

# Misure delle proprietà del bosone di Higgs all'esperimento ATLAS

Marcello Fanti  
(per la Collaborazione ATLAS)

University of Milano and INFN

# Contenuti

Una nuova particella è stata osservata nei decadimenti

$$H \rightarrow ZZ \rightarrow 4\ell \quad , \quad H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu} \quad , \quad H \rightarrow \gamma\gamma$$

con una massa  $m_H \simeq 125$  GeV

(vd slides di E.Rossi, M.Testa, L.Carminati)

## La nuova particella scoperta è veramente il bosone di Higgs?

- Modi di decadimento accessibili
- Misura della massa  $m_H$
- Misure di spin / parità
- Misure di “signal strength”  $\mu \stackrel{\text{def}}{=} \sigma / \sigma_{SM}$
- Misure di “couplings”

(vd anche poster di A.Gabrielli)

# Se fosse il bosone di Higgs del Modello Standard...

... sarebbe l'ultimo tassello mancante del Modello Standard;  
 ... la sua massa  $m_H$  sarebbe l'ultimo parametro mancante del Modello

$$V(\phi) = \lambda (\phi^\dagger \phi)^2 - \mu^2 (\phi^\dagger \phi)$$

VEV:  $v = \mu / \sqrt{\lambda} = 2m_W / g$   
 massa:  $m_H = \sqrt{2} \cdot \mu$

Tutte le altre proprietà sarebbero determinate:

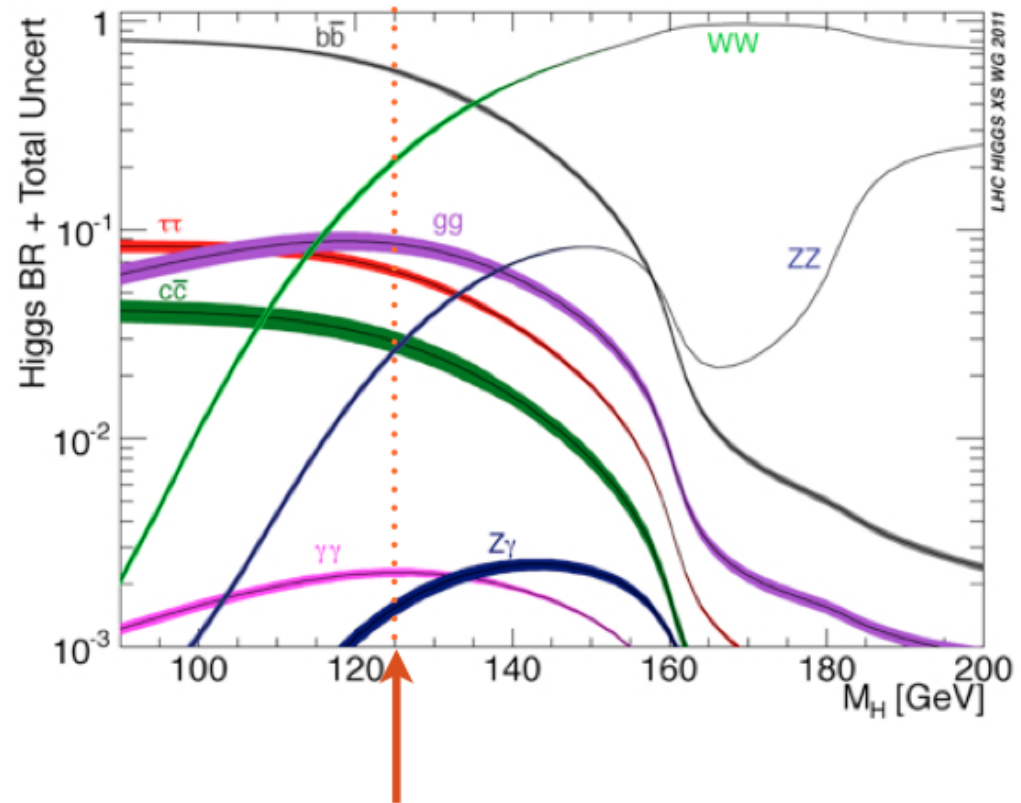
- accoppiamenti con i bosoni elettrodeboli:

$$gm_W \cdot (HW^+W^-) + \frac{gm_Z}{2 \cos \theta_W} \cdot (HZZ)$$

- accoppiamenti con i fermioni (Yukawa)

$$\frac{m_f}{v} \cdot (H\bar{f}f)$$

- spin = 0 ; parità +



alla massa osservata  $m_H \approx 125$  GeV molti modi di decadimento sono accessibili

# Modelli statistici

**Funzione di likelihood estesa:**  $\mathcal{L}(\vec{\alpha}; \vec{\nu})$ :

$$-\ln \mathcal{L}(\vec{\alpha}; \vec{\nu}) = (n_s + n_b) - \sum_e \left[ \overbrace{n_s \cdot f_s(\vec{x}_e | \vec{\alpha}, \vec{\nu}_s)}^{\text{pdf del segnale}} + \overbrace{n_b \cdot f_b(\vec{x}_e | \vec{\nu}_b)}^{\text{pdf del fondo}} \right] - \overbrace{\sum_k \ln \pi_k(\nu_k)}^{\text{pdf ancillari}}$$

- $n_s, n_b$ : eventi di segnale / fondo
- $\vec{x}$ : osservabili
- $f_s, f_b$ : pdf per segnale / fondo
- $\vec{\alpha}$ : parametri di interesse  
(es.: massa, sezione d'urto, spin, ...)
- $\vec{\nu}$ : "nuisance parameters"  
(parametri di forma, sistematici, ...)
- $\pi_k$ : pdf derivate da misure ancillari  
(normalmente Gaussiane, ma anche log-normali, oppure "rettangolari")

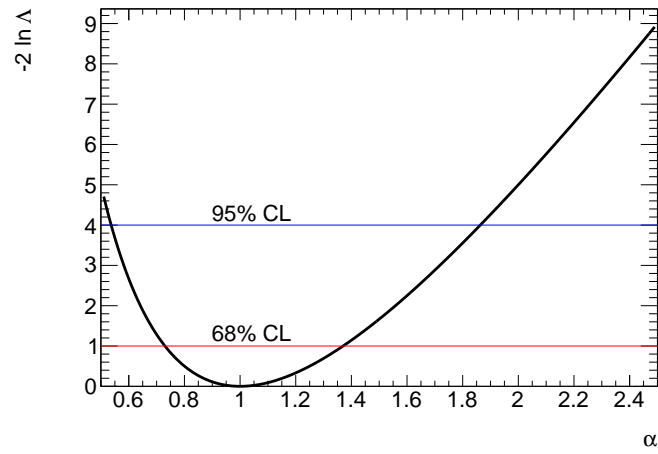
**Statistica di test:** "Profiled Likelihood Ratio" (PLR)

$$q_{\vec{\alpha}} = -2 \ln \Lambda(\vec{\alpha}) = -2 \ln \frac{\mathcal{L}(\vec{\alpha}; \hat{\nu}(\vec{\alpha}))}{\mathcal{L}(\hat{\alpha}; \hat{\nu})}$$

$\mathcal{L}(\hat{\alpha}; \hat{\nu})$ : likelihood massimizzata per  $\vec{\alpha}, \vec{\nu}$   
 $\mathcal{L}(\vec{\alpha}; \hat{\nu}(\vec{\alpha}))$ : likelihood per  $\vec{\alpha}$  fissato e "profilata" per  $\vec{\nu}$

**Teorema di Wilks** : se  $\vec{\alpha} = \vec{\alpha}^{vero}$  la quantità  $q_{\vec{\alpha}}$  è distribuita come una variabile  $\chi_D^2$  dove  $D$  è il numero dei parametri di interesse  $\vec{\alpha}$

⇒ È possibile determinare intervalli di confidenza per  $\vec{\alpha}$



$D = 2$  parametri di interesse: contorni di confidenza definiti da :

- 68% CL ⇒  $-2 \ln \Lambda < 2.3$
- 95% CL ⇒  $-2 \ln \Lambda < 6.0$

# Misura della massa

(ATLAS-CONF-2013-014)

# Misura della massa

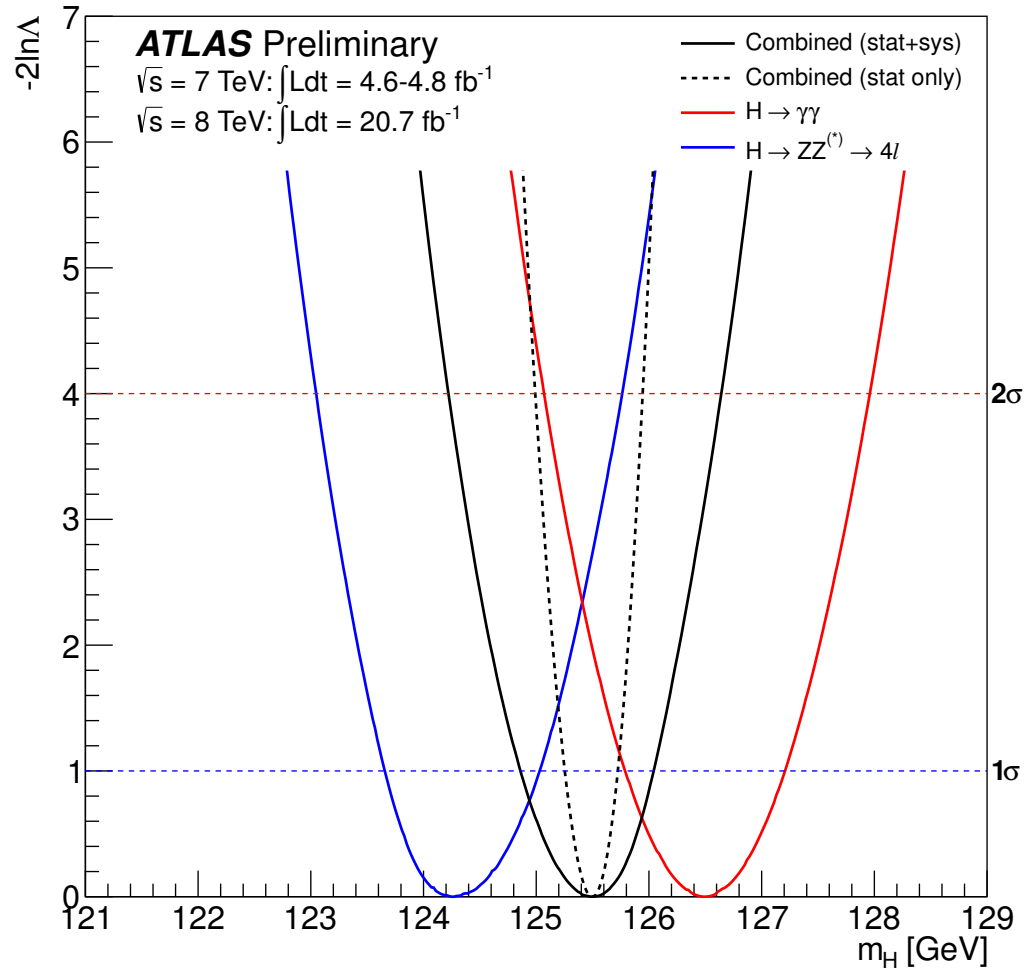
Misure sui singoli canali:

$H \rightarrow \gamma\gamma \Rightarrow m_H^{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst) \text{ GeV}$

$H \rightarrow 4\ell \Rightarrow m_H^{4\ell} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst) \text{ GeV}$

**Sistematiche:**

- scala di energia dei muoni (dominante per  $H \rightarrow 4\ell$ ): (calibrata con  $Z \rightarrow \mu^+\mu^-$ ,  $\Upsilon \rightarrow \mu^+\mu^-$ )  $\Rightarrow 0.2\%$  su  $m_{4\mu}$
  - scala elettromagnetica (specialmente per  $H \rightarrow \gamma\gamma$ )
    - scala da  $Z \rightarrow e^+e^-$  ed estrapolazione  $e \rightarrow \gamma$  : 0.3%
    - materiale di fronte al calorimetro : 0.3% - 0.7%
    - calibrazione relativa presampler/calorimetro : 0.1%
    - $E_1/E_2$ , linearità, leakage laterale, ... : 0.32%
- $\Rightarrow$  in tutto **0.55%** su  $m_{\gamma\gamma}$  ( $\Rightarrow 0.7 \text{ GeV}$ )



**Combinazione:** il parametro di interesse è  $m_H$ , comune ai due canali

$\hat{m}_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst) \text{ GeV}$

# Massa: controlli di consistenza

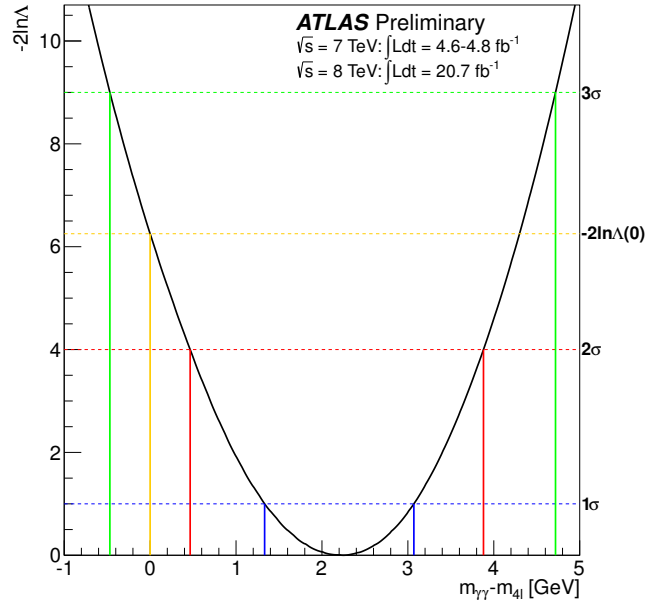
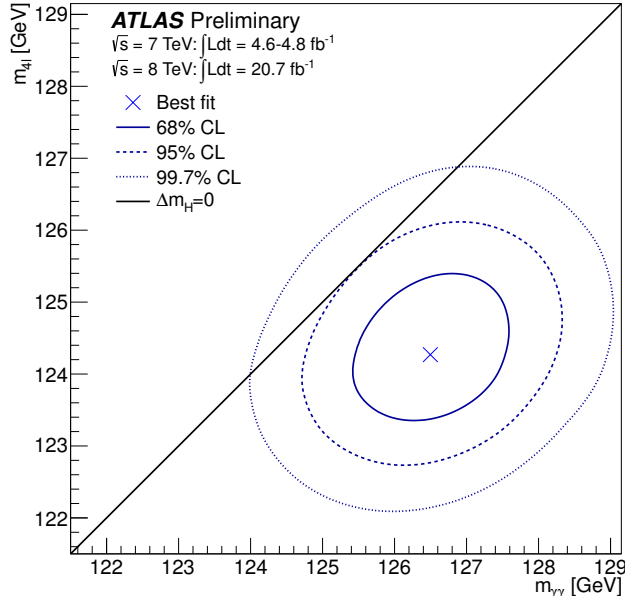
Parametri di interesse:  $m_H^{\gamma\gamma}$  e  $m_H^{4\ell}$   
 Parzialmente correlati dalla scala di energia EM

Oppure: parametro di interesse  $\Delta m_H \stackrel{\text{def}}{=} m_H^{\gamma\gamma} - m_H^{4\ell}$

$$\Delta m_H = 2.3^{+0.6}_{-0.7}(\text{stat}) \pm 0.6(\text{syst}) \text{ GeV}$$

⇒ discrepanza a  $2.4 \sigma$  (p-valore = 1.5%) (con pdf Gaussiane)

Assumendo pdf ancillari rettangolari per la scala di energia EM, la conoscenza del materiale davanti al calorimetro, e la scala di energia del presampler, il p-valore sale a 8%



# Misure di spin

( ATLAS-CONF-2013-029 , ATLAS-CONF-2013-031 , ATLAS-CONF-2013-013 )



# Misure di spin: introduzione

I decadimenti osservati in  $\gamma\gamma$ ,  $ZZ$ ,  $W^+W^-$  implicano **spin intero**

Il decadimento in  $\gamma\gamma$  **esclude la possibilità spin-1** (teorema di Landau-Yang)

Il bosone Higgs Modello Standard deve essere nello stato spin-parità  $J^P = 0^+$

$\Rightarrow$  le ipotesi alternative più interessanti da confrontare sono  $0^-$ ,  $2^\pm$  (ma  $H \rightarrow 4\ell$  è sensibile anche a  $1^\pm$ )

In pratica la più generica lagrangiana per una particella a spin-2 ha molti parametri liberi, e sarebbe impossibile escluderla nel caso più generale

$\Rightarrow$  si sceglie lo scenario “minimal coupling”  $2_m^+$

Inoltre i meccanismi di produzione  $gg \rightarrow (2_m^+)$  e  $q\bar{q} \rightarrow (2_m^+)$  producono stati di polarizzazione diversi, quindi distribuzioni angolari osservabili differenti.

