

Ricerca del bosone di Higgs e misura delle sue proprietà

1. La ricerca a LEP
2. Sezioni d'urto di produzione ai collider adronici
3. Decadimenti del bosone di Higgs nel Modello Standard
4. Risultati Tevatron
5. La scoperta a LHC
6. Determinazione di Spin Parità
7. Determinazione degli accoppiamenti
8. Prospettive

Sensibilita' a m_H

$m_H < 285$ @ 95% CL dopo Lep1, Lep2

Confronta con $m_H < 152$ @ 95% CL dopo m_W , m_{top} a Tevatron

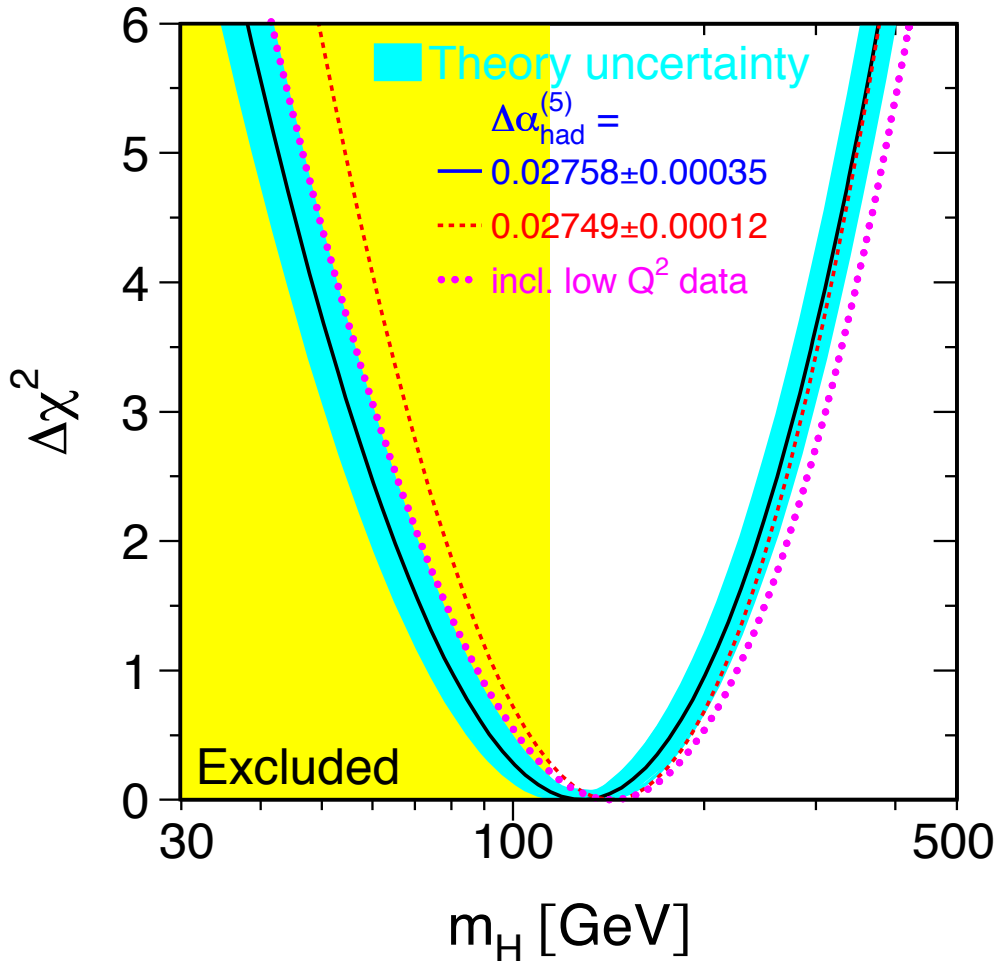
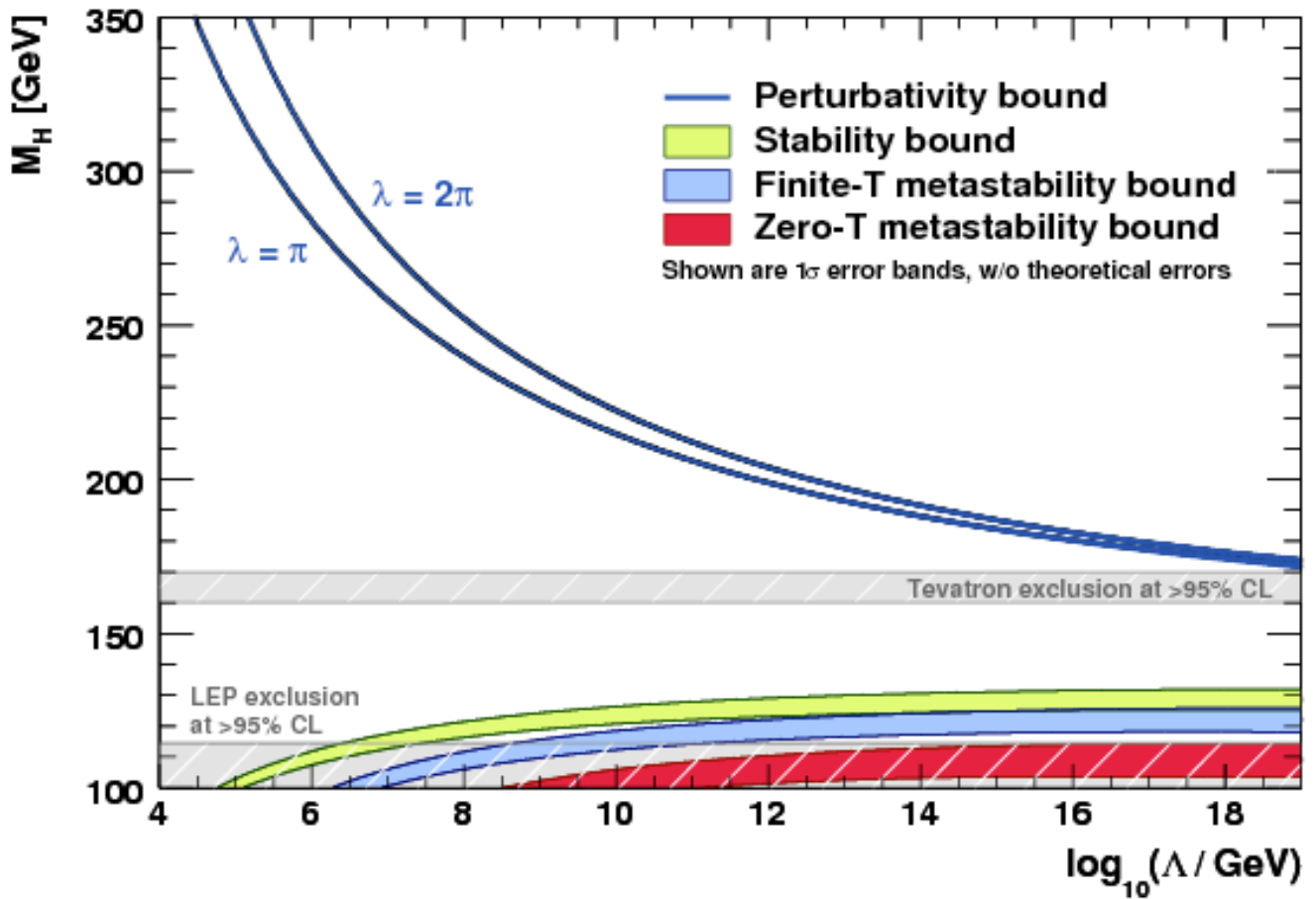
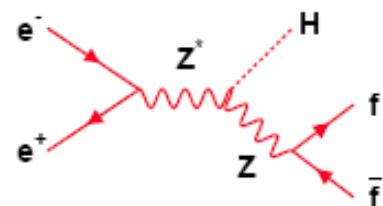
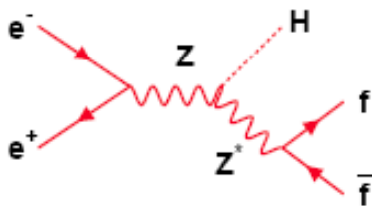
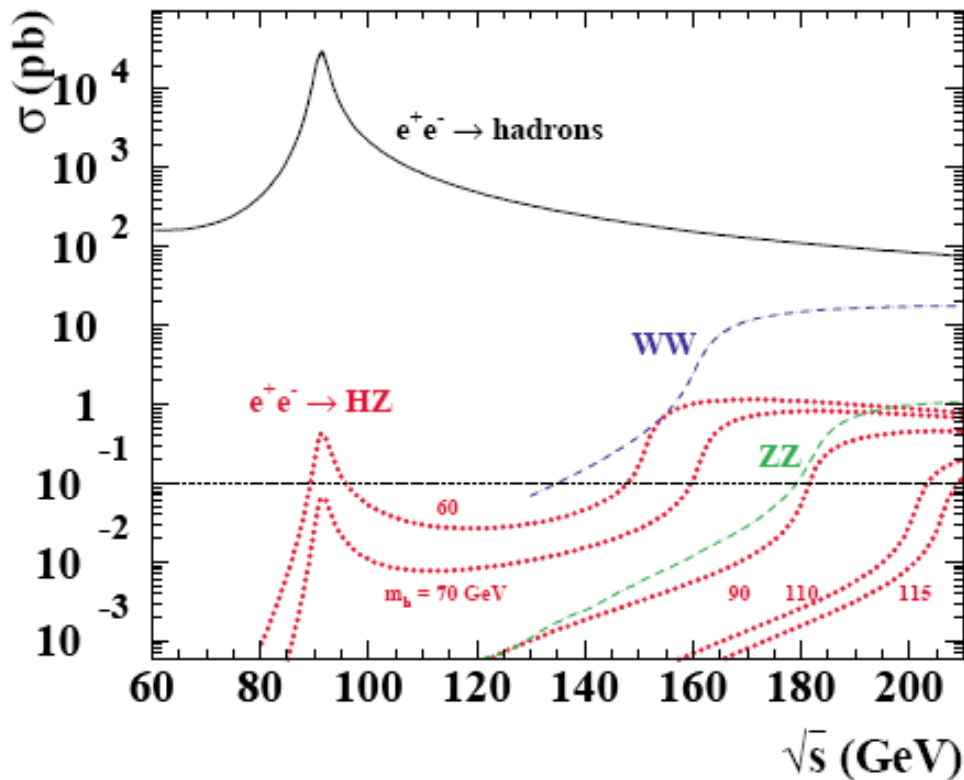


Figure 8.13: $\Delta\chi^2(m_H) = \chi_{\text{min}}^2(m_H) - \chi_{\text{min}}^2$ as a function of m_H . The line is the result of the fit using all 18 results. The associated band represents the estimate of the theoretical uncertainty due to missing higher-order corrections as discussed in Section 8.4. The vertical band shows the 95% confidence level exclusion limit on m_H of 114.4 GeV derived from the direct search at LEP-II [39]. The dashed curve is the result obtained using the theory-driven $\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)$ determination of Equation 8.4. The direct measurements of m_W and Γ_W used here are preliminary.

Dove trovare Higgs



Sez. d'urto produzione di Higgs a LEP



- Alle energie di LEP1 Higgs-strahlung da bosoni Z reali
- Alle energie di LEP1 Higgs-strahlung da bosoni Z virtuali

Sez. d'urto produzione di Higgs a LEP

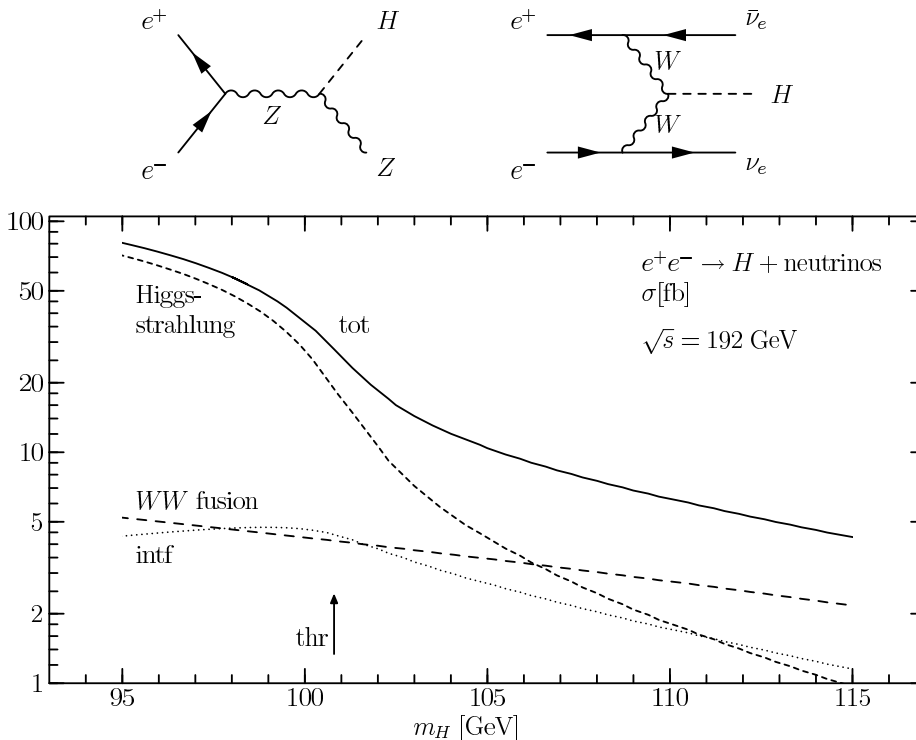
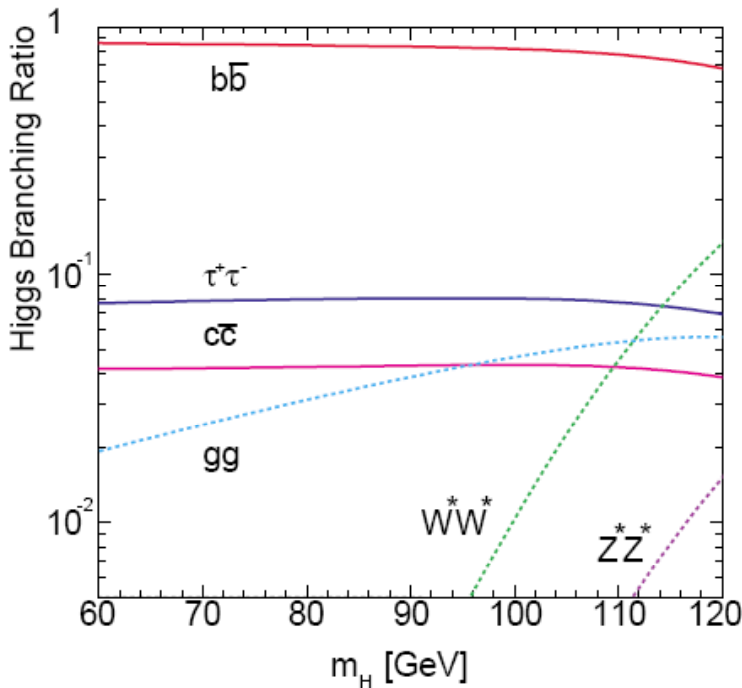


Figure 4: Higgs production cross section $\sigma[e^+e^- \rightarrow H\bar{\nu}\nu]$ [32]. The total cross section is built up by Higgs-strahlung HZ with Z decaying to neutrinos, WW fusion and their interference (*intf*). Higgs-strahlung falls off rapidly above the threshold (*thr*) region. Other than $\bar{\nu}\nu$ final states in Higgs-strahlung can be derived from the short-dashed curve by re-adjusting the Z -decay branching ratio properly. Diagrams on top describe the Higgs-strahlung and the vector-boson fusion mechanism for Higgs production in e^+e^- collisions.

