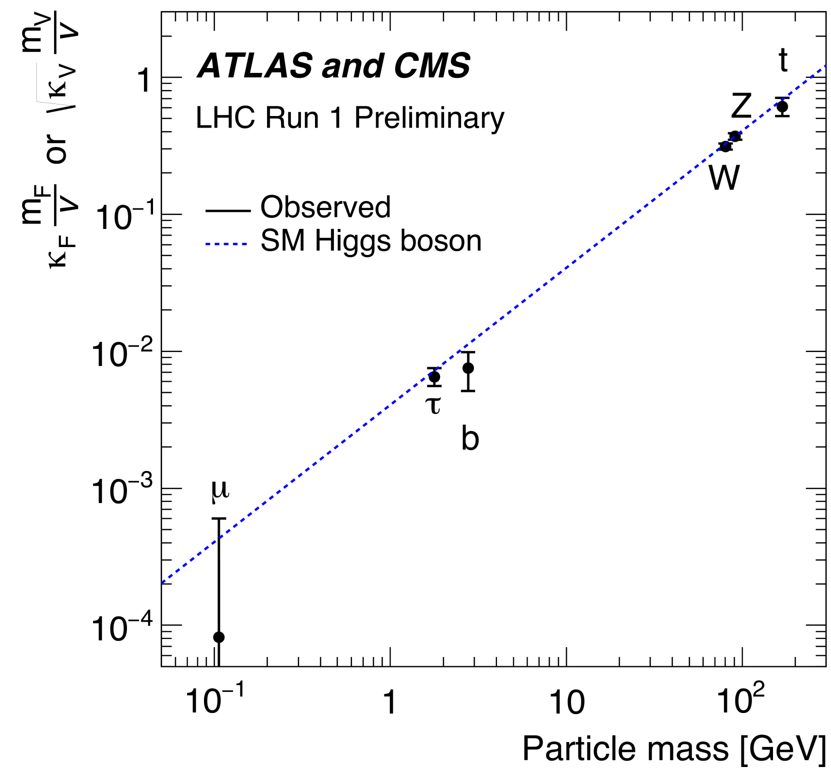


κ_F<0 molto sfavorito

SSB / Yukawa

Accoppiamenti





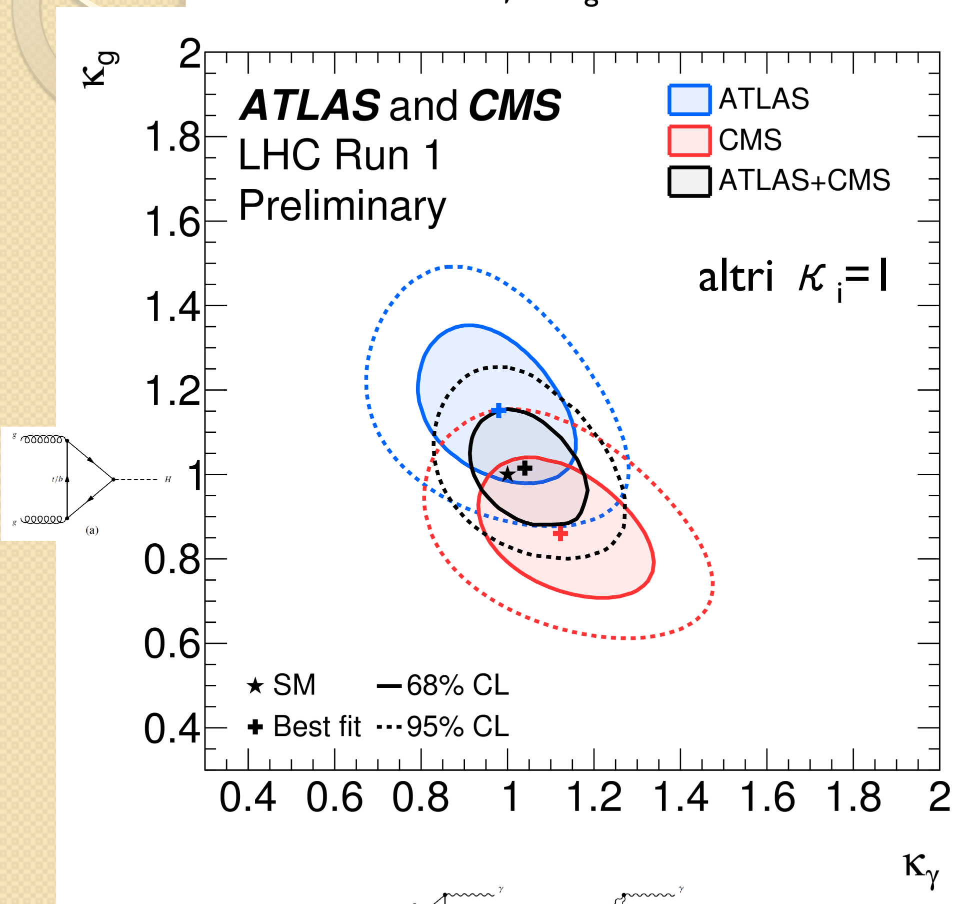
κ_t determinato da GF($\gamma\gamma$)