Si esplorano 5 possibili “miscele” dei due modi di produzione:

$$f_{q\bar{q}} \stackrel{\text{def}}{=} \frac{\sigma(q\bar{q} \rightarrow 2_m^+)}{\sigma(q\bar{q} \rightarrow 2_m^+) + \sigma(gg \rightarrow 2_m^+)} \in \{ 0.00, 0.25, 0.50, 0.75, 1.00 \}$$

Statistica di test: qui si confrontano ipotesi alternative  $\mathcal{H}_0, \mathcal{H}_A \Rightarrow$  Ratio of Profiled Likelihoods (RPL)

$$q = \ln \frac{\mathcal{L}(\mathcal{H}_0; \hat{\nu}(\mathcal{H}_0))}{\mathcal{L}(\mathcal{H}_A; \hat{\nu}(\mathcal{H}_A))}$$

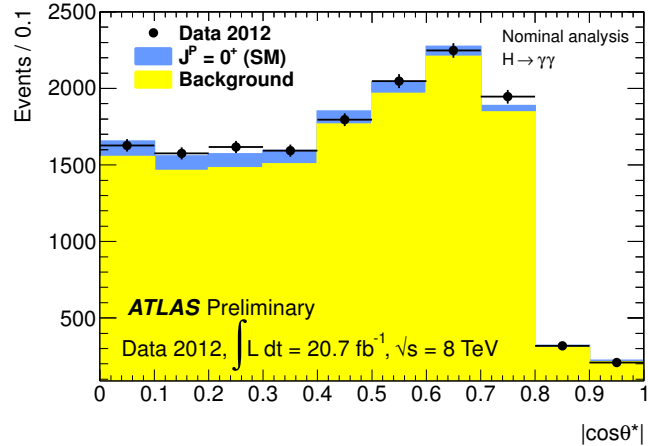
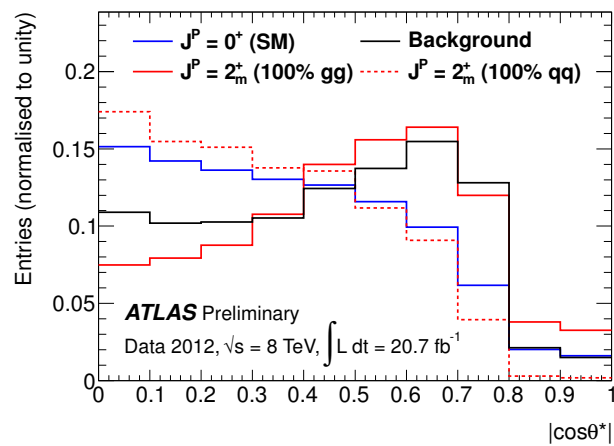
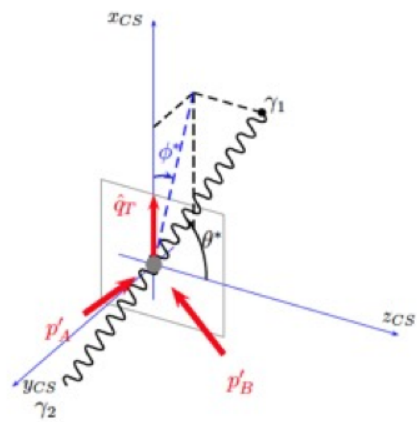
# Misura di spin nel canale $H \rightarrow \gamma\gamma$

Osservabile: angolo di decadimento  $\theta^*$  dei fotoni nel centro di massa del sistema  $\gamma\gamma$

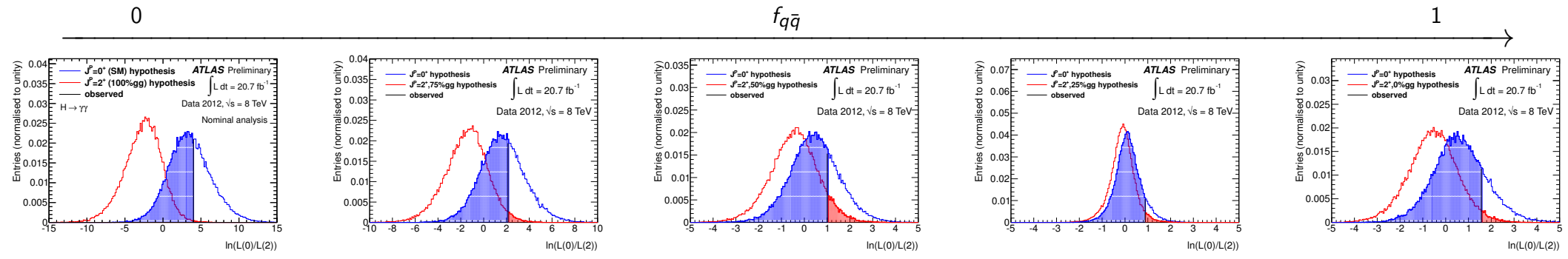
$\Rightarrow$  distribuzione isotropa per spin-0 ( $\cos \theta^*$  uniforme) prima dei tagli cinematici

$\Rightarrow d\sigma(gg \rightarrow (2_m^+) \rightarrow \gamma\gamma)/d(\cos \theta^*) \propto (1 + 6 \cos^2 \theta^* + \cos^4 \theta^*)$

$\Rightarrow d\sigma(q\bar{q} \rightarrow (2_m^+) \rightarrow \gamma\gamma)/d(\cos \theta^*) \propto (1 - \cos^4 \theta^*)$

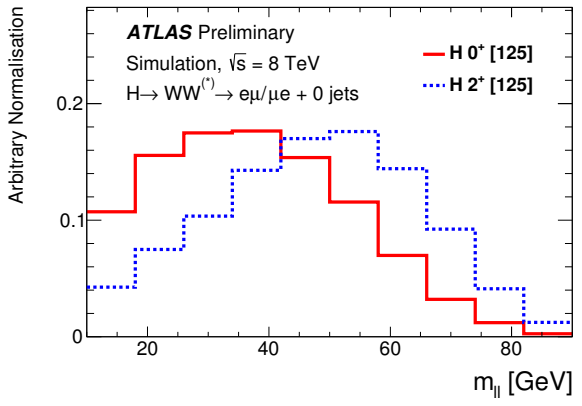
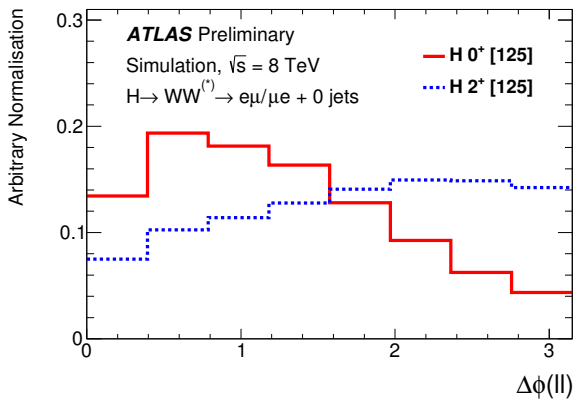
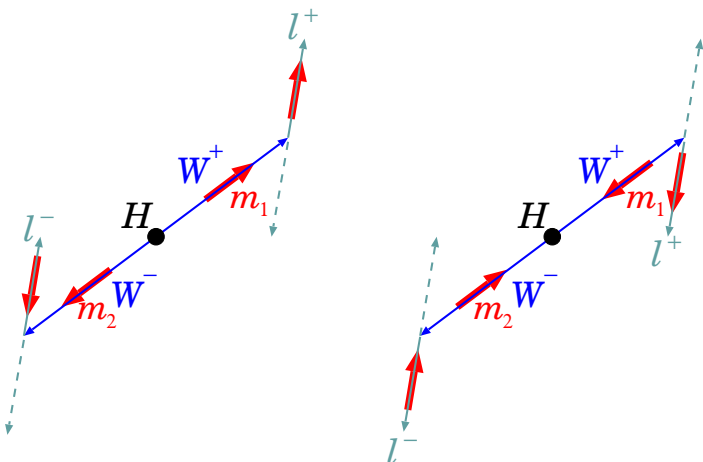


Rapporto  $S/B \approx 3\%$   $\Rightarrow$  cruciale un'ottima comprensione della forma del background (estratta dai dati)



# Misura di spin nel canale $H \rightarrow W^+W^- \rightarrow e\nu\mu\nu$

Per spin-0 i leptoni tendono ad essere vicini in angolo (correlazione fra le elicità di  $W^\pm$ , decadimento  $V - A$ )

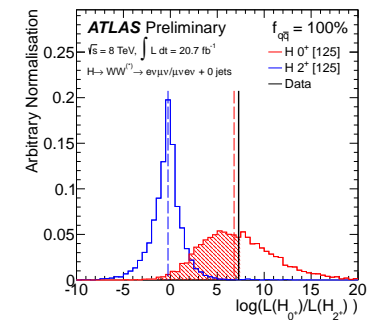
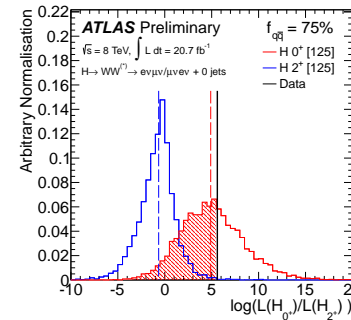
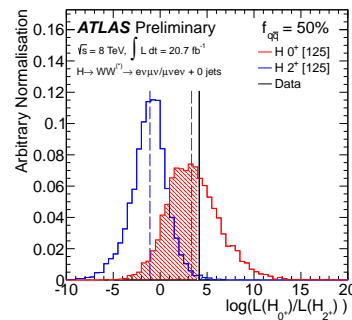
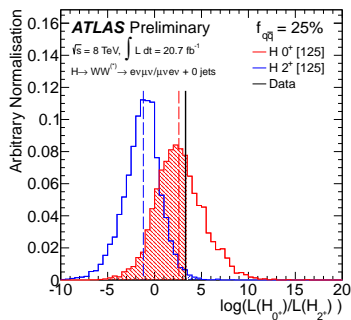
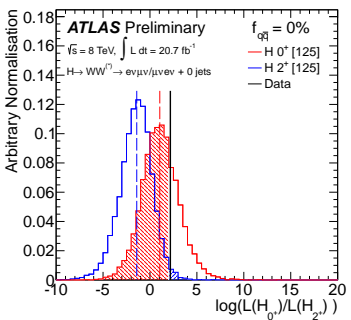


## Osservabili discriminanti

$\Delta\phi_{\ell\ell}$ ,  $m_{\ell\ell}$ ; inoltre:  $p_T^{\ell\ell}$ ,  $E_{T,rel}^{miss} \equiv E_T^{miss} \cdot \sin \Delta\phi^{\text{nearest}}$

$\Rightarrow$  analisi multivariata

0  $f_{q\bar{q}}$  1  $\rightarrow$

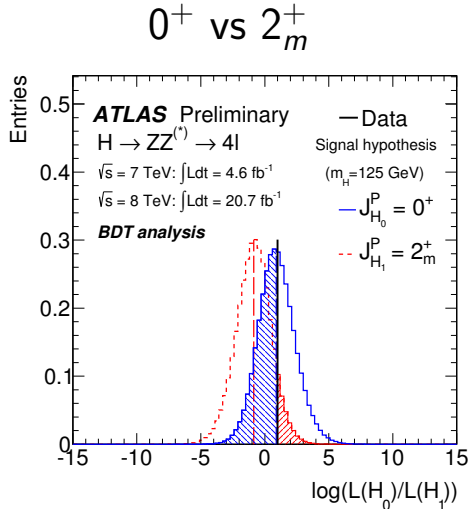
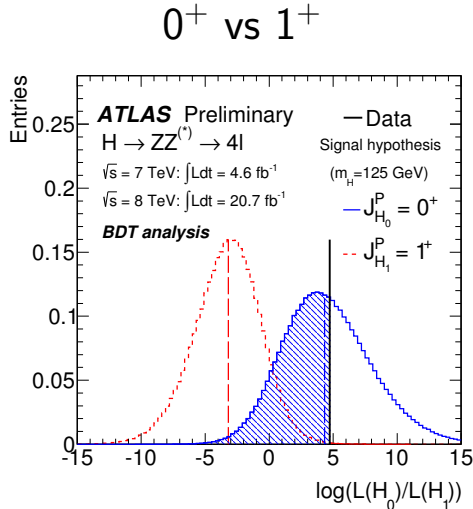
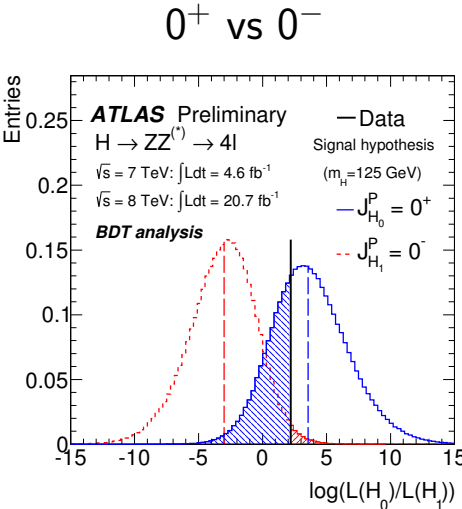
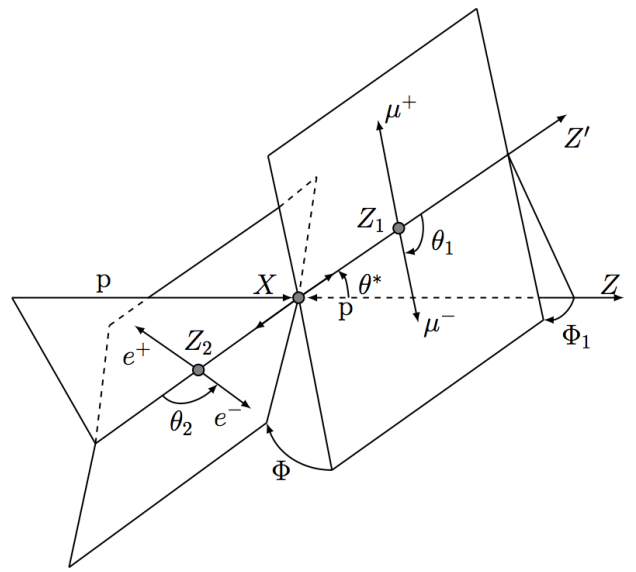


# Misura di spin nel canale $H \rightarrow ZZ \rightarrow 4\ell$

La completa ricostruzione dello stato finale dà accesso a informazioni sulla polarizzazione della risonanza e dei bosoni Z

**Osservabili sensibili:**

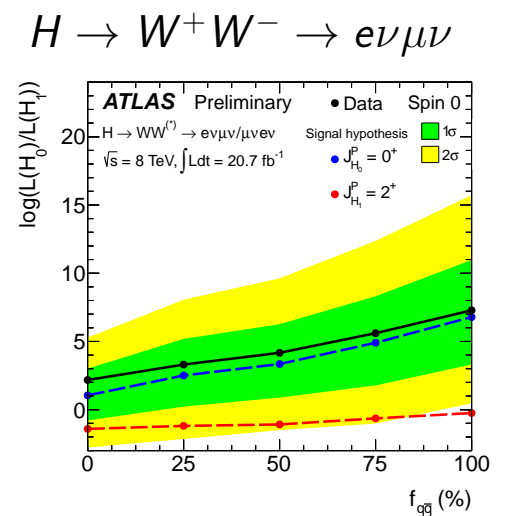
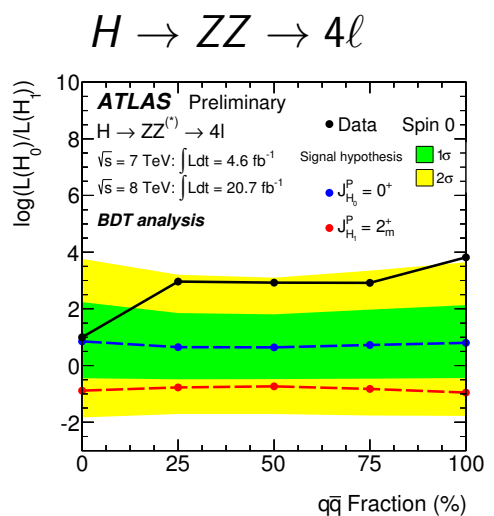
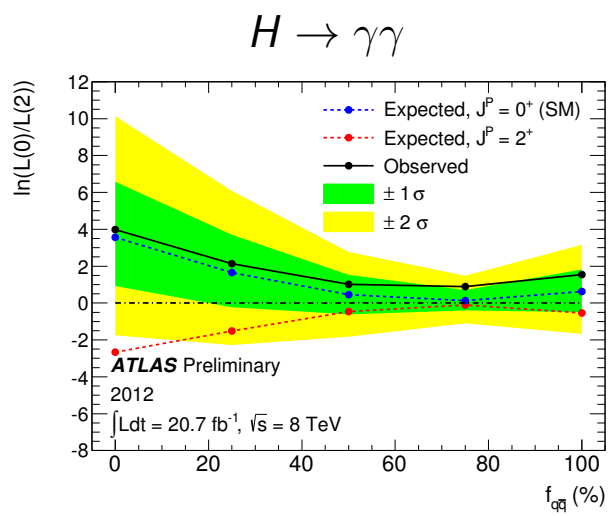
- 2 masse invarianti  $m_{12}$ ,  $m_{34}$  e 5 angoli  $\theta^*$ ,  $\Phi_1$ ,  $\Phi$ ,  $\theta_{1,2}$
- Casi  $J^P = 0^\pm$ : isotropo in  $\cos \theta^*$ ,  $\Phi_1$ ;  $\Phi$ ,  $\theta_{1,2}$  sensibili alla parità
- Casi  $J^P = 1^\pm, 2_m^\pm$ : tutte le variabili sono discriminanti
- $\Rightarrow$  analisi multivariata