- Essenzialmente la sezione d'urto si esaurisce per $\sqrt{s} - M_Z < M_H$
- Diagramma sotto-dominante per lo stato finale $H\nu\nu \rightarrow$ estensione di sensibilita' ad alta massa

Decadimenti del bosone di Higgs



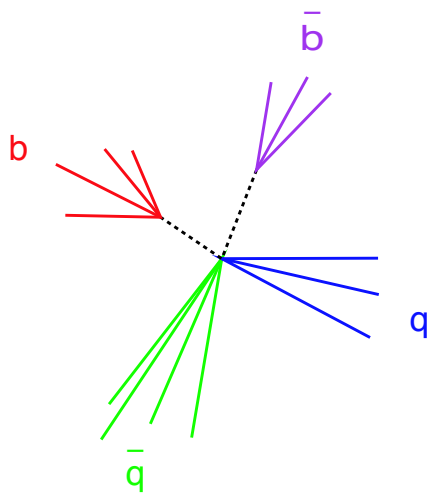
| BR(%) | Higgs 115 GeV | Z boson |
|-----------|------------------|---------|
| qq | | 70 |
| bb | 74 | 15 |
| cc | 4 | 12 |
| gg | 6 | 0 |
| l+l- | | 10 |
| tau+tau- | 7 | 3 |
| nu nu-bar | | 20 |
| W*W* | 8 | |
| Z*Z* | 1 | |

- Nel range di interesse di LEP essenzialmente decadimenti in coppie di quark b e coppie di tau sono state utilizzate, con Z in coppie di quark, leptoni carichi o neutrini
- Background dominato dalla produzione di di-bosoni: ZZ, WW, Z(γ) (radiative return to the Z)

Topologia degli eventi studiati al LEP

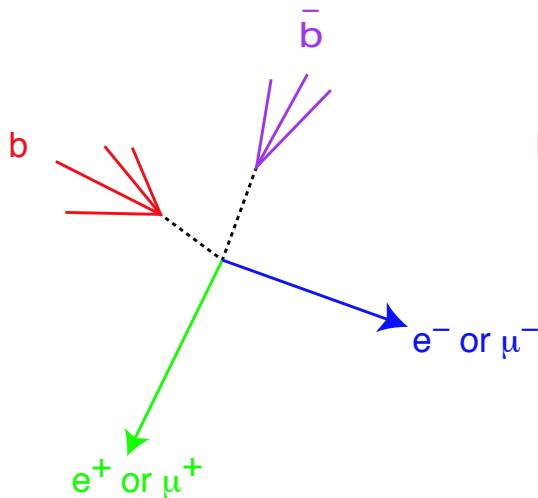
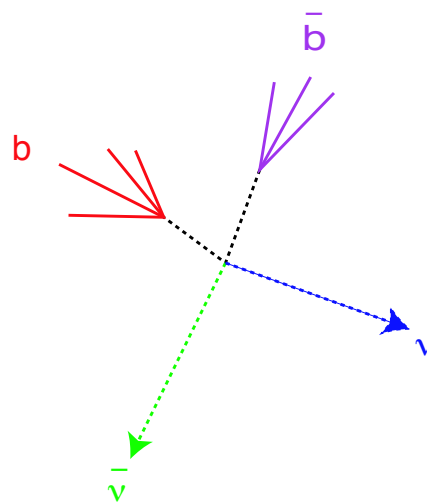
Four jets, 60%

$H \rightarrow b\bar{b}$, $Z \rightarrow q\bar{q}$



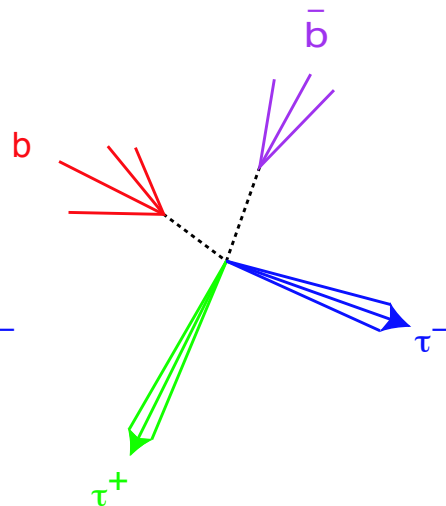
Missing energy, 18%

$H \rightarrow b\bar{b}$, $Z \rightarrow \nu\bar{\nu}$



Leptonic, 6%

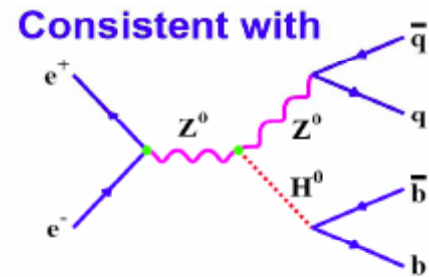
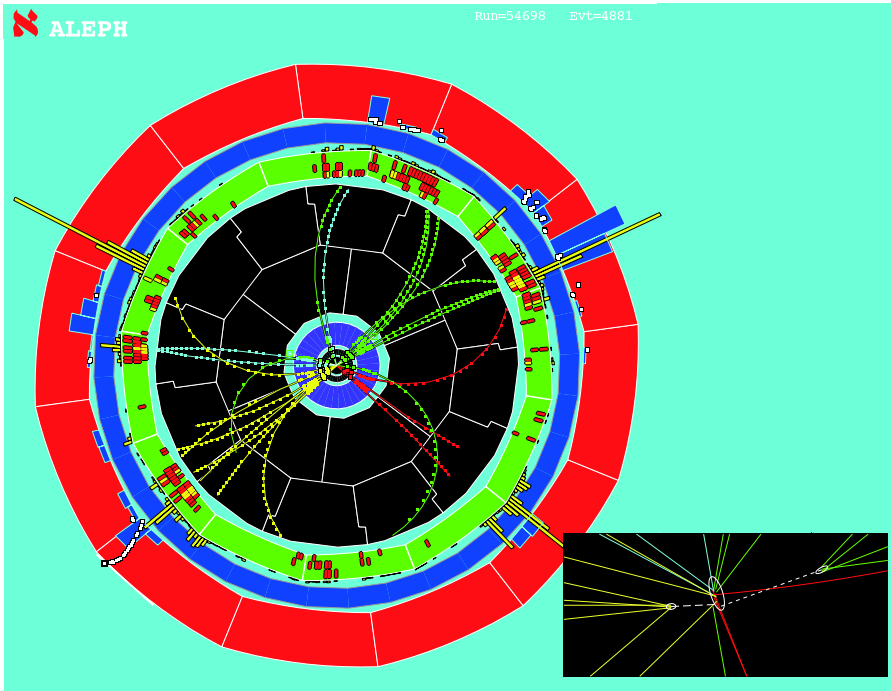
$H \rightarrow b\bar{b}$, $Z \rightarrow \ell^+\ell^-$



Tau channels, 9%

$H \rightarrow b\bar{b}(\tau^+\tau^-)$, $Z \rightarrow \tau^+\tau^-(q\bar{q})$

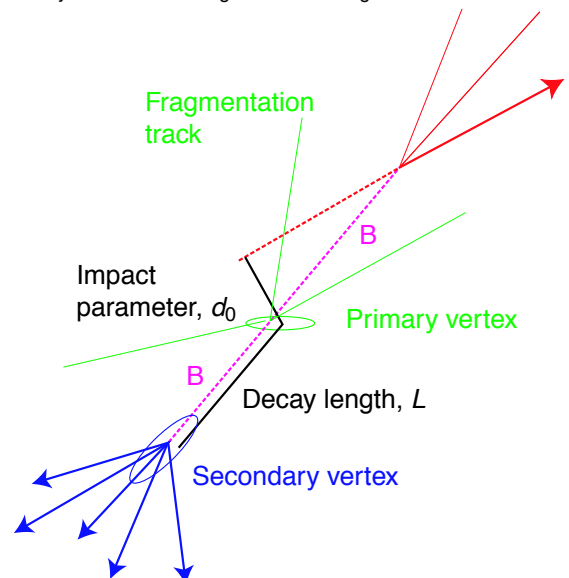
A “good” Higgs event



Tagging heavy quarks - lifetimes

- Per separare i jet originati da b-quark dagli altri essenziali i rivelatori di vertice al silicio installati in larga scala nei primi anni 90 a LEP e Tevatron

Heavy hadrons have long lifetime and large boost at LEP



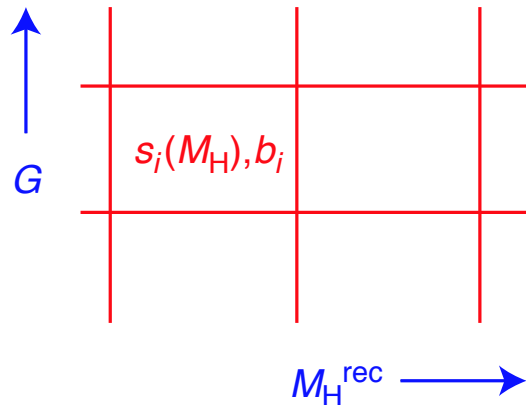
d_0 and L are signed quantities. A badly measured track may intercept the “wrong-side” of the beam spot. Rely on silicon microvertex detectors for resolution. Use several variables together.

Test Statistics

b_i expected background

$s_i(M_H)$ expected signal, function of “test mass” M_H

Count these in bins of event reconstructed Higgs mass M_H^{rec} and global discriminating variable G



Discriminant takes into account b-tagging, τ -id, kinematic variables that distinguish signal and background.

Expectations account for luminosity, E_{cm} , resolution, efficiency...

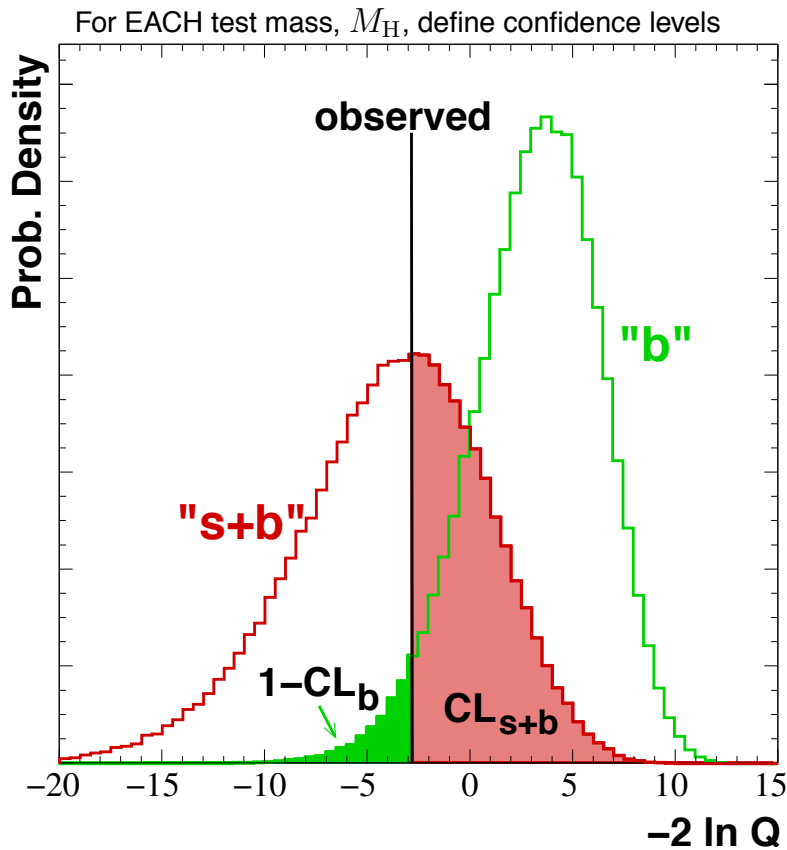
Compare likelihoods of “ $s + b$ ” and “ b only”. Likelihood from Poisson probability of observing n_i data events in bin.

$$Q(M_H) = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b} = \prod_i \frac{(s_i + b_i)^{n_i} e^{-(s_i+b_i)} / n_i}{b_i^{n_i} e^{-b_i} / n_i}$$

$$-2 \ln Q(M_H) = 2s_{\text{tot}} - 2 \sum_i n_i \ln \left(1 + \frac{s_i(M_H)}{b_i} \right)$$

Sum is over all bins, channels (four jet, missing energy...), and experiments.

Test Statistics



$$1 - CL_b$$

Measure of inconsistency with "b" →

Anche chiamato p-value o $p_0 = 1 - CL_b$

$$CL_{s+b}$$

Measure of inconsistency with "s + b"

$$CL_s = CL_{s+b} / CL_b$$

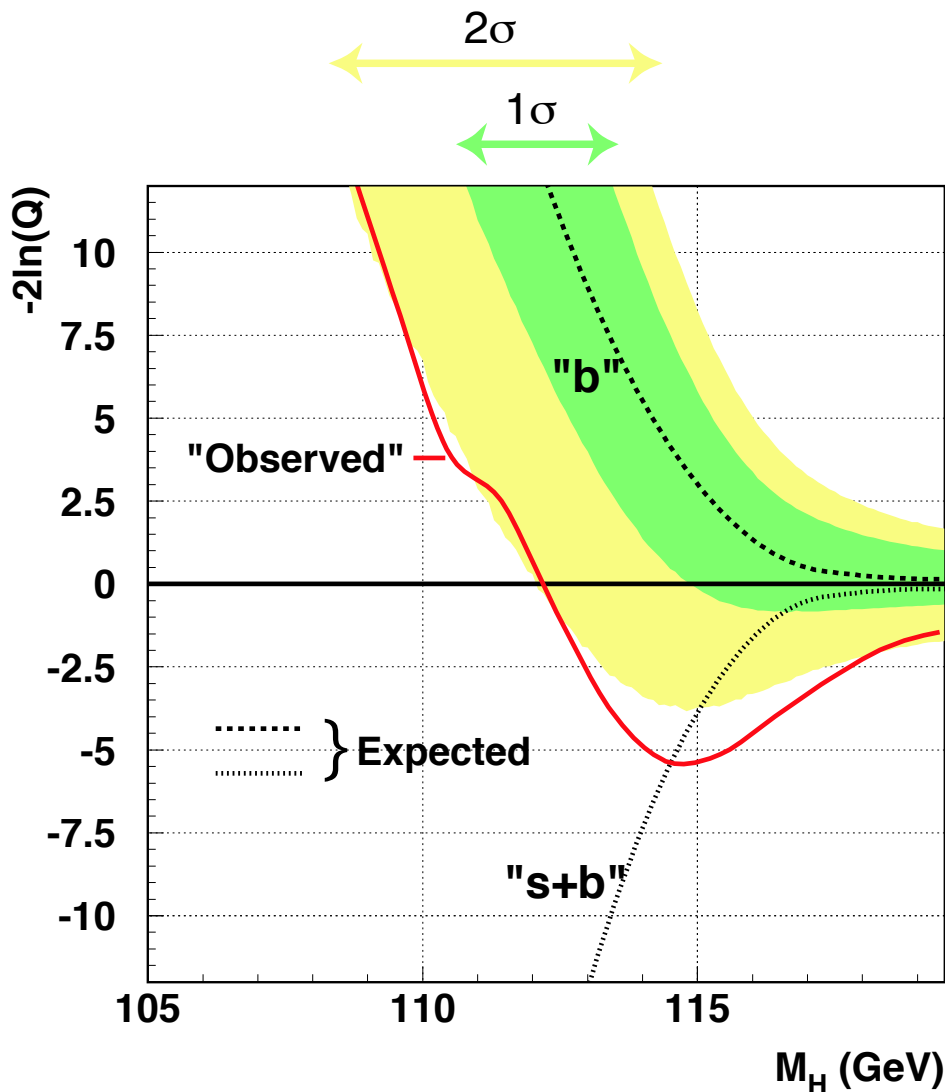
Lower bound on Higgs mass

Separation of b and s+b curves indicates sensitivity of analysis.

- In linea generale in un approccio statistico frequentista I livelli di confidenza vengono calcolati sulle distribuzioni della statistica di test utilizzando moltissime repliche indipendenti dell'esperimento generate via tecniche MonteCarlo
- Per proteggere il risultato rispetto a fluttuazioni del livello di confidenza osservato dovuto alla bassa statistica nel caso di scarsa separazione tra segnale e fondo si introduce il concetto di CLs. Si impedisce di fare un claim di esclusione quando non c'è la sensibilità sufficiente per poterlo fare (ovvero quando le curve rosse e verde sono quasi sovrapposte).

