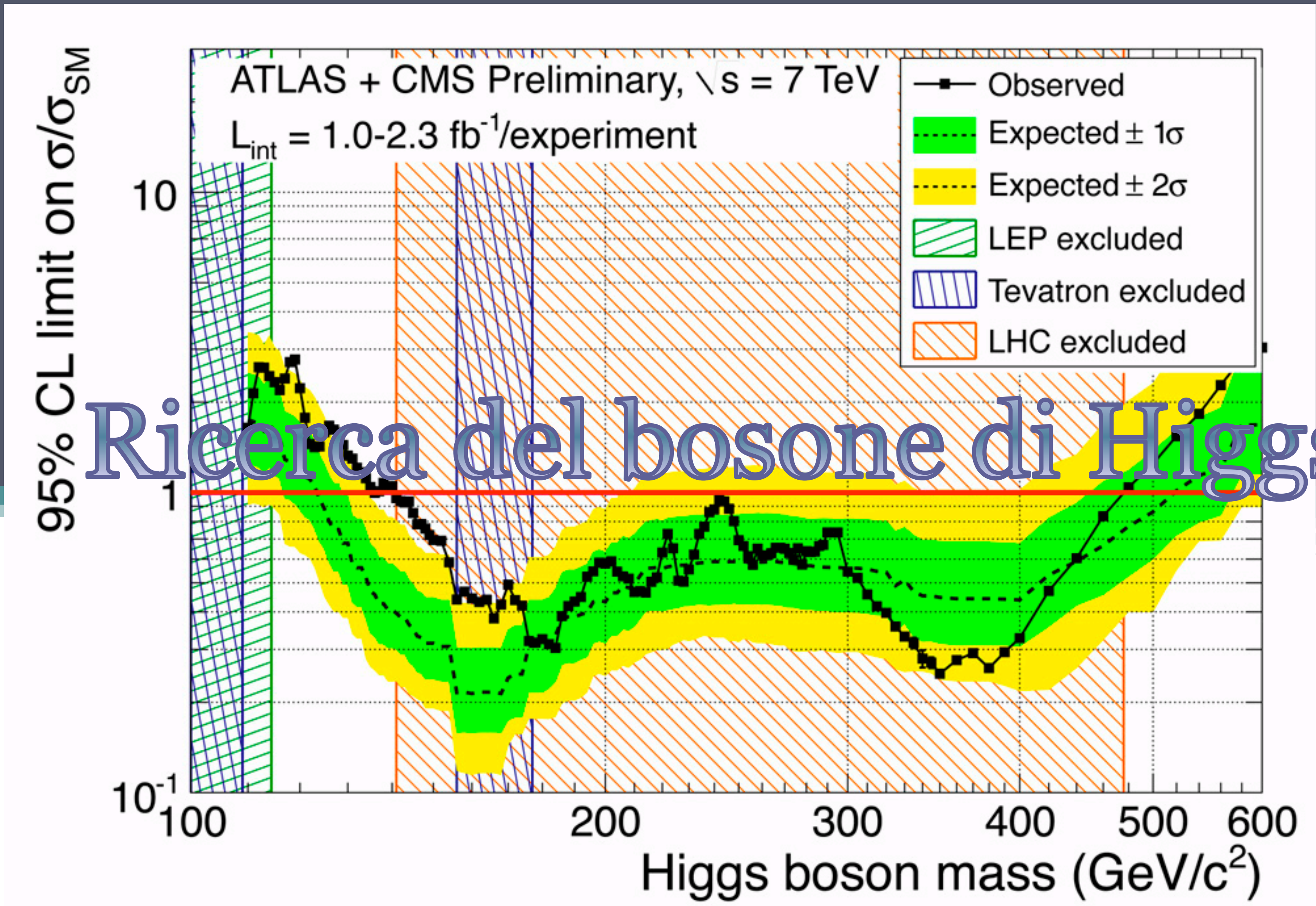
Ricerca del bosone di Higgs



F. Conventi 21/11/2011

Il meccanismo di Higgs nel MS

- Un termine esplicito di massa nella Lagrangiana del MS viola l'invarianza (locale) di gauge
- Un doppietto di Higgs SU(2) è incluso nella Lagrangiana

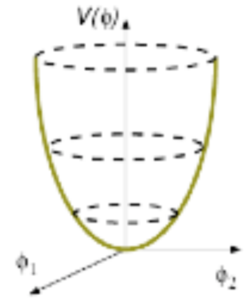
$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi 3 + i\phi_4\end{pmatrix} = \begin{pmatrix}\varphi^+ \\ \varphi^0\end{pmatrix}$$

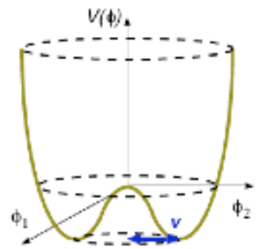
- Il termine di potenziale è dato dall'espressione:

$$V(\Phi) = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

Il potenziale di Higgs

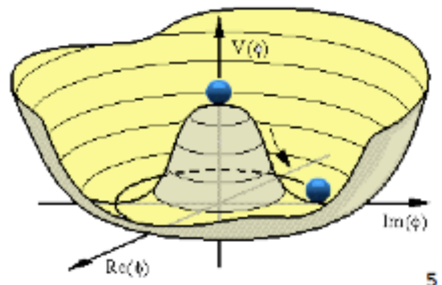
- Lo stato di vuoto ⇒ minimo del potenziale V
- If $\mu^2 > 0$ (massive particle) ⇒ $\Phi_{min} = 0$ (nothing special happens…)
- If $\mu^2 < 0 \Rightarrow \Phi_{min} = \pm v = \pm(-\mu^2/\lambda)^{1/2}$





$v = (\sqrt{2}G_F)^{-1/2} = 246$ GeV

La scelta di un particolare stato di minimo (e.g. at +v) corrisponde ad assegnare allo stato di minimo una particolare direzione nello spazio di isospin ⇒ spontaneous symmetry breaking.



Espandendo **$L = \frac{1}{2}(\partial_\mu\Phi)^2 - \frac{1}{2}\mu^2\Phi^2 - \frac{1}{4}\lambda\Phi^4$** intorno al valore di minimo $\Phi = v + \sigma(x)$ otteniamo:

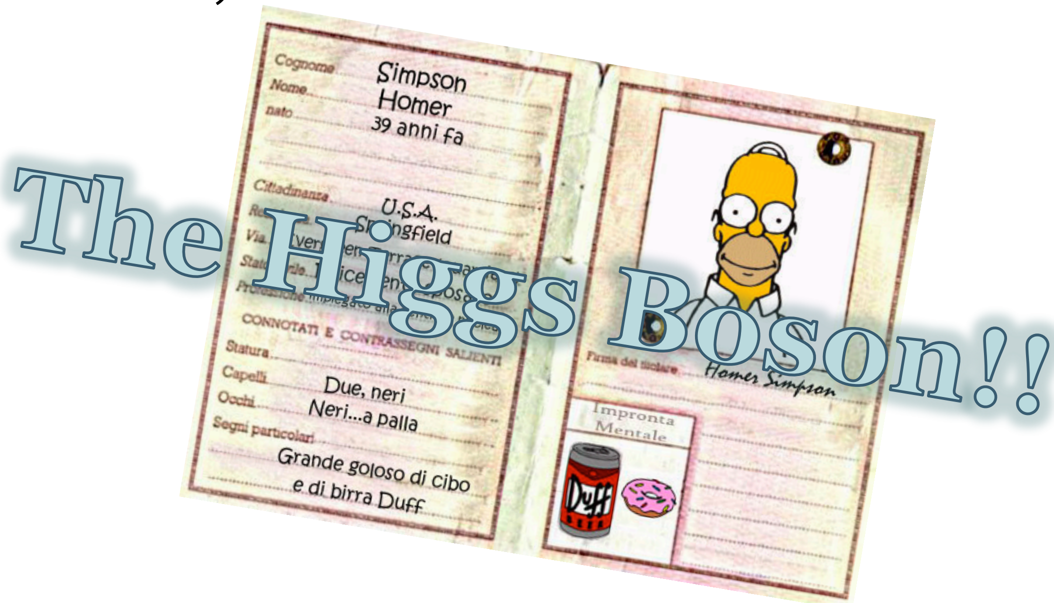
$$L = \frac{1}{2}(\partial_\mu \sigma)^2 - \boxed{\lambda v^2 \sigma^2} - \boxed{\lambda(v\sigma^3 + \frac{1}{4}\sigma^4)}$$

Termine di massa

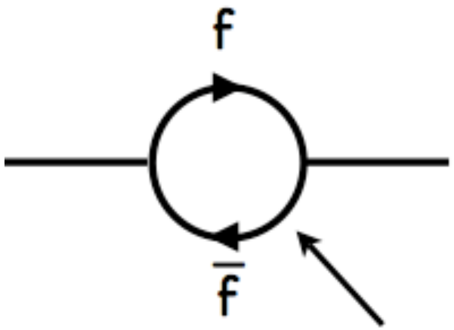
Termine di auto-interazione

Otteniamo una particella scalare, massiva con termini di autointerazione:

Carica	**0**
Spin	**0**
M	**??**



Higgs: fluttuazioni dello stato di vuoto in QFT



Loop: produzione di coppie “virtuali” particelle-antiparticelle

$$\Delta E\, \Delta t < h$$

particelle vituali: hanno gli stessi numeri quantici e proprietà delle particelle reali ma non vale la condizione:

$$E^2 - p^2 = m^2$$

The masses do not emerge alone from the SM.

According to the Standard Model,

the vacuum is filled with a condensate of Higgs particles: quarks, leptons, W and Z bosons continuously collide with these Higgs particles as they travel through the "vacuum". The Higgs condensate acts like molasses and slows down anything that interacts with it. The stronger the interactions between the particles and the Higgs condensate are, the heavier the particles become.

In altri termini:

L’accoppiamento di Higgs è proporzionale alla massa!!


To understand the Higgs mechanism, imagine that a room full of physicists quietly chattering is like space filled only with the Higgs field....
... a well known scientist walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step ...
... this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field ...
... if a rumour crosses the room ...
... it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.

Higgs: cosa sappiamo sul valore di m_H?

Limiti teorici diretti: **Unitarietà**

Consideriamo lo scattering di bosoni W_L ad alta energia (*):

$$W_L^+ W_L^- \rightarrow W_L^+ W_L^-$$

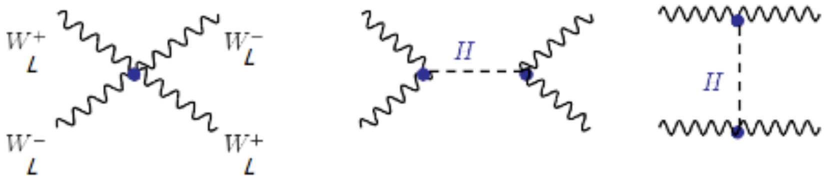


Figure 1.15: Some Feynman diagrams for the scattering of W bosons at high energy.

Per il teorema ottico:

$$\sigma = \frac{1}{s}\,\mathrm{Im}\,[\,A(\theta=0)\,] \;=\; \frac{16\pi}{s}\sum^{\infty}(2\ell+1)|a_\ell|^2$$

$\Rightarrow$ $\mathbf{m_H < 1.2\ TeV}$

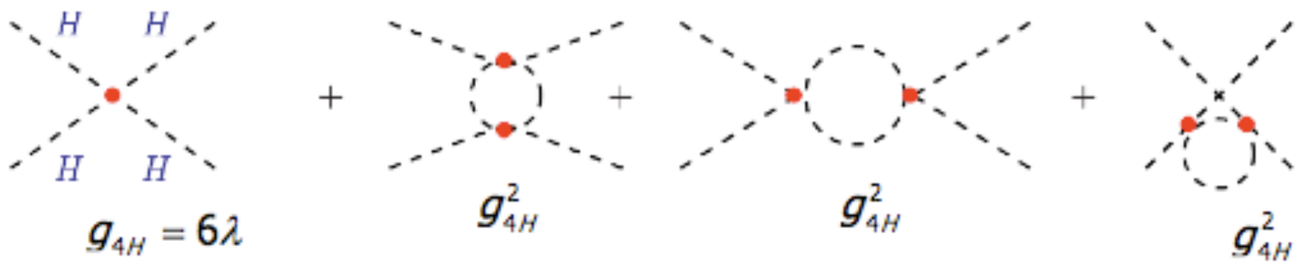
(*) www.roma1.infn.it/people/dionisi/docs_specialistica/higgs-II.pdf

Higgs: cosa sappiamo sul valore di m_H?