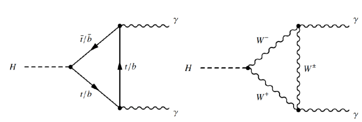
κ_H<1 (Γ_H<SM) da κ_b

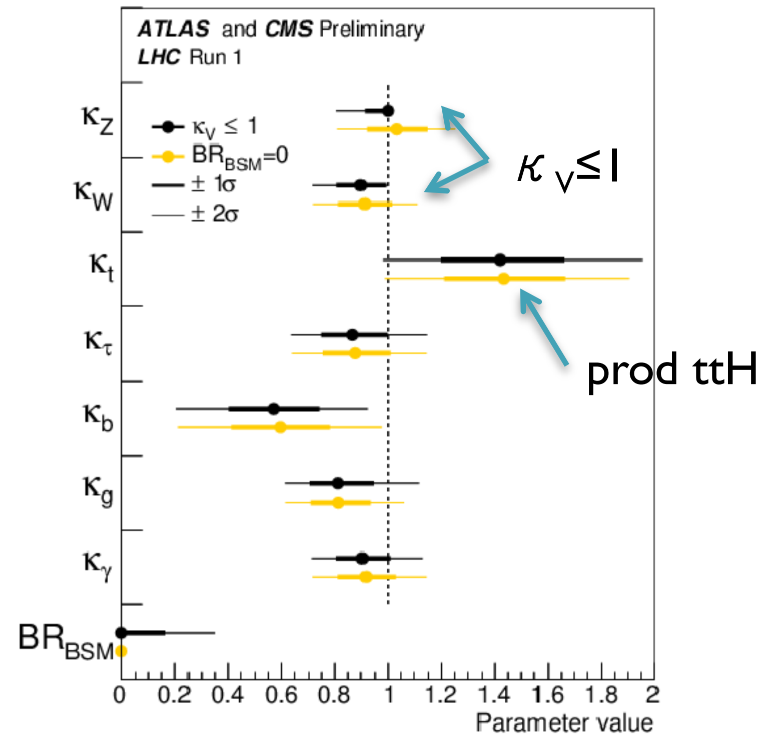
BSM

parametri κ_γ, κ_g BR(BSM)=0

BR(BSM)>0 $\Gamma_H = \dfrac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$

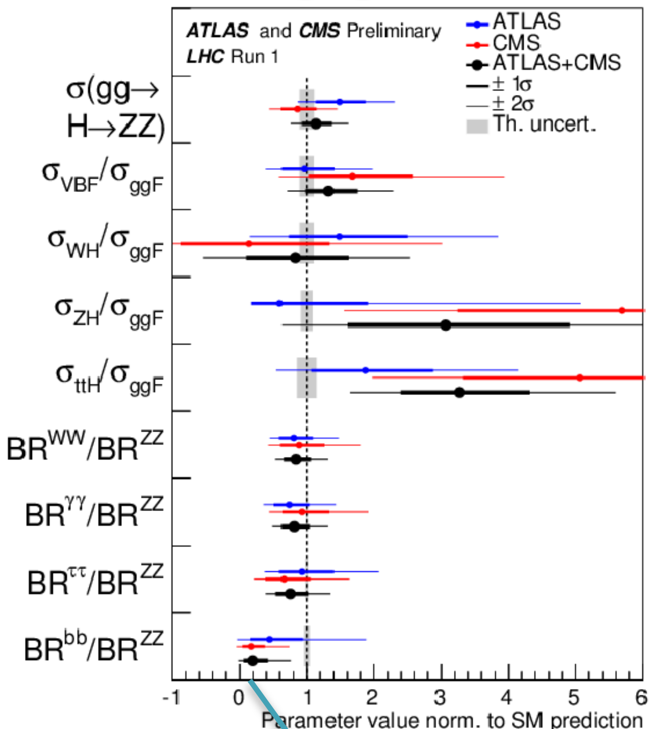




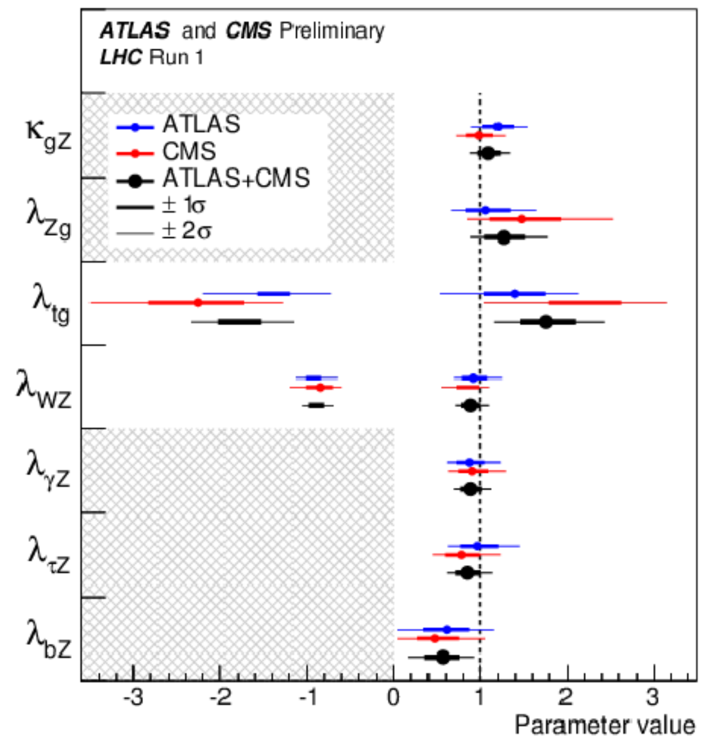


BR(BSM)<0.34 al 95% CL

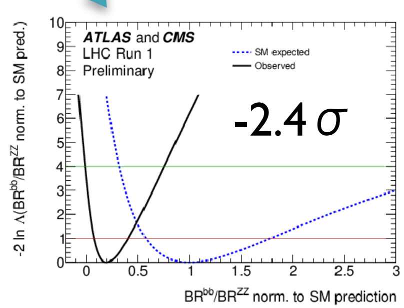
Accoppiamenti: rapporti



esplorazione più generica
incertezze sistematiche ridotte



bb/ZZ



H→bb ?

i fit indicano un BR(H→bb) basso (<-2 σ)
è determinato anche da eccessi nelle produzioni VH, ttH in altri canali