Test Statistics plot

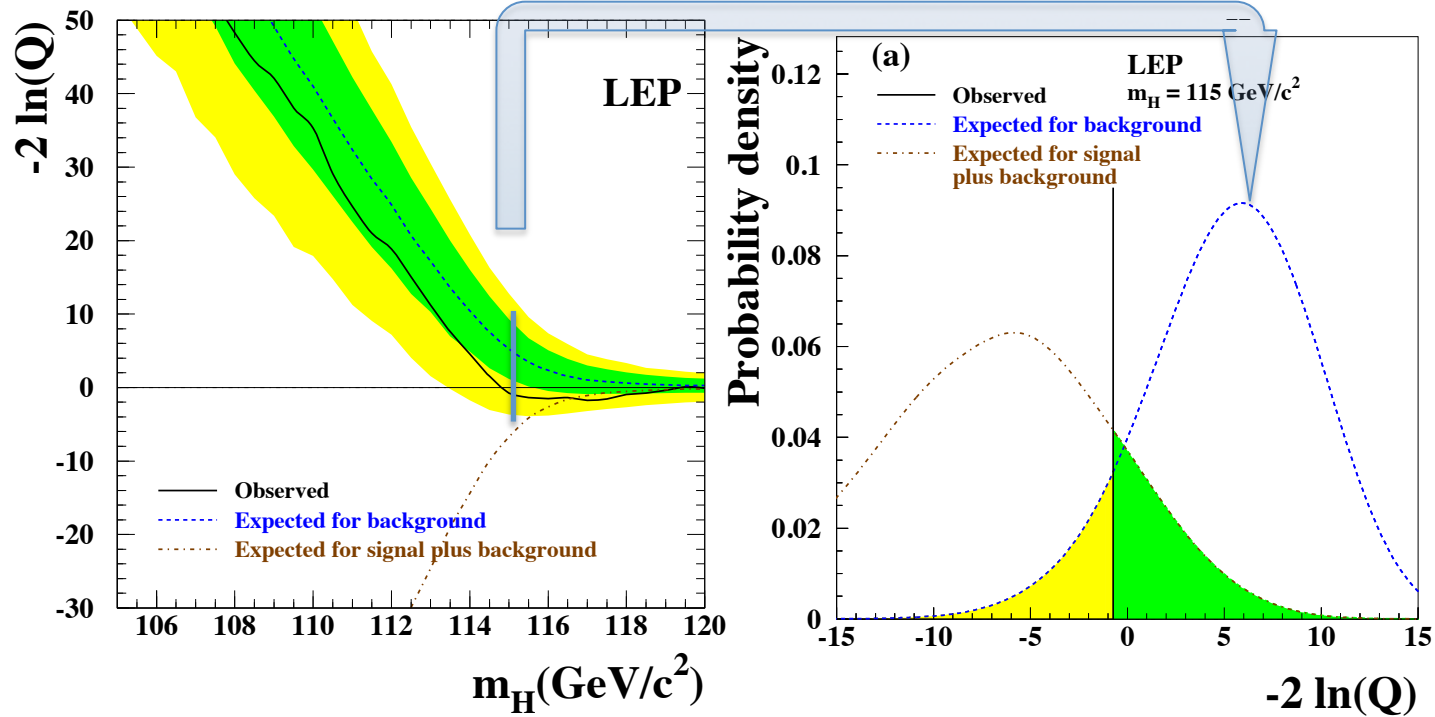
1σ / 2σ band : rappresentano le bande in cui cade il risultato della ricerca il 68% o il 95% delle volte che ripetissimo il nostro esperimento



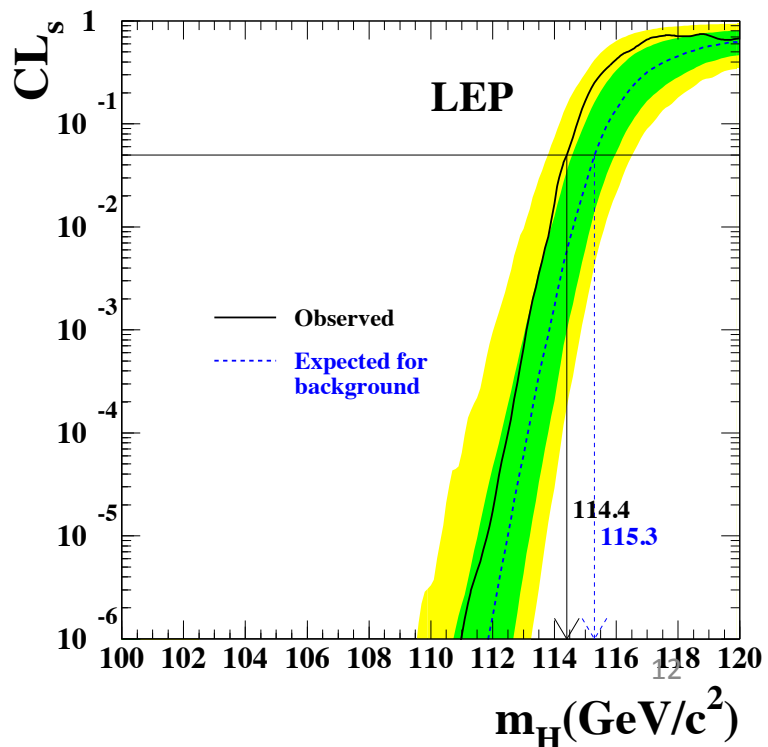
Take slices at different test masses - separation of b and s+b decreases as mass increases.

Risultato finale a Lep 2

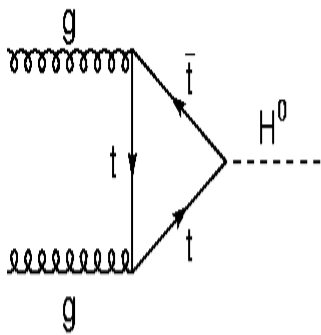
Phys.Lett.B 565:61-75, 2003



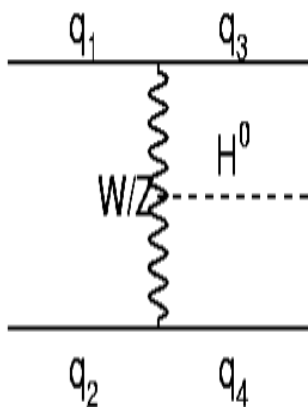
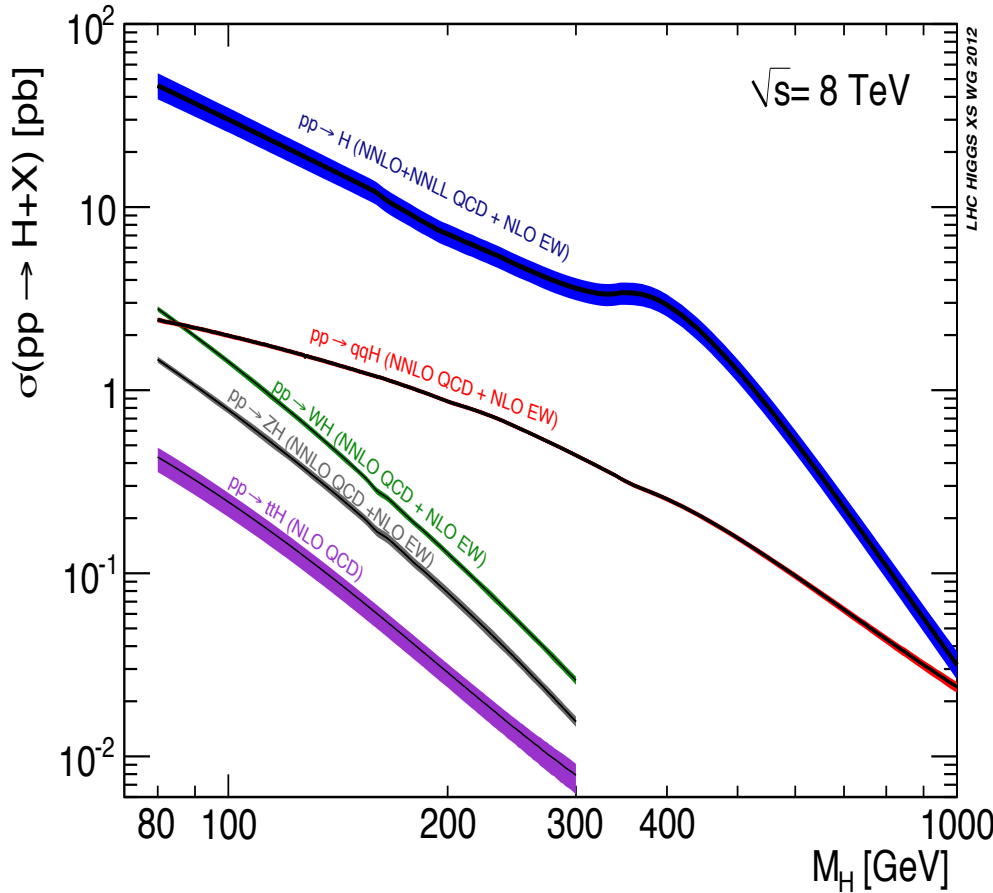
- Il bosone di Higgs ha massa $m_H > 114.4 \text{ GeV}$ @ 95 % CL
- Limite aspettato 115.3 GeV



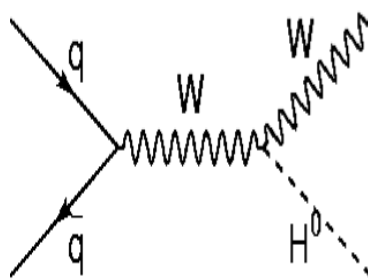
Modi di produzione di Higgs al collider (pp)



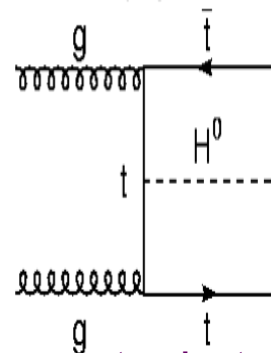
Gluon fusion provide dominant Higgs boson production mechanism
 Top loop dominant (-10% interference from bottom loop).



V B F ~ 7 % inclusive xsec, distinct signature, access to W/Z Higgs couplings

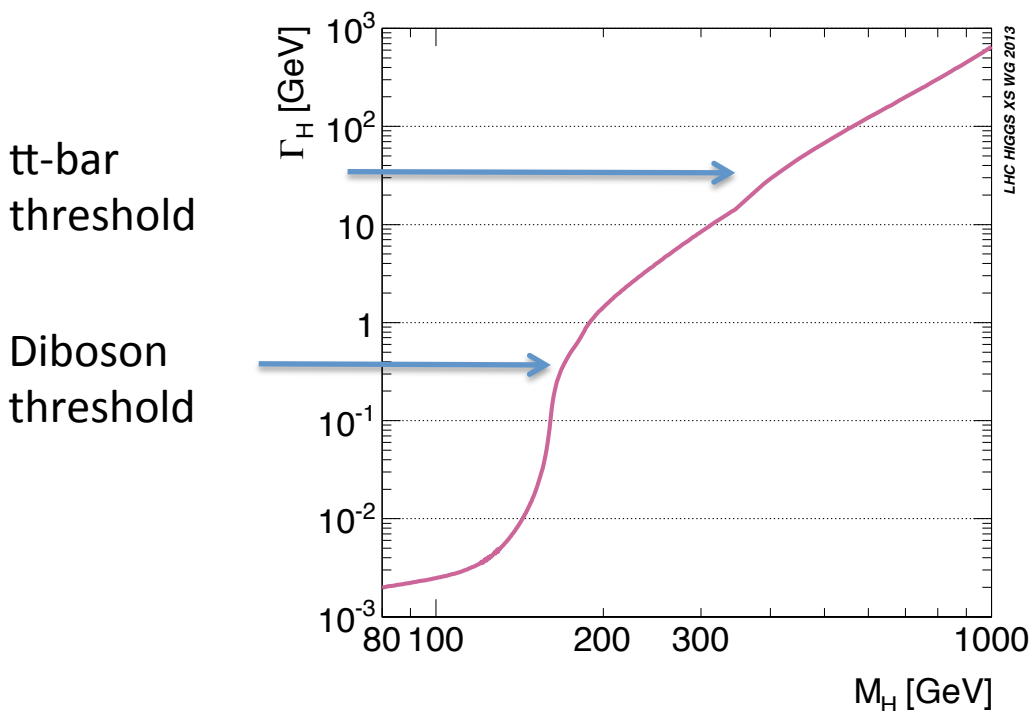
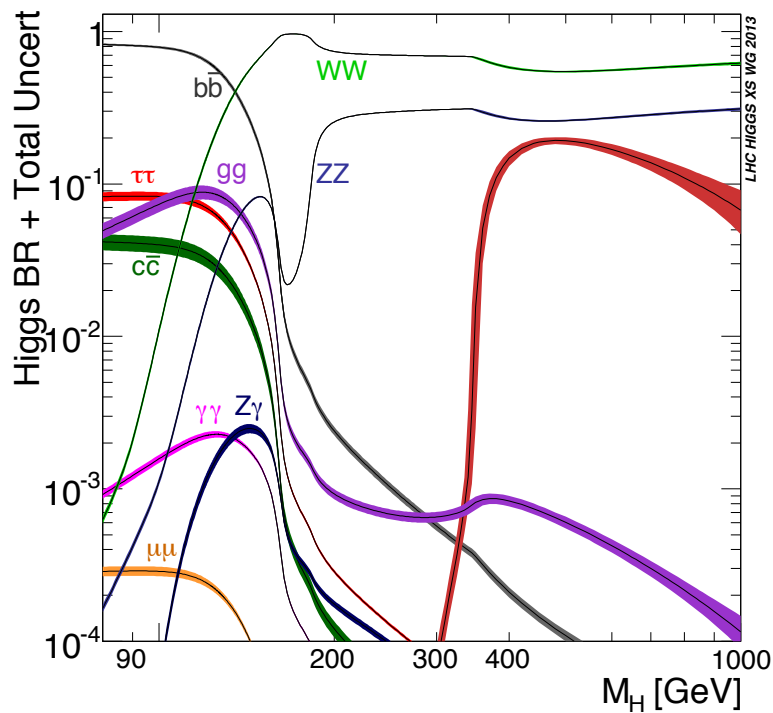


Clean signature with leptons, allowing access to $H \rightarrow bb$ and W/Z Higgs coupling