Limiti teorici diretti

Triviality bound

- Consideriamo l'accoppiamento quartico tra i bosoni di Higgs e le relative correzioni radiative ad un loop:



dalla rinormalizzazione si ottiene l'equazione per il running coupling:

$$\lambda(Q^2) = \lambda(v^2)\left[1 - \frac{3}{4\pi^2}\lambda(v^2)\log\frac{Q^2}{v^2}\right]^{-1}$$

Higgs: cosa sappiamo sul valore di m_H?

La richiesta che λ rimanga diverso da zero e finito pone dei limiti su M_H.

Per evitare il polo di Landau, infatti, deve essere:

$$\frac{3}{4\pi^2}\lambda(v^2)\log\frac{Q^2}{v^2}<1 \quad\Rightarrow\quad \frac{3}{8\pi^2 v^2}M_H^2\log\frac{Q^2}{v^2}<1 \quad\Rightarrow\quad M_H^2<\frac{8\pi^2 v^2}{3\log\frac{Q^2}{v^2}}$$

Stability bound

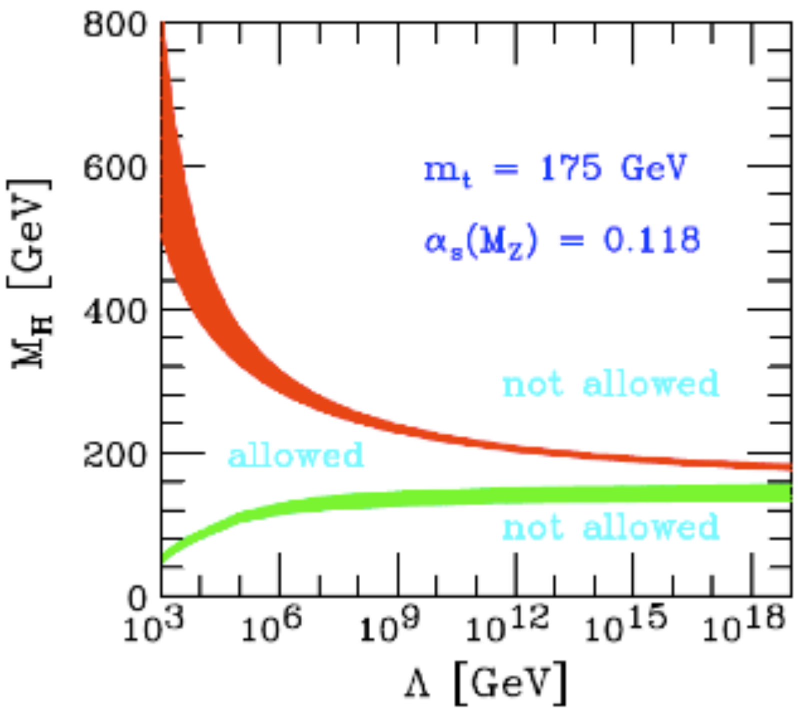
• Finora nel running non abbiamo considerato i contributi dei fermioni e dei bosoni di Gauge.

$$M_H^2>\frac{v^2}{8\pi^2}\left[-12\frac{m_t^4}{v^4}+\frac{3}{16}\left(2g_2^4+(g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

Diagrams for the one–loop contributions of fermions and gauge bosons to λ.

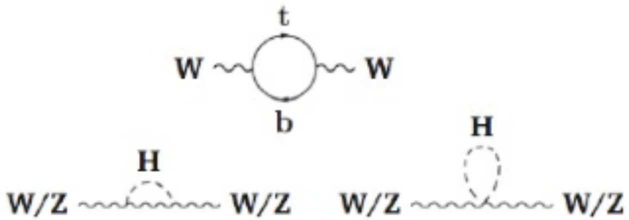
Higgs: cosa sappiamo sul valore di m_H?

Considerando insieme lo Stability e il Triviality Bound si ottengono delle limitazioni su m_H per varie scale di nuova fisica



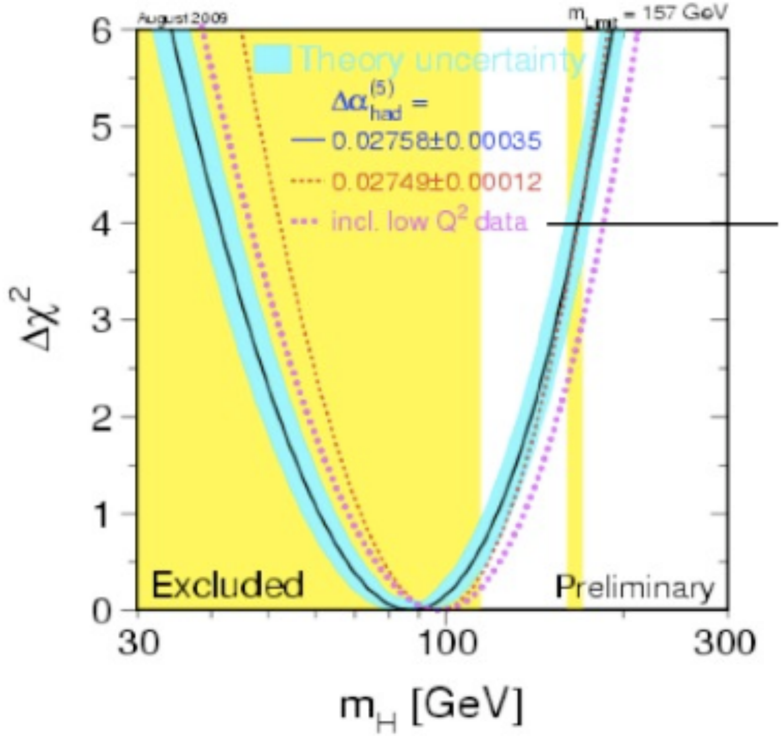
Higgs: cosa sappiamo sul valore di m_H?

Nel MS m_t, m_W e m_H sono legate tramite termini di correzioni radiative del tipo:



- Misure di fisica elettrodebole di alta precisione (ad .es. LEP1,LEP2,Tevatron) sensibli a queste correzioni

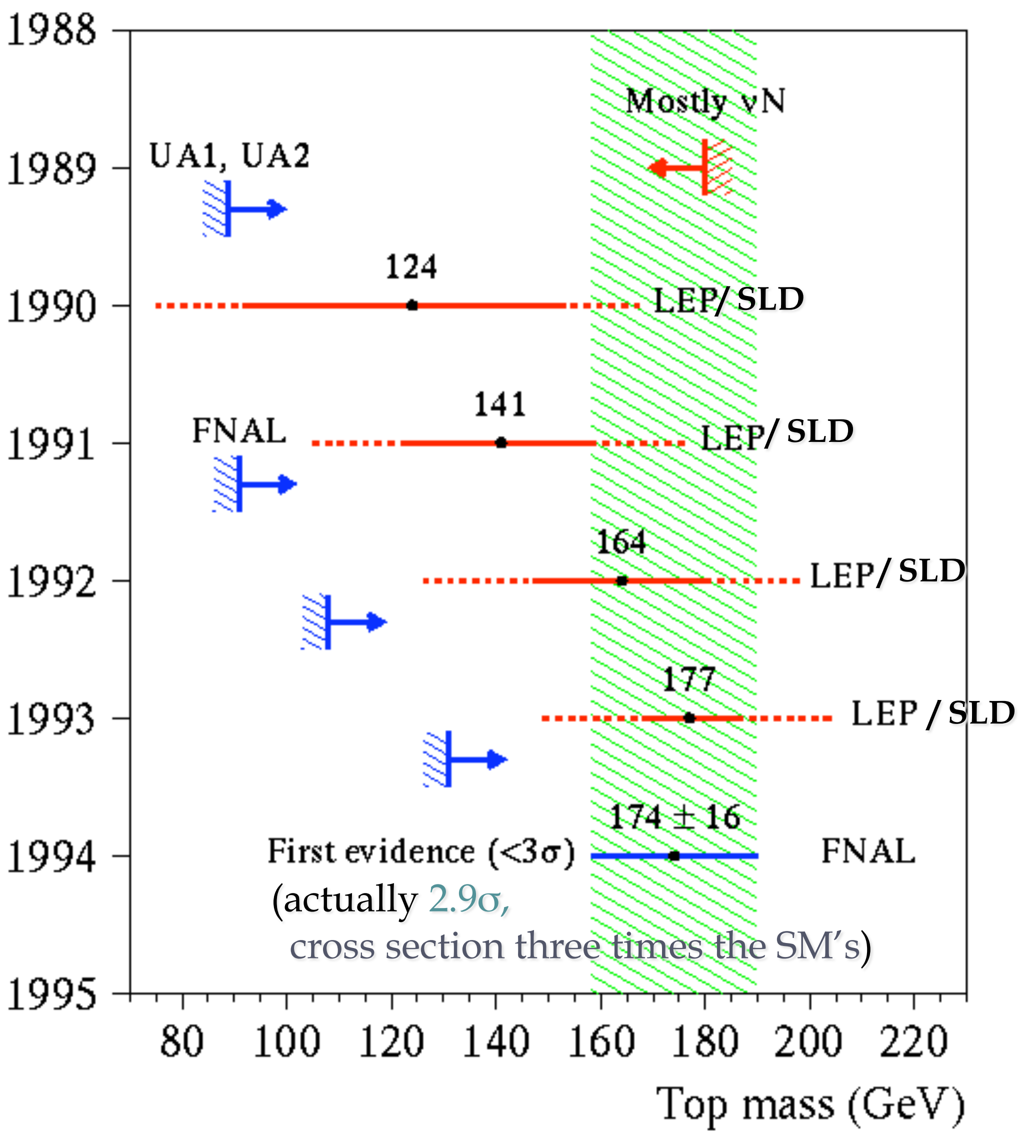
- "Screening effect": le correzioni ad 1 loop sono per m_H di tipo logaritmico (quadratico nel caso di m_T -> cfr. "Scoperta" del top al LEP)



$$M_H = 76^{+33}_{-24}\ \text{GeV}$$
$$M_H < 144\,\text{GeV}\ (95\%\ \text{CL})$$

LEP EWWG, march 2007

Top "discovery" @ LEP



A top mass of 177 GeV/c² was predicted by LEP & SLC with a precision of 10 GeV/c² in March 1994.

One month later, FNAL announced the first 3σ evidence of the top.

In 2001:

$$m_{\rm top}^{\rm EW} = 180.5 \pm 10.0\ {\rm GeV}/c^2$$

$$m_{\rm top}^{\rm direct} = 174.3 \pm 5.1\ {\rm GeV}/c^2$$

Perfect consistency between prediction and direct measurement. Allows a global fit of the SM (with m_H) to be performed.

Ricapitolando….

- Il meccanismo di Higgs è introdotto nel MS per generare I termini di massa.