(si assume 100%  $gg \rightarrow H$ )

# Misure di spin-parità : sommario

## Standard Model Higgs vs $2_m^+$



## Livelli di esclusione per stati $J^P \neq 0^+$

stato $J^P$ (100% $gg \rightarrow H$ )	livello di esclusione ( $CL_S$ )		
	$H \rightarrow \gamma\gamma$	$H \rightarrow 4\ell$	$H \rightarrow e\nu\mu\nu$
$0^-$	—	0.022	—
$1^+$	—	0.002	—
$1^-$	—	0.060	—
$2^+$	0.007	0.168	0.011
$2^-$	—	0.258	—

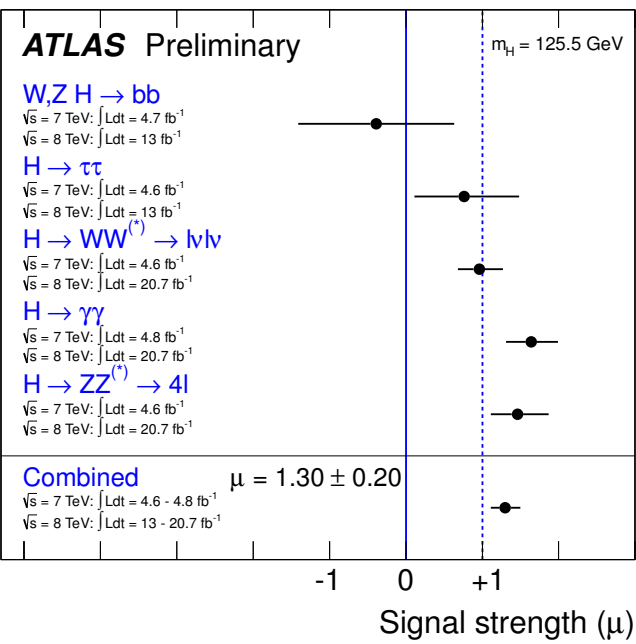
$J^P \equiv 2_m^+$ $f_{q\bar{q}}$	livello di esclusione ( $CL_S$ )		
	$H \rightarrow \gamma\gamma$	$H \rightarrow 4\ell$	$H \rightarrow e\nu\mu\nu$
0.00	0.007	—	0.051
0.25	0.054	—	0.026
0.50	0.26	—	0.018
0.75	0.34	—	0.012
1.00	0.12	0.168	0.011

Stati  $0^-$  e  $2_m^+$  sfavoriti al 98% o più  
 stiamo lavorando per la combinazione di questi risultati

# Misure di “signal strength” $\sigma / \sigma_{\text{SM}}$

(ATLAS-CONF-2013-034)

# Signal strength $\sigma/\sigma_{SM}$



canale	$\hat{\mu}$
VH $\rightarrow$ Vbb $\bar{b}$	$-0.4 \pm 1.0$
H $\rightarrow$ $\tau^+\tau^-$	$0.8 \pm 0.7$
H $\rightarrow$ W <sup>+</sup> W <sup>-</sup>	$1.0 \pm 0.3$
H $\rightarrow$ $\gamma\gamma$	$1.6 \pm 0.3$
H $\rightarrow$ ZZ	$1.5 \pm 0.4$

Massa di riferimento:

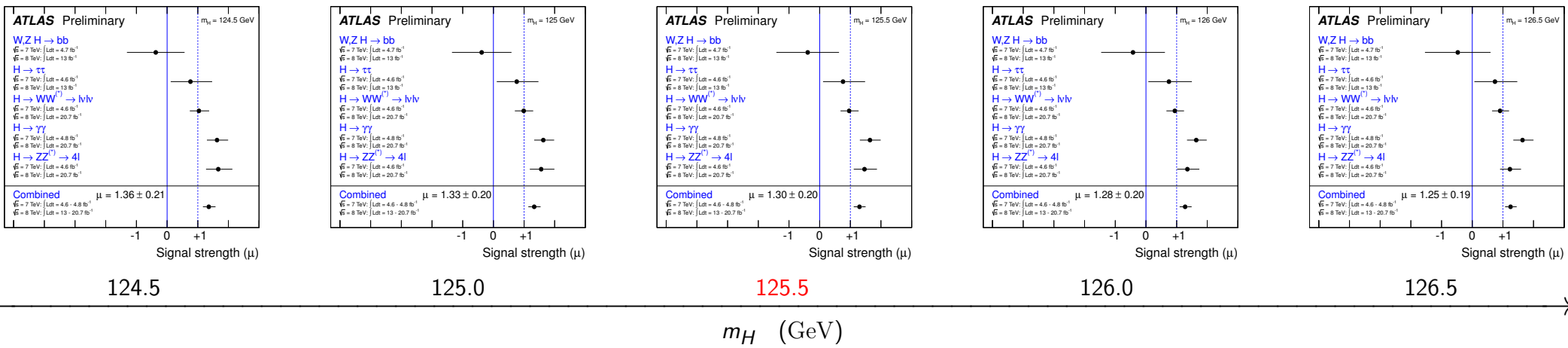
$m_H = 125.5 \text{ GeV}$

$\Rightarrow$  compatibilit  al 13% fra i  $\mu$  dei singoli canali

$\hat{\mu} = 1.30 \pm 0.13(\text{stat}) \pm 0.14(\text{syst})$

$\Rightarrow$  compatibilit  al 9% con il Modello Standard

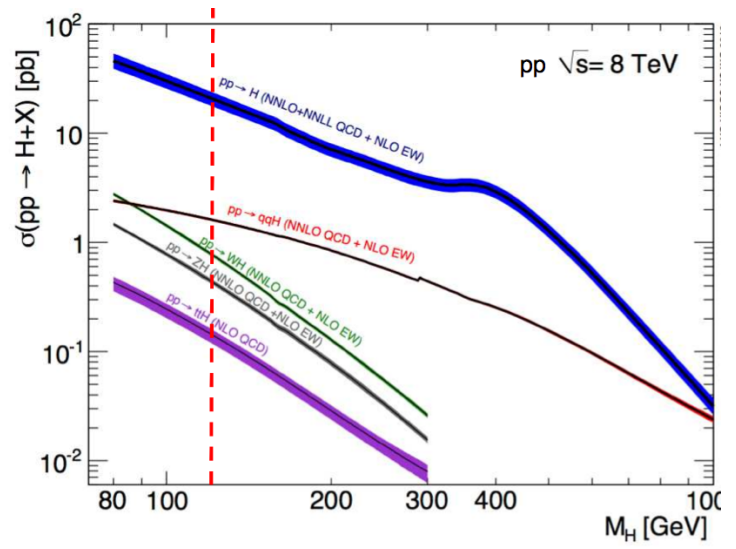
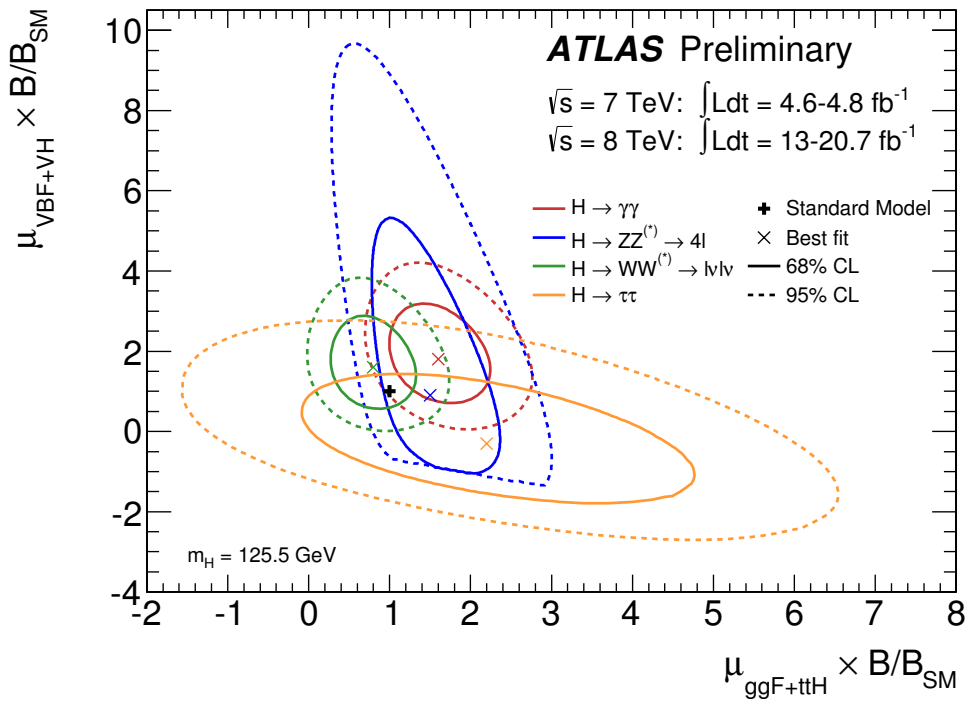
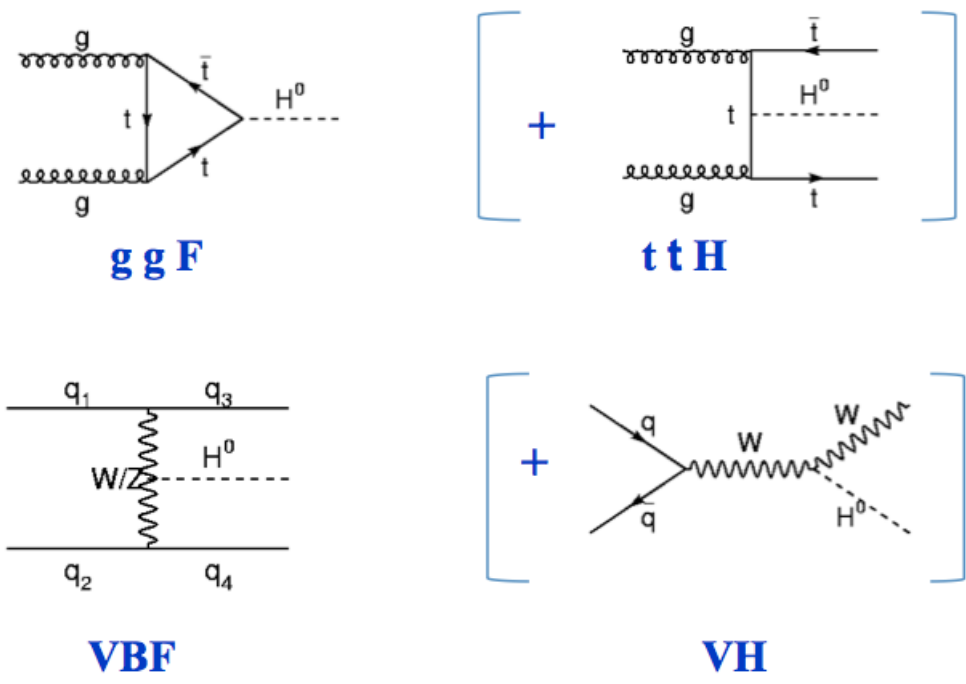
Debole dipendenza dal valore ipotizzato di  $m_H$ :



# Meccanismi di produzione

Si definiscono due “signal strengths” relative ai diversi meccanismi di produzione:

- mediati da coupling con fermioni (specialmente vertice  $ttH$ ):  $\mu_{ggF+ttH}$
- mediati da coupling con bosoni di gauge ( $WWH$  e  $ZZH$ ):  $\mu_{VBF+VH}$





# Meccanismi di produzione

Per eliminare la dipendenza dalle BR si usano i rapporti  $\mu_{VBF+VH} / \mu_{ggF+ttH}$  come parametro di interesse per ciascun canale di decadimento

La combinazione (assumendo solo che la stessa risonanza sia responsabile di tutti i processi) dà:

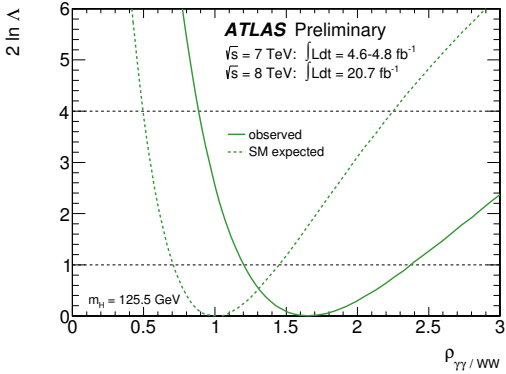
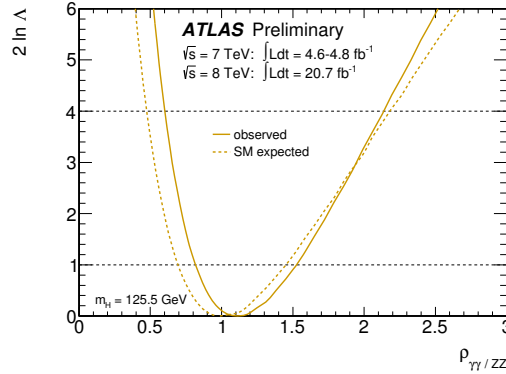
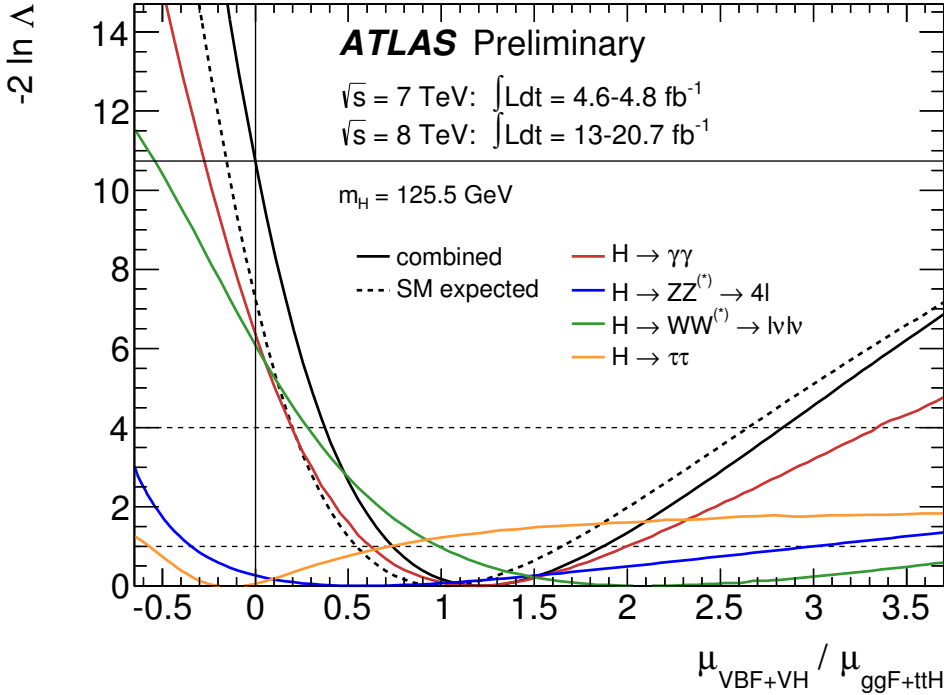
$$\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} = 1.2^{+0.7}_{-0.5}$$

(evidenza di esistenza di VBF a  $3.1 \sigma$ )

Oppure si eliminano le sezioni d'urto di produzione confrontando le branching ratios:

$$\rho_{XX/YY} \stackrel{\text{def}}{=} \frac{BR(H \rightarrow XX)}{BR(H \rightarrow YY)} / \left[ \frac{BR(H \rightarrow XX)}{BR(H \rightarrow YY)} \right]_{SM}$$

$$\rho_{\gamma\gamma/ZZ} = 1.1^{+0.4}_{-0.3} ; \rho_{\gamma\gamma/WW} = 1.7^{+0.7}_{-0.5} ; \rho_{ZZ/WW} = 1.6^{+0.8}_{-0.5}$$