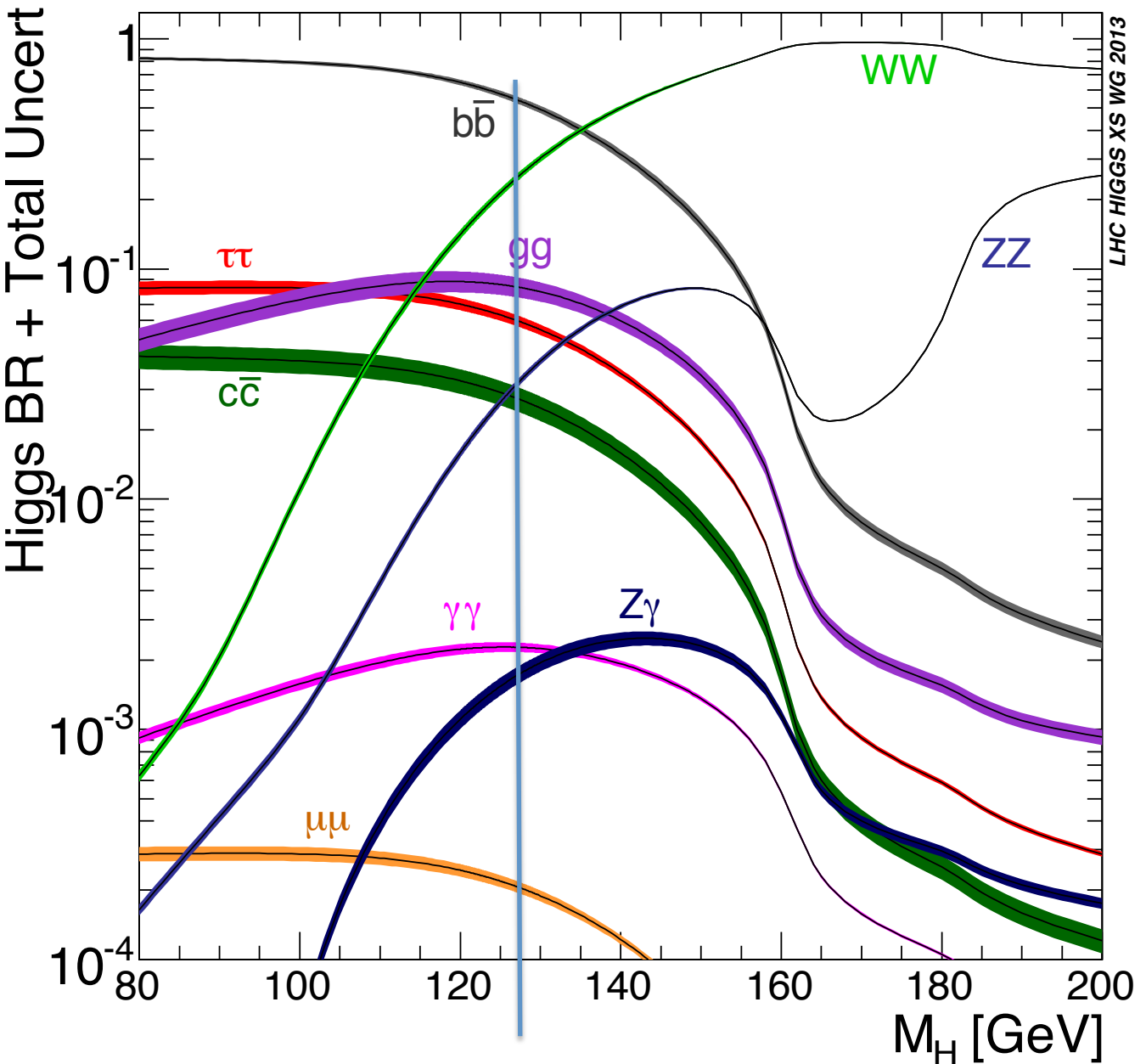


Low rate, but will test directly Top Yukawa coupling

Modi di decadimento del bosone di Higgs

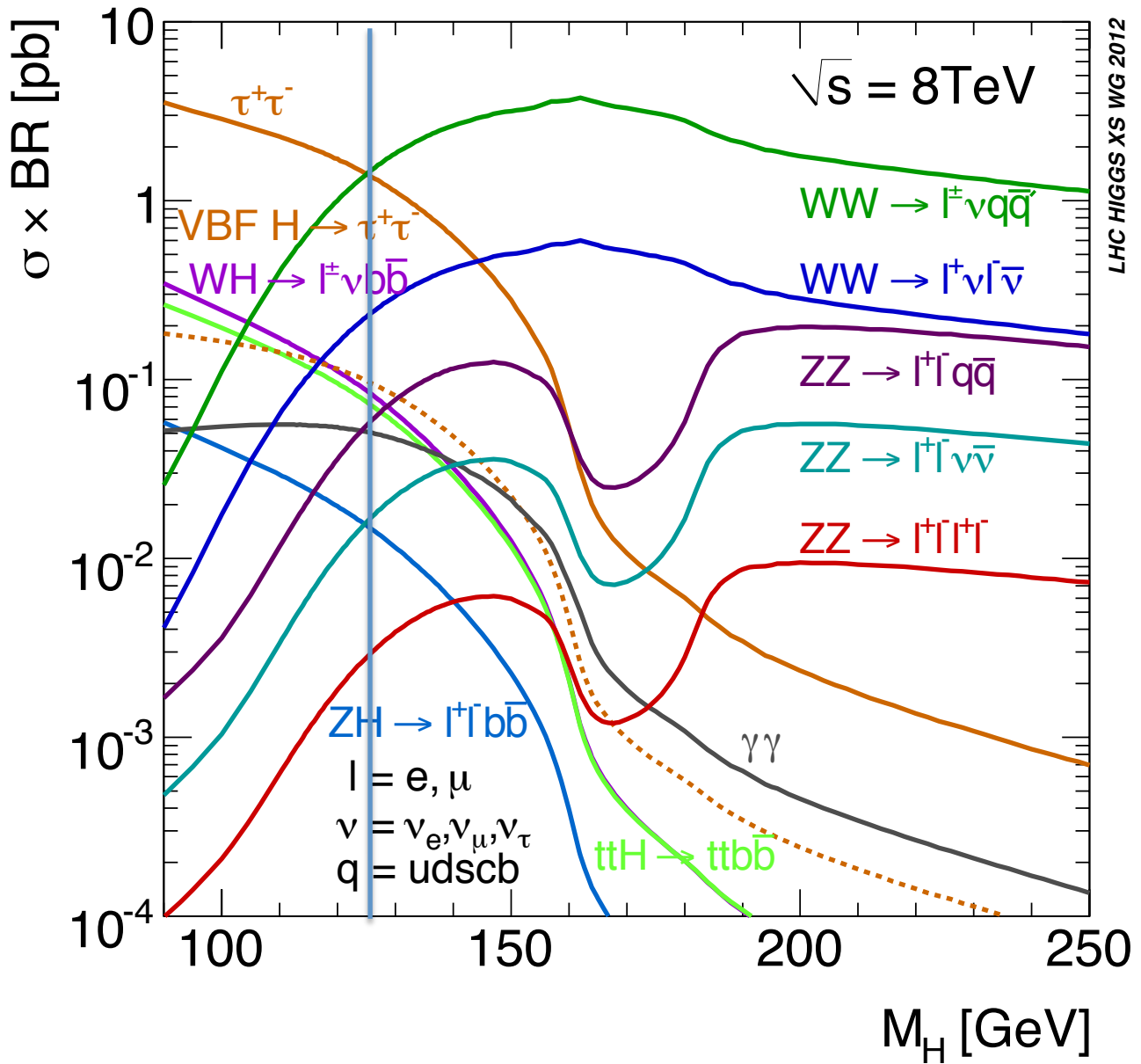


Modi di decadimento del bosone di Higgs



Praticamente tutti i modi di decadimenti saranno visibili ad LHC
 N.B. BR di Z e W negli stati finali osservabili (ad esempio leptoni carichi) non sono inclusi nel grafico (vedi pag. seguente)

Modi di decadimento del bosone di Higgs

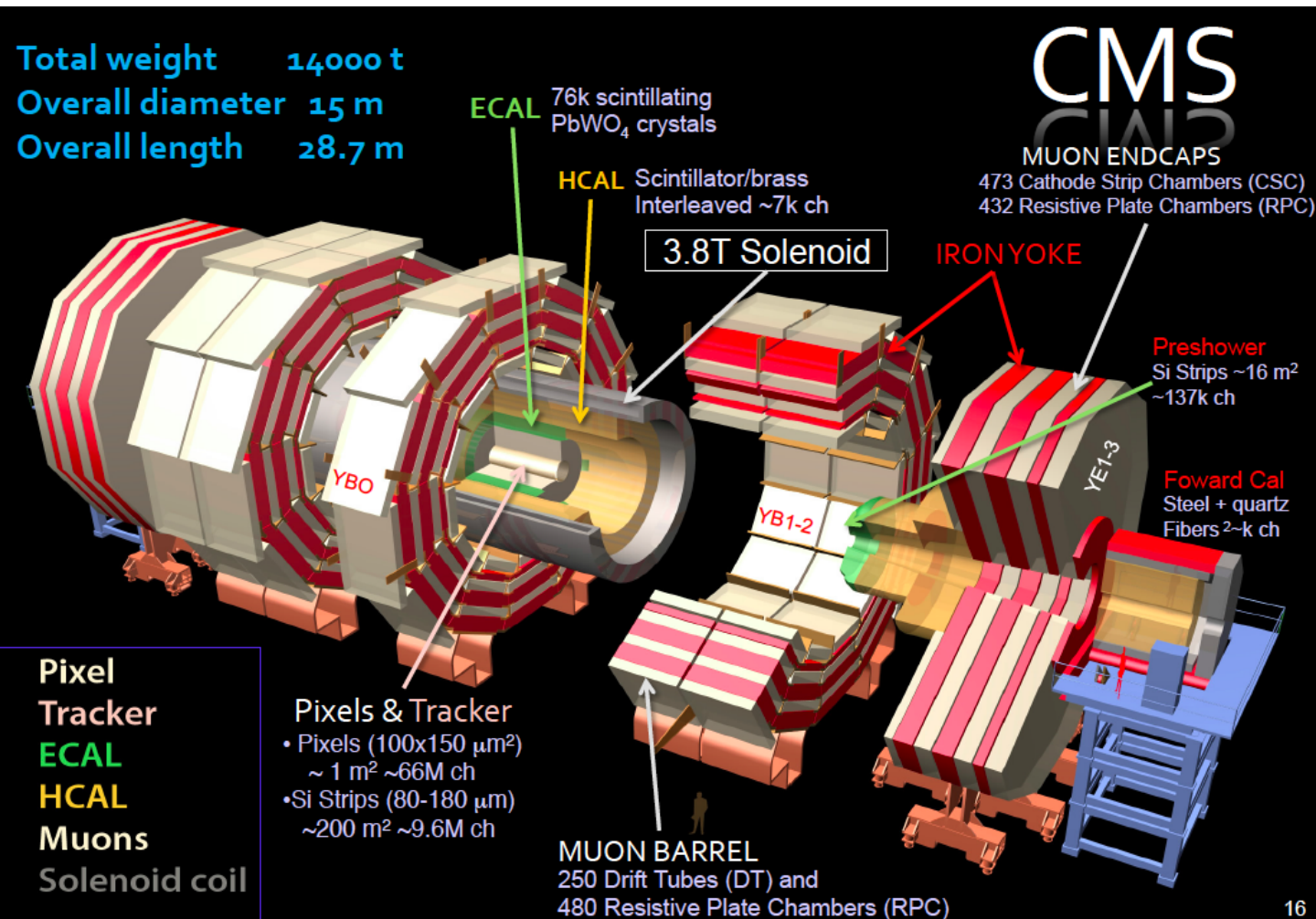


Praticamente tutti i modi di decadimenti saranno visibili ad LHC

Design dei rivelatori

- La ricerca dell'Higgs ha determinato in larga parte le stringenti richieste nella concezione dei rivelatori di LHC
- La capacita' di riconoscere fotoni rigettando il fondo e di misurarli con ottima risoluzione per risolvere il picco di massa invariante gamma-gamma (Higgs a bassa massa)
- La grande accettazione in pseudo-rapidita' e in impulso per muoni ed elettroni per sfruttare il "golden mode"
 $H \rightarrow ZZ \rightarrow 4l$
- La possibilita' di misurare jet adronici a grande rapidita' (VBF jets)
- La riduzione della risoluzione nella missing transverse energy per riconoscere i decadimenti con neutrini/tau (estensione dei calorimetri a grande pseudo-rapidita')
- Altri aspetti di fondamentale importanza nel design degli esperimenti, riguardano:
 - La capacita' di sopportare flussi di particelle ionizzanti molte elevate specialmente nelle zone in avanti (radiation hardness di rivelatori ed elettronica associata)
 - La necessita' di raccogliere i segnali senza dover integrare su troppe collisioni successive (bunch spacing 25 ns, cf. Tevatron 396 ns)
 - Trigger sofisticati in grado di riconoscere e taggare il bunch crossing corretto in modo da temporizzare l'intera acquisizione

Esperimento CMS

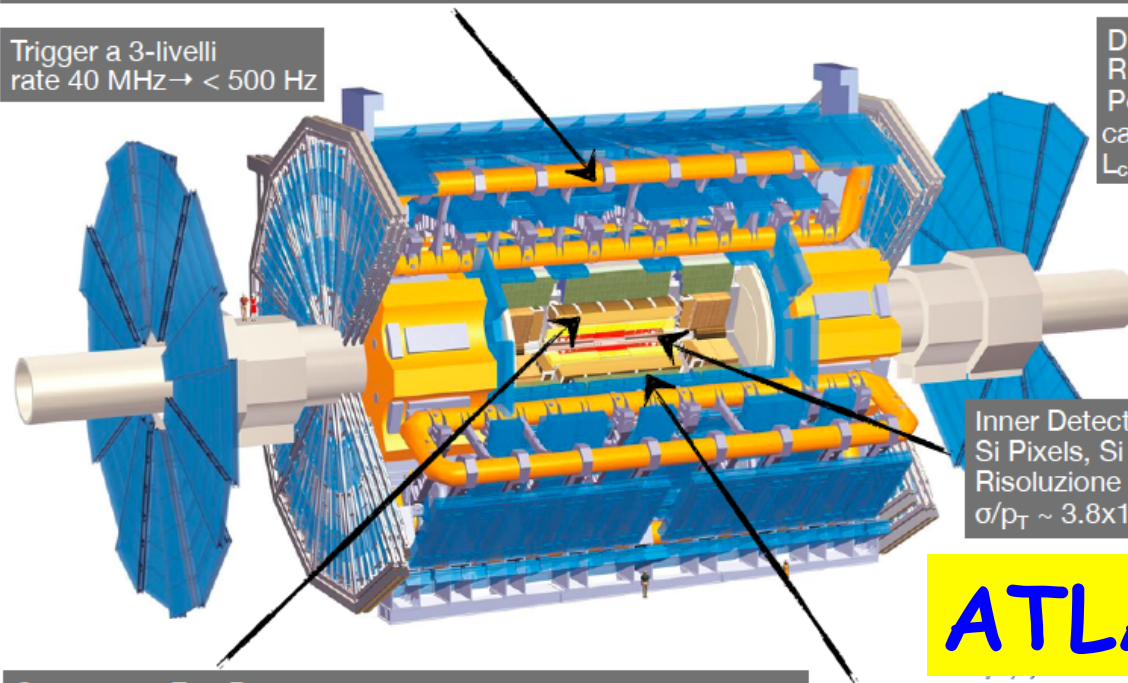


Esperimento ATLAS

Spettrometro per muoni ($|\eta| < 2.7$) : air-core toroids + gas-based muon chambers
 Trigger muonico standalone e misura di impulso con risoluzione $< 10\%$ fino a $E_\mu \sim 1 \text{ TeV}$

Trigger a 3-livelli
 rate 40 MHz \rightarrow $< 500 \text{ Hz}$

Dim. : LxR $\sim 46 \times 12 \text{ m}^2$
 R : $\sim 12 \text{ m}$
 Peso : $\sim 7000 \text{ tonn.}$
 canali elettronica: $\sim 10^8$
 $L_{\text{cavi}} \sim 3000 \text{ km}$



Inner Detector ($|\eta| < 2.5$, $B=2\text{T}$):
 Si Pixels, Si strips, TRT (straws)
 Risoluzione in impulso:
 $\sigma/p_T \sim 3.8 \times 10^{-4} p_T (\text{GeV}) \oplus 0.015$

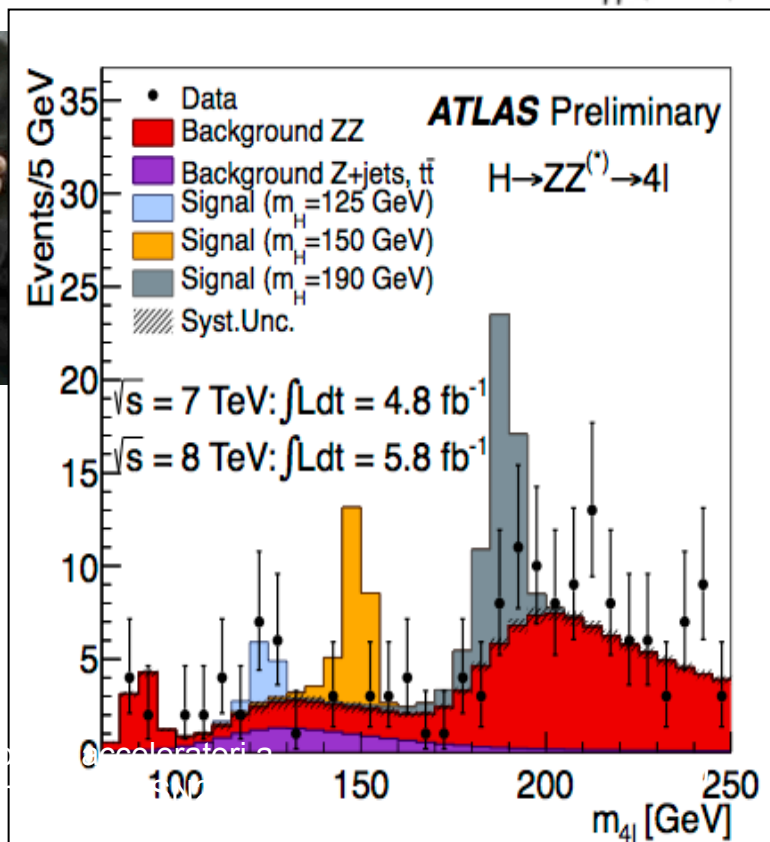
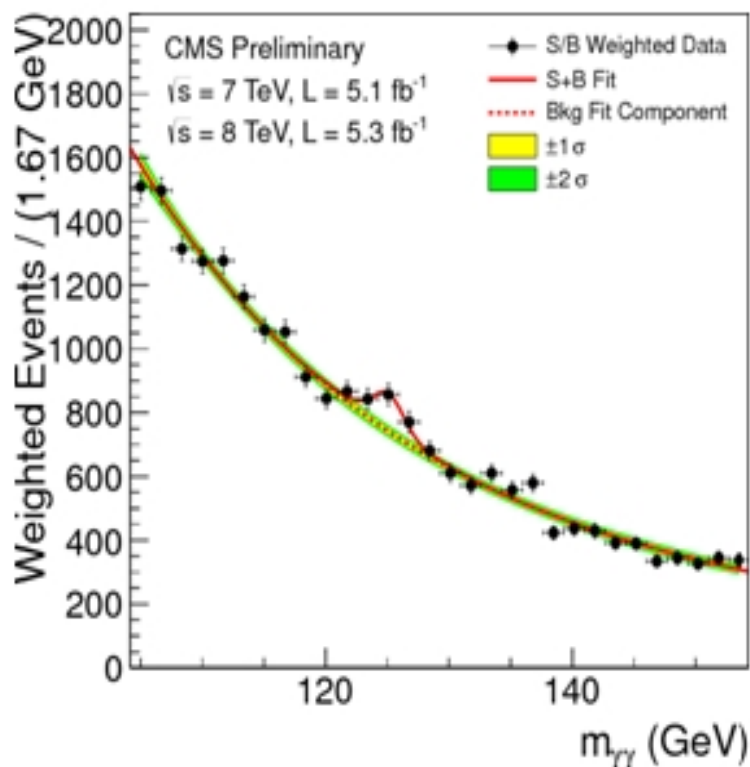
ATLAS