- Nella Lagrangiana viene introdotto un doppietto di Higgs Φ con un termine di autointerazione

- "Prima" della ***spontaneous symmetry breaking*** i bosoni Wi, B and complex Φ Higgs sono privi di massa

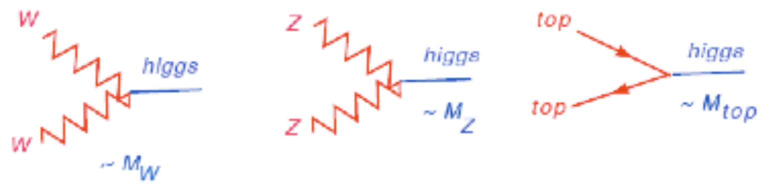
- v.e.v. ≠ 0 viola la simmetria di gauge (locale) SU(2) x U(1)
- Dopo la ***spontaneous symmetry breaking***: W± and Z hanno massa, γ è privo di massa, Higgs boson H
- Il meccanismo introduce 2 soli nuovi parametri: la massa dell'Higgs (M_H) e il v.e.v. (v). L'accoppiamento è, per costruzione, **proporzionale alle masse.**

- Il meccnismo di Higgs rappresenta una possibilità tra tante ma ha il pregio di essere semplice, alquanto "naturale" all'interno dell'apparato teorico del MS e soprattutto….**verificabile con misure sperimentali!!**

Higgs Hunter’s Guide: produzione

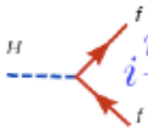
Una particella elementare neutra
con termini di autointerazione

I termini di interazioni sono maggiori
nel caso di particelle con alta massa
(e bassa vita media)



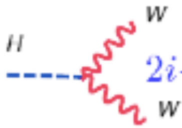
Difficile da “trovare” in quanto l’interazione di H con le particella che sono utlizzate ai collider (e, u, d) è molto debole -> negli esperimenti ai colliders Higgs viene prodotto “indirettamente” da stati quali W, Z, top

Higgs: Accoppiamenti



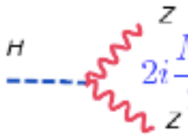
$$i\frac{m_f}{v}\delta_{ij}$$

$$\Gamma\left(H \to f\bar{f}\right) = \frac{M_H}{8\pi}\left(\frac{M_f}{v}\right)^2 N_c \left(1 - \frac{4M_f^2}{M_H^2}\right)^{\frac{3}{2}}$$



$$2i\frac{M_W^2}{v}g_{\mu\nu}$$

$$\Gamma\left(H \to WW\right) = \frac{M_H}{16\pi}\left(\frac{M_H}{v}\right)^2 \left(1 - \frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}} \times \left[1 - 4\left(\frac{M_W^2}{M_H^2}\right) + 12\left(\frac{M_W^2}{M_H^2}\right)^2\right]$$



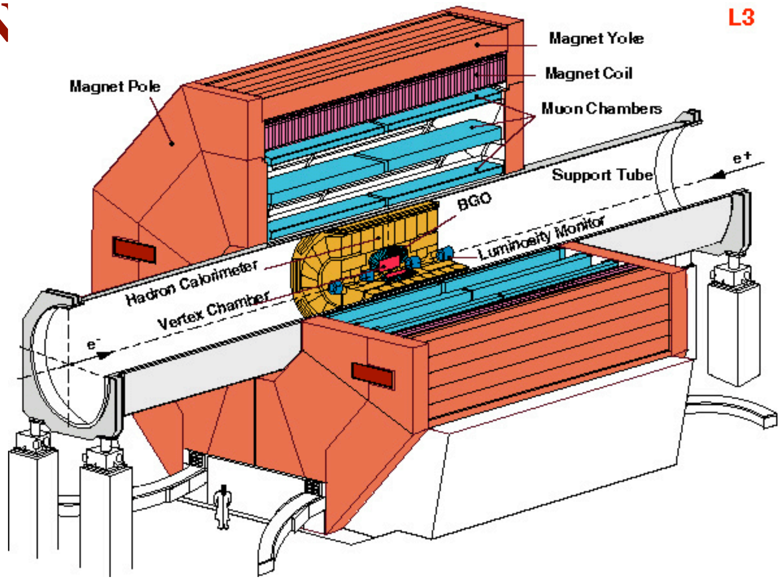
$$2i\frac{M_Z^2}{2v}g_{\mu\nu}$$

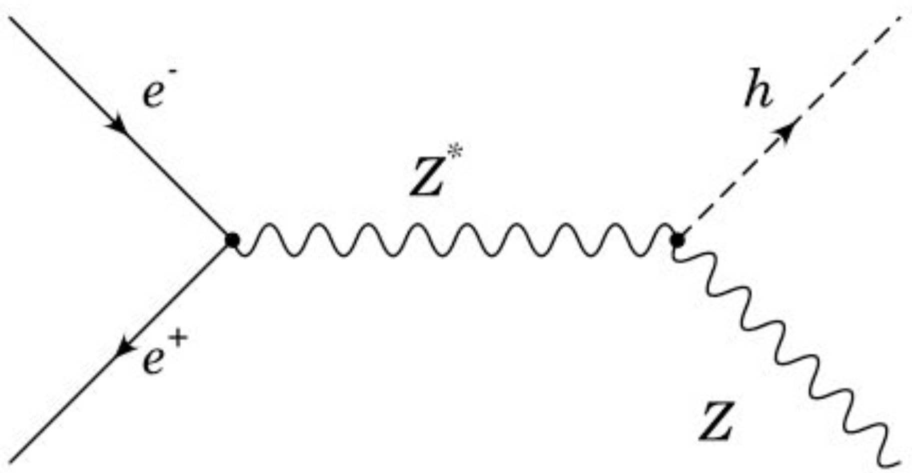
$$\Gamma\left(H \to ZZ\right) = \frac{M_H}{32\pi}\left(\frac{M_H}{v}\right)^2 \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}} \times \left[1 - 4\left(\frac{M_Z^2}{M_H^2}\right) + 12\left(\frac{M_Z^2}{M_H^2}\right)^2\right]$$

Higgs Hunter's Guide: produzione

LEP Electron-positron collider @CERN

- 27 km circonferenza
- Presa dati dal <u>1989 al 2000</u>
- $(\sqrt{s})_{max} = 209$ GeV
- 4 detectors: ALEPH, DELPHI, OPAL and L3





Higgsstrahlung

Higgs Hunter's Guide: produzione

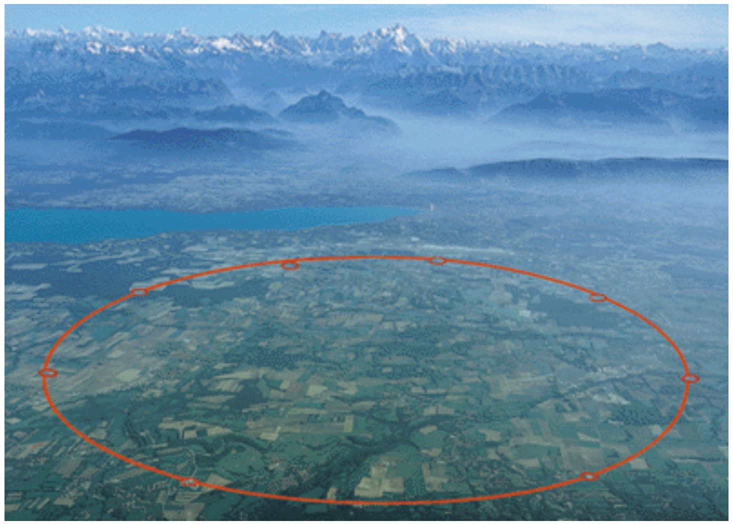
Tevatron Collider@Fermilab

- 6.5 km circonferenza
- Presa dati:

  RunI dal 1990 al 1996

  RunIIa dal 2001 al 2006

  RunIIb dal 2006 ad oggi
- $(\sqrt{s})_{max}$ = 1.96 TeV
- 2 detectors: D0 e CDF



LHC@CERN

- 27 km circonferenza
- Presa dati:

  RunI dal 2009 → in corso
- $(\sqrt{s})_{max}$ = 7 TeV
- 4 detectors: ATLAS, CMS, Alice, LHCB

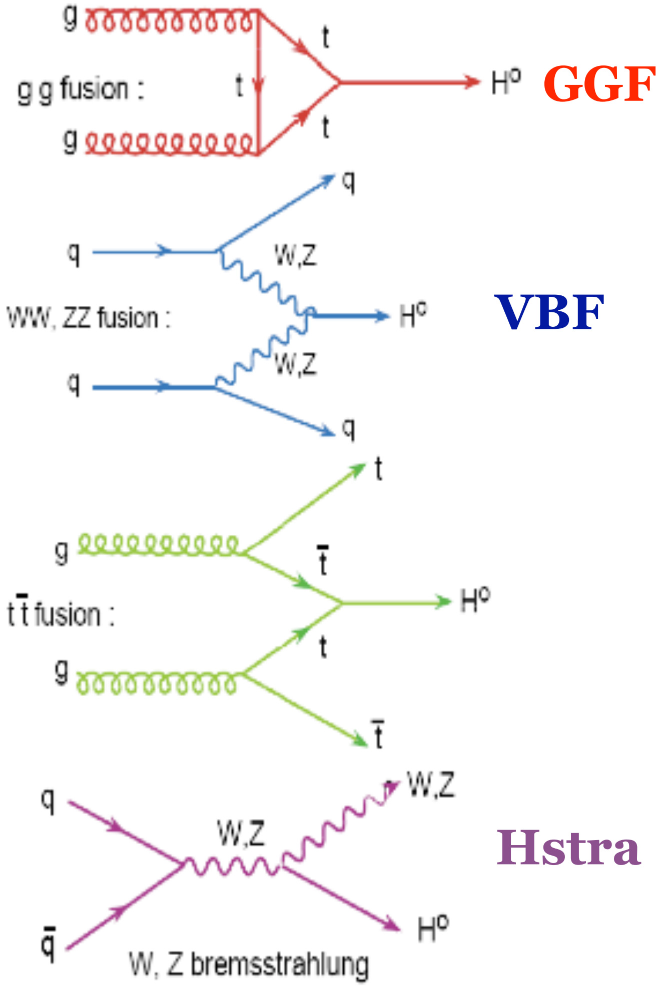
Higgs Hunter's Guide: produzione

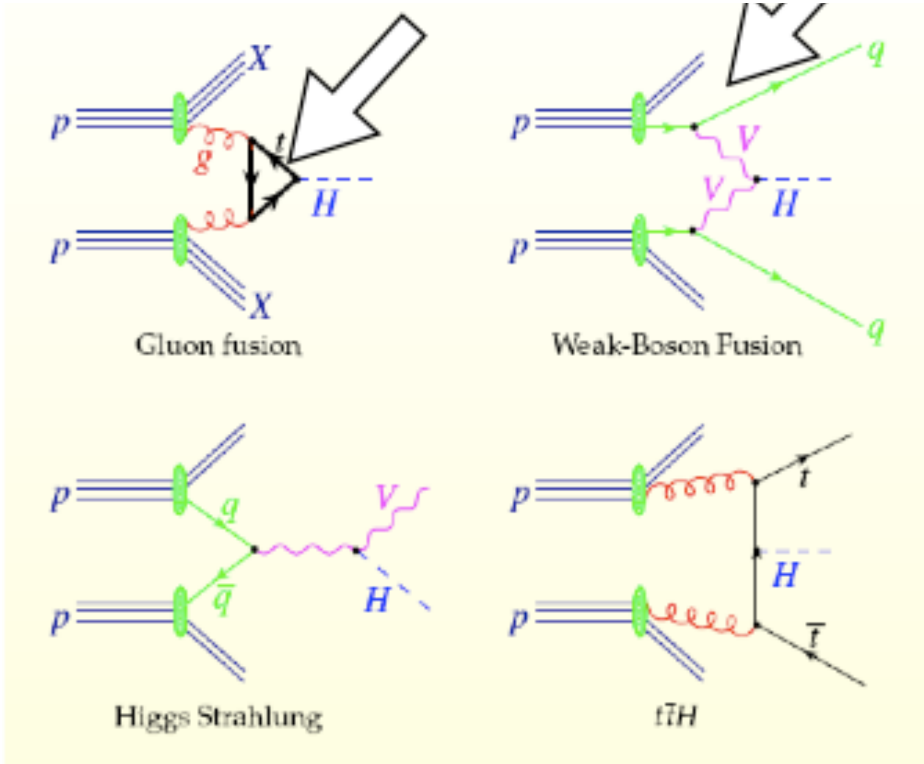
Comparison of the LHC and Tevatron machine parameters