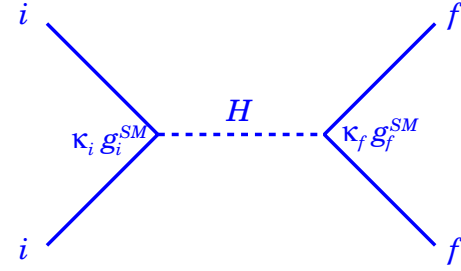
# Misure dei “couplings”

(ATLAS-CONF-2013-034)

# Couplings efficaci

Modello tree-level di un processo  $ii \rightarrow H \rightarrow ff$  con couplings efficaci:

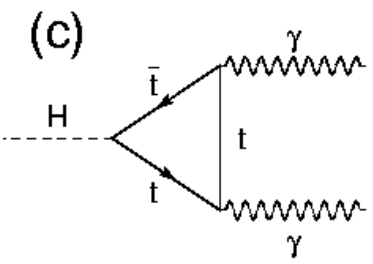
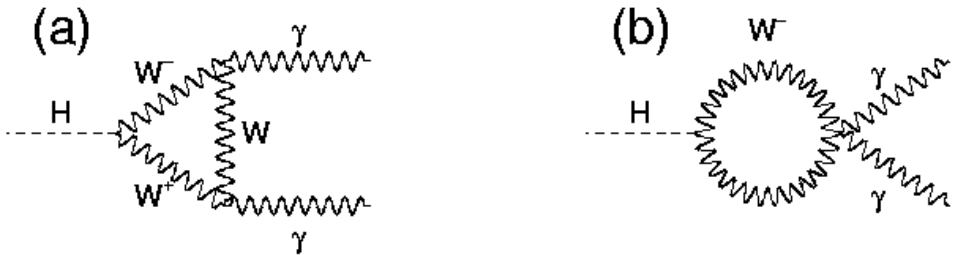
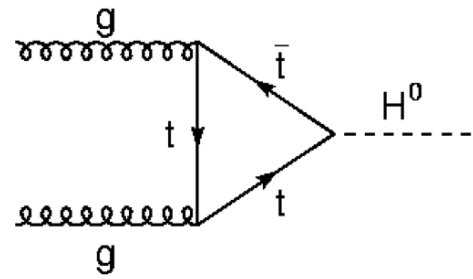
$$\sigma(ii \rightarrow H) \times BR(H \rightarrow ff) = \frac{\sigma_{ii} \Gamma_{ff}}{\Gamma_H} = \left[ \sigma(ii \rightarrow H) \times BR(H \rightarrow ff) \right]_{SM} \times \left[ \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2} \right]$$



i  $\kappa_X$  sono fattori di scala rispetto ai couplings del Modello Standard  $g_X^{SM}$   
il loro segno non è definito...

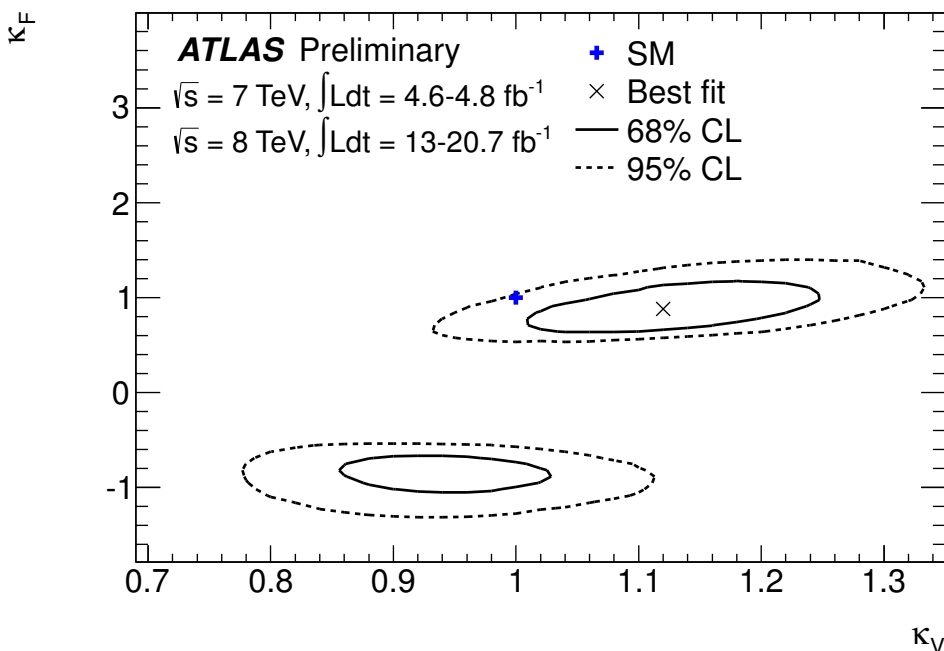
## Alcune assunzioni

- universalità dei fattori di scala  $\kappa$ :  
fermionici :  $\kappa_t = \kappa_b = \kappa_\tau = \kappa_F$   
e bosonici (di gauge) :  $\kappa_W = \kappa_Z = \kappa_V$
- gg-fusion  $gg \rightarrow H$  mediata da un loop di top  
 $\Rightarrow \kappa_g = \kappa_F$
- decadimento  $H \rightarrow \gamma\gamma$  mediato da loop di top e W  
 $\Rightarrow \kappa_\gamma^2 = (1.26 \cdot \kappa_V - 0.26 \cdot \kappa_F)^2$   
(sensibilità al segno relativo fra  $\kappa_F, \kappa_V$ )
- nel Modello Standard  $BR(H \rightarrow f\bar{f}, gg) = 0.75$  e  
 $BR(H \rightarrow ZZ, W^+W^-, \gamma\gamma) = 0.25$   
 $\Rightarrow \kappa_H^2 = 0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2$



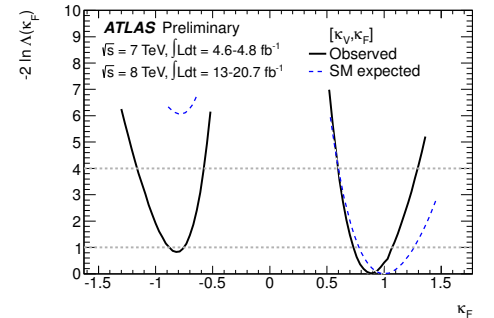
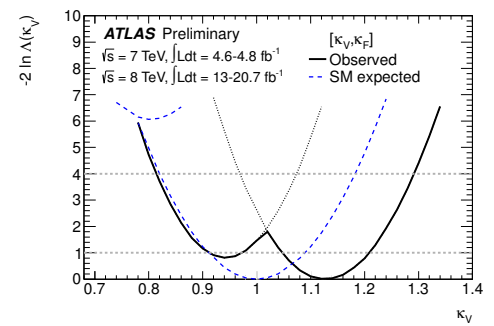
# Couplings efficaci : fermioni vs bosoni di gauge

Assumendo  $gg \rightarrow H$  e  $H \rightarrow \gamma\gamma$  descritti solo da loops Standard Model

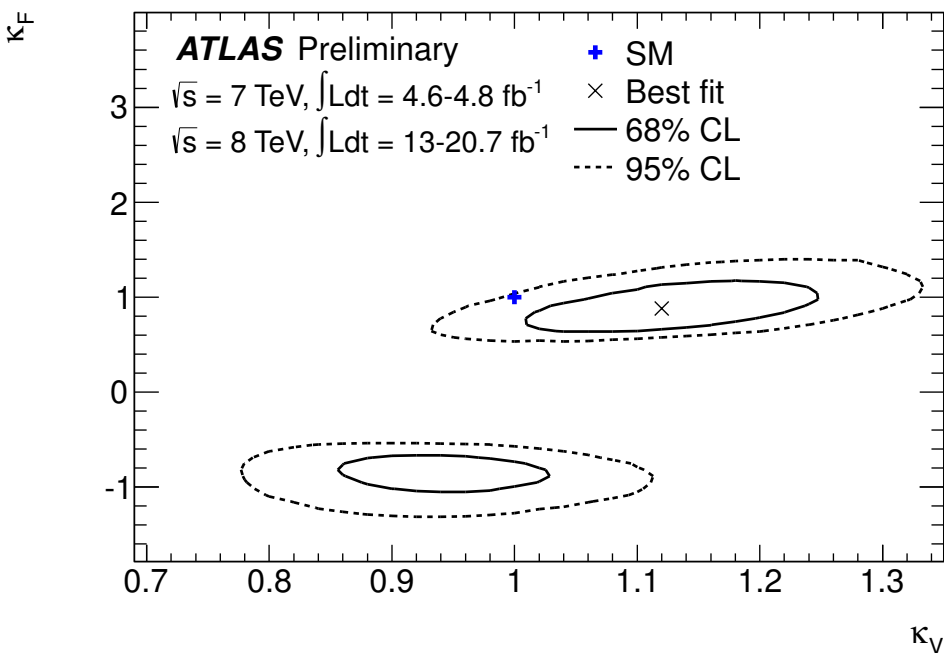
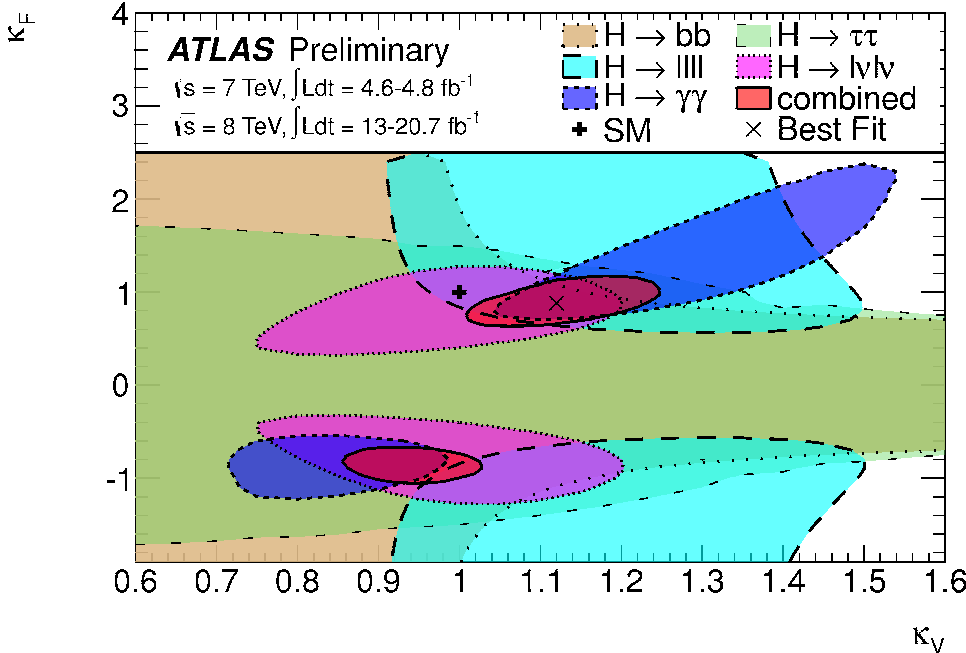


Due minimi:  
 minimo assoluto ha  $\kappa_V, \kappa_F$   
 concordi

Compatibilità 2-D con il  
 Modello Standard: 8%

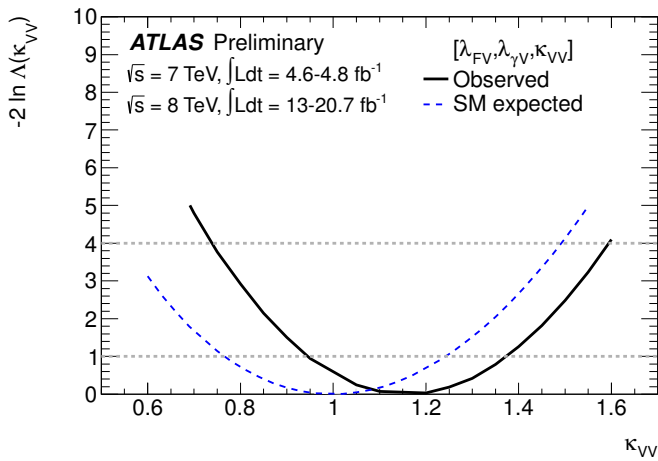
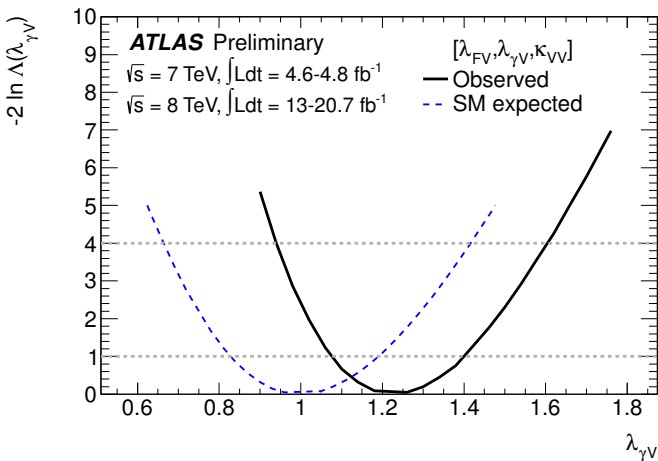
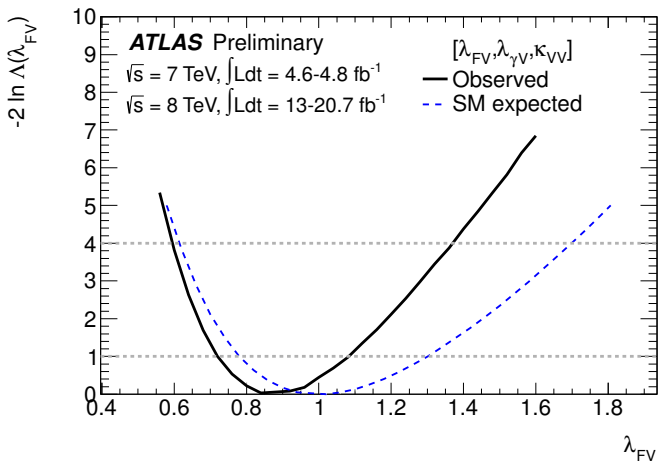


# Couplings efficaci : $\kappa_V$ vs $\kappa_F$ nei diversi canali



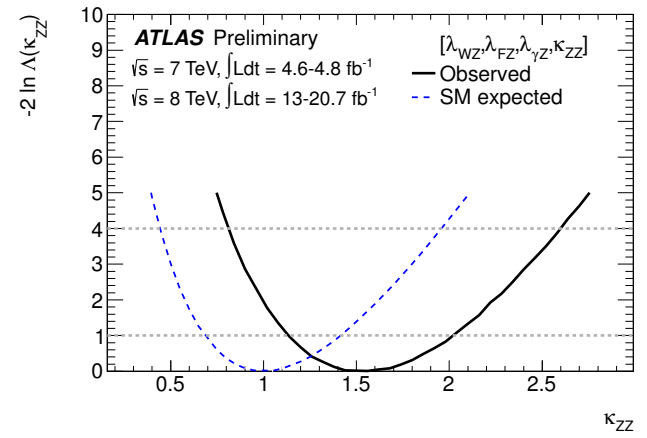
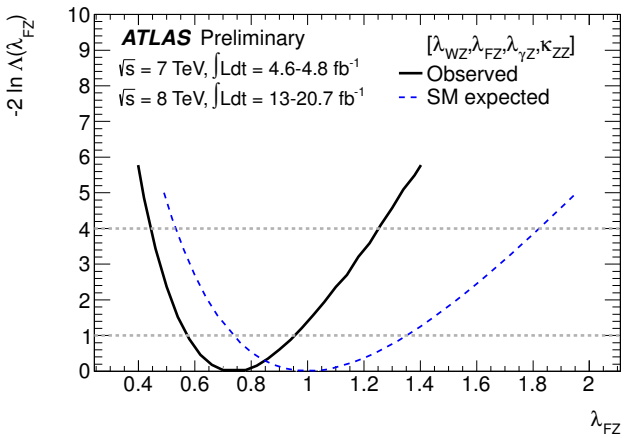
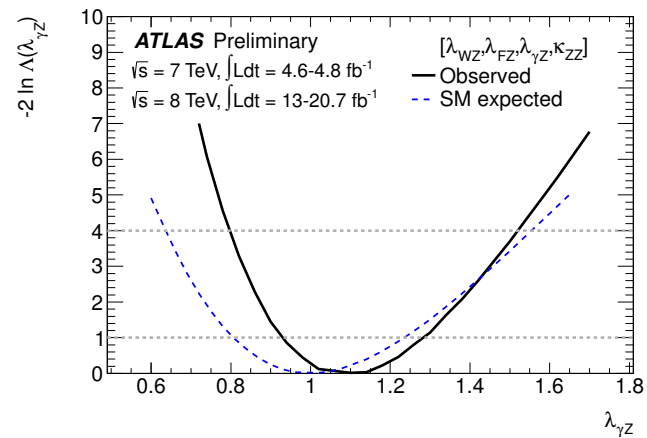
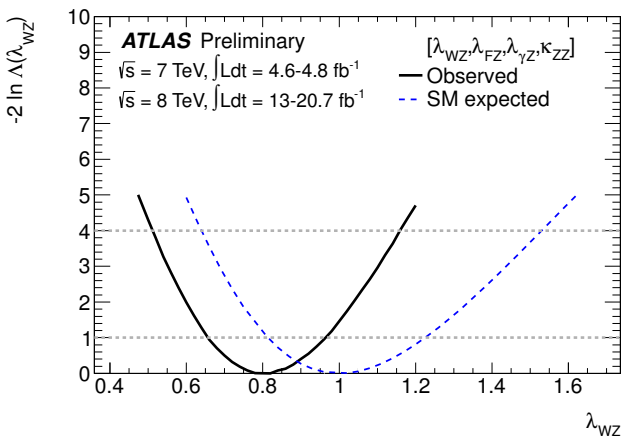
# Couplings efficaci : rilassando ipotesi su $\kappa_\gamma, \kappa_H$