Calorimetro EM: Pb-LAr geometria a fisarmonica
 e/ γ trigger, ID
 Risoluzione in energia: $\sigma/E \sim 10\%/\sqrt{E}$

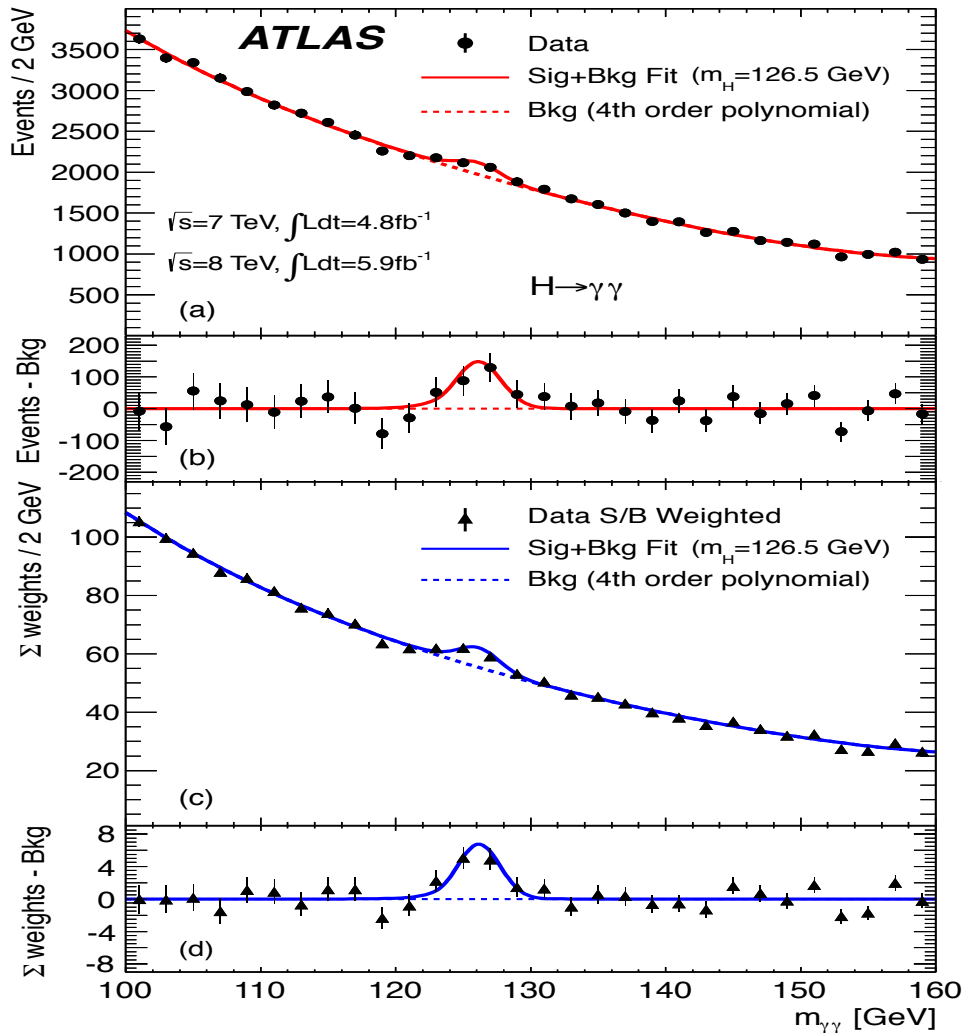
Calorimetro Adronico ($|\eta| < 5$): segmentato, ermetico
 Fe/scintill. (central), Cu-LAr (fwd)
 Trigger, ricostruzione Jets, missing E_T
 Risoluzione in energia: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

- rivelatore general purpose
- design ottimizzato per le dure condizioni imposte da LHC

4 Luglio 2012

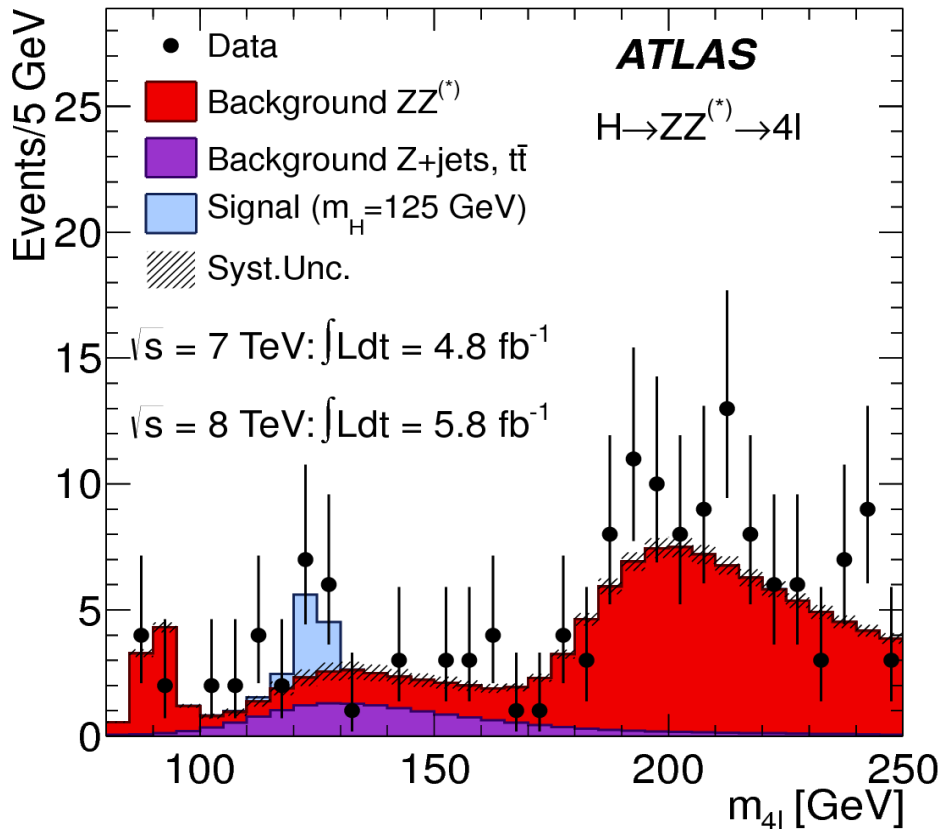


$H \rightarrow \gamma\gamma$ (ATLAS)



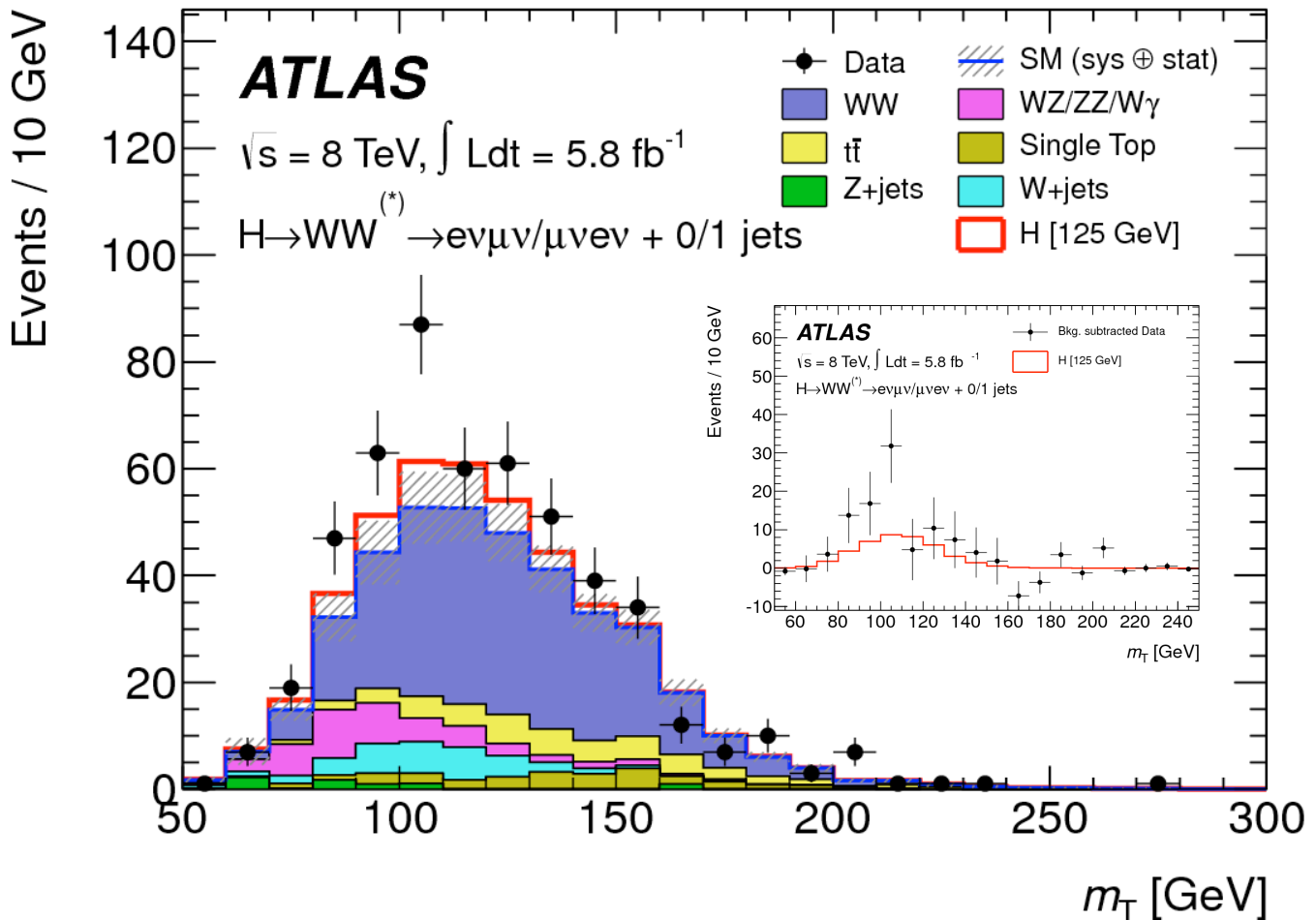
- Poche centinaia di eventi
- $S/B \sim O(1\%)$
- Fondo riducibile $pp \rightarrow jj$; $pp \rightarrow j\gamma$
- Fondo irriducibile $pp \rightarrow \gamma\gamma$

$H \rightarrow ZZ^*$ (ATLAS)



- ~ 10 eventi ma $S/B > 1$
- Fondo riducibile $pp \rightarrow Z+jj$; $pp \rightarrow t\bar{t}$
- Fondo irriducibile $pp \rightarrow ZZ$

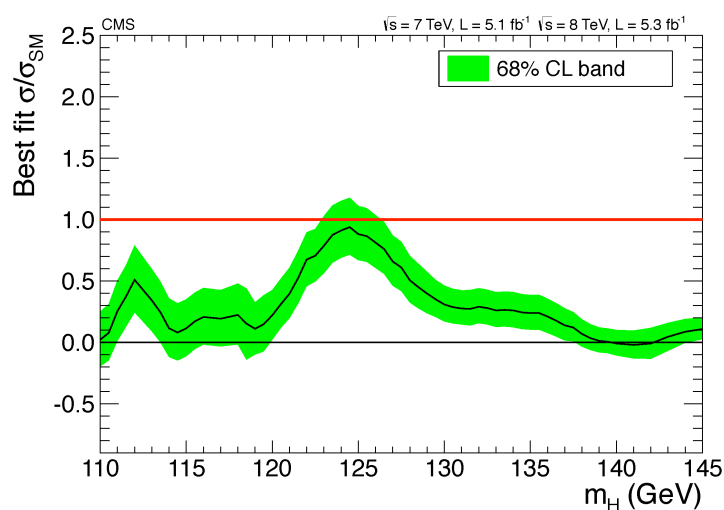
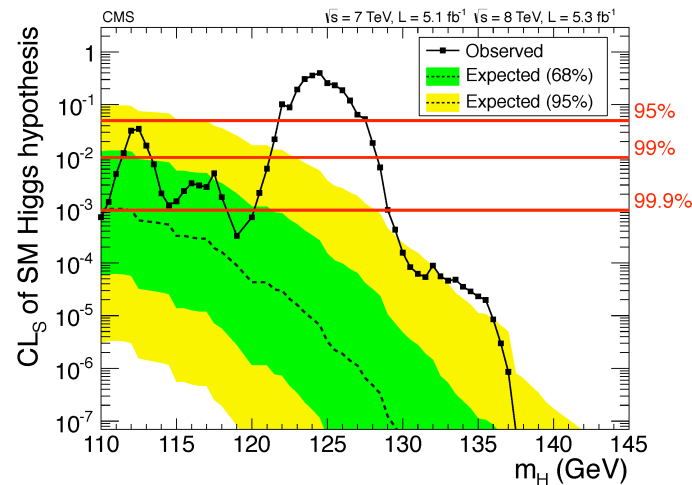
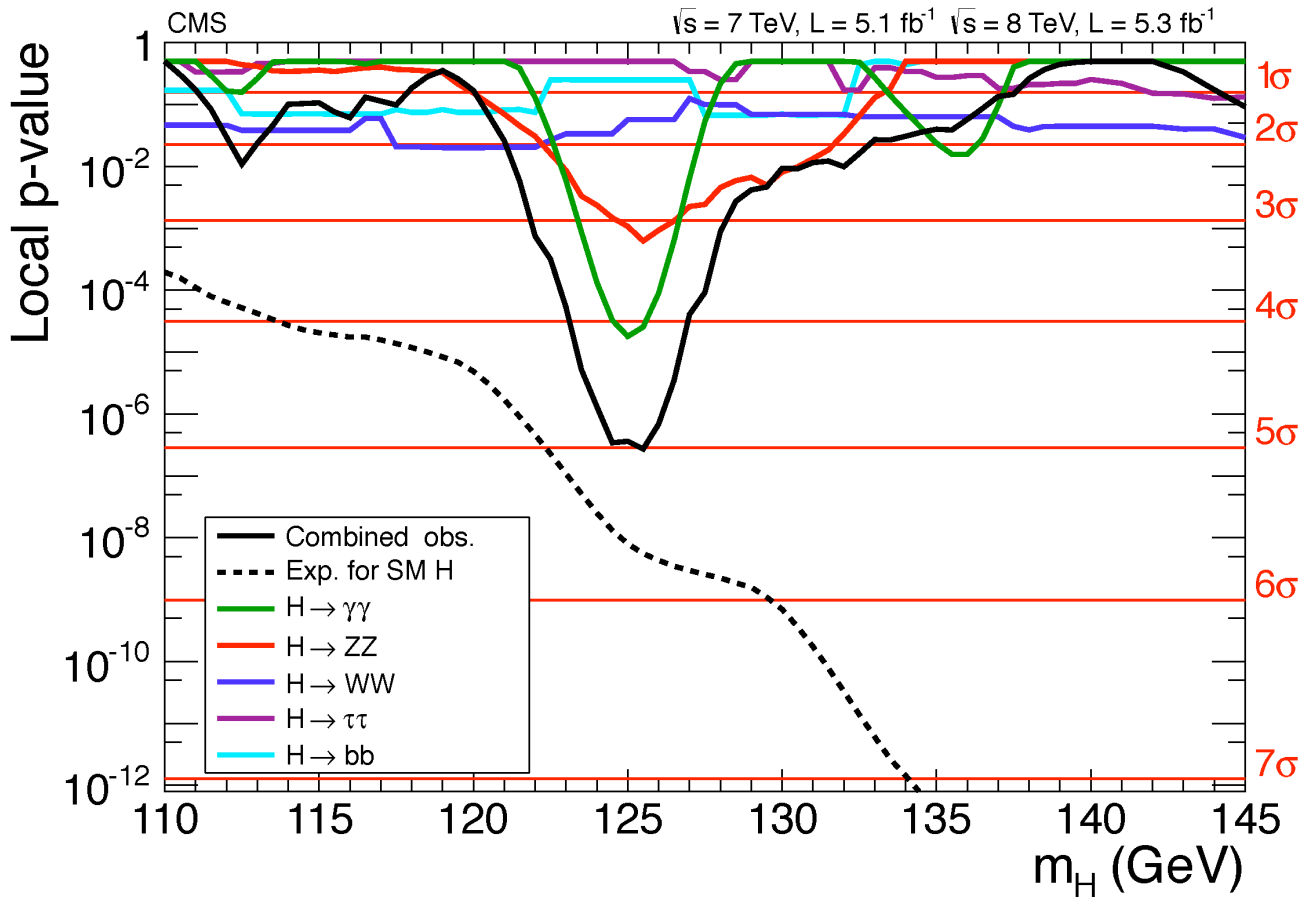
$H \rightarrow WW \rightarrow e\nu\mu\nu$ (Atlas)



- Circa 100 eventi con $S/B \sim 10\%$
- Massa Higgs non ricostruibile, uso della massa trasversa
- Fondo dominante $pp \rightarrow WW; Z+jj$; $pp \rightarrow tt$
- Altri fondi $pp \rightarrow Z+X$; $pp \rightarrow WZ$ etc.