	LHC (design)	Tevatron (achieved)
Centre-of-mass energy	14 TeV	1.96 TeV
Number of bunches	2808	36
Bunch spacing	25 ns	396 ns
Energy stored in beam	360 MJ	1 MJ
Peak Luminosity	10^{33}-10^{34} $cm^{-2}s^{-1}$	4 x 10^{32} $cm^{-2}s^{-1}$
Integrated Luminosity / year	10-100 fb^{-1}	~ 2 fb^{-1}

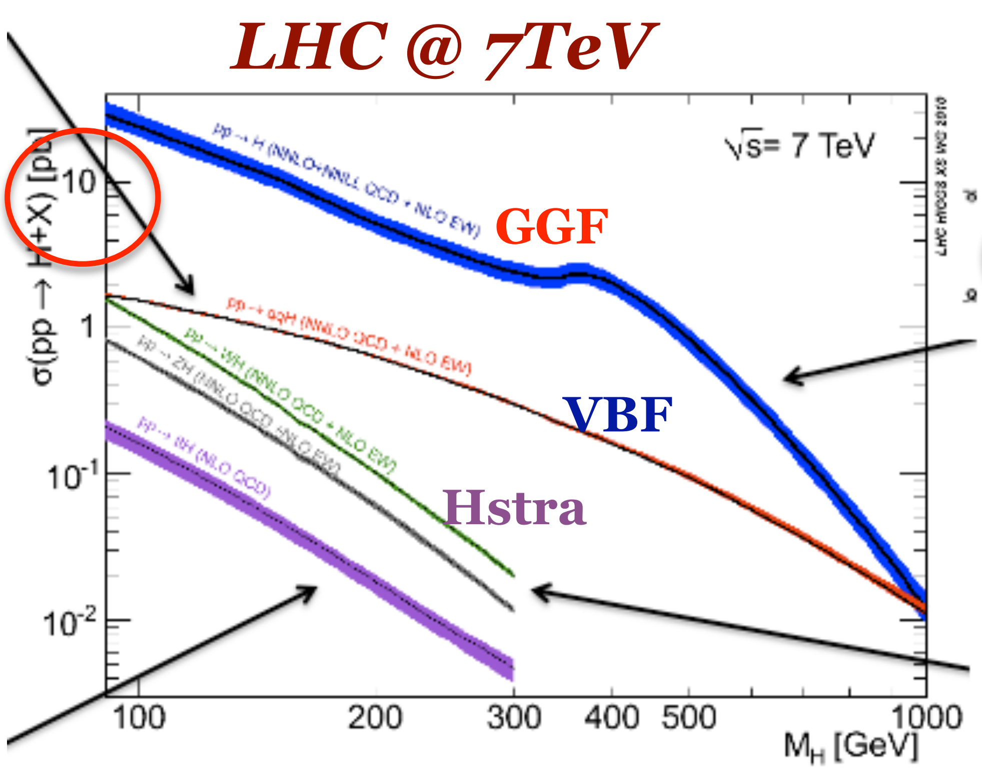
- 7 times more energy (after initial 3.5 TeV phase)
- Factor 3-30 times more luminosity
- Physics cross sections factor 10-100 larger

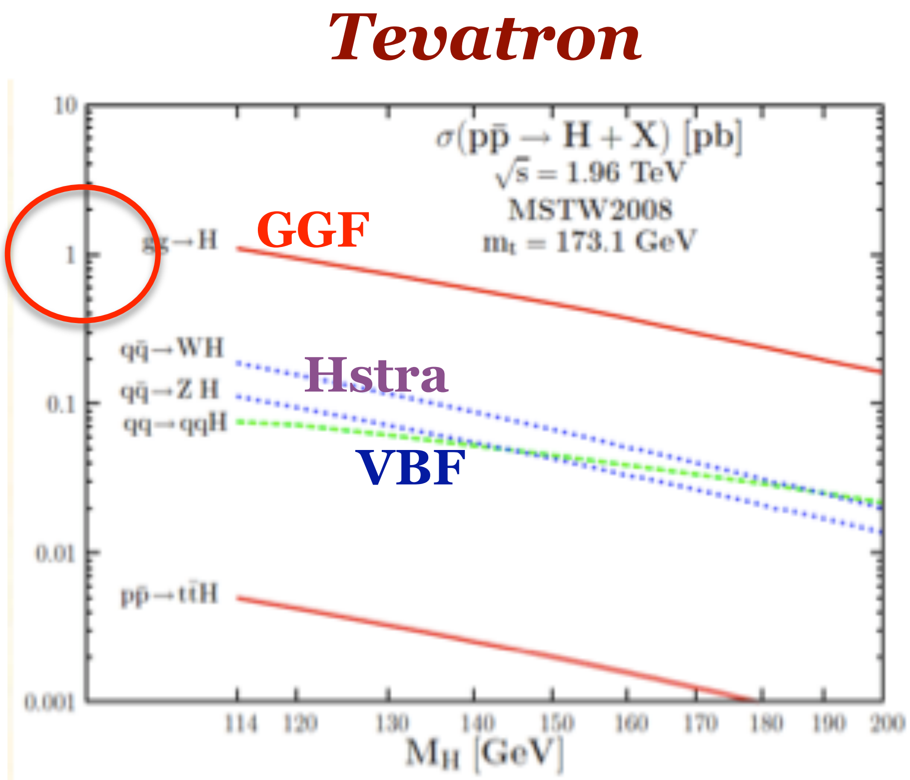
Higgs: produzione @ LHC/Tevatron





Higgs: sezioni d'urto @ LHC/Tevatron



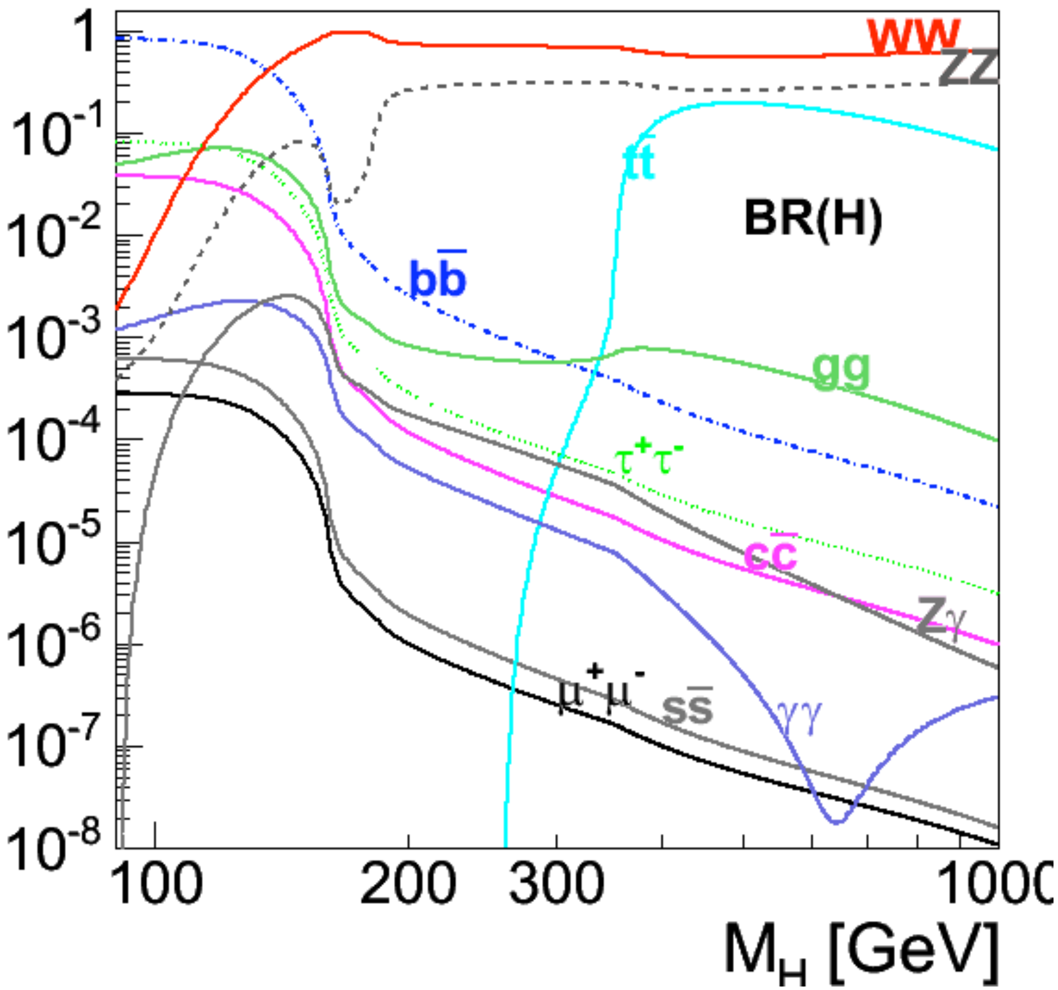


Assumendo σ≈ 10 pb e $\mathcal{L}$ =10 fb-1/anno

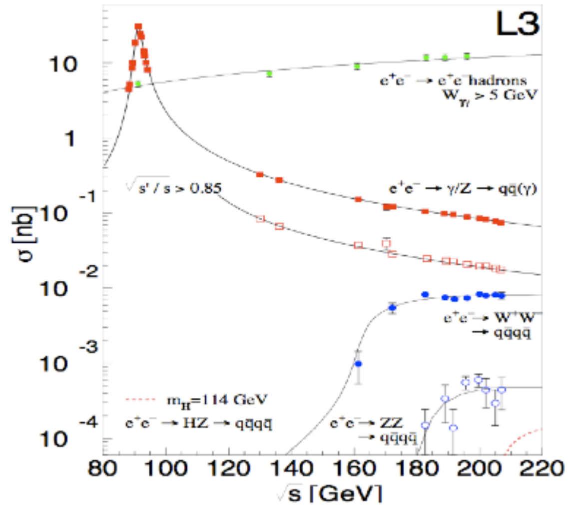
Rate di produzione atteso @ LHC:

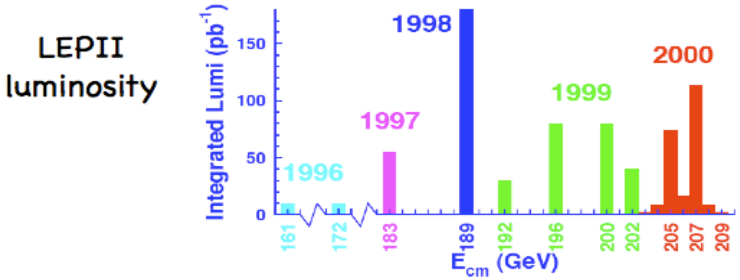
$(\sigma\times\mathcal{L}) = 10 * 10.000 = 100.000$ Higgs/ anno (???)