Lasciando  $\kappa_\gamma, \kappa_H$  indipendenti:



$$\lambda_{FV} \stackrel{\text{def}}{=} \kappa_F / \kappa_V = 0.85^{+0.23}_{-0.13} ; \lambda_{\gamma V} \stackrel{\text{def}}{=} \kappa_\gamma / \kappa_V = 1.22^{+0.18}_{-0.14} ; \kappa_{VV} \stackrel{\text{def}}{=} \kappa_V^2 / \kappa_H = 1.15 \pm 0.21$$

# Couplings efficaci : rilassando ipotesi su $\kappa_Z, \kappa_W$



Test della “simmetria custodiale”  
lasciando indipendenti  $\kappa_Z, \kappa_W$ :

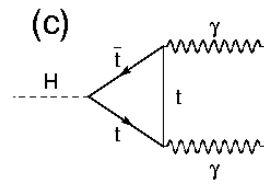
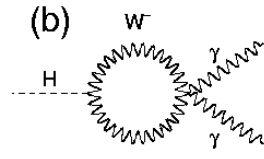
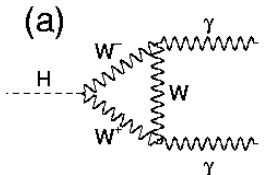
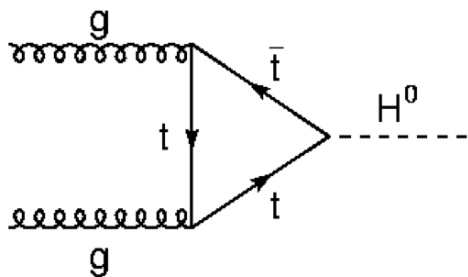
$$\lambda_{WZ} \stackrel{\text{def}}{=} \kappa_W / \kappa_Z = 0.80 \pm 0.15$$

$$\lambda_{\gamma Z} \stackrel{\text{def}}{=} \kappa_\gamma / \kappa_Z = 1.10 \pm 0.18$$

$$\lambda_{FZ} \stackrel{\text{def}}{=} \kappa_F / \kappa_Z = 0.74^{+0.21}_{-0.17}$$

$$\kappa_{ZZ} \stackrel{\text{def}}{=} \kappa_Z^2 / \kappa_H = 1.5^{+0.5}_{-0.4}$$

# Couplings efficaci : interazioni $ggH$ e $H\gamma\gamma$

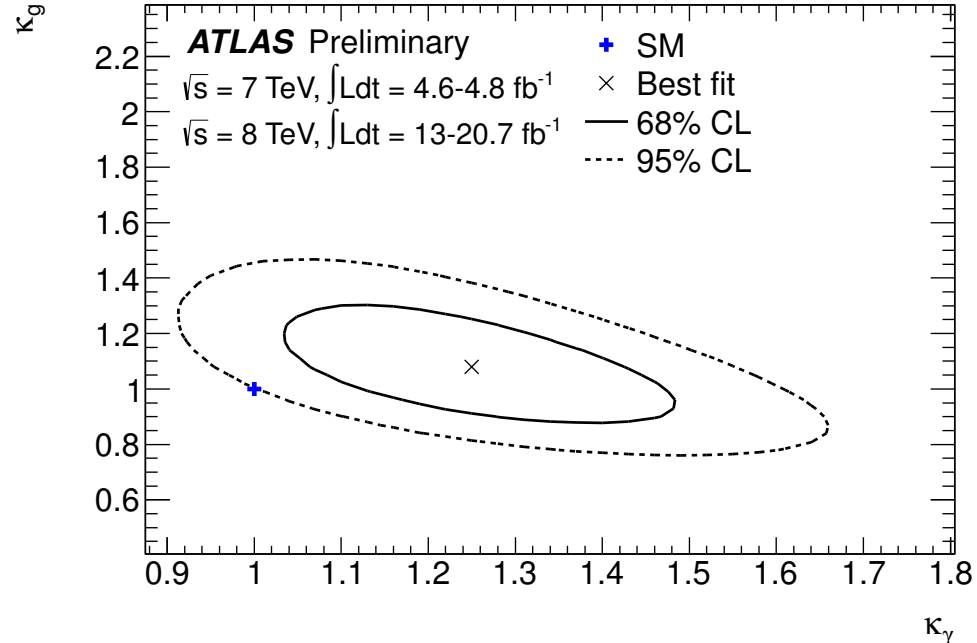


Le interazioni  $ggH$  e  $H\gamma\gamma$  sono mediate da loops  
 $\Rightarrow$  particolarmente sensibili a nuova fisica oltre il Modello Standard

Ipotesi: tutti i  $\kappa$  sono = 1 tranne  $\kappa_\gamma$  e  $\kappa_g$  che sono liberi

$$\kappa_g = 1.08 \pm 0.14 \quad ; \quad \kappa_\gamma = 1.23^{+0.16}_{-0.13}$$

Compatibilità 2-D con il Modello Standard: 5%





# Sommario

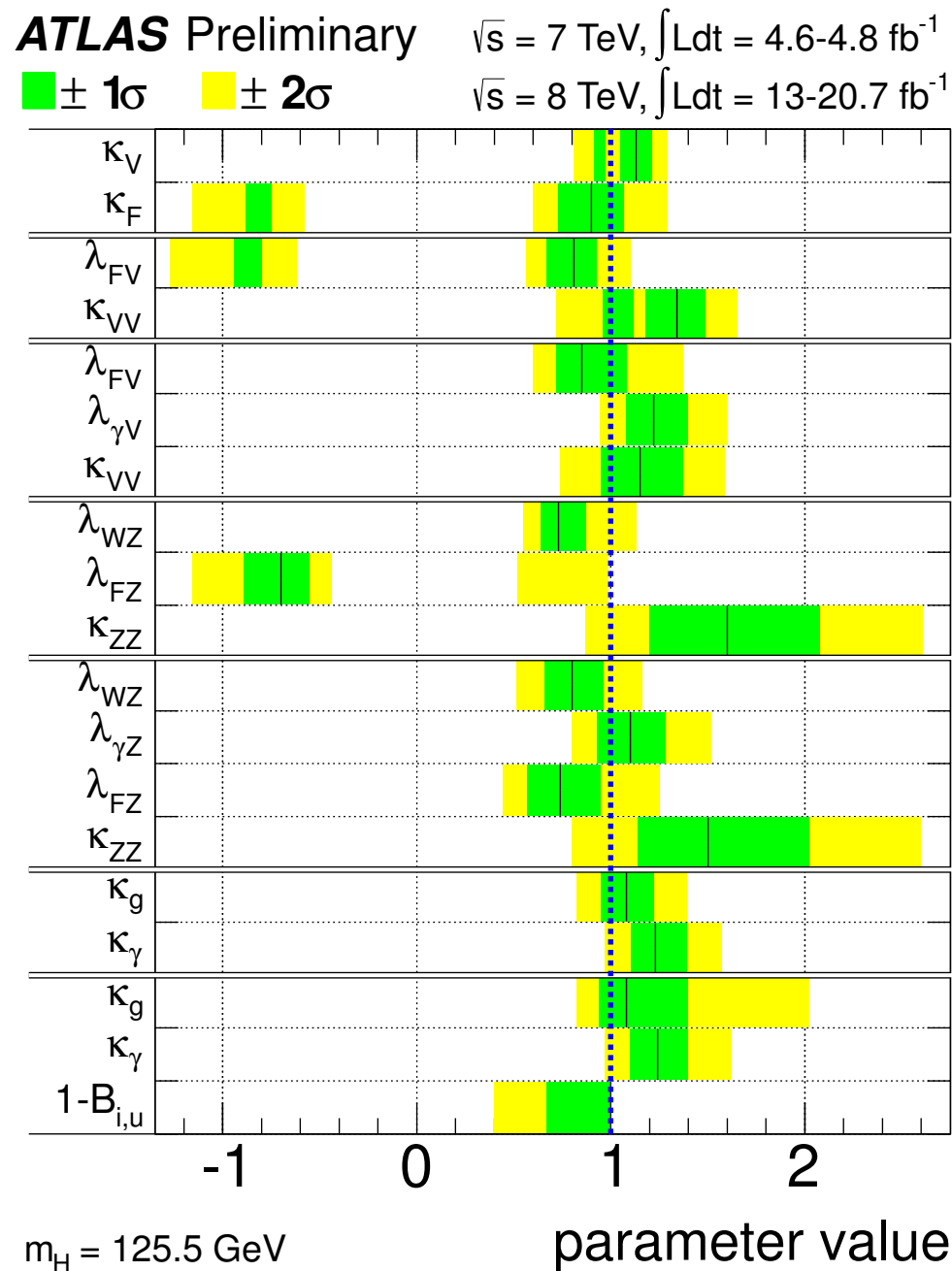
La “nuova particella” ha massa

$$m_H = 125.5 \pm 0.2(stat)_{-0.6}^{+0.5}(syst) \text{ GeV}$$

La risonanza è compatibile con uno stato  $J^P = 0^+$ ,  
 stati  $0^-$  e  $2_m^+$  sono sfavoriti al 98% o più

Le misure di couplings sono compatibili con il Modello Standard a livelli 5%–10%.

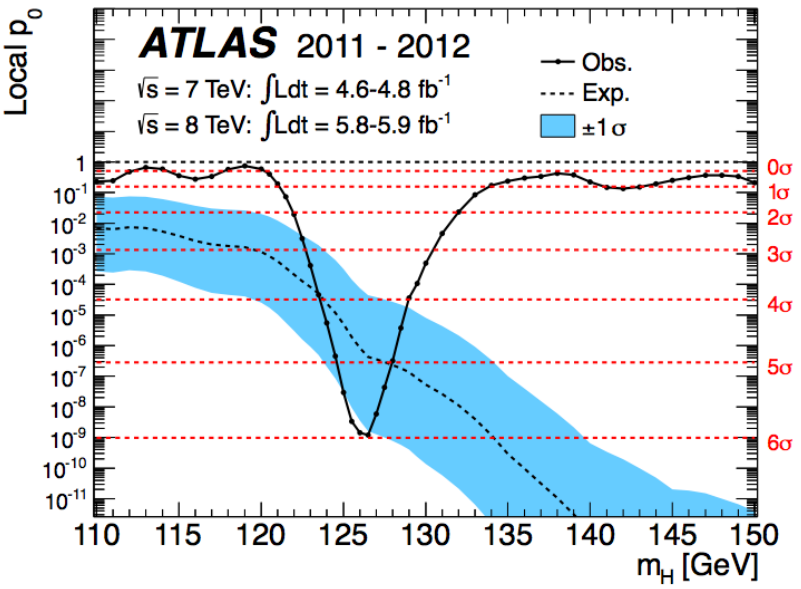
In nessuno dei test sono state osservate deviazioni significative dal Modello Standard



# 4 luglio 2012 : la scoperta

Nella ricerca del bosone di Higgs, ATLAS e CMS riportano evidenza di una **nuova risonanza**, che decade sia in due fotoni ( $H \rightarrow \gamma\gamma$ ) sia in 4 leptoni tramite produzione di coppie di Z ( $H \rightarrow ZZ \rightarrow 4\ell$ )

Si osserva anche un eccesso di eventi  $W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$



**“We have a discovery!”**

ATLAS: evidenza a  $6\sigma$   
 la probabilità che l'insieme delle osservazioni sia dovuto a fluttuazioni statistiche dei background è valutata  $p_0 \approx 10^{-9}$

[Phys. Lett. B 716 (2012) 1-29]

## “New results indicate that particle discovered at CERN is a Higgs boson”

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

Whether or not it is a Higgs boson is demonstrated by how it interacts with other particles, and its quantum properties. For example, a Higgs boson is postulated to have no spin, and in the Standard Model its parity — a measure of how its mirror image behaves — should be positive. CMS and ATLAS have compared a number of options for the spin-parity of this particle, and these all prefer no spin and positive parity. This, coupled with the measured interactions of the new particle with other particles, strongly indicates that it is a Higgs boson.

“The preliminary results with the full 2012 data set are magnificent and to me it is clear that we are dealing with a Higgs boson though we still have a long way to go to know what kind of Higgs boson it is” said CMS spokesperson Joe Incandela.

“The beautiful new results represent a huge effort by many dedicated people. They point to the new particle having the spin-parity of a Higgs boson as in the Standard Model. We are now well started on the measurement programme in the Higgs sector” said ATLAS spokesperson Dave Charlton.

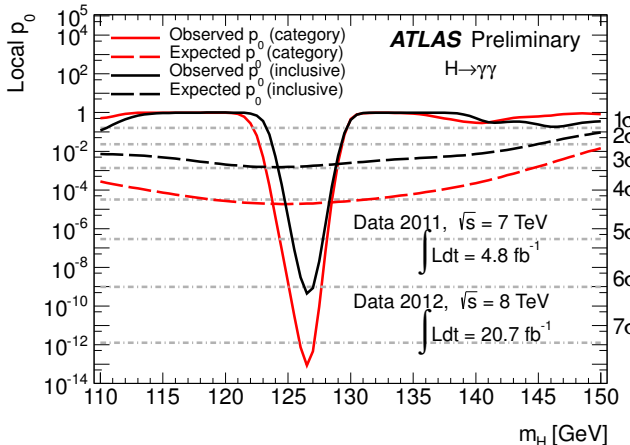
To determine if this is the Standard Model Higgs boson, the collaborations have, for example, to measure precisely the rate at which the boson decays into other particles and compare the results to the predictions. The detection of the boson is a very rare event — it takes around 1 trillion (10<sup>12</sup>) proton-proton collisions for each observed event. To characterize all of the decay modes will require much more data from the LHC.