Discovery (CMS)

Phys. Lett. B 716 (2012) 30



Discovery (ATLAS)

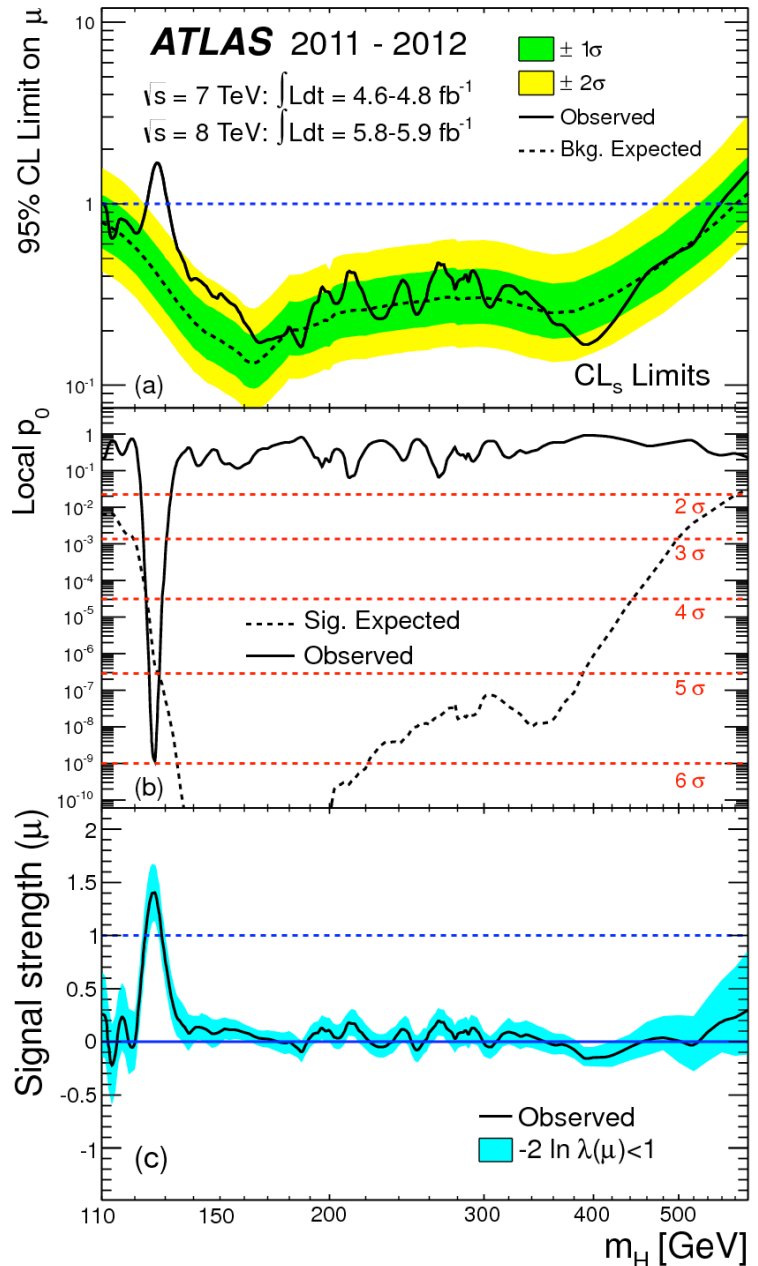
Phys. Lett. B 716 (2012) 1-29

$$CL_s = CL_{(s+b)} / (1 - CL_b)$$

Esprime il livello di confidenza "corretto per l'ipotesi di fluttuazione del fondo" per l'ipotesi di segnale+background

$$p_0 = 1 - CL_b$$

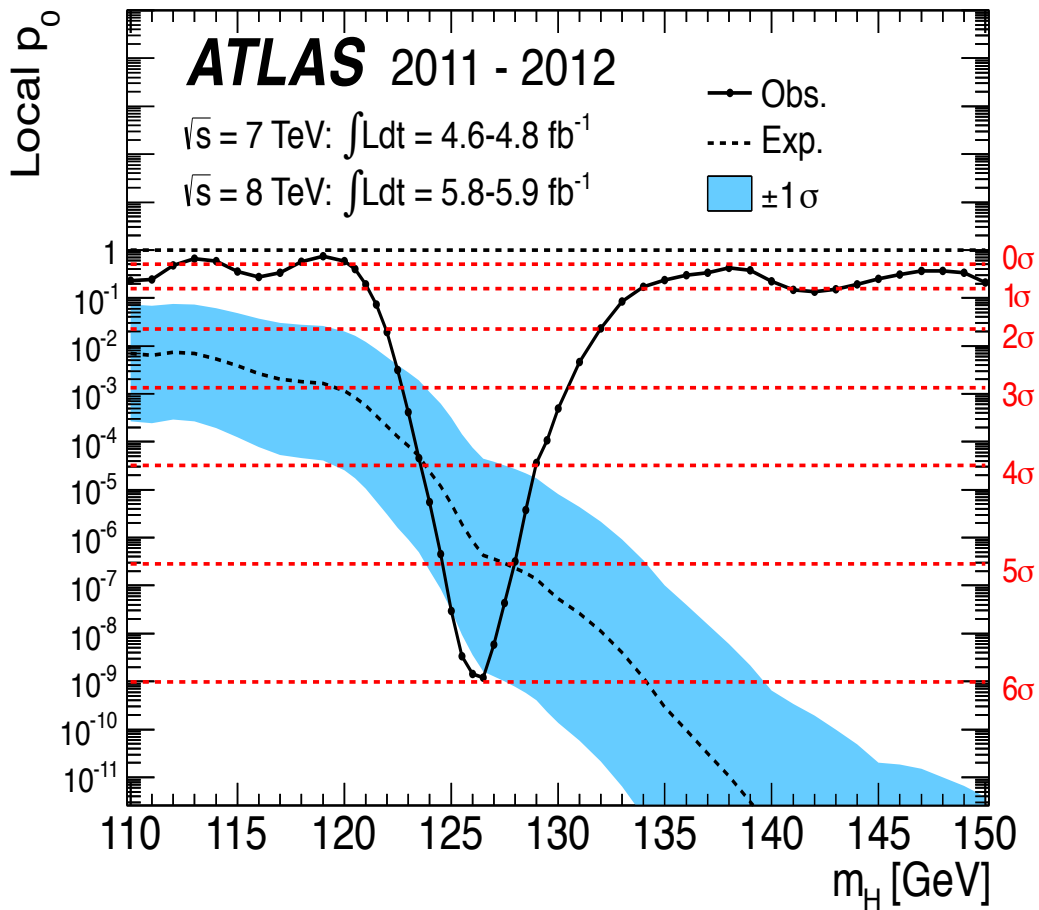
Esprime la probabilita' che data il background atteso osserviamo una deviazione con significanza pari o superiore a quella osservata



- Signal strength $\mu = \sigma * Br / (\sigma * Br)_{SM}$

p0 combinato (ATLAS)

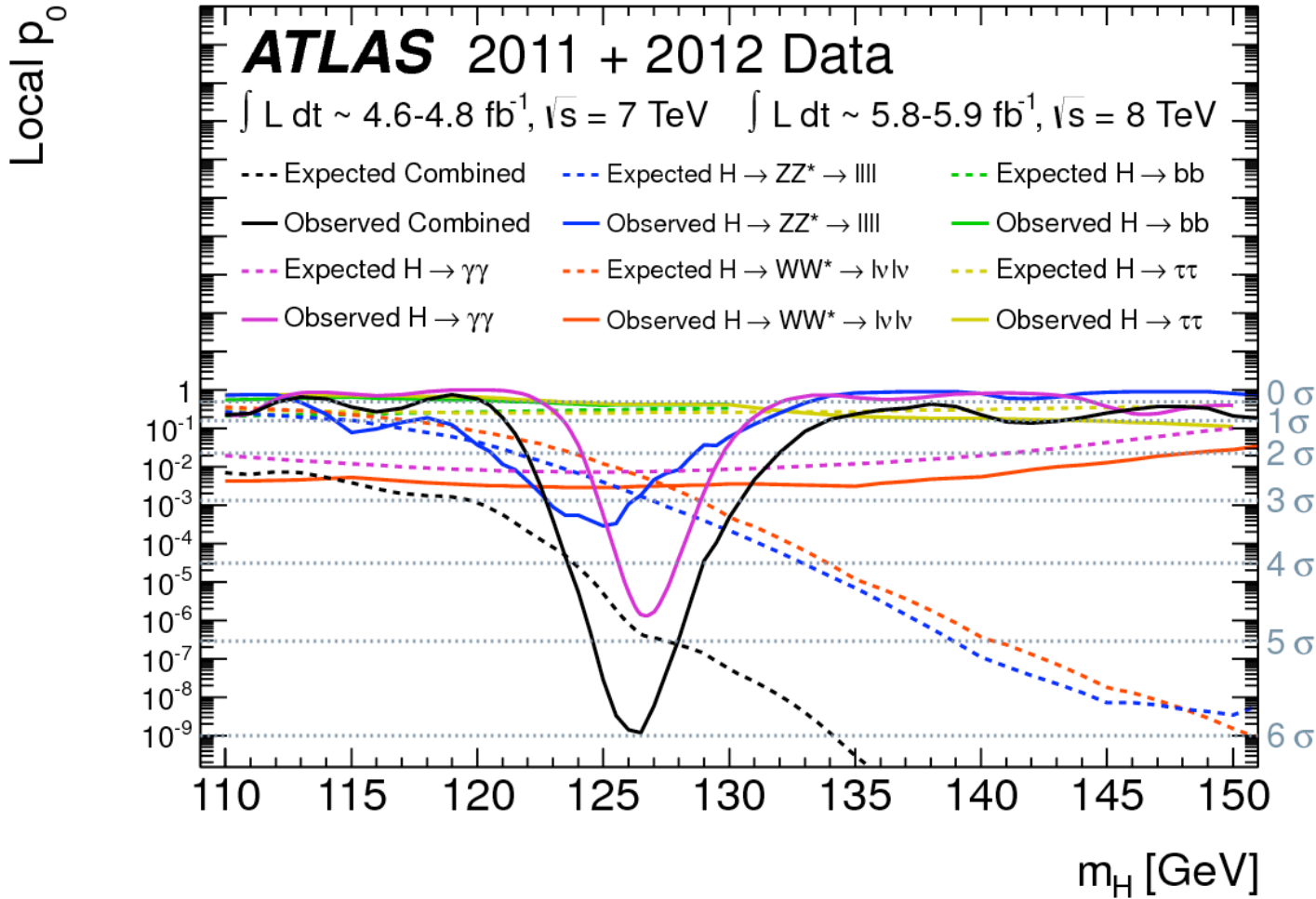
[*Phys. Lett. B 716 \(2012\) 1-2*](#)



- Esattamente 6 sigma ($\gamma\gamma$, WW + ZZ)

p0 per componenti

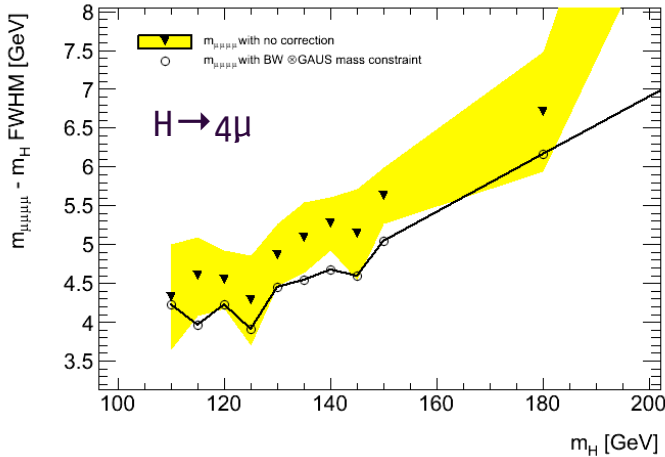
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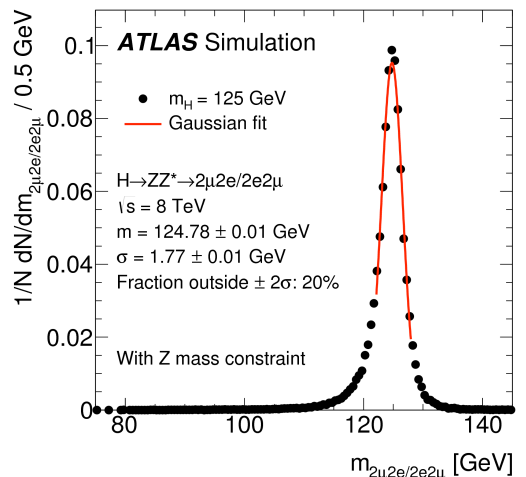
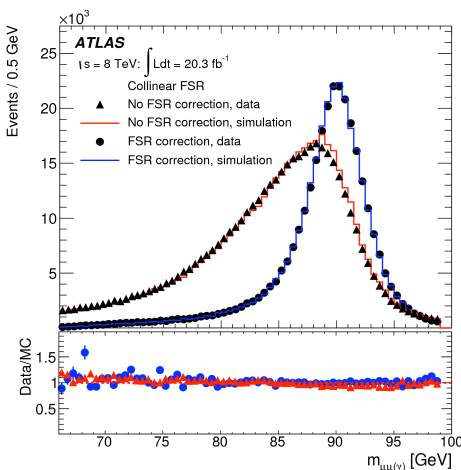
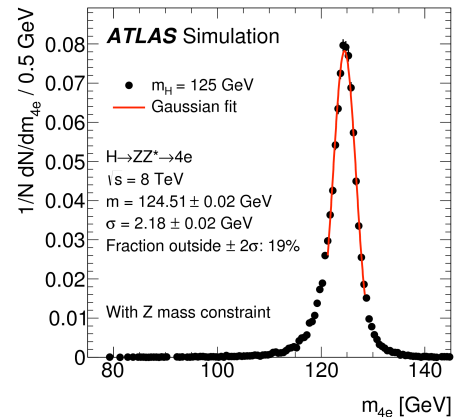
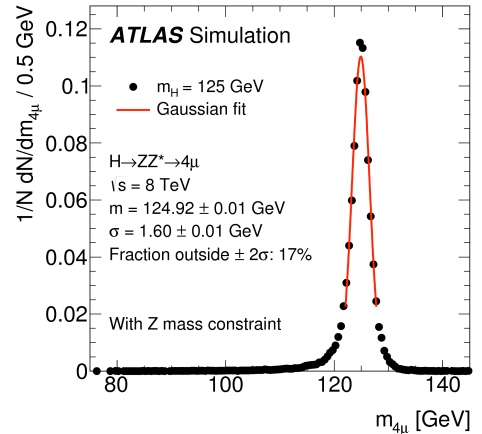
**UPDATE CON TUTTI I DATI
DEL RUN1 A 7+8 TEV DI LHC**

H → ZZ* (latest/ATLAS)

Phys. Rev. D 91, 012006 (2015)