ATLAS Hbb

VH: μ =0.52±0.40
ttH : μ =1.5±1.1

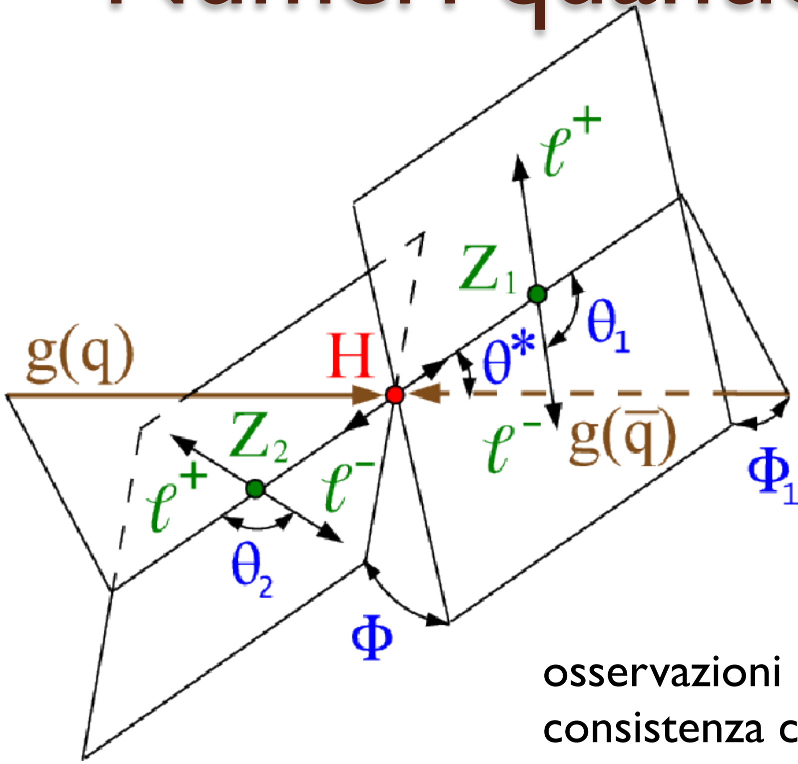
CMS Hbb

$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
$t\bar{t}$H	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

+ Tevatron: ttH : μ =1.6±0.7

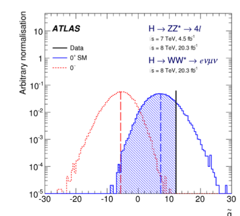
Come accoppia l'Higgs ai quark-down ?

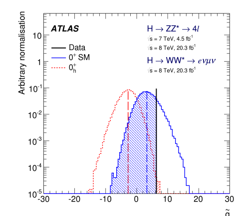
Numeri quantici

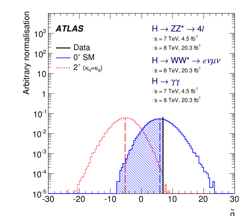


H→$\gamma\gamma$ ➔ J=2N, C=+1

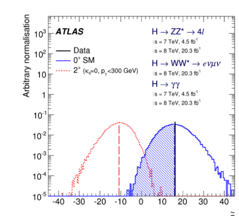
Test di $J^P=0^+$ vs 0^-, 0_h^+, 2^+
in H→ZZ*,WW, $\gamma\gamma$







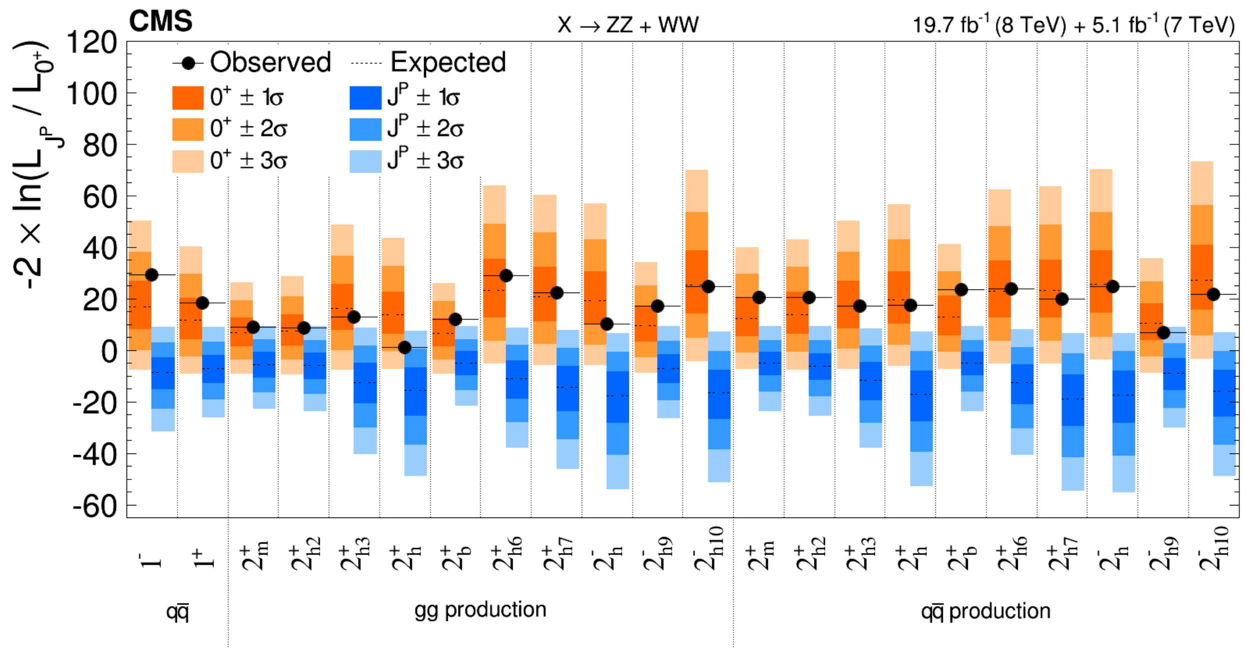
osservazioni indicano una forte consistenza con $J^P=0^+$, sfavorendo le altre ipotesi con CL>99.9%



ATLAS Phys. Lett. **B726** (2013) 120, arXiv:1307.1432 [hep-ex]
ATLAS **arXiv:1506.05669 [hep-ex],** submitted to EPJC.