Higgs: Branching ratios

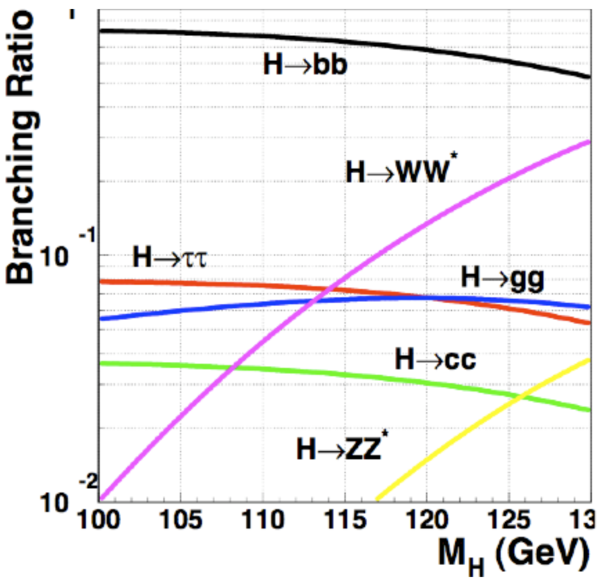


Ricerca dell'Higgs @ LEP

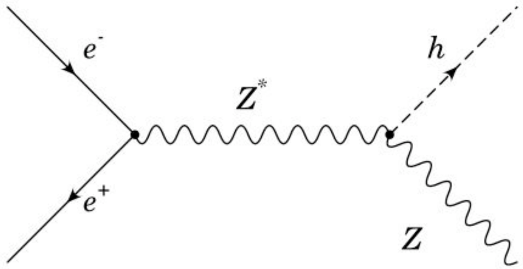




Al LEP con una luminosità O(100pb-1)
È possibile misurare $\sigma(H) \approx 0.1$ pb
Limite cinematico: $M_H \approx \sqrt{s} - m_Z$

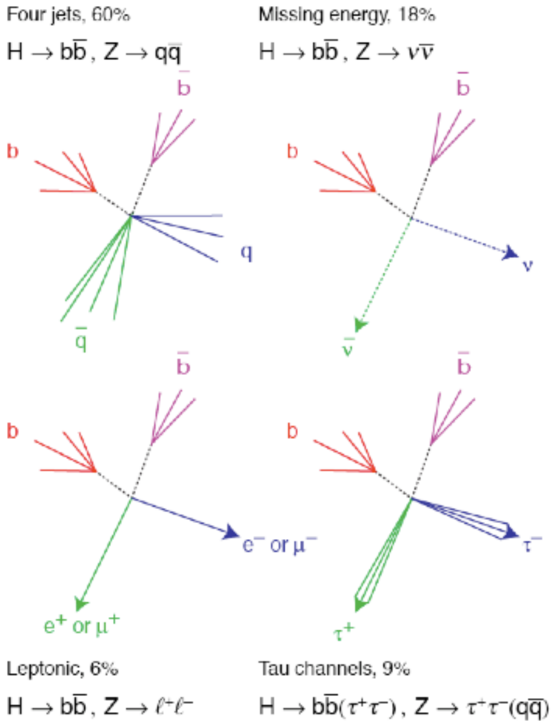


BR(%)	Higgs 115 GeV	Z boson
$q\bar{q}$		70
bb	74	15
$c\bar{c}$	4	12
gg	6	0
$\ell^+\ell^-$		10
$\tau^+\tau^-$	7	3
$\nu\bar{\nu}$		20
W^*W^*	8	
Z^*Z^*	1	

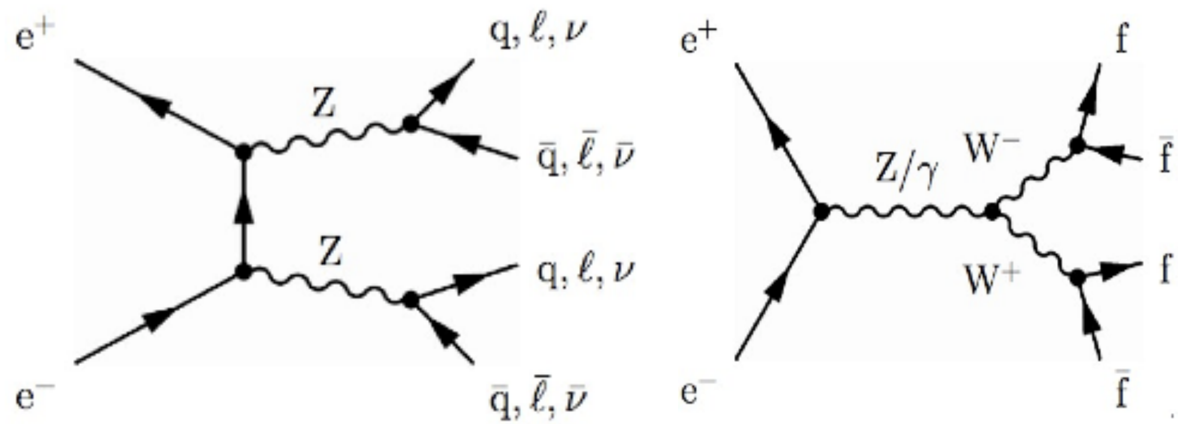


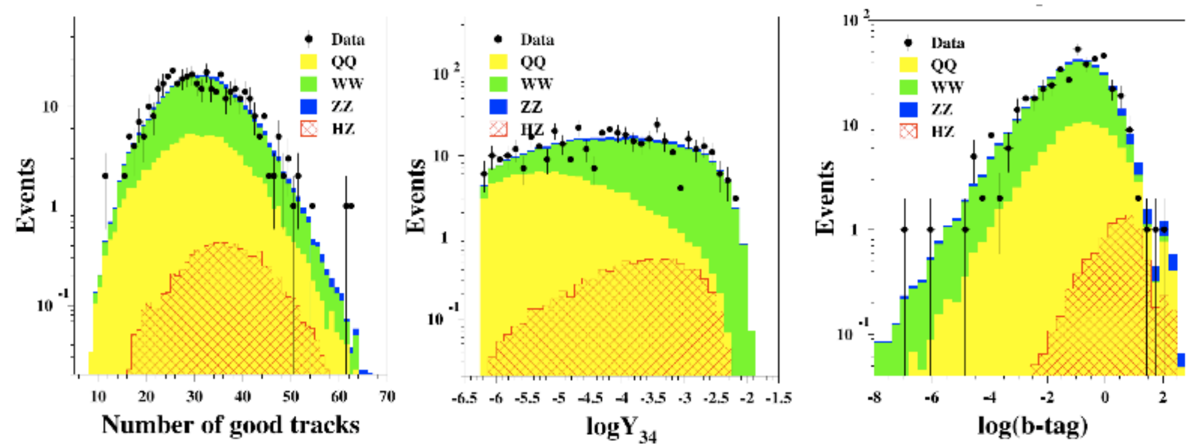
Canale sperimentale favorito è :
H -> bb
Z -> qq

Ricerca dell'Higgs @ LEP



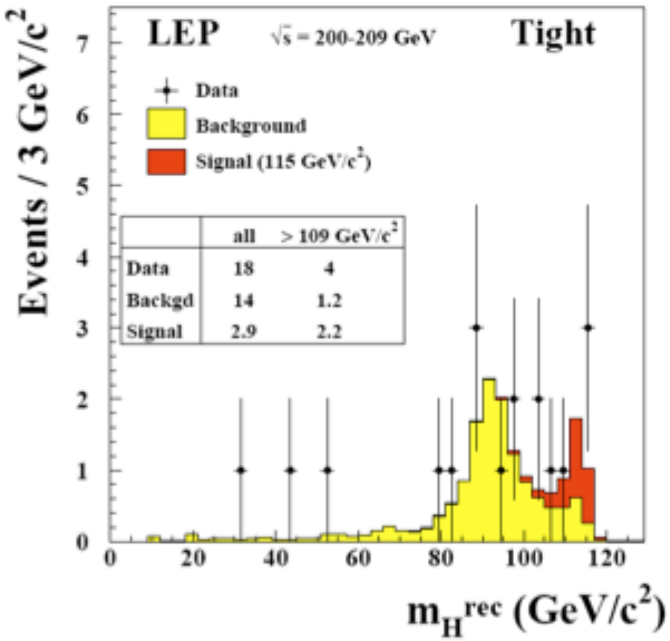
Principali processi di fondo @LEP

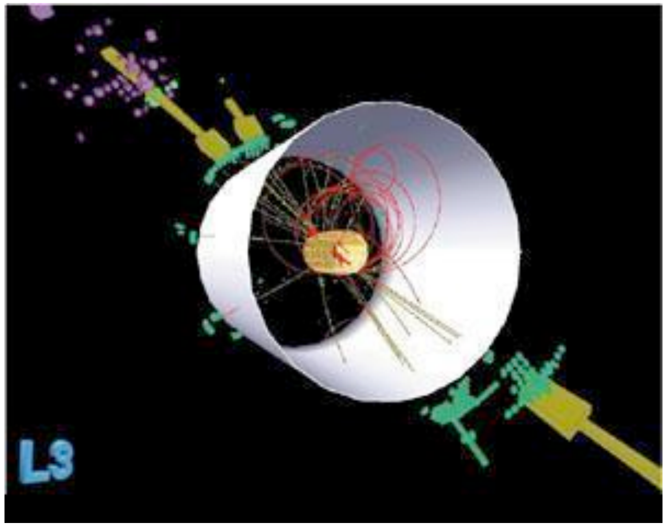




Anche la modalità di dcadimento:
HZ-> bb νν
 è stata studiata al LEP!

Did *LEP* find the *Higgs* ?

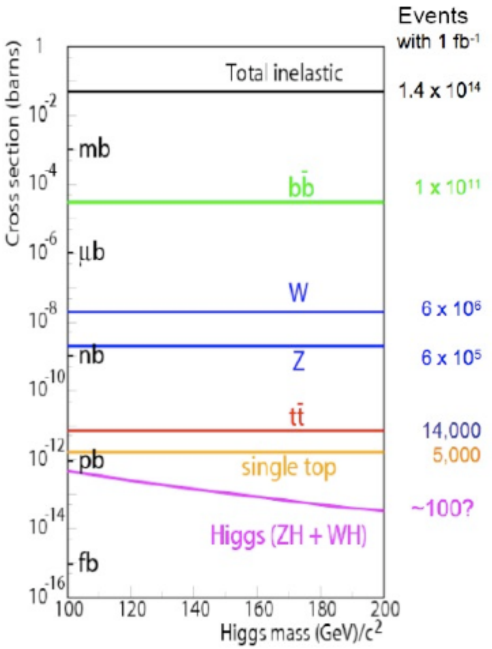


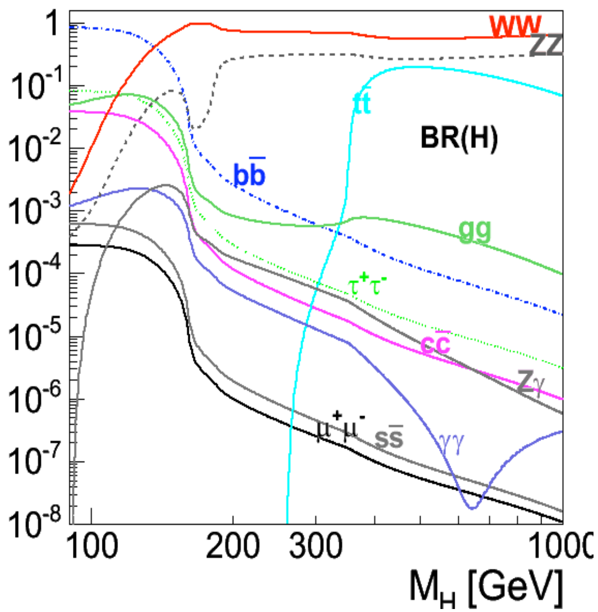


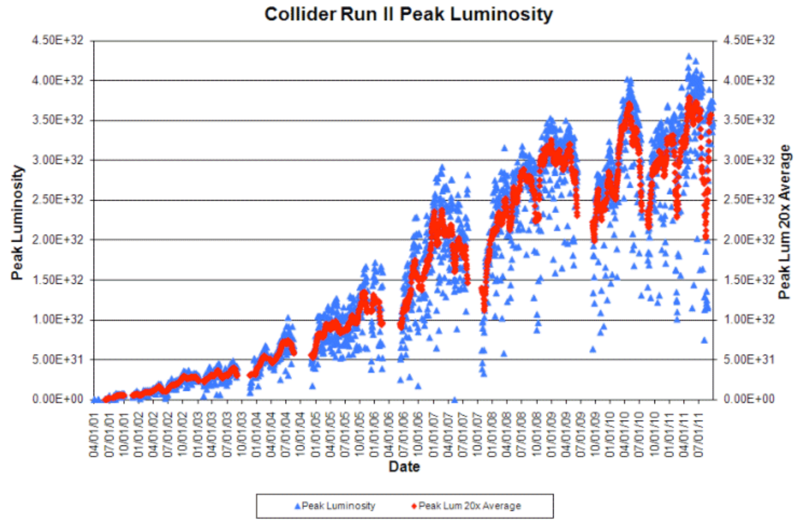
Evento candidato H (bb νν) @ L3
m_H = 114 GeV/c²
$\sigma(m_H)$= 3 GeV/c²