# MATERIALE EXTRA

# Osservazioni del bosone di Higgs a fine run-1

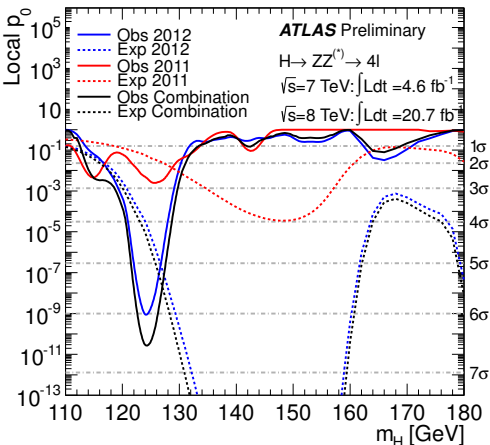
A dicembre 2012 è finito il run-1 di LHC

Luminosità integrata raccolta ad ATLAS:  $\int L dt = 4.6 \text{ fb}^{-1}$  a  $\sqrt{s} = 7 \text{ TeV}$  ;  $\int L dt = 20.7 \text{ fb}^{-1}$  a  $\sqrt{s} = 8 \text{ TeV}$



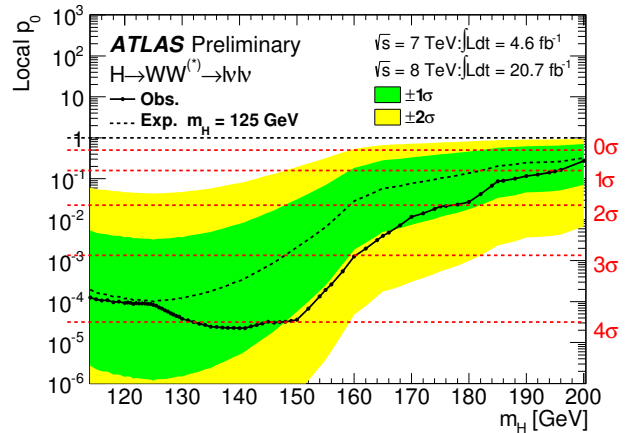
$H \rightarrow \gamma\gamma$

(ATLAS-CONF-2013-012)



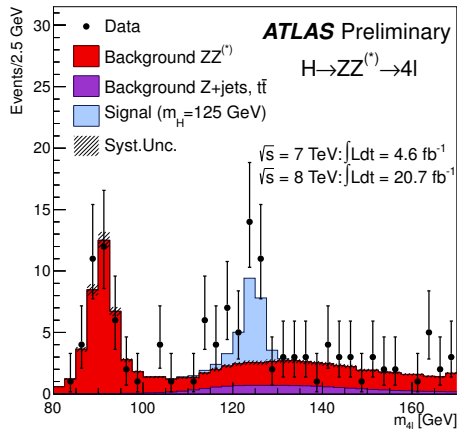
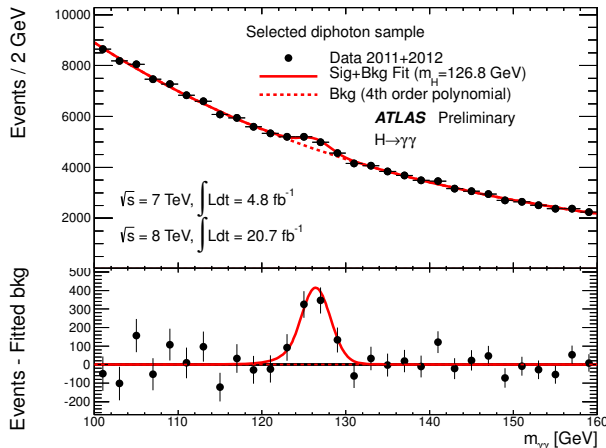
$H \rightarrow ZZ \rightarrow 4\ell$

(ATLAS-CONF-2013-013)



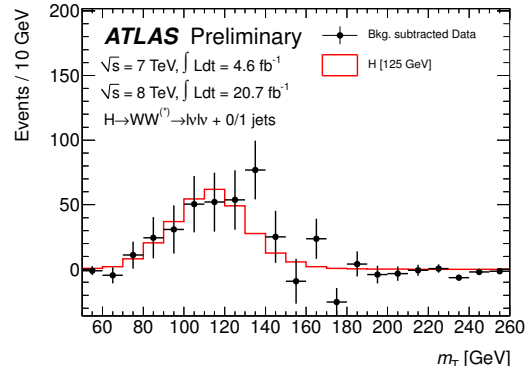
$H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$

(ATLAS-CONF-2013-030)



$$m_T = \sqrt{(E_T^{\ell\ell} + \cancel{E}_T)^2 - (\vec{p}_T^{\ell\ell} + \vec{\cancel{P}}_T)^2}$$

(background sottratto)



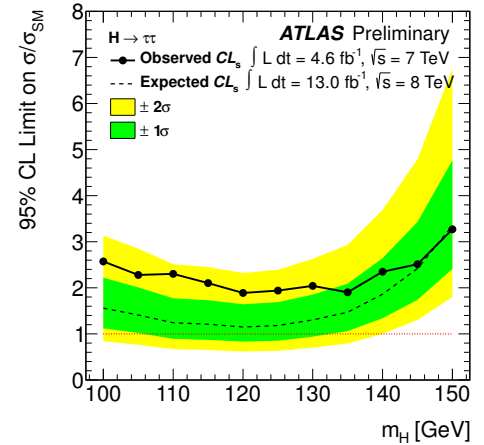
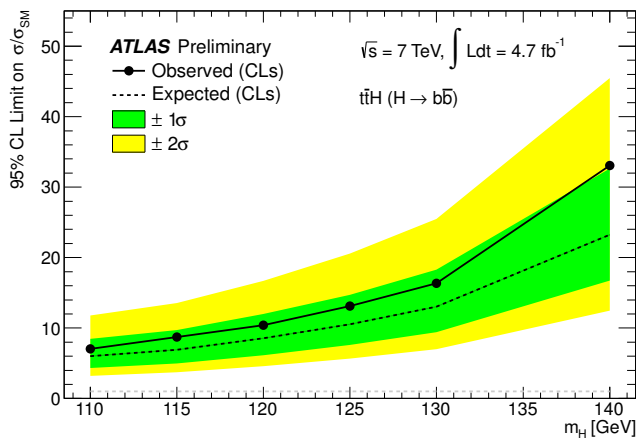
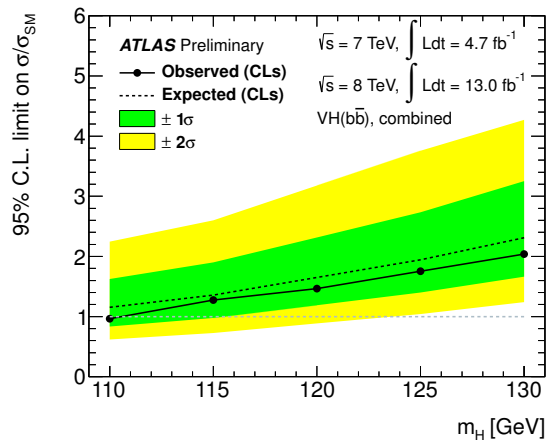
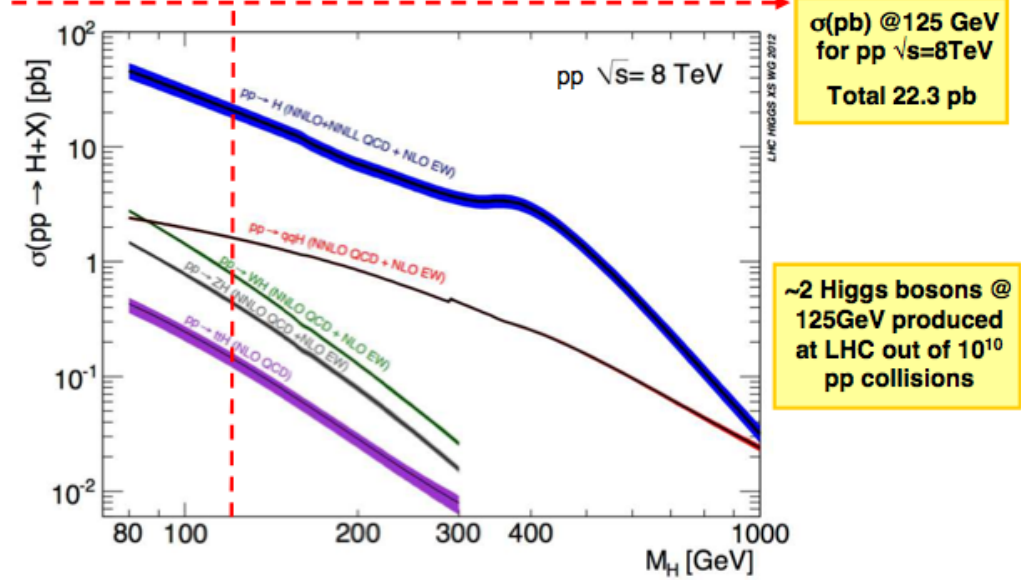
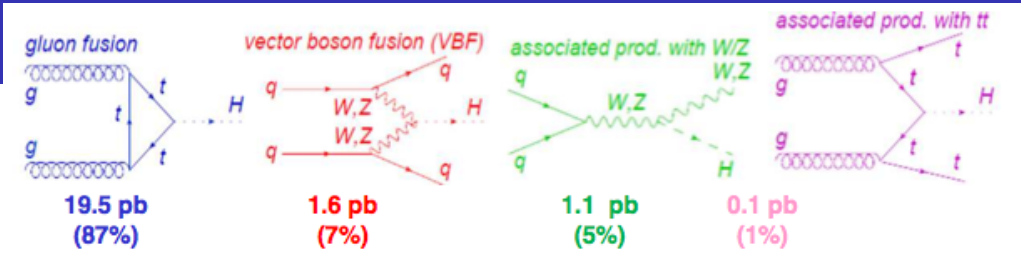
I canali  $H \rightarrow \gamma\gamma$  e  $H \rightarrow ZZ \rightarrow 4\ell$  consentono una precisa misura di massa  $\Rightarrow m_H \approx 125 \text{ GeV}$

# Decadimenti in fermioni

Decadimenti accessibili:  $H \rightarrow b\bar{b}$  e  $H \rightarrow \tau^+\tau^-$   
 ... ma selezioni più difficili ( $b$ -tag,  $\tau$ -ID,  $\cancel{E}_T$ )  
 ... e fondo QCD più elevato

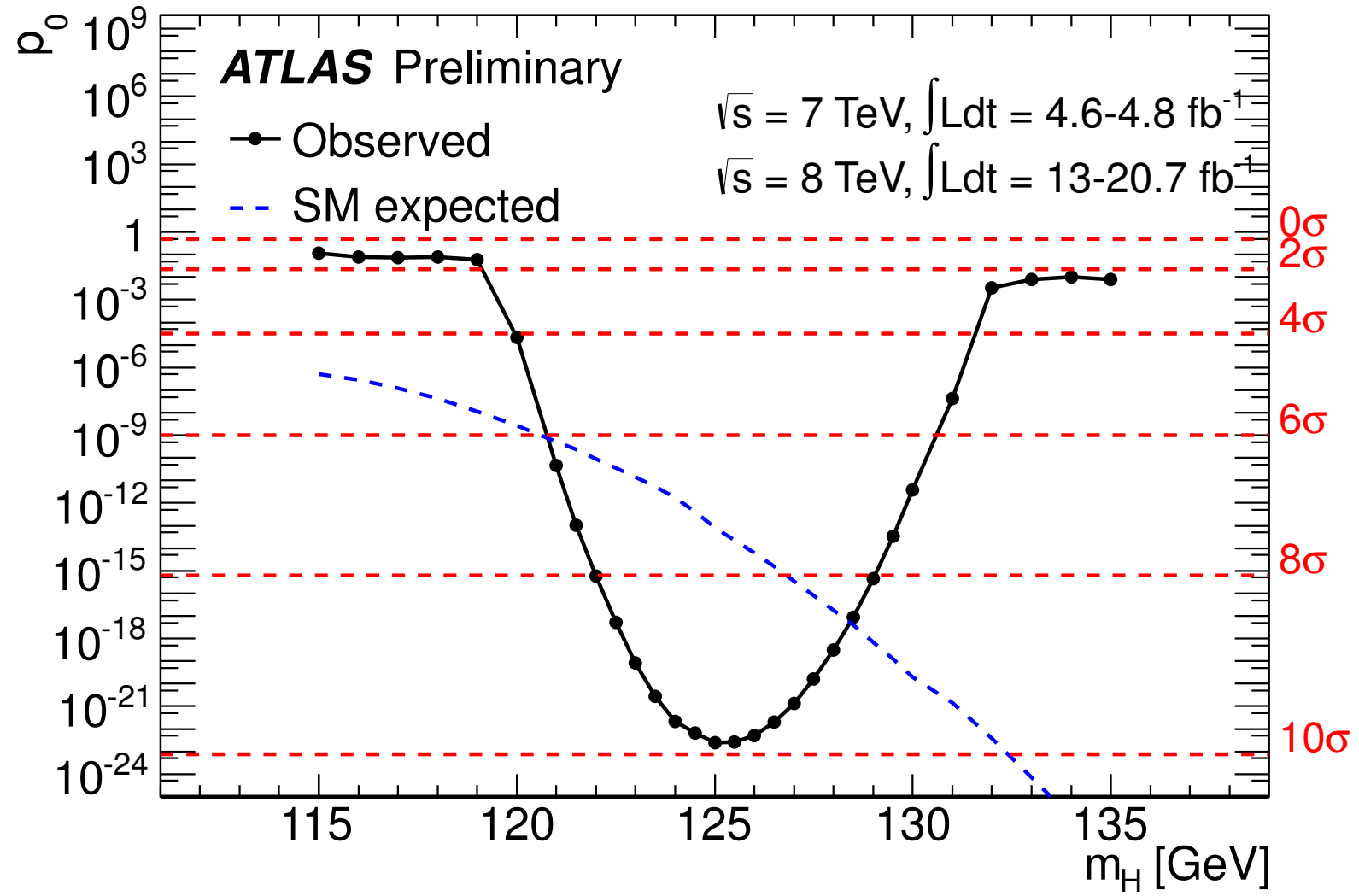
⇒ si fa uso di topologie più esclusive, usando meccanismi di produzione VBF o associati

Ad oggi nessuna evidenza di segnale, risultati espressi finora come limiti superiori su  $\sigma/\sigma_{SM}$   
 ... ma comunque utili in analisi combinate, per indagare i couplings della nuova particella



( ATLAS-CONF-2012-161 , ATLAS-CONF-2012-135 , ATLAS-CONF-2012-160 )