Numeri quantici

CMS Phys. Rev. Lett. **110** no. 8, (2013) 081803, arXiv:1212.6639 [hep-ex]
CMS Phys. Rev. D **92**, 012004 (2015) arXiv:1411.3441 [hep-ex]



J=1 in ZZ,WW escluso al 99.999% (>4 σ)
Frazione di pseudoscalare f_{a3}<0.43 @95%CL

iniziata anche l'esplorazione della struttura degli accoppiamenti (HWW, HZZ, …): precisione molto limitata per ora

Conclusioni

La scoperta del bosone di Higgs è la legacy più celebrata del Run 1 di LHC
Completamento del SM dopo ~50 anni di ricerche

Massa mH=125.1 GeV misurata al **0.2%** (δ ~% / ~100 eventi)

Intensità di produzione, BR di decadimento ed accoppiamenti consistenti con SM minimale al **>10%**

Deviazioni BSM potrebbero essere accessibili al Run 2

Backup

Likelihood ratio

per limiti superiori e significatività del segnale

$$q_0 = -2\ln\frac{\mathcal{L}(\text{data}\,|\,b,\hat{\theta}_0)}{\mathcal{L}(\text{data}\,|\,\hat{\mu}\,s+b,\hat{\theta})}, \text{with } \hat{\mu} > 0,$$

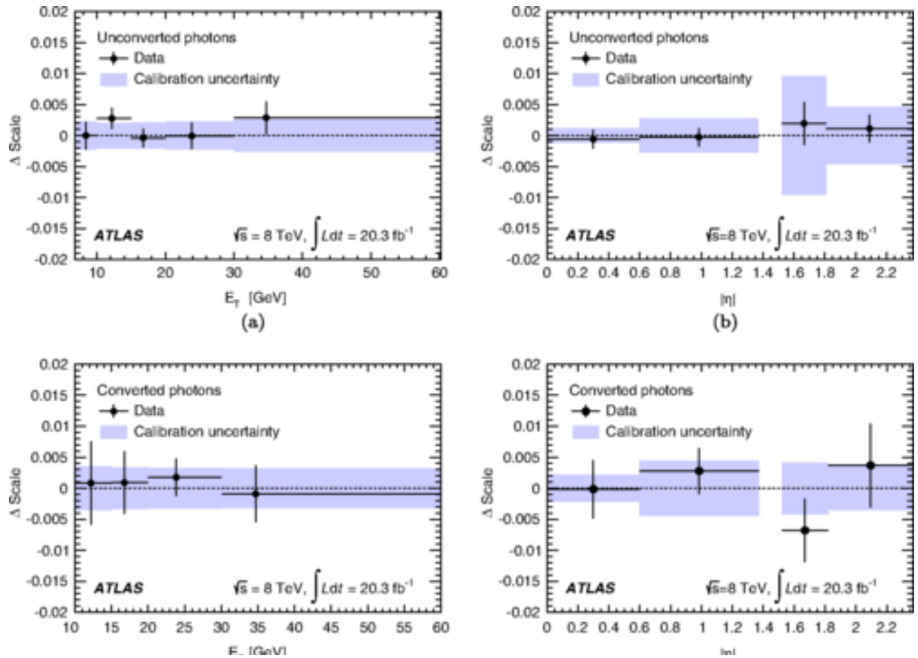
$$p_0 = \mathrm{P}\left(q_0 \geq q_0^{\text{data}} \,\middle|\, b\right)$$

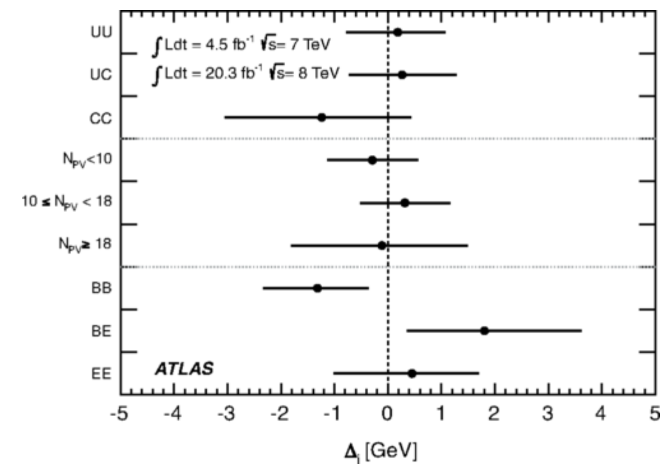
modified frequentist CLs per i limiti

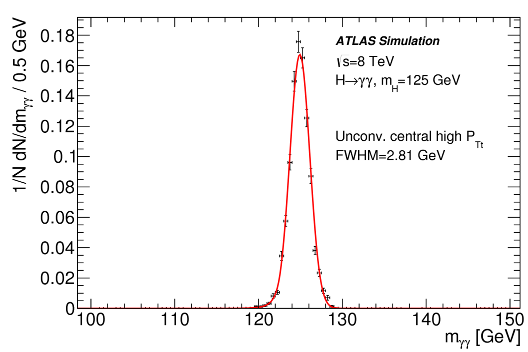
per misure dei parametri di interesse (POI) *a*

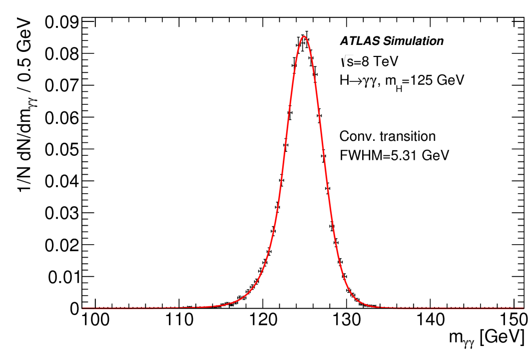
$$q(a) = -2\Delta\ln\mathcal{L} = -2\ln\frac{\mathcal{L}(\text{data}\,|\,s(a)+b,\hat{\theta}_a)}{\mathcal{L}(\text{data}\,|\,s(\hat{a})+b,\hat{\theta})}$$