● Higgs candidates in *e+e- interactions at √s=206.6GeV. The L3 Collaboration CERN-EP/2000-140*
● *Search for the Standard Model Higgs boson in e+e- collisions at √s up to 202GeV. The L3 Collaboration CERN-EP/2000-146*

Ricerca dell'Higgs @ Tevatron

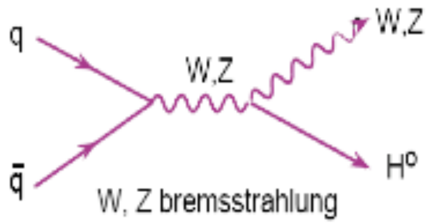


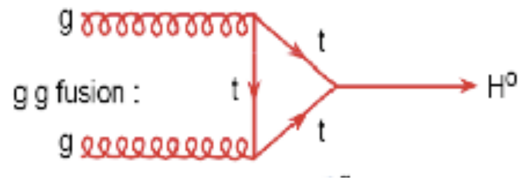




Ricerca per m_H < 135 GeV/c²
(processo Hstra con H->bb)

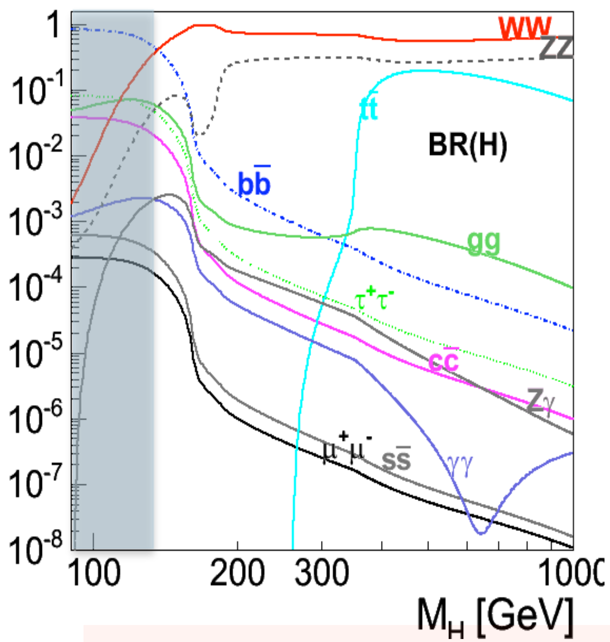
Ricerca per m_H > 135 GeV/c²
(processo GGF con H->WW)

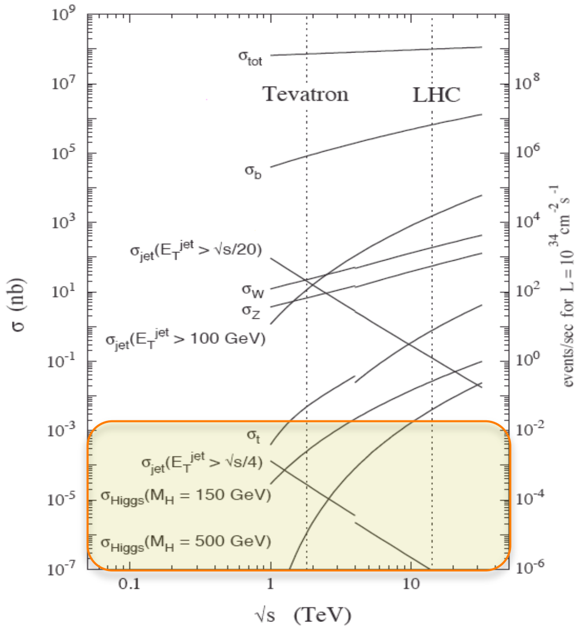




(*) http://tevnphwg.fnal.gov/results/SM_Higgs_Summer_11/

Ricerca dell'Higgs @ LHC (m_H<140 GeV)





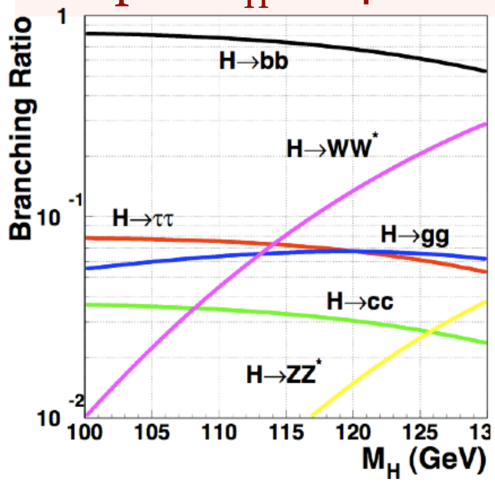
Enorme fondo di QCD:

$$\sigma(gg \to H \to b\bar{b}) \sim 20\ pb$$

$$\sigma(b\bar{b}) \sim 500\ \mu b$$

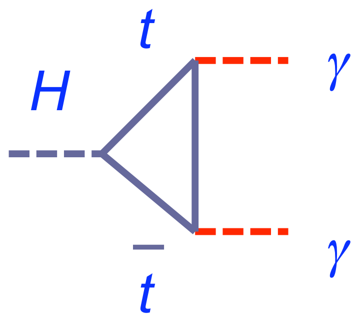
Possibilità di analisi di canali con stati finali completamente adronici non considerate!

BR per m_H < 140 GeV

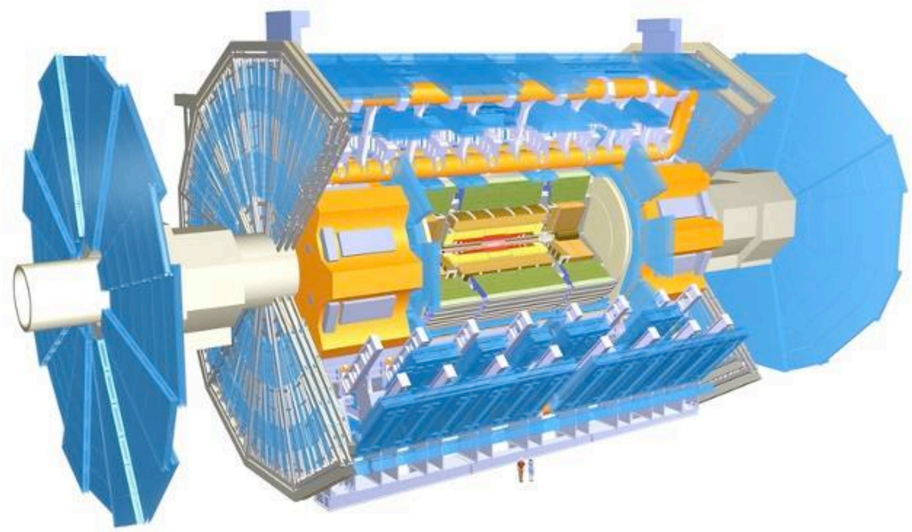


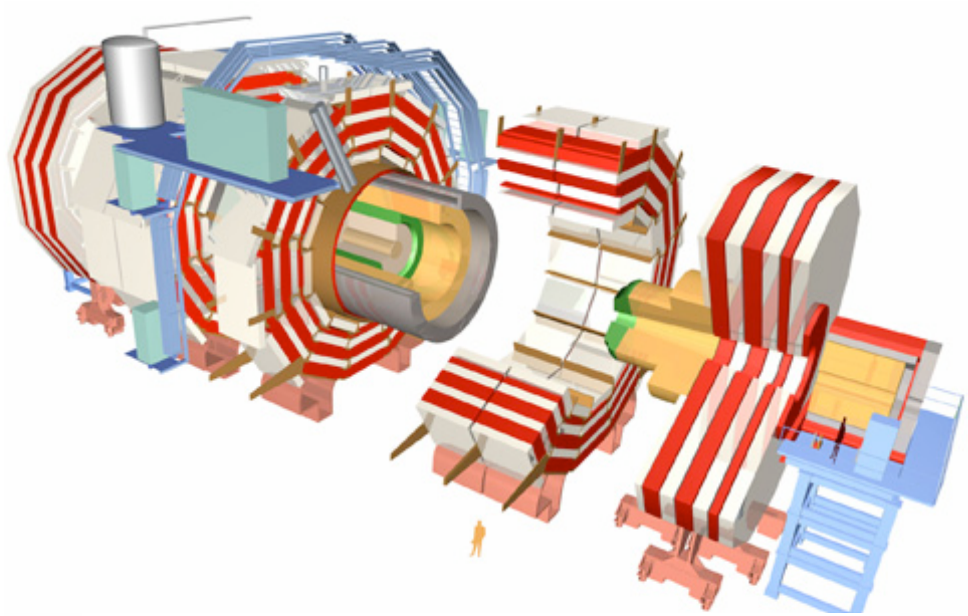
La modalità di decadimento per mH< 140 GeV:

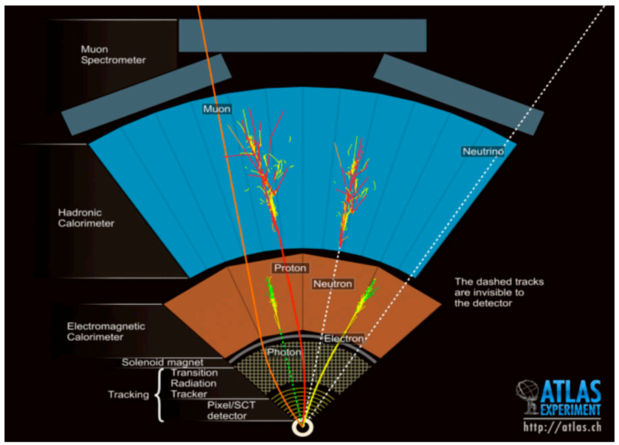
H->γγ (B.R: ≈ 10^{-3})

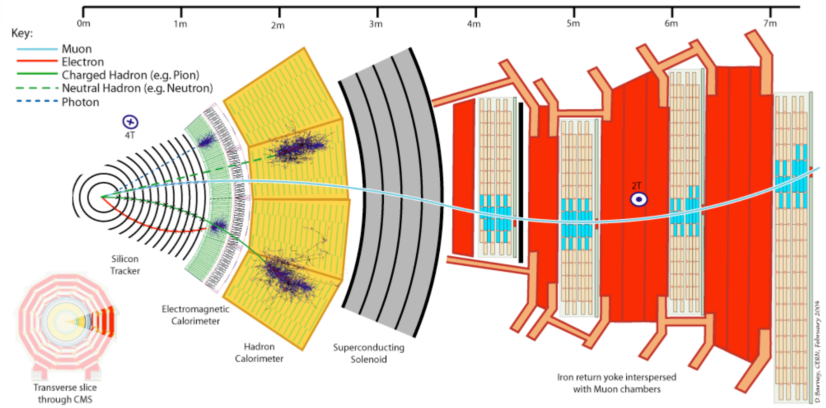


Atlas e CMS





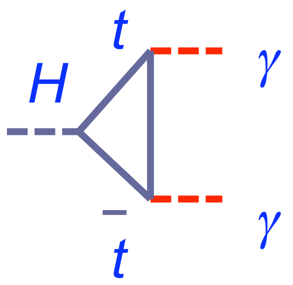

Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Photon
Electron
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS

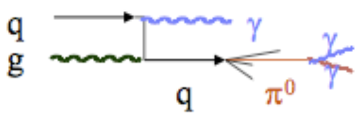
Ricerca dell'Higgs @ LHC (m_H<140 GeV)

H->γγ (B.R: ≈ 10^{-3}): è possibile lo studio di questo canale @ LHC?