# Evidenza del bosone di Higgs

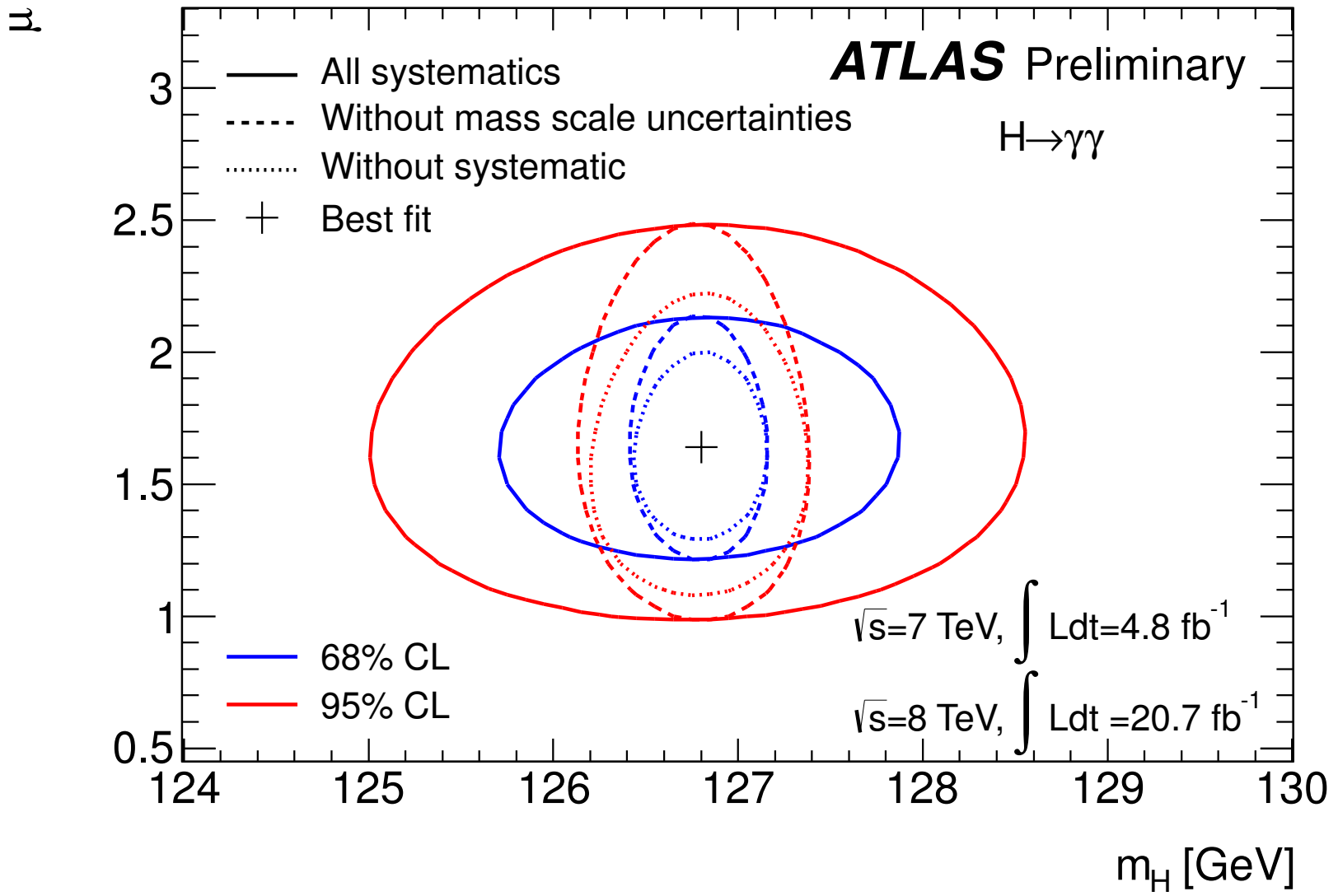




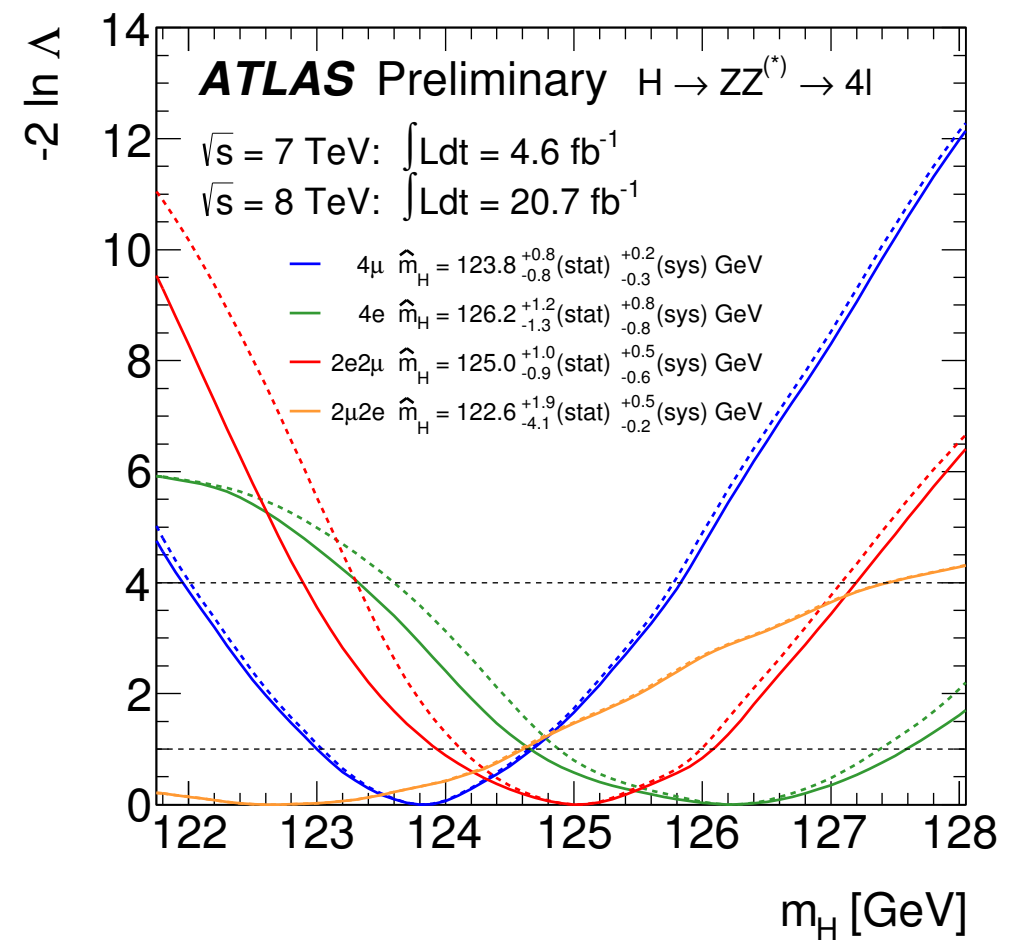
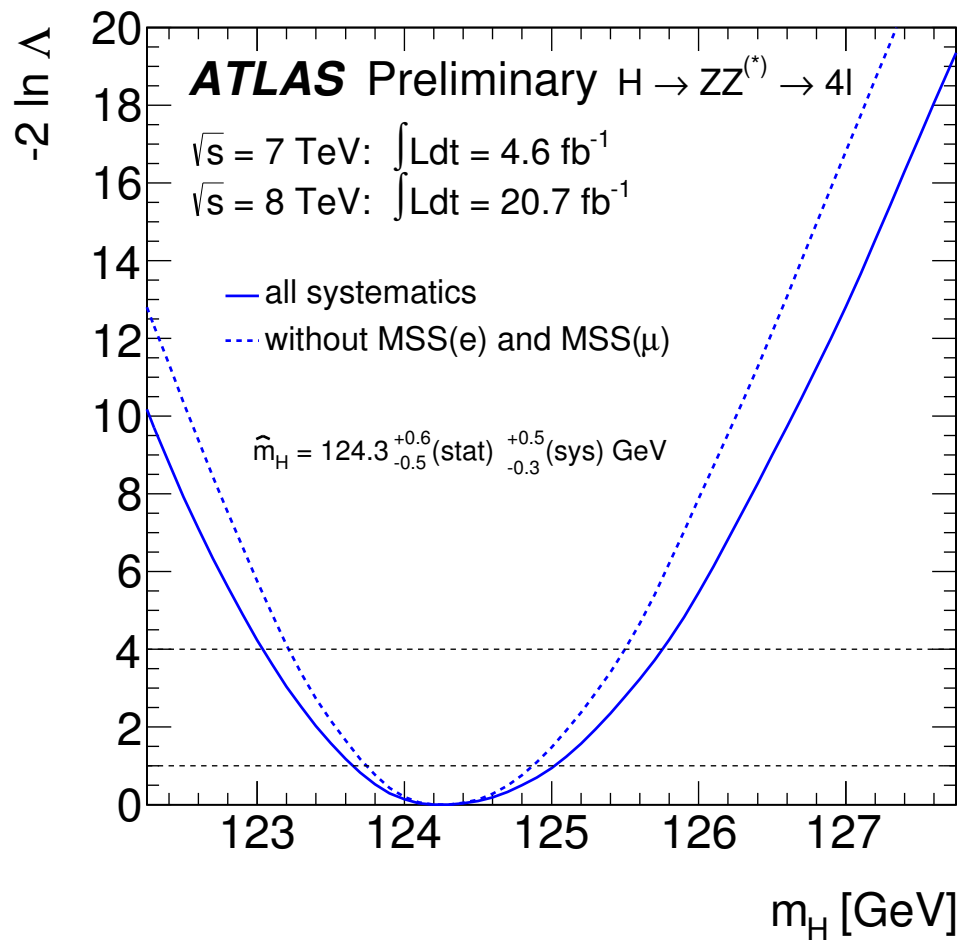
# Tutte le categorie

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L dt$ [fb <sup>-1</sup> ]
2011 $\sqrt{s} = 7$ TeV			
$H \rightarrow ZZ^{(*)}$	$4\ell$	$\{4e, 2e2\mu, 2\mu2e, 4\mu, 2\text{-jet VBF}, \ell\text{-tag}\}$	4.6
$H \rightarrow \gamma\gamma$	–	10 categories $\{p_{Tl} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{2\text{-jet VBF}\}$	4.8
$H \rightarrow WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{0\text{-jet}, 1\text{-jet}, 2\text{-jet VBF}\}$	4.6
$H \rightarrow \tau\tau$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\{e\mu\} \otimes \{0\text{-jet}\} \oplus \{\ell\ell\} \otimes \{1\text{-jet}, 2\text{-jet}, p_{T,\tau\tau} > 100 \text{ GeV}, VH\}$	4.6
	$\tau_{\text{lep}}\tau_{\text{had}}$	$\{e, \mu\} \otimes \{0\text{-jet}, 1\text{-jet}, p_{T,\tau\tau} > 100 \text{ GeV}, 2\text{-jet}\}$	4.6
	$\tau_{\text{had}}\tau_{\text{had}}$	$\{1\text{-jet}, 2\text{-jet}\}$	4.6
$VH \rightarrow Vbb$	$Z \rightarrow \nu\nu$	$E_T^{\text{miss}} \in \{120 - 160, 160 - 200, \geq 200 \text{ GeV}\} \otimes \{2\text{-jet}, 3\text{-jet}\}$	4.6
	$W \rightarrow \ell\nu$	$p_T^W \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	4.7
	$Z \rightarrow \ell\ell$	$p_T^Z \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	4.7
2012 $\sqrt{s} = 8$ TeV			
$H \rightarrow ZZ^{(*)}$	$4\ell$	$\{4e, 2e2\mu, 2\mu2e, 4\mu, 2\text{-jet VBF}, \ell\text{-tag}\}$	20.7
$H \rightarrow \gamma\gamma$	–	14 categories $\{p_{Tl} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{2\text{-jet VBF}\} \oplus \{\ell\text{-tag}, E_T^{\text{miss}}\text{-tag}, 2\text{-jet VH}\}$	20.7
$H \rightarrow WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{0\text{-jet}, 1\text{-jet}, 2\text{-jet VBF}\}$	20.7
$H \rightarrow \tau\tau$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\{\ell\ell\} \otimes \{1\text{-jet}, 2\text{-jet}, p_{T,\tau\tau} > 100 \text{ GeV}, VH\}$	13
	$\tau_{\text{lep}}\tau_{\text{had}}$	$\{e, \mu\} \otimes \{0\text{-jet}, 1\text{-jet}, p_{T,\tau\tau} > 100 \text{ GeV}, 2\text{-jet}\}$	13
	$\tau_{\text{had}}\tau_{\text{had}}$	$\{1\text{-jet}, 2\text{-jet}\}$	13
$VH \rightarrow Vbb$	$Z \rightarrow \nu\nu$	$E_T^{\text{miss}} \in \{120 - 160, 160 - 200, \geq 200 \text{ GeV}\} \otimes \{2\text{-jet}, 3\text{-jet}\}$	13
	$W \rightarrow \ell\nu$	$p_T^W \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	13
	$Z \rightarrow \ell\ell$	$p_T^Z \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	13

# Massa e signal strength da $H \rightarrow \gamma\gamma$

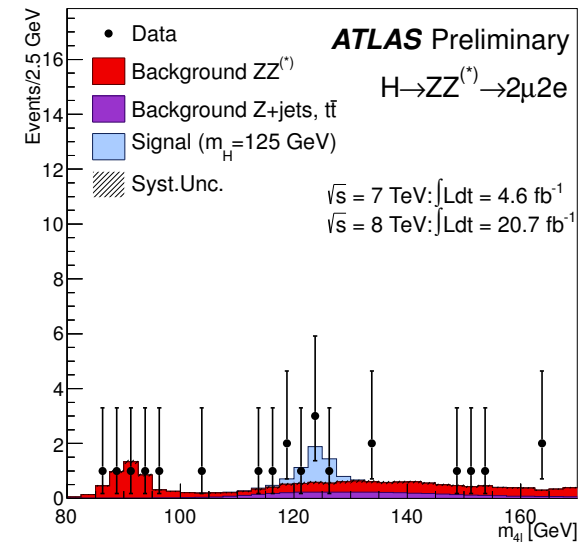
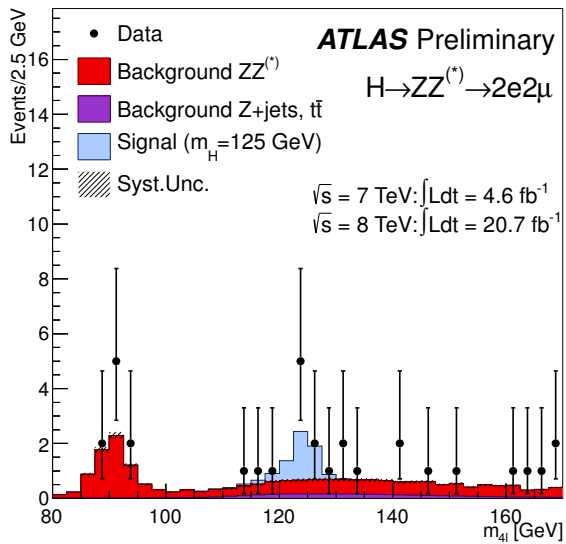
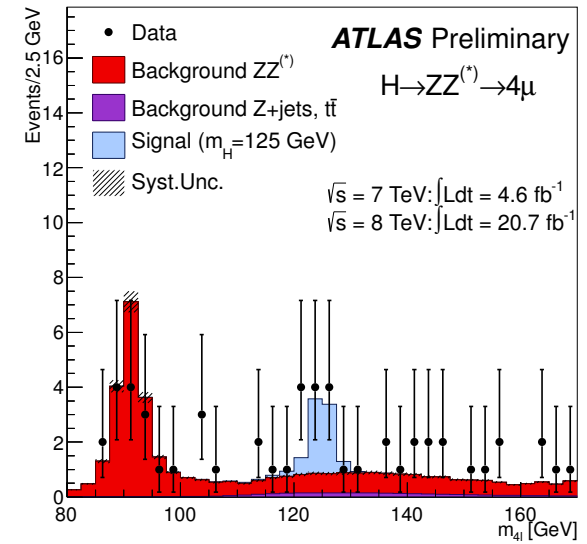
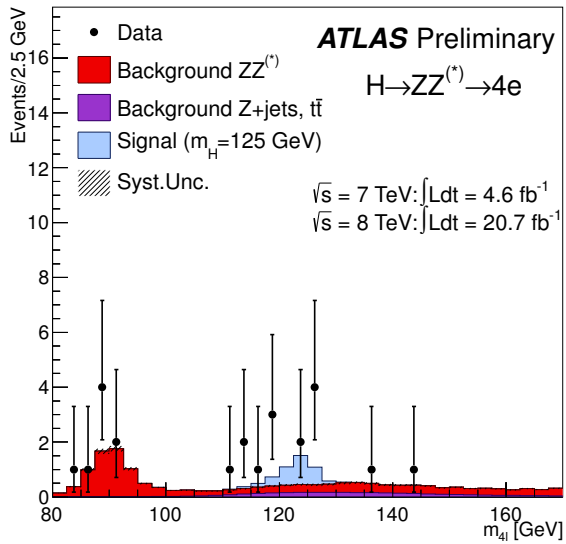


# Massa da $H \rightarrow 4\ell$

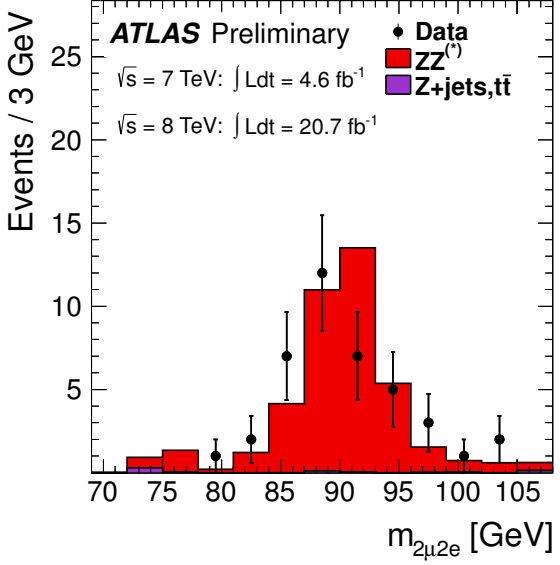
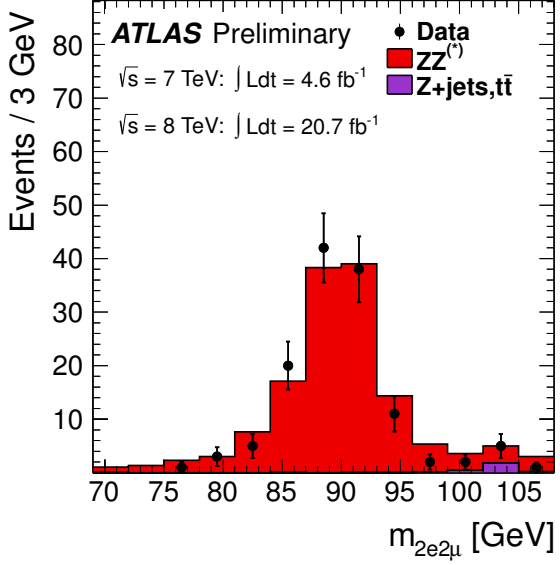
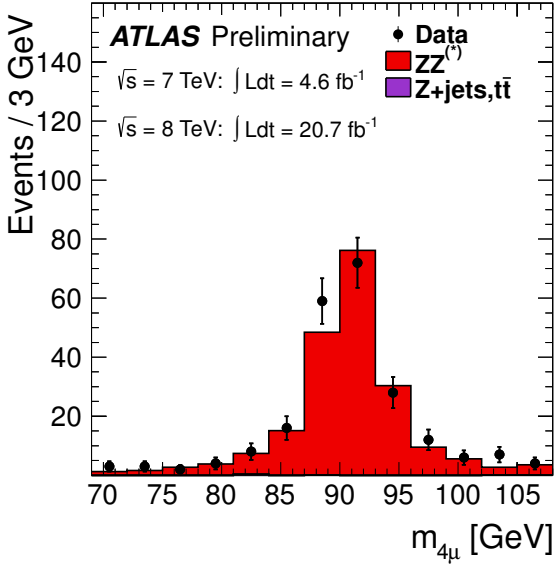
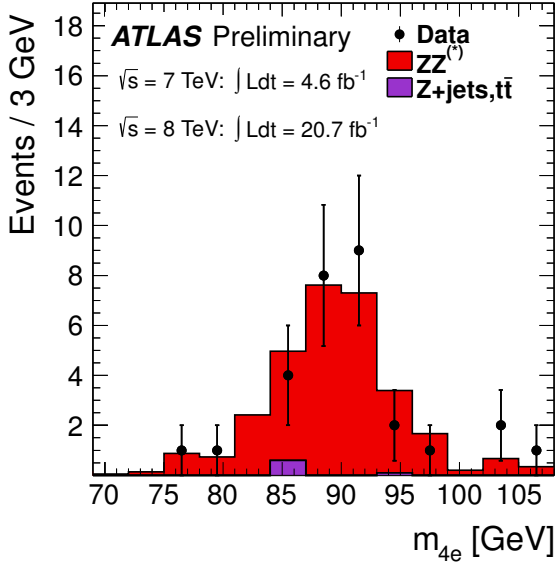