m_H da $H \rightarrow \gamma\gamma$ ATLAS







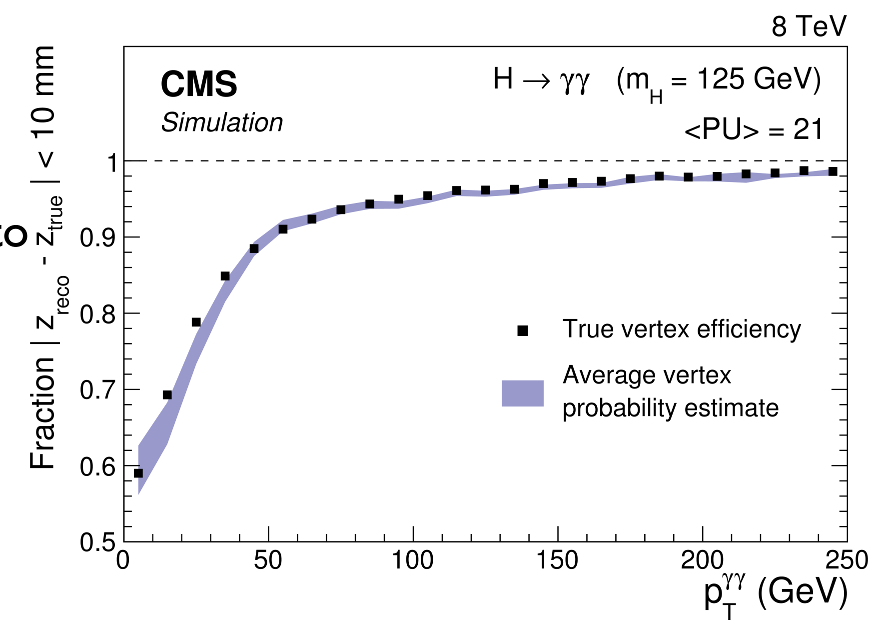


m_H da H→ $\gamma\ \gamma$ CMS

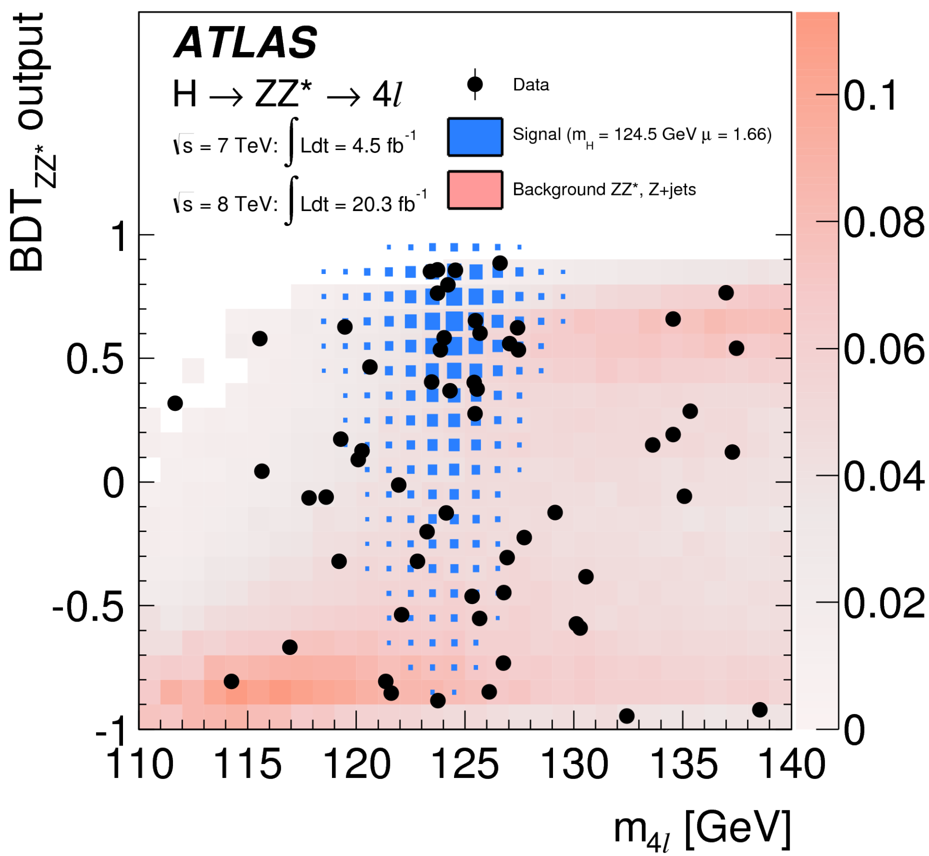
BDT per classificare gli eventi (S/B) usa

- cinematica dei fotoni e di-fotoni
- qualità dei fotoni e profilo sciame
- stima risoluzione $\delta m(\gamma\ \gamma)$ evento