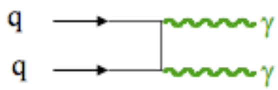
- Higgs signal:

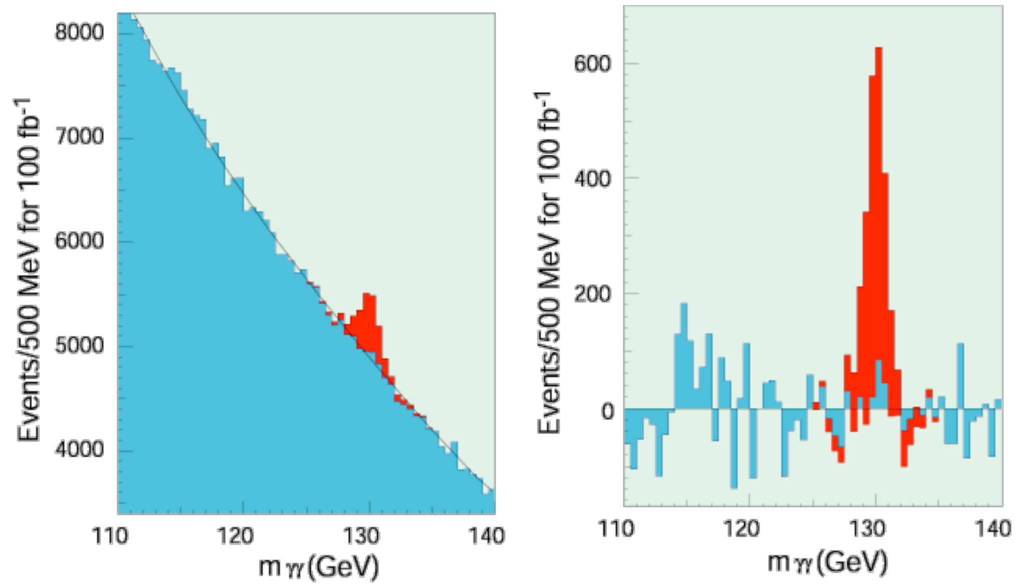


- Main backgrounds:
  - Reducible (γ-jet and Jet-jet)



  - Irreducible (γγ and Drell-Yan)





Supponiamo che sia prodotta una risonanza stretta in X → γ γ

⊙ Significanza del segnale $S = N_s / \sqrt{N_b}$

N_s numero di eventi di segnale, N_b numero di eventi di fondo

⊙ Convenzione per "scoperta": S > 5.

⊙ Il segnale è 5 volte l'errore sul fondo; la probabilità che il fondo fluttui per più di 5σ vale 10^{-7}

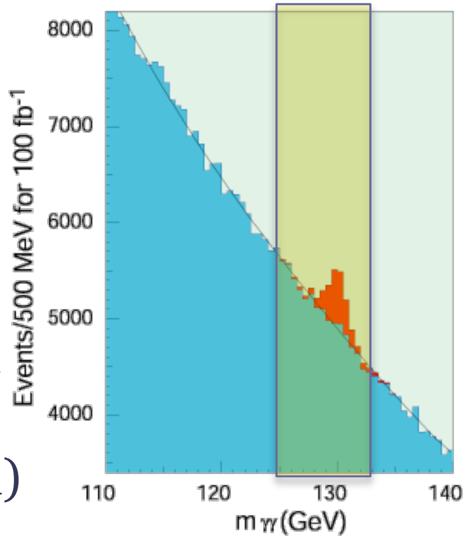
Ricerca dell'Higgs @ LHC (m_H<140 GeV)

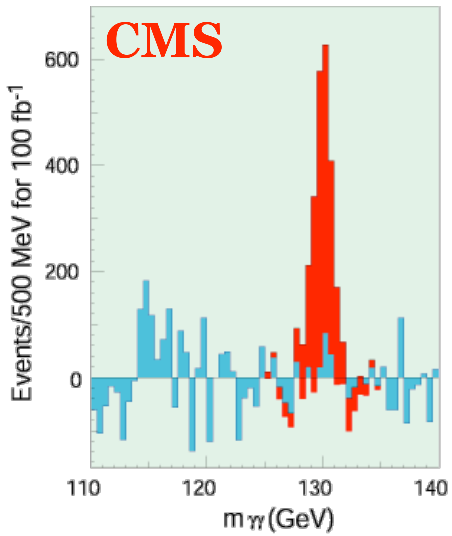
H->γγ (B.R: ≈ 10^{-3}): è possibile lo studio di questo canale @ LHC?

$$S = N_s / \sqrt{N_b}$$

Due sono i parametri critici per ottimizzare S:

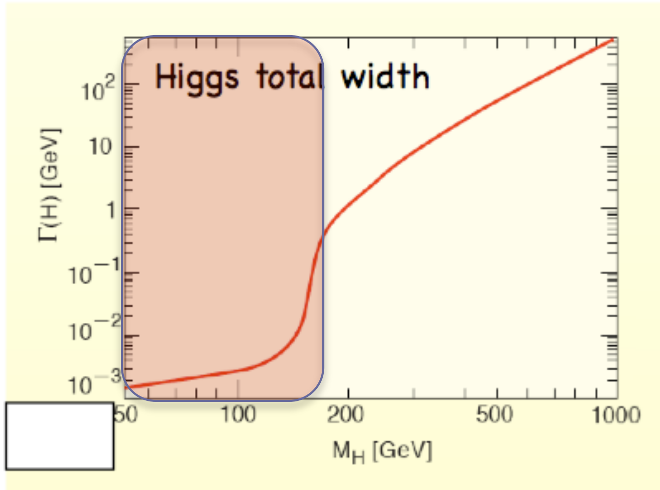
- **Risoluzione del rivelatore σ(m):**
  - Se la risoluzione aumenta di α, S scala come $1/\sqrt{\alpha}$ (il segnale resta invariato mentre si integra più fondo) → **$S \sim 1/\sqrt{\sigma(m)}$**
  - Tutto ciò resta valido finchè $\Gamma(H) \ll \sigma(m)$





- **Luminosità:**
  $N_S \sim L$; $N_B \sim L$ → **$S \sim \sqrt{L}$**

σ(m)≈ 1 GeV (Atlas and CMS)

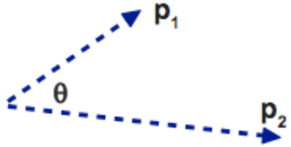


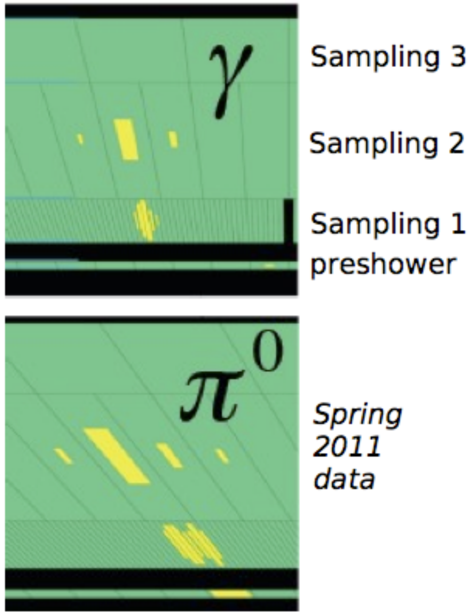
Ricerca dell'Higgs @ LHC (m_H<140 GeV)

Mass reconstruction

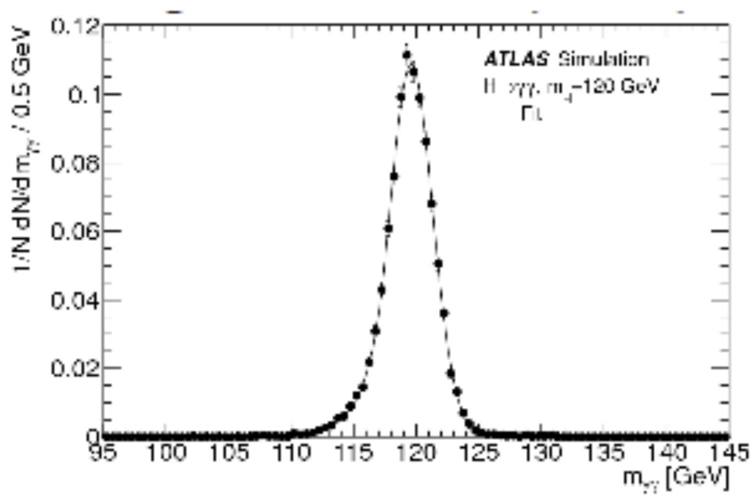
$m^2 = 2p_1p_2(1-\cos\theta) \cong p_1p_2\,\theta^2$

$\delta m/m = (1/\sqrt{2})(\delta p/p) \oplus \delta\theta/\theta$

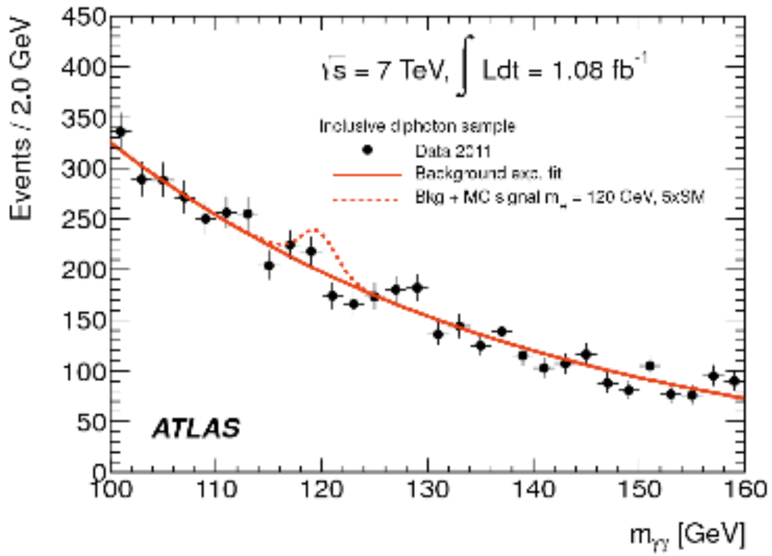




Atlas:
Ricostruzione di m_H per il processo H->γγ
(mH = 120 GeV/c²)
σ(mH) = 1.7 GeV

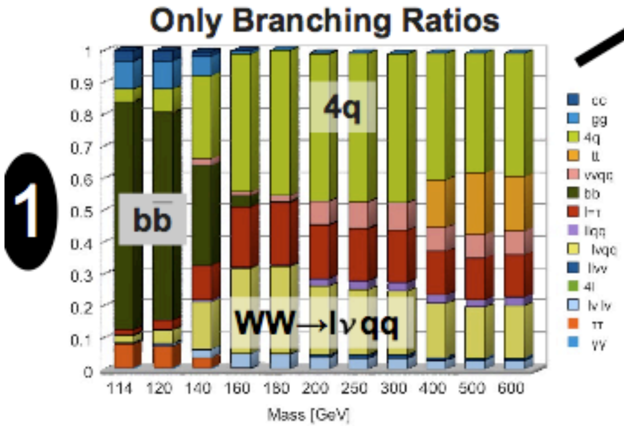


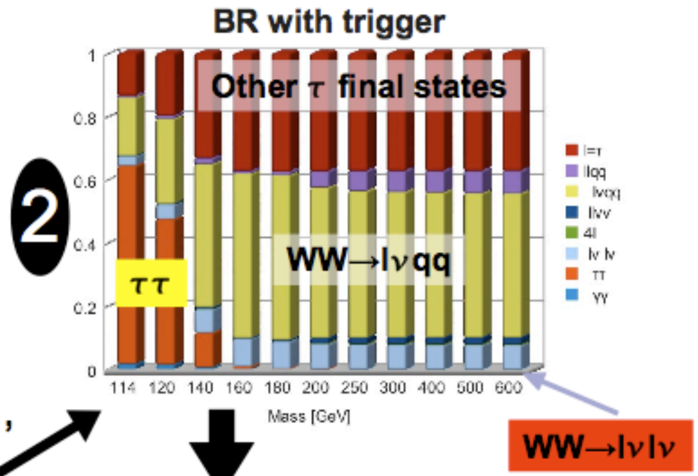
Atlas:
Risultati analisi del processo H->γγ per 1fb⁻¹
(mH = 120 GeV/c²)
σ(mH) = 1.7 GeV