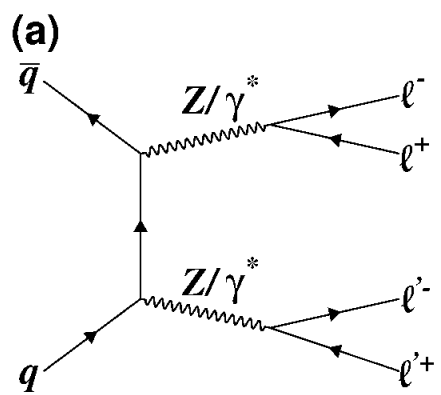
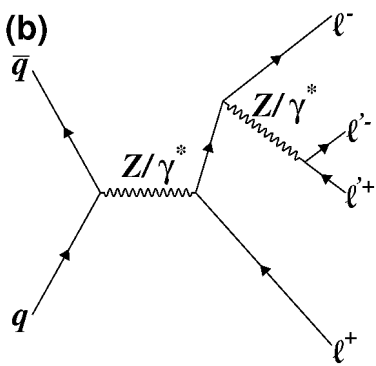
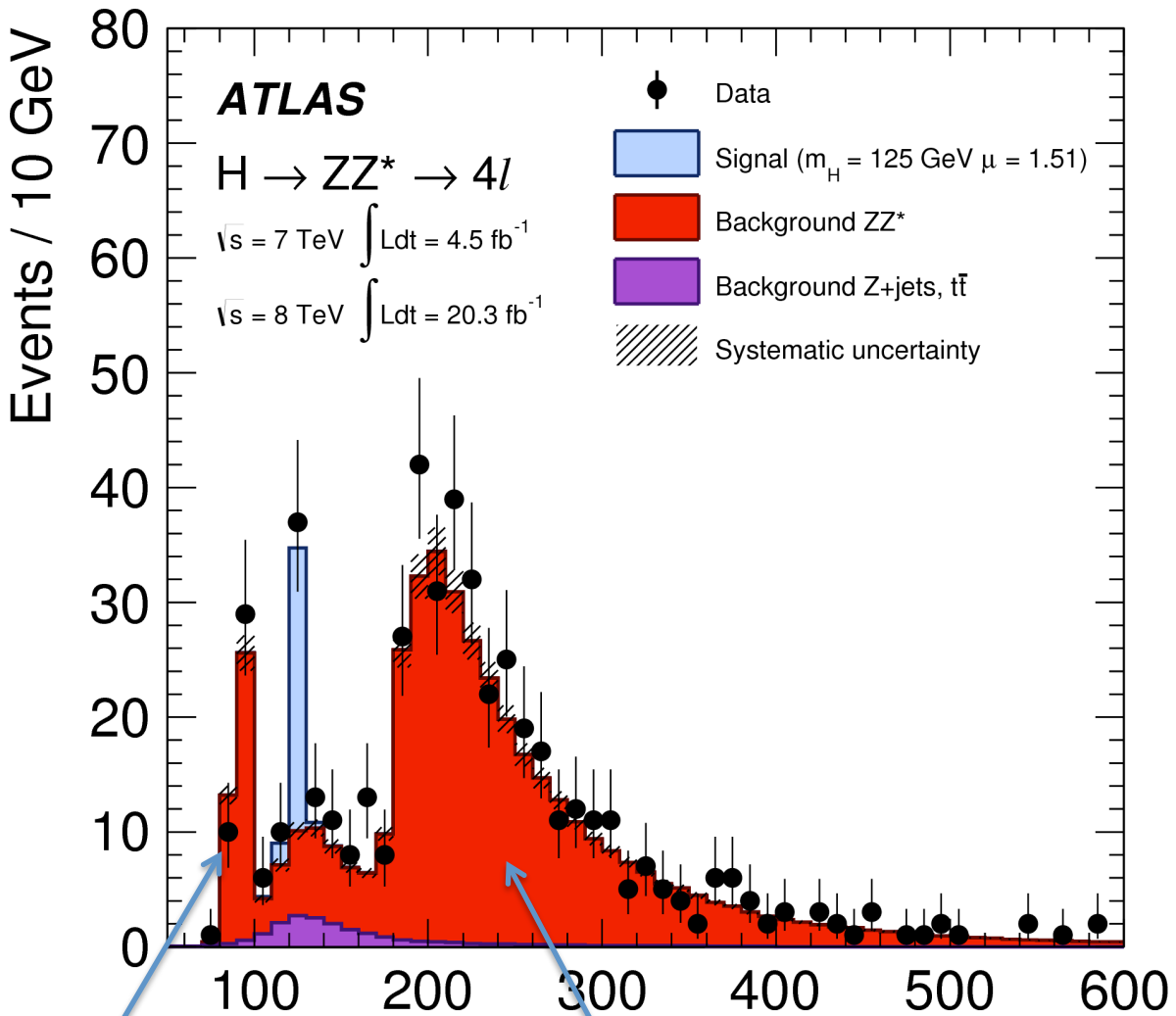


- Due trucchi per migliorare la risoluzione in massa invariante:
- Constraint cinematico alla massa dello Z per una coppia di leptoni
- Recovery dei fotoni emessi per radiazione di stato finale dai muoni



$H \rightarrow ZZ^*$ (latest/ATLAS)

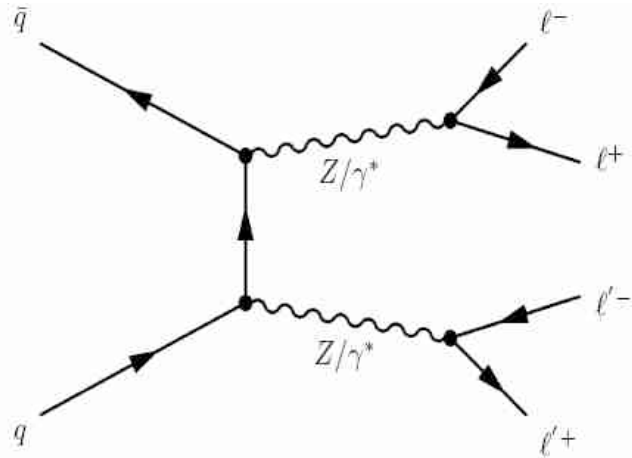
[Phys. Rev. D 91, 012006 \(2015\)](#)



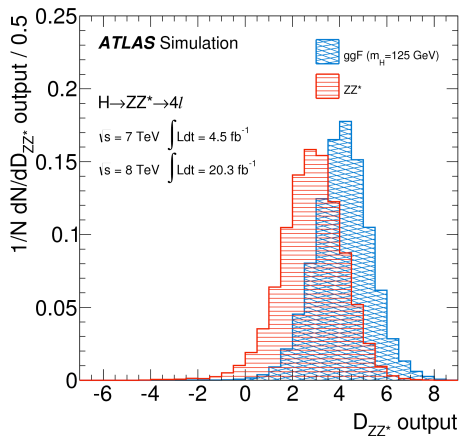
H → ZZ* (latest/ATLAS)

Phys. Rev. D 91, 012006 (2015)

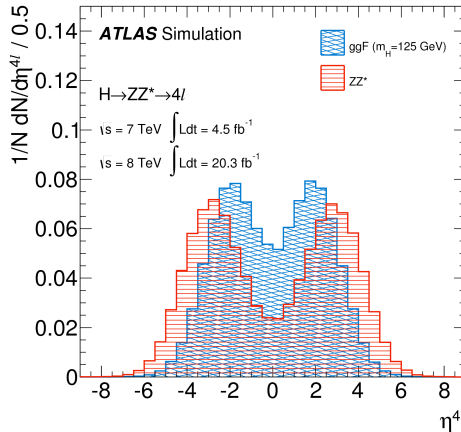
- Soppressione del fondo pp → ZZ utilizzando la differente cinematica e le correlazioni attese nel segnale di Higgs con $J^P=0^+$



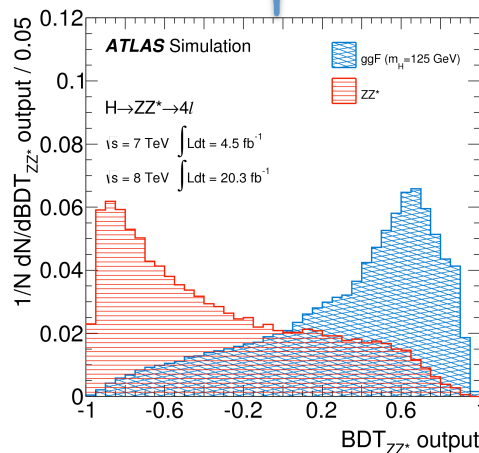
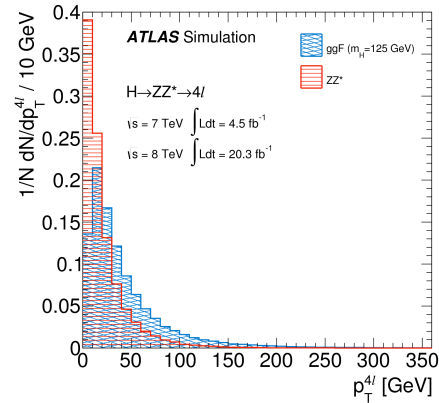
Spin correlations



t channel

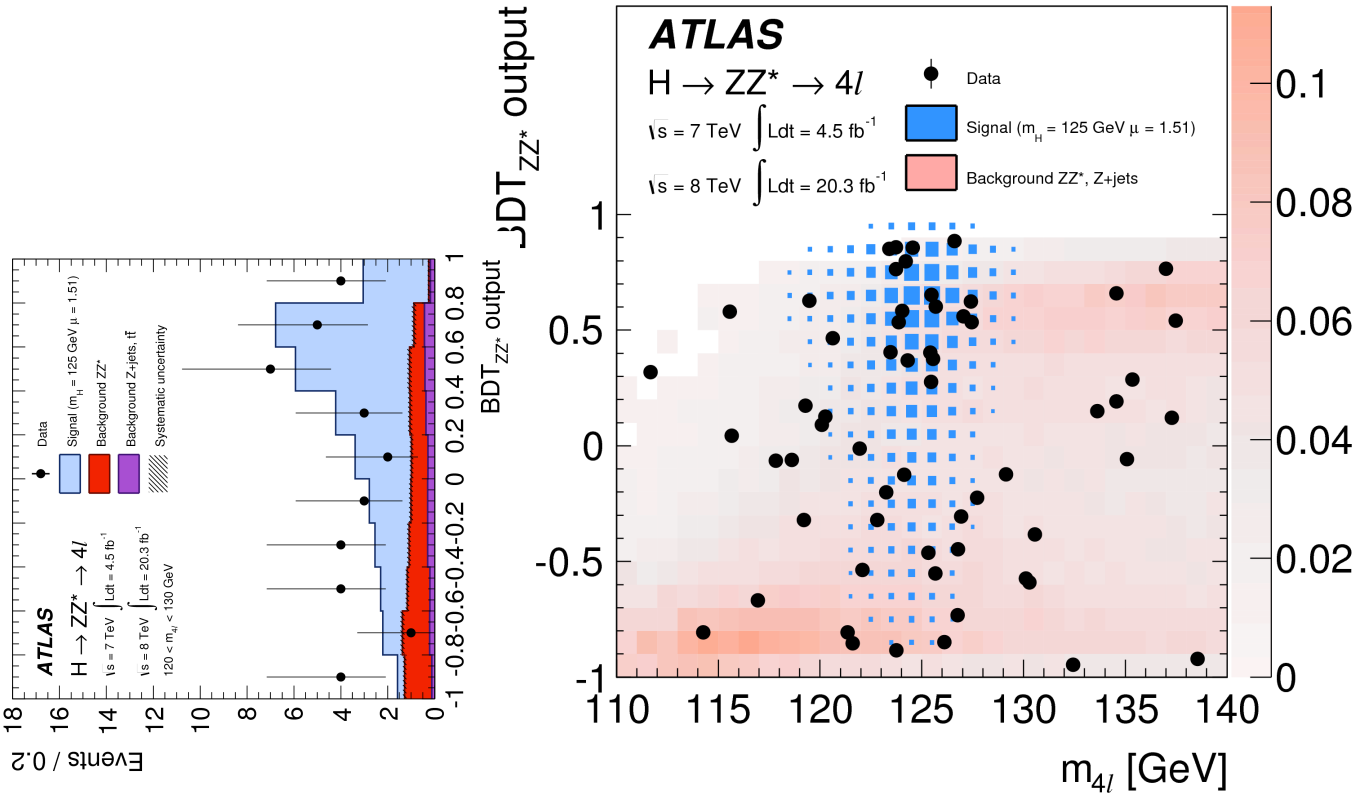


qq inisital state vs gg

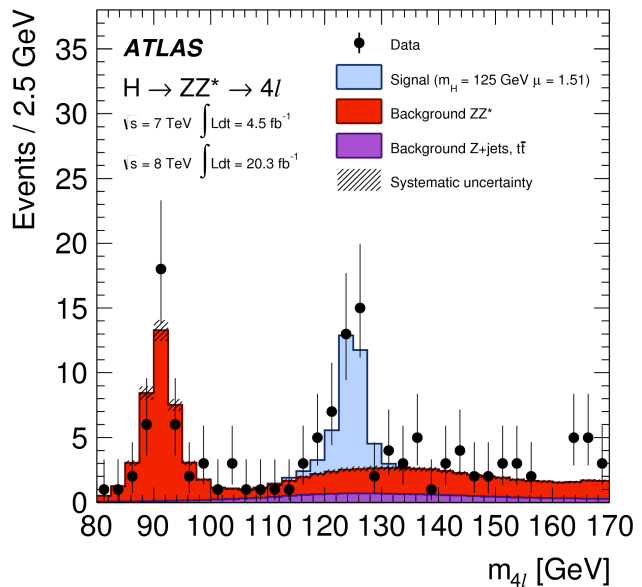


H → ZZ* (latest/ATLAS)

Phys. Rev. D 91, 012006 (2015)

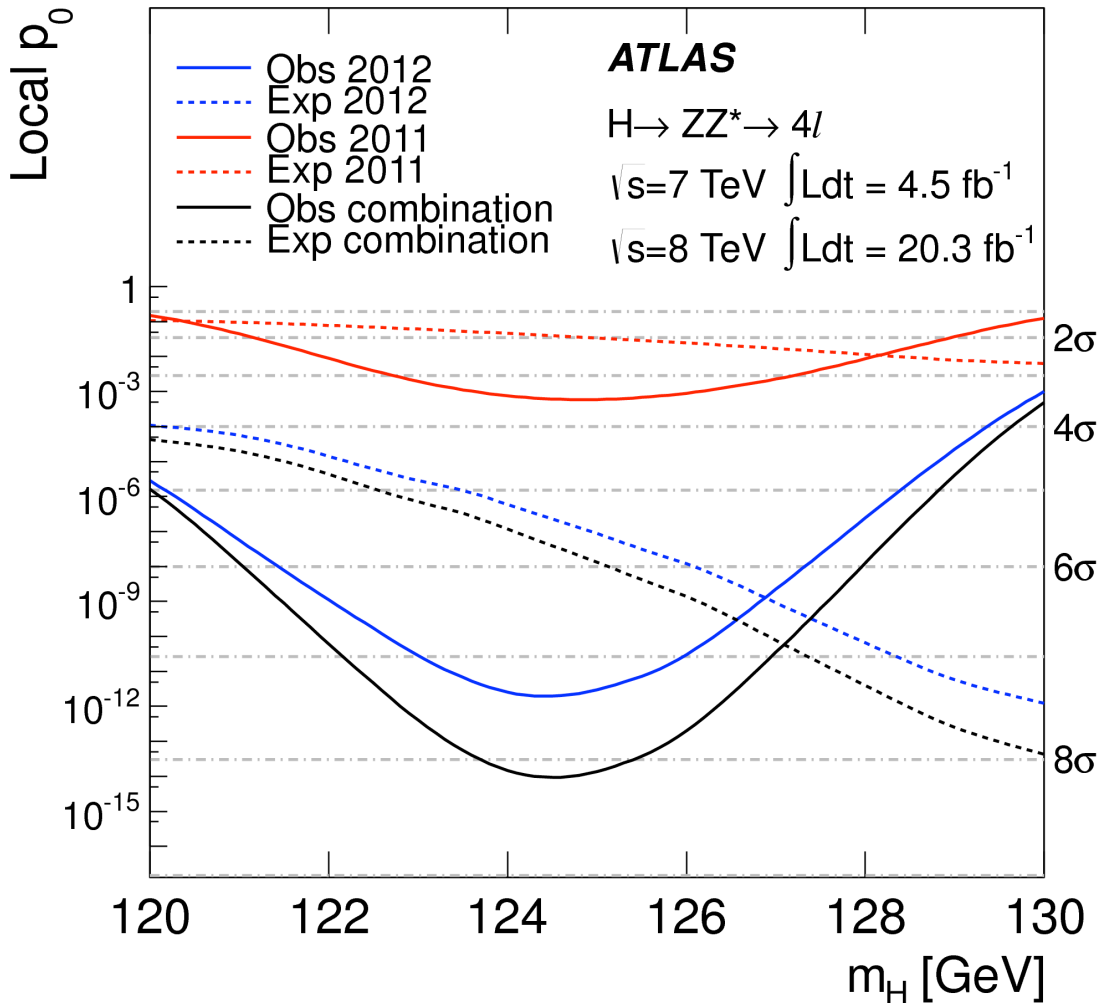


Fit alle distribuzioni
 2D di segnale e fondo



H → ZZ* (latest/ATLAS)

[Phys. Rev. D 91, 012006 \(2015\)](#)