Vertice primario selezionato con BDT che usa le tracce dell'evento

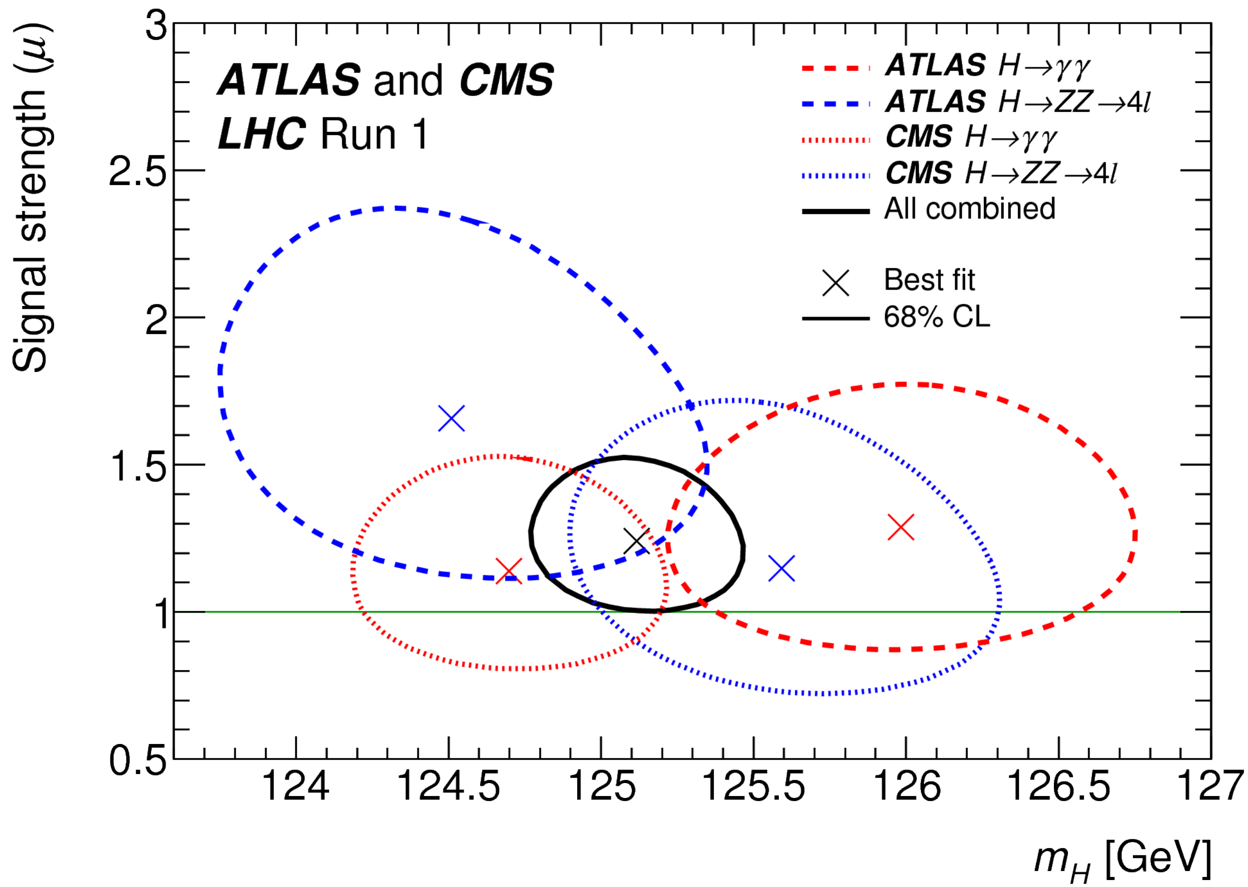


m_H da H→4l ATLAS



m_H da H→4l CMS

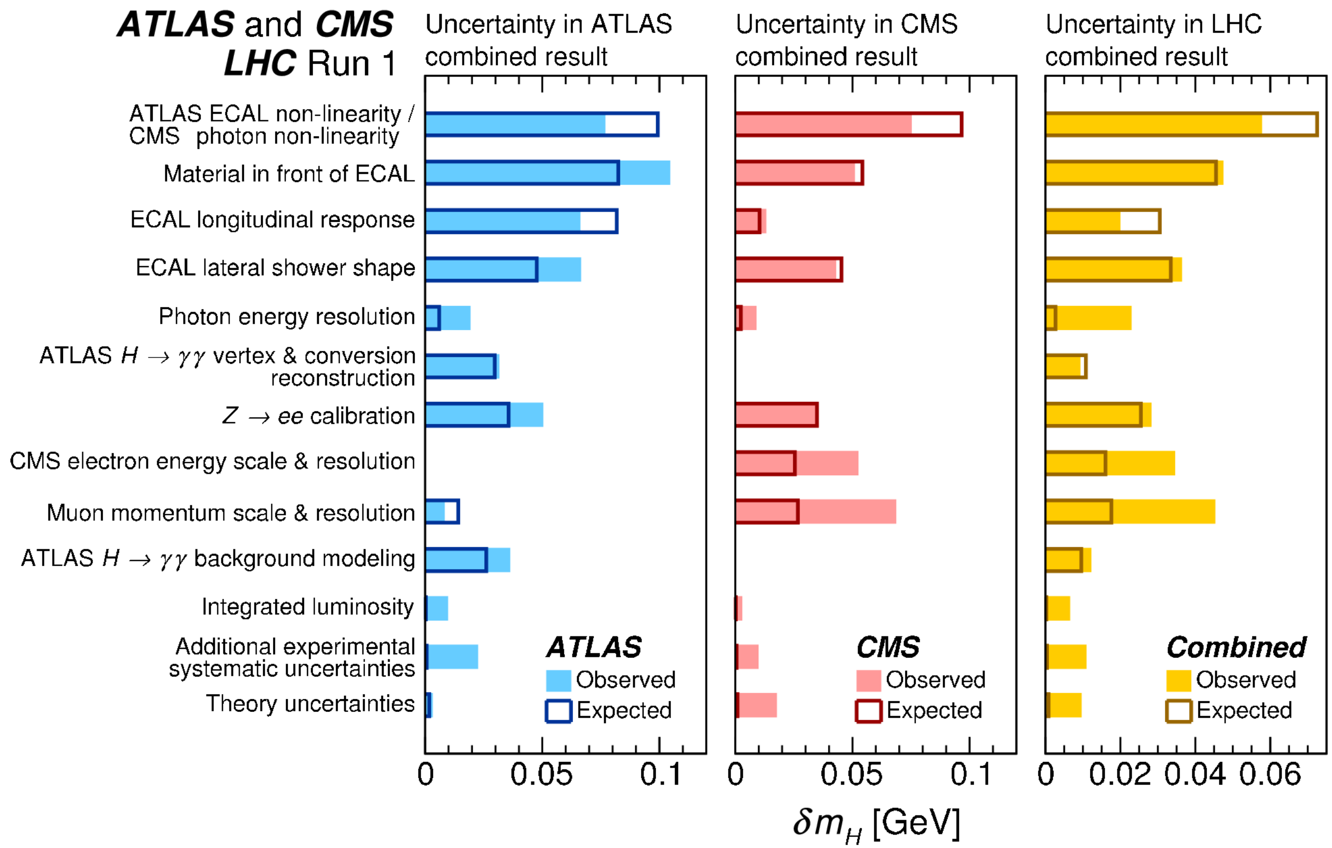
misura di m_H


ATLAS and CMS
LHC Run 1
ATLAS $H\rightarrow\gamma\gamma$
ATLAS $H\rightarrow ZZ\rightarrow 4l$
CMS $H\rightarrow\gamma\gamma$
CMS $H\rightarrow ZZ\rightarrow 4l$
All combined
Best fit
68% CL
Signal strength (μ)
m_H [GeV]
3
2.5
2
1.5
1
0.5
124
124.5
125
125.5
126
126.5
127