	$4\mu$	$2\mu2e + 2e2\mu$	$4e$
background ( $m_{4\ell} < 160 \text{ GeV}$ )	$16.7 \pm 0.8$	$25.7 \pm 1.9$	$10.8 \pm 0.9$
eventi ( $m_{4\ell} < 160 \text{ GeV}$ )	35	33	15

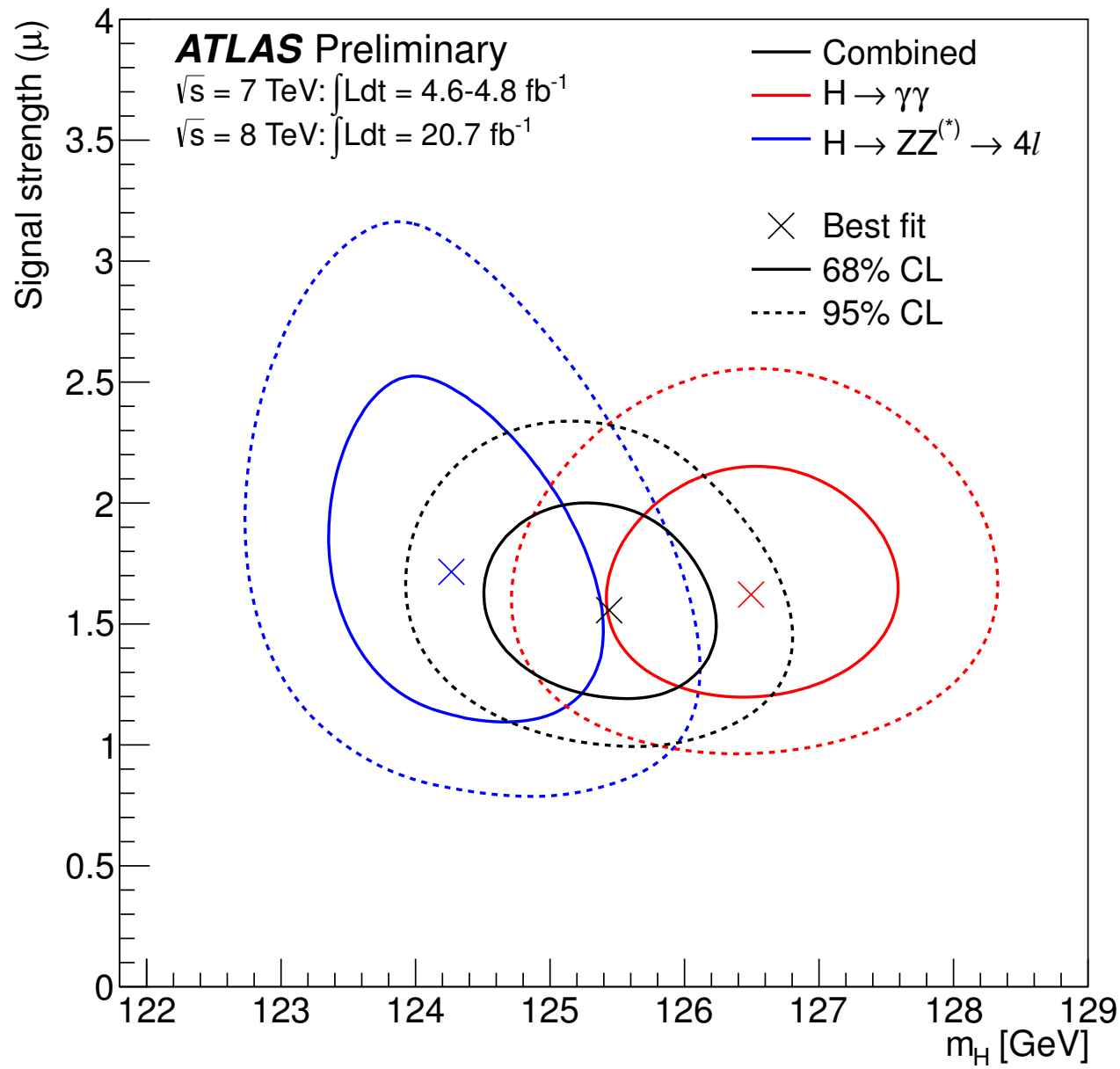
# $m_{4\ell}$ da $Z \rightarrow 4\ell$



# $m_{4\ell}$ da $Z \rightarrow 4\ell$ ("single-resonant")



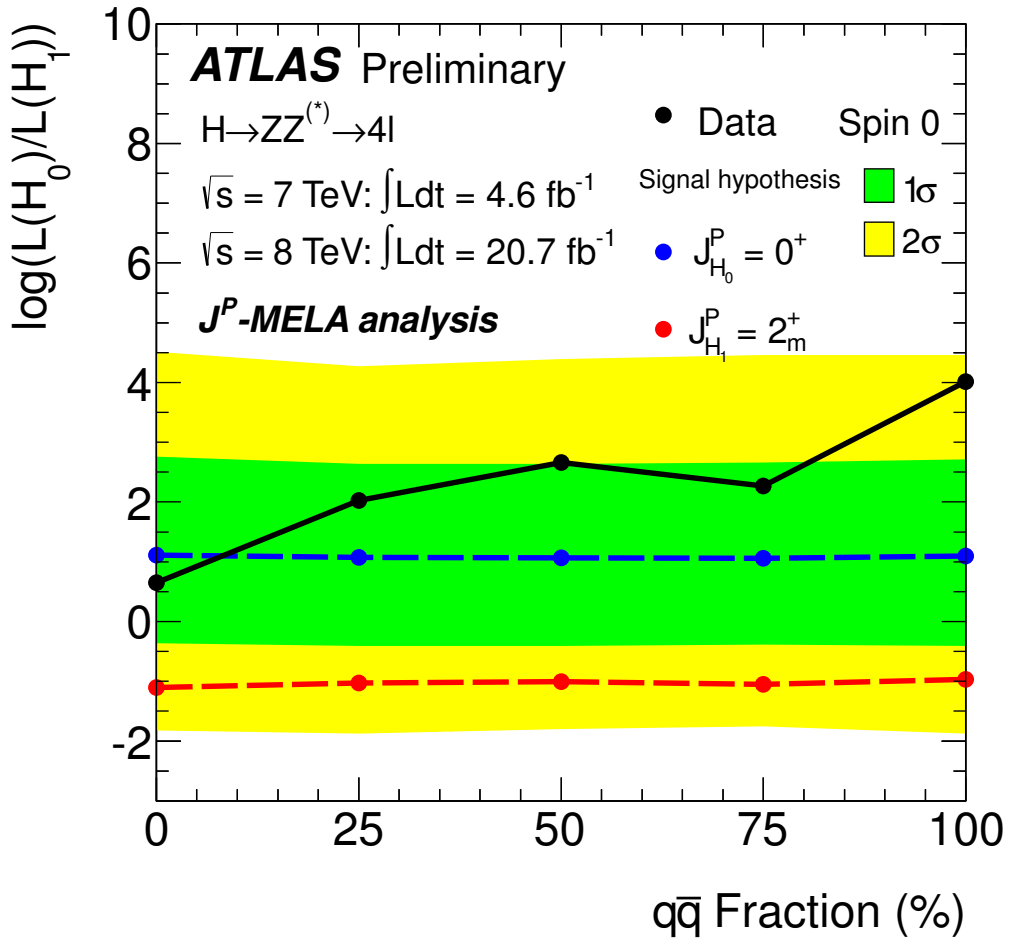
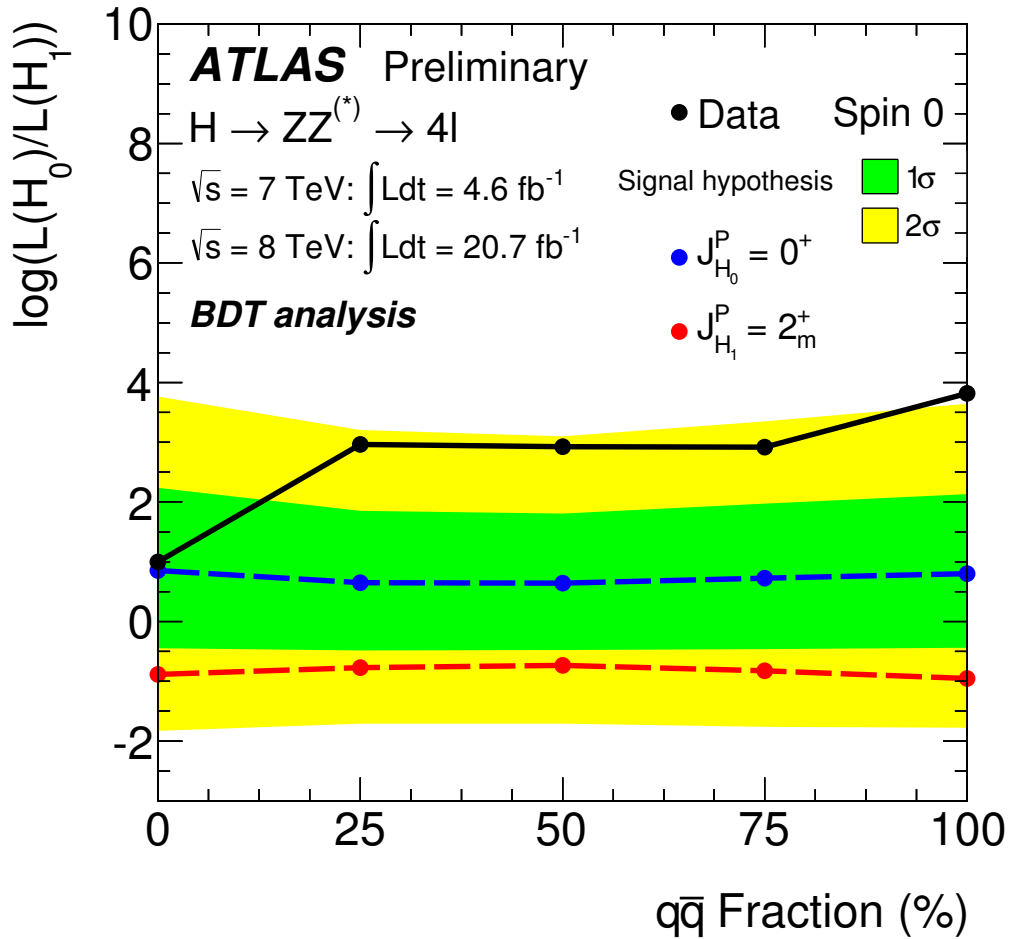
# Massa e signal strength



# Modello per spin 2

$$\begin{aligned}
 A(X \rightarrow VV) = \Lambda^{-1} & \left[ 2g_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\alpha} \right. \\
 & + g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f_{\mu\alpha}^{*2} + f^{*2,\mu\nu} f_{\mu\alpha}^{*1}) + g_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f_{\alpha\beta}^{*(2)} \\
 & + m_V^2 \left( 2g_5 t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\
 & + g_8 \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f_{\alpha\beta}^{*(2)} + g_9 t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \\
 & \left. + \frac{g_{10} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_1^{*\nu} (q \epsilon_2^*) + \epsilon_2^{*\nu} (q \epsilon_1^*)) \right],
 \end{aligned}$$

# Spin da $H \rightarrow ZZ \rightarrow 4\ell$ : BDT vs MELA





# Test statistici : la funzione di likelihood

Tutte le misure vengono affrontati con tecniche statistiche.

- Per ogni evento  $e$  abbiamo una o più quantità osservabili:  $\vec{x}_e$
- $n_s$  è il numero di eventi di segnale,  $n_b$  è il numero di eventi di fondo
- Il **segnale** (Higgs) viene modellato con una pdf  $p_s(\vec{x}_e|\vec{\alpha}, \vec{\nu}_s)$  dipendente da diversi parametri:
  - $\vec{\alpha}$  sono i **parametri di interesse**, cioè quelli che si vuole misurare (per es. massa, sezione d'urto, spin, ...)
  - $\vec{\nu}_s$  sono i **“nuisance parameters” (NP)** (per es. parametri di forma, risoluzione, sistematici...);
- Il **fondo** (background) è modellato con una pdf  $p_b(\vec{x}_e|\vec{\nu}_b)$ , dipendente da altri nuisance parameters (parametri di forma, frazione di componenti...)

Si definisce un modello tramite una “funzione di likelihood estesa”  $\mathcal{L}$ :

$$-\ln \mathcal{L}(\vec{\alpha}; \vec{\nu}) = (n_s + n_b) - \sum_e [n_s \cdot p_s(\vec{x}_e|\vec{\alpha}, \vec{\nu}_s) + n_b \cdot p_b(\vec{x}_e|\vec{\nu}_b)]$$

Alcuni NP possono essere vincolati da misure “ancillari” (es.: da regioni di controllo); in tal caso la pdf ancillare  $\pi_k(\nu_k)$  viene moltiplicata alla funzione di likelihood:

$$-\ln \mathcal{L}(\vec{\alpha}; \vec{\nu}) \longrightarrow -\ln \mathcal{L}(\vec{\alpha}; \vec{\nu}) - \sum_k \ln \pi_k(\nu_k)$$

la  $\pi_k(\nu_k)$  può essere Gaussiana (di solito) oppure log-Normale, Poissoniana, oppure uniforme su un dato intervallo

# Test statistici : ipotesi a parametri continui

I parametri di interesse sono continui (per esempio massa, sezione d'urto, couplings, ...)

Un'ipotesi  $\vec{\alpha}$  viene confrontata con tutte le possibili ipotesi alternative, in particolare si sceglie l'alternativa che meglio descrive i dati (cioè minimizza  $-\ln \mathcal{L}$ ) :  $\hat{\alpha}$ .

I NP vengono "profilati" massimizzando la likelihood per un dato valore di  $\vec{\alpha}$ :  $\vec{v} \rightarrow \hat{v}(\vec{\alpha})$

$$q_{\vec{\alpha}} = -2 \ln \Lambda(\vec{\alpha}) = -2 \ln \frac{\mathcal{L}(\vec{\alpha}; \hat{v}(\vec{\alpha}))}{\mathcal{L}(\hat{\alpha}; \hat{v})} \quad (\text{"profiled likelihood ratio", PLR})$$

Il **teorema di Wilks** garantisce che se  $\vec{\alpha} = \alpha^{vero}$  la quantità  $q_{\vec{\alpha}}$  è distribuita come una variabile  $\chi_D^2$  dove  $D$  è il numero dei parametri di interesse  $\vec{\alpha}$

$$\Rightarrow \text{pdf}(q_{\vec{\alpha}}) = \chi_{\text{dim}(\vec{\alpha})}^2(q)$$

$\Rightarrow$  È possibile determinare intervalli di confidenza per  $\vec{\alpha}$

CL	numero di parametri di interesse	
	D = 1	D = 2
68%	$-2 \ln \Lambda < 1$	$-2 \ln \Lambda < 2.3$
95%	$-2 \ln \Lambda < 4$	$-2 \ln \Lambda < 6.0$

L'intervallo di confidenza dei valori  $\vec{\alpha}$  accettati è tale che

$$\int_{q_{\vec{\alpha}}^{obs}}^{+\infty} dq \chi_D^2(q) > 1 - CL$$

# Test statistici : ipotesi a parametri discreti

Il parametro di interesse è discreto (per esempio lo stato di spin)  
 Due ipotesi  $\vec{\alpha}_1$  e  $\vec{\alpha}_2$  sono confrontate, i NP sono “profilati”  $\vec{v} \rightarrow \hat{v}(\vec{\alpha}_{1,2})$

$$q = \ln \frac{\mathcal{L}(\vec{\alpha}_1; \hat{v}(\vec{\alpha}_1))}{\mathcal{L}(\vec{\alpha}_2; \hat{v}(\vec{\alpha}_2))} \quad (\text{“ratio of profiled likelihoods”, RPL})$$

La pdf ( $q|\vec{\alpha}_{1,2}$ ) non è nota a priori, occorre generare pseudo-esperimenti per ciascuna ipotesi  $\vec{\alpha}_{1,2}$  e sottoporli all’analisi.

L’ipotesi  $\vec{\alpha}_1$  è scartata  
 se  $p_{\vec{\alpha}_1} \stackrel{\text{def}}{=} \int_{-\infty}^{q^{obs}} dq \text{pdf}(q|\vec{\alpha}_1) < 1 - CL$   
 Analogamente, l’ipotesi  $\vec{\alpha}_2$  è scartata  
 se  $p_{\vec{\alpha}_2} \stackrel{\text{def}}{=} \int_{q^{obs}}^{+\infty} dq \text{pdf}(q|\vec{\alpha}_2) < 1 - CL$