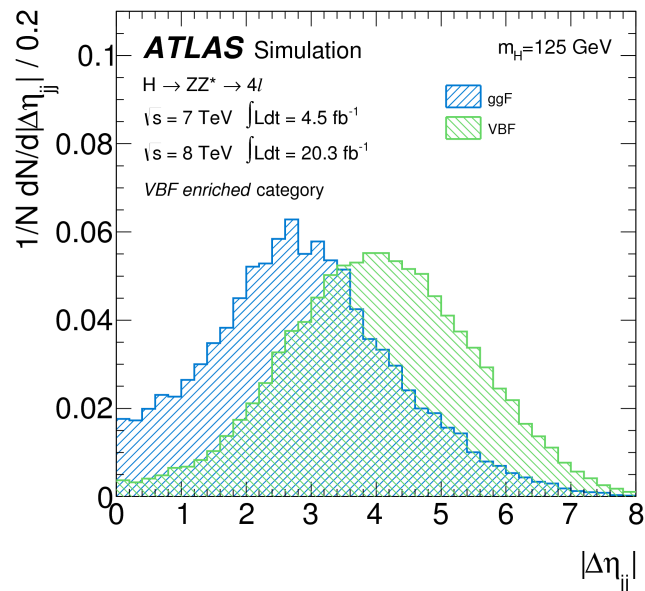
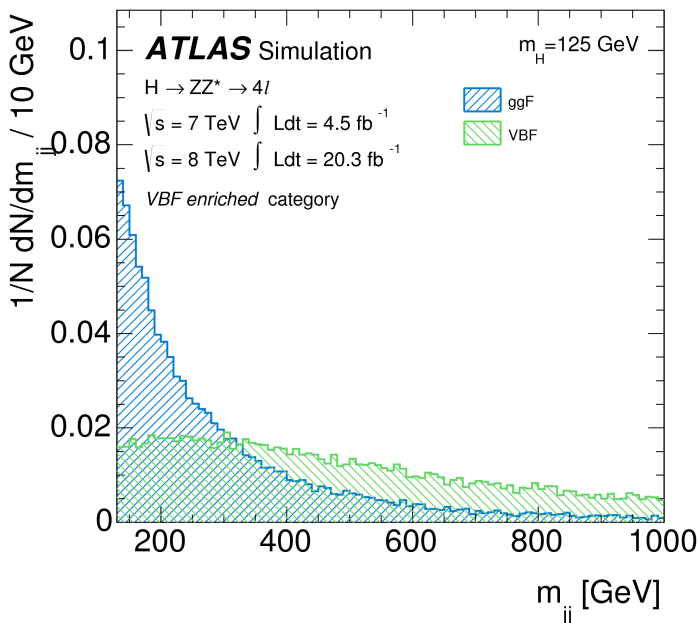
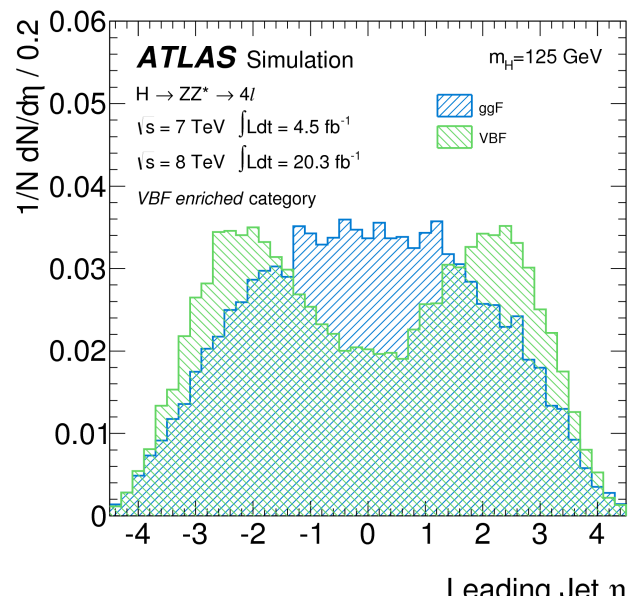
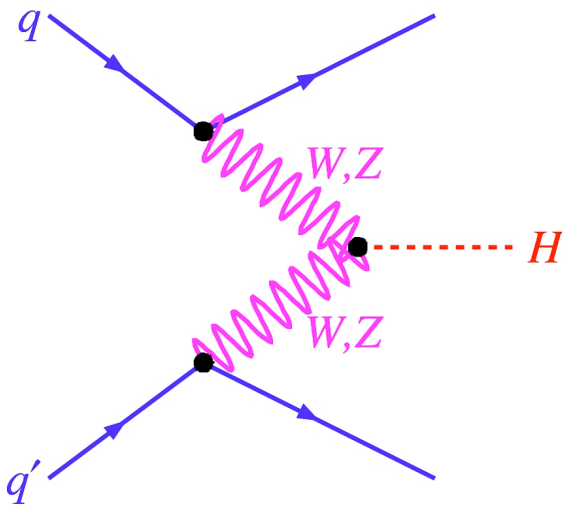
Improved analysis after 2 yr of work

| Reference | Significance | $\mu = \sigma / \sigma_{SM}$ |
|----------------------|--------------|------------------------------|
| ATLAS-CONF-2013-013 | 6.6 σ | $1.7^{+0.5}_{-0.4}$ |
| PRD 91, 012006(5015) | 8,2 σ | $1.44^{+0.44}_{-0.33}$ |

$H \rightarrow ZZ^*$ (latest/ATLAS)

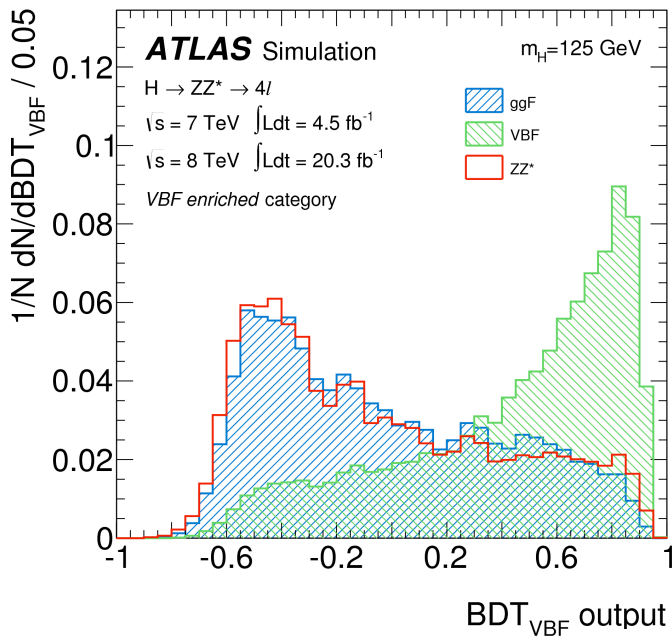
[Phys. Rev. D 91, 012006 \(2015\)](#)

- Separazione della componente VBF, principale “fondo” ggF Higgs+2 jets addizionali



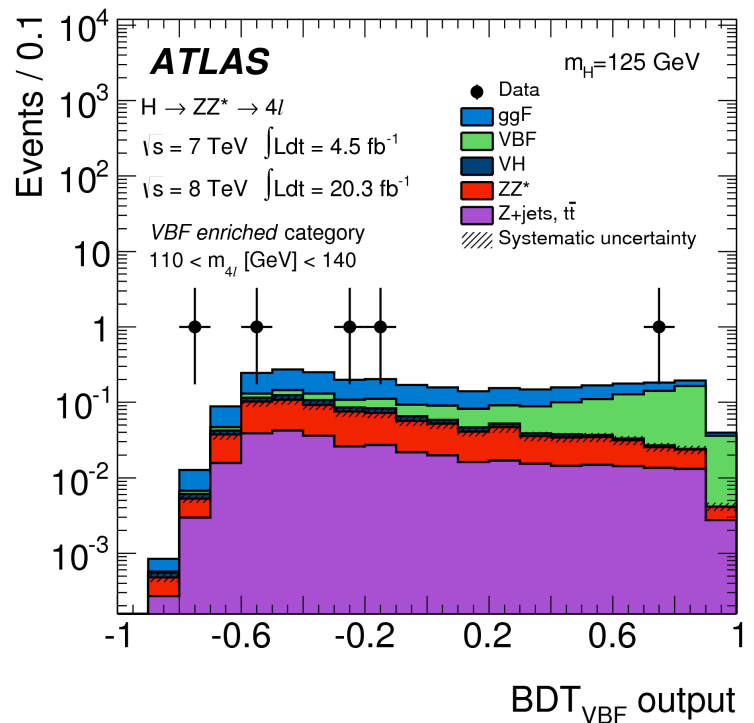
$H \rightarrow ZZ^*$ (latest/ATLAS)

[Phys. Rev. D 91, 012006 \(2015\)](#)



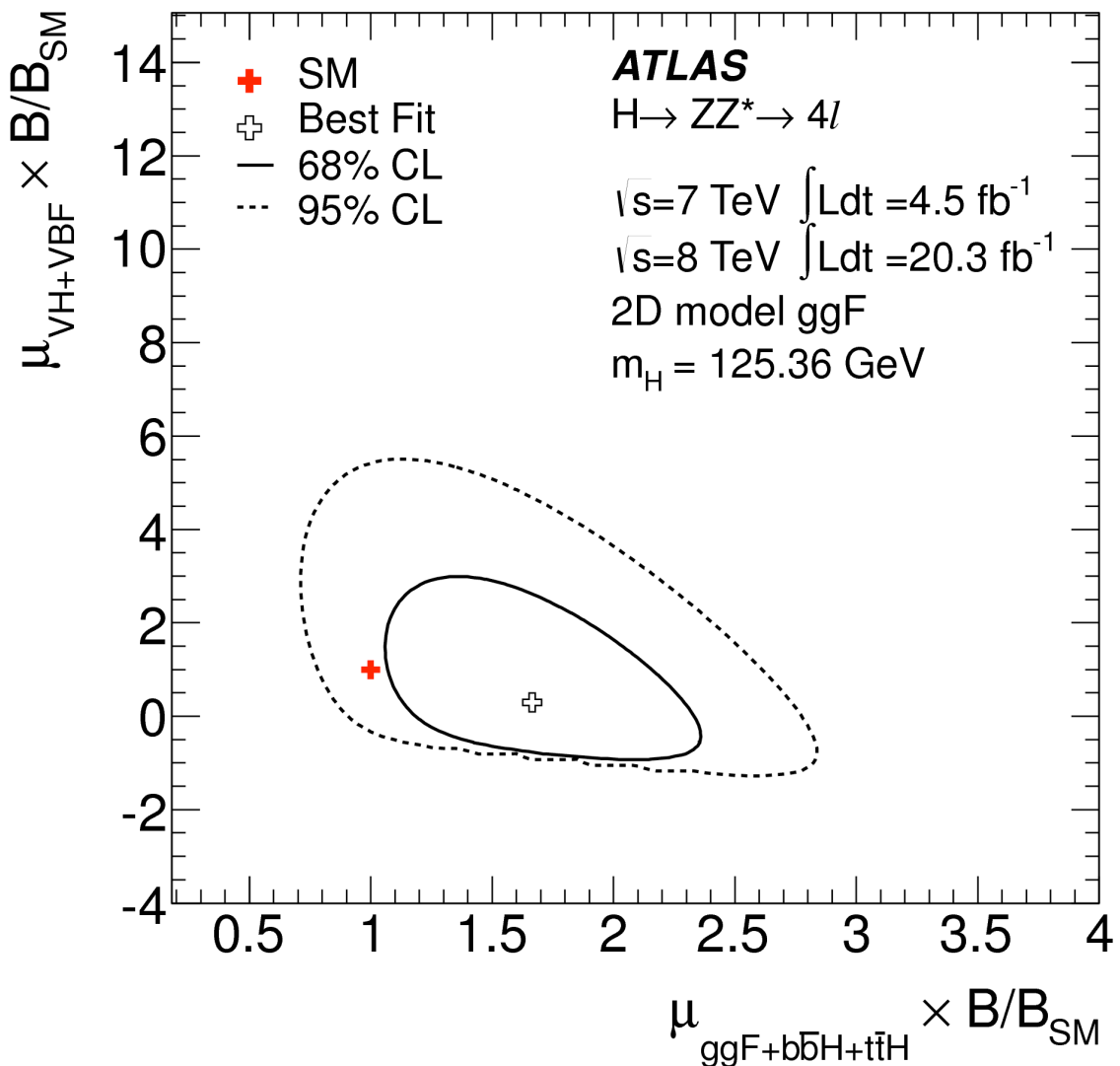
- Discriminante combinato che utilizza le variabili cinematiche VBF

- Discriminante combinato con la normalizzazioni aspettate per segnale ggF, segnale VBF e fondo



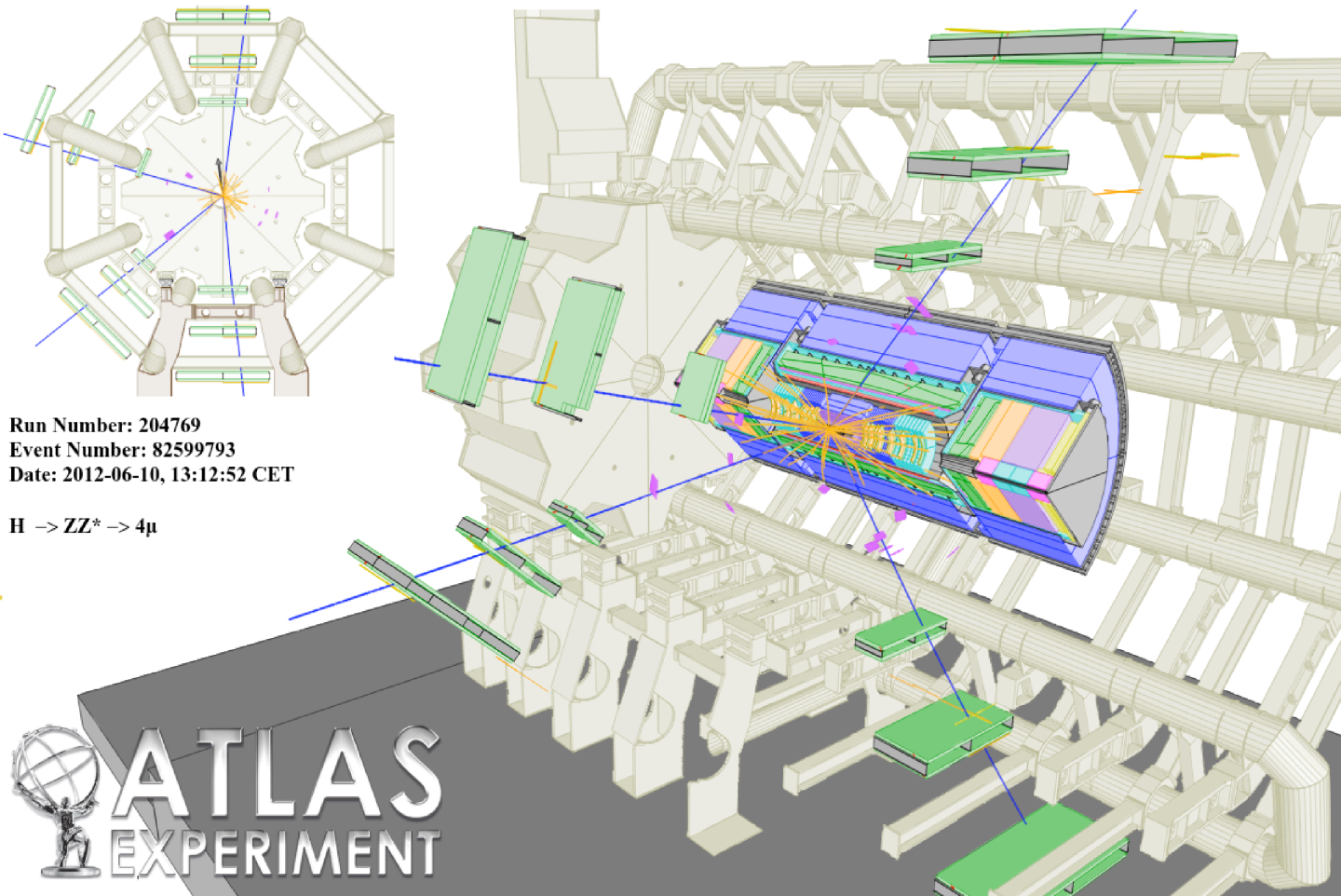
$H \rightarrow ZZ^*$ (latest/ATLAS)

[Phys. Rev. D 91, 012006 \(2015\)](#)



$H \rightarrow ZZ^*$ (latest/ATLAS)

[Phys. Rev. D 91, 012006 \(2015\)](#)



Run Number: 204769
Event Number: 82599793
Date: 2012-06-10, 13:12:52 CET

$H \rightarrow ZZ^* \rightarrow 4\mu$