Incertezze sistematiche su m_H

	Uncertainty in ATLAS results [GeV]: observed (expected)		Uncertainty in CMS results [GeV]: observed (expected)		Uncertainty in combined result [GeV]: observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ$llll	$H \to \gamma\gamma$	$H \to ZZ$llll	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL non-linearity / CMS photon non-linearity	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 & 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 & resolution	–	–	–	0.12 (0.09)	–	0.03 (0.02)
Muon momentum scale & 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%)	–	

Incertezze sistematiche su m_H



Accoppiamenti

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

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

Production process	Event generator ATLAS	Event generator CMS
ggF	Powheg [29–33]	Powheg
VBF	Powheg	Powheg
WH	Pythia8 [34]	Pythia6.4 [35]
ZH ($qq \to ZH$ or $qg \to ZH$)	Pythia8	Pythia6.4
$ggZH$ ($gg \to ZH$)	Powheg	See text
ttH	Powhel [43]	Pythia6.4
tHq ($qb \to tHq$)	MadGraph [45]	aMC@NLO [28]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	Pythia8	Pythia6, aMC@NLO

Intensità μ

Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$	$1.25^{+0.24}_{-0.21}$	$0.84^{+0.19}_{-0.16}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$	$1.21^{+0.33}_{-0.30}$	$1.13^{+0.37}_{-0.34}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$	$1.25^{+0.56}_{-0.52}$	$0.46^{+0.57}_{-0.54}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$	$0.30^{+0.51}_{-0.46}$	$1.35^{+0.58}_{-0.54}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$

Accoppiamenti

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06\cdot\kappa_t^2 + 0.01\cdot\kappa_b^2 - 0.07\cdot\kappa_t\kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74\cdot\kappa_W^2 + 0.26\cdot\kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27\cdot\kappa_Z^2 + 0.37\cdot\kappa_t^2 - 1.64\cdot\kappa_Z\kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84\cdot\kappa_t^2 + 1.57\cdot\kappa_W^2 - 2.41\cdot\kappa_t\kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4\cdot\kappa_t^2 + 3.56\cdot\kappa_W^2 - 5.96\cdot\kappa_t\kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59\cdot\kappa_W^2 + 0.07\cdot\kappa_t^2 - 0.66\cdot\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57\cdot\kappa_b^2 + 0.22\cdot\kappa_W^2 + 0.09\cdot\kappa_g^2 + 0.06\cdot\kappa_\tau^2 + 0.03\cdot\kappa_Z^2 + 0.03\cdot\kappa_c^2 + 0.0023\cdot\kappa_\gamma^2 + 0.0016\cdot\kappa_{Z\gamma}^2 + 0.0001\cdot\kappa_s^2 + 0.00022\cdot\kappa_\mu^2$

Accoppiamenti

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[27]	[50]	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6
			$(^{+0.26}_{-0.24})$	$(^{+0.24}_{-0.22})$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	[51]	[52]	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
			$(^{+0.33}_{-0.27})$	$(^{+0.31}_{-0.26})$	(5.5)	(6.8)
$H \to WW$	[53, 54]	[55]	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
			$(^{+0.21}_{-0.20})$	$(^{+0.23}_{-0.20})$	(5.8)	(5.6)
$H \to \tau\tau$	[56]	[57]	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
			$(^{+0.37}_{-0.33})$	$(^{+0.31}_{-0.29})$	(3.3)	(3.7)
$H \to bb$	[37]	[38]	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
			$(^{+0.39}_{-0.37})$	$(^{+0.45}_{-0.43})$	(2.7)	(2.5)
$H \to \mu\mu$	[58]	[59]	-0.7 ± 3.6	0.8 ± 3.5		
			(± 3.6)	(± 3.5)		
ttH production	[60–62]	[64]	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			$(^{+0.72}_{-0.66})$	$(^{+0.88}_{-0.80})$	(1.6)	(1.3)

Accoppiamenti

Parameter	ATLAS+CMS Best-fit value	ATLAS+CMS Uncertainty Stat	ATLAS+CMS Uncertainty Syst	ATLAS Best-fit value	ATLAS Uncertainty Stat	ATLAS Uncertainty Syst	CMS Best-fit value	CMS Uncertainty Stat	CMS Uncertainty Syst
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$	$1.10^{+0.11}_{-0.11}$	$^{+0.09}_{-0.09}$	$^{+0.07}_{-0.06}$	$1.20^{+0.16}_{-0.15}$	$^{+0.14}_{-0.14}$	$^{+0.08}_{-0.06}$	$0.99^{+0.14}_{-0.13}$	$^{+0.12}_{-0.12}$	$^{+0.07}_{-0.06}$
	$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.06}_{-0.05}\right)$	$\left(^{+0.16}_{-0.15}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.07}_{-0.06}\right)$
$\lambda_{Zg} = \kappa_Z / \kappa_g$	$1.26^{+0.23}_{-0.19}$	$^{+0.18}_{-0.16}$	$^{+0.15}_{-0.12}$	$1.06^{+0.26}_{-0.21}$	$^{+0.21}_{-0.18}$	$^{+0.14}_{-0.11}$	$1.47^{+0.44}_{-0.34}$	$^{+0.34}_{-0.28}$	$^{+0.29}_{-0.19}$
	$\left(^{+0.20}_{-0.17}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.12}_{-0.10}\right)$	$\left(^{+0.28}_{-0.23}\right)$	$\left(^{+0.23}_{-0.20}\right)$	$\left(^{+0.16}_{-0.11}\right)$	$\left(^{+0.27}_{-0.23}\right)$	$\left(^{+0.22}_{-0.19}\right)$	$\left(^{+0.17}_{-0.12}\right)$
$\lambda_{tg} = \kappa_t / \kappa_g$	$1.76^{+0.32}_{-0.29}$	$^{+0.21}_{-0.20}$	$^{+0.23}_{-0.20}$	$1.39^{+0.34}_{-0.33}$	$^{+0.25}_{-0.24}$	$^{+0.23}_{-0.22}$	$-2.25^{+0.51}_{-0.55}$	$^{+0.39}_{-0.36}$	$^{+0.39}_{-0.30}$
	$\left(^{+0.29}_{-0.39}\right)$	$\left(^{+0.20}_{-0.21}\right)$	$\left(^{+0.21}_{-0.24}\right)$	$\left(^{+0.38}_{-0.54}\right)$	$\left(^{+0.28}_{-0.28}\right)$	$\left(^{+0.26}_{-0.33}\right)$	$\left(^{+0.42}_{-0.64}\right)$	$\left(^{+0.31}_{-0.33}\right)$	$\left(^{+0.29}_{-0.46}\right)$
$\lambda_{WZ} = \kappa_W / \kappa_Z$	$0.89^{+0.10}_{-0.09}$	$^{+0.09}_{-0.08}$	$^{+0.04}_{-0.04}$	$0.92^{+0.14}_{-0.12}$	$^{+0.13}_{-0.11}$	$^{+0.05}_{-0.04}$	$-0.85^{+0.13}_{-0.15}$	$^{+0.13}_{-0.11}$	$^{+0.07}_{-0.06}$
	$\left(^{+0.12}_{-0.10}\right)$	$\left(^{+0.11}_{-0.09}\right)$	$\left(^{+0.05}_{-0.04}\right)$	$\left(^{+0.18}_{-0.15}\right)$	$\left(^{+0.16}_{-0.13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.17}_{-0.14}\right)$	$\left(^{+0.15}_{-0.13}\right)$	$\left(^{+0.07}_{-0.07}\right)$
$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$	$0.89^{+0.11}_{-0.10}$	$^{+0.11}_{-0.09}$	$^{+0.04}_{-0.03}$	$0.88^{+0.16}_{-0.14}$	$^{+0.15}_{-0.13}$	$^{+0.04}_{-0.03}$	$0.91^{+0.17}_{-0.14}$	$^{+0.16}_{-0.13}$	$^{+0.05}_{-0.04}$
	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.13}_{-0.11}\right)$	$\left(^{+0.04}_{-0.03}\right)$	$\left(^{+0.20}_{-0.17}\right)$	$\left(^{+0.19}_{-0.17}\right)$	$\left(^{+0.06}_{-0.04}\right)$	$\left(^{+0.18}_{-0.16}\right)$	$\left(^{+0.17}_{-0.15}\right)$	$\left(^{+0.05}_{-0.04}\right)$
$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$	$0.85^{+0.14}_{-0.12}$	$^{+0.12}_{-0.10}$	$^{+0.07}_{-0.06}$	$0.97^{+0.22}_{-0.18}$	$^{+0.18}_{-0.15}$	$^{+0.11}_{-0.09}$	$0.78^{+0.20}_{-0.17}$	$^{+0.16}_{-0.15}$	$^{+0.10}_{-0.08}$
	$\left(^{+0.17}_{-0.15}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.27}_{-0.23}\right)$	$\left(^{+0.23}_{-0.19}\right)$	$\left(^{+0.14}_{-0.12}\right)$	$\left(^{+0.23}_{-0.20}\right)$	$\left(^{+0.19}_{-0.17}\right)$	$\left(^{+0.12}_{-0.11}\right)$
$\lambda_{bZ} = \kappa_b / \kappa_Z$	$0.56^{+0.18}_{-0.18}$	$^{+0.12}_{-0.11}$	$^{+0.10}_{-0.11}$	$0.61^{+0.24}_{-0.24}$	$^{+0.20}_{-0.18}$	$^{+0.14}_{-0.15}$	$0.47^{+0.26}_{-0.17}$	$^{+0.17}_{-0.15}$	$^{+0.15}_{-0.16}$
	$\left(^{+0.25}_{-0.22}\right)$	$\left(^{+0.21}_{-0.18}\right)$	$\left(^{+0.14}_{-0.11}\right)$	$\left(^{+0.36}_{-0.29}\right)$	$\left(^{+0.31}_{-0.24}\right)$	$\left(^{+0.18}_{-0.14}\right)$	$\left(^{+0.38}_{-0.37}\right)$	$\left(^{+0.32}_{-0.25}\right)$	$\left(^{+0.20}_{-0.17}\right)$

Accoppiamenti

Model	p-value	DoF	Parameters
Global signal strength	34%	1	μ
Production processes	24%	5	$\mu_{ggF}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	60%	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{b\bar{b}}$
μ_V and μ_F per decay	88%	10	$\mu_V^{\gamma\gamma}, \mu_V^{ZZ}, \mu_V^{WW}, \mu_V^{\tau\tau}, \mu_V^{b\bar{b}}, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{b\bar{b}}$
μ_V/μ_F ratio	72%	6	$\mu_V/\mu_F, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{b\bar{b}}$
Ratios of σ and BR relative to $\sigma(gg \to H \to ZZ)$	16%	9	$\sigma(gg \to H \to ZZ)$, $\sigma_{VBF}/\sigma_{ggF}$, σ_{WH}/σ_{ggF}, σ_{ZH}/σ_{ggF}, $\sigma_{ttH}/\sigma_{ggF}$, BR^{WW}/BR^{ZZ}, $BR^{\gamma\gamma}/BR^{ZZ}$, $BR^{\tau\tau}/BR^{ZZ}$, $BR^{b\bar{b}}/BR^{ZZ}$
Ratios of σ and BR relative to $\sigma(gg \to H \to WW)$	16%	9	$\sigma(gg \to H \to WW)$, $\sigma_{VBF}/\sigma_{ggF}$, σ_{WH}/σ_{ggF}, σ_{ZH}/σ_{ggF}, $\sigma_{ttH}/\sigma_{ggF}$, BR^{ZZ}/BR^{WW}, $BR^{\gamma\gamma}/BR^{WW}$, $BR^{\tau\tau}/BR^{WW}$, $BR^{b\bar{b}}/BR^{WW}$
Coupling ratios	13%	7	$\kappa_{gZ}, \lambda_{Zg}, \lambda_{tg}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{bZ}$
Couplings, SM loops	65%	6	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu$
Couplings, BSM loops	11%	7	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_g, \kappa_\gamma$
BSM loops only	82%	2	κ_g, κ_γ
Up vs down couplings	67%	3	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$
Lepton vs quark couplings	78%	3	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$
Fermion and vector couplings	59%	2	κ_V, κ_F