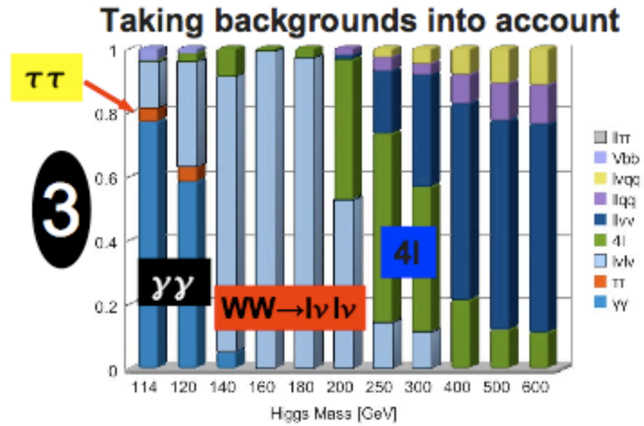


Ricerca dell'Higgs @ LHC (m_H>140 GeV)

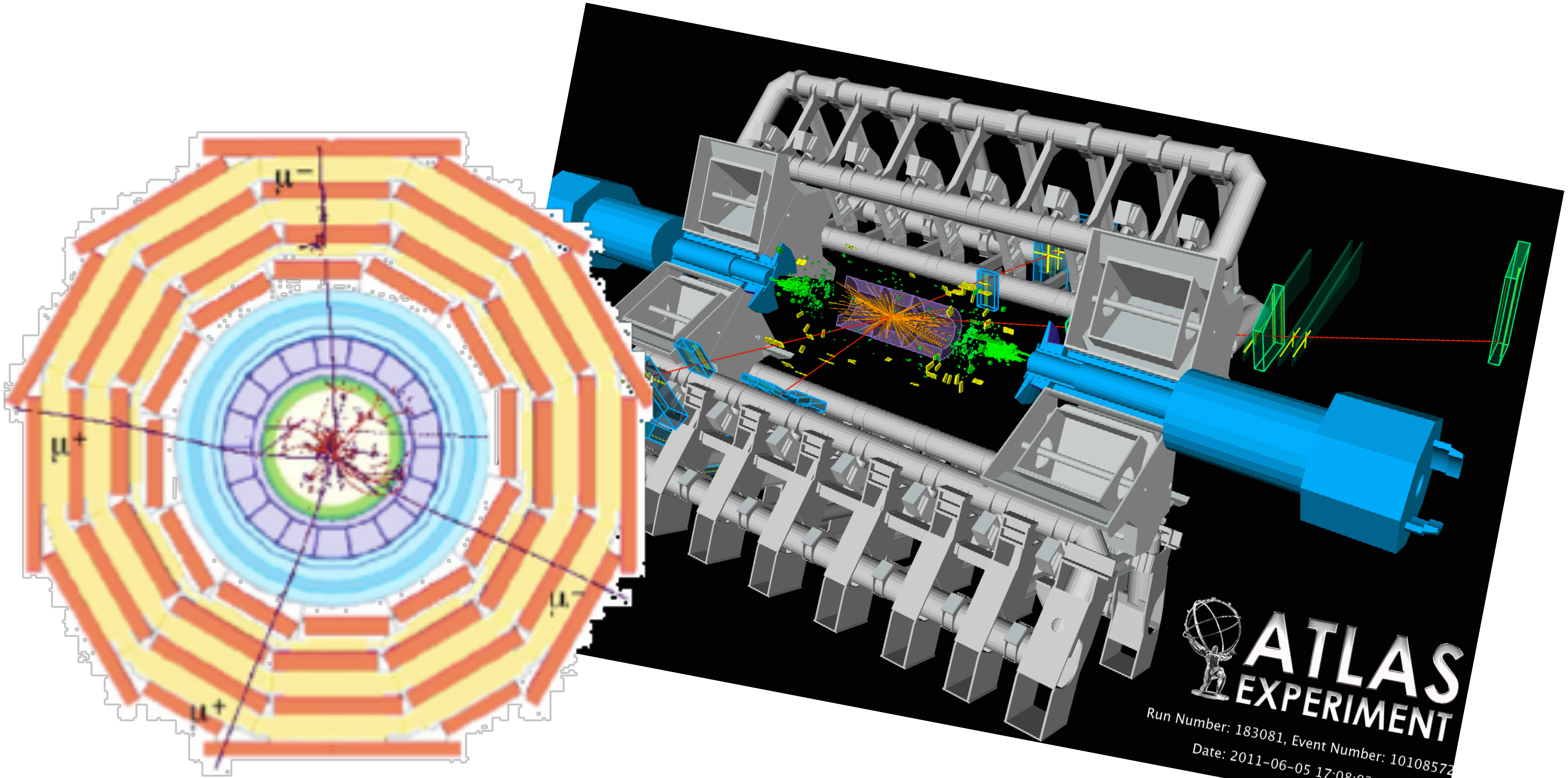
- So far, the integrated luminosity allows mainly for a Higgs search in gg→H production
- Viable channels need:
  - (1) High branching ratio
  - (2) Good trigger
  - (3) Low background level
- Channels remaining in the end: H→WW→lνlν , H→ZZ→4l , H→γγ , H→ττ and W/ZH(H→$b\bar{b}$)







The golden channel: H->ZZ->4l



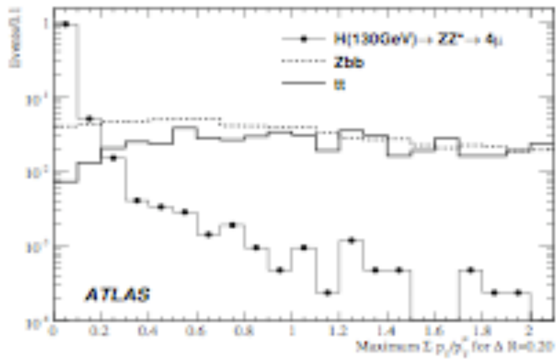
The golden channel: H->ZZ->4l

Tre categorie di stati finali : 4μ, 2e2μ, 4e
Principali processi di fondo:
ZZ(*), tt e Z+jets

$m_H(GeV)$	130	150	200	240	300	400	500
$\sigma\cdot BR(H\to 4\ell)$(fb)	2.87	4.38	6.77	5.35	3.75	2.66	1.11

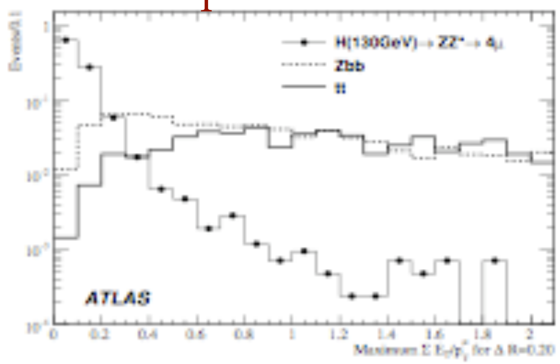
Leptoni aggiuntivi nei processi di fondo da decadimenti semileptonici di heavy flavour o jet erroneamente identificati come leptoni.

Track Isolation



Idea base della selezione è relativamente semplice:I leptoni provenienti dal decadimento dell’Higgs sono “isolati” e provengono da un vertice comune.

E_T Isolation



Isolamento è applicato richiedendo:
-$(\Sigma p_T)/p_{T(leptone)}$ in un cono di apertura $\Delta R = 0.2 < 0.15$
- $(\Sigma E_T)/p_{T(leptone)}$ in un cono di apertura $\Delta R = 0.2 < 0.30$

The golden channel: H->ZZ->4l

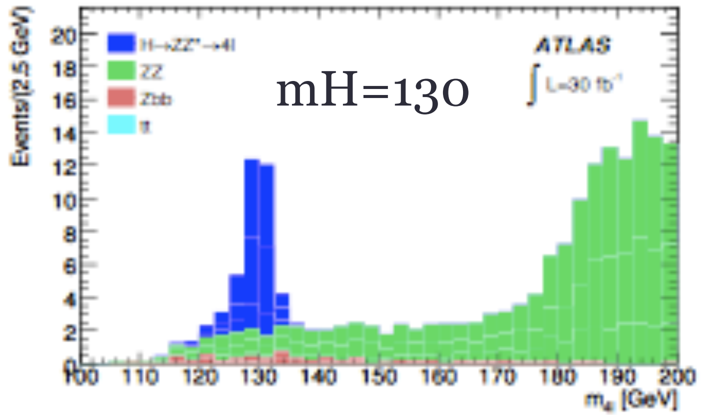
ATLAS

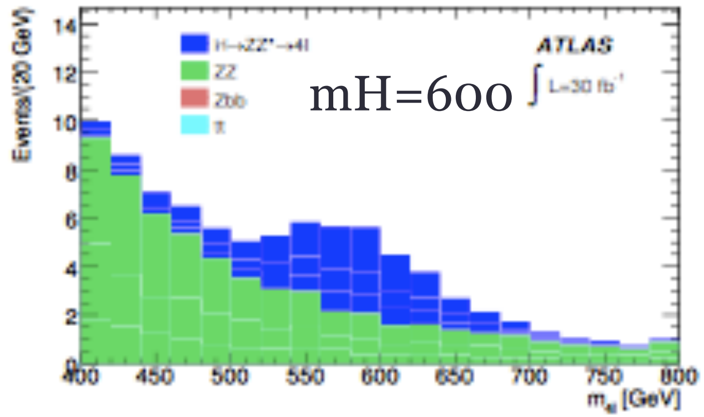
I candidati Higgs sono selezionati richiedendo:

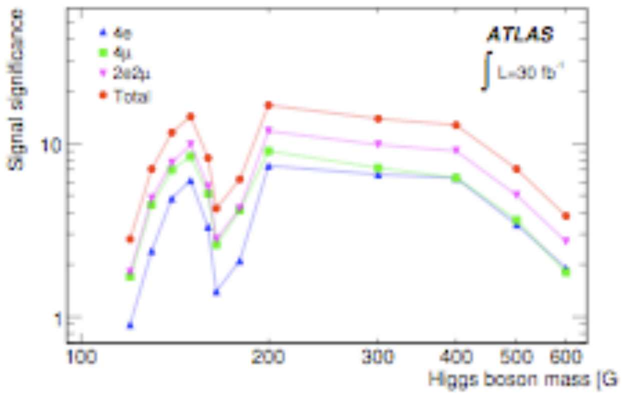
- 2 coppie di leptoni isolati con carica opposta
- pT > pT_soglia (O(10 GeV))
- minima separazione angolare: $\Delta R>0.1$
- Le 2 masse invarianti formate dalle 2 coppie

di leptoni m_{12} e m_{34} :

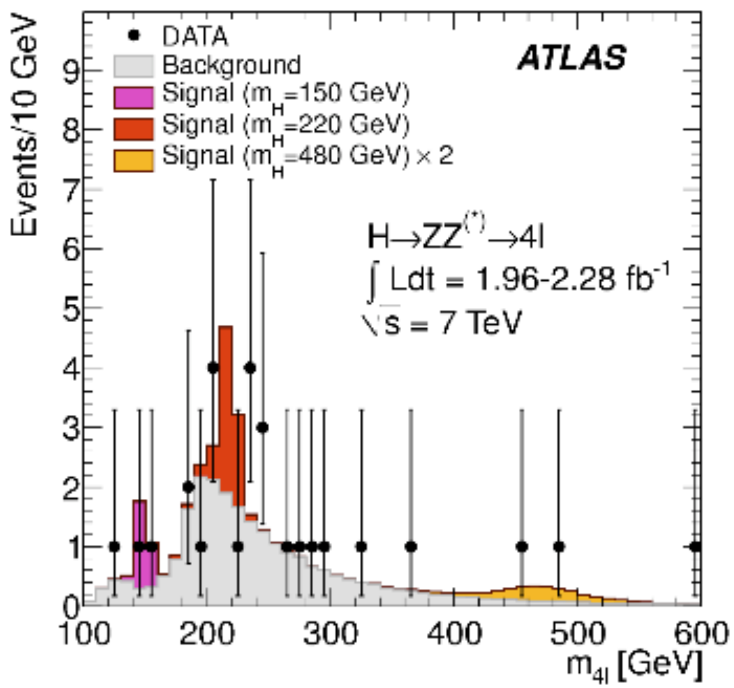
- $|m_{12}\text{-mz}| < 15$ GeV
- $m_{34} > m_{soglia}(mH)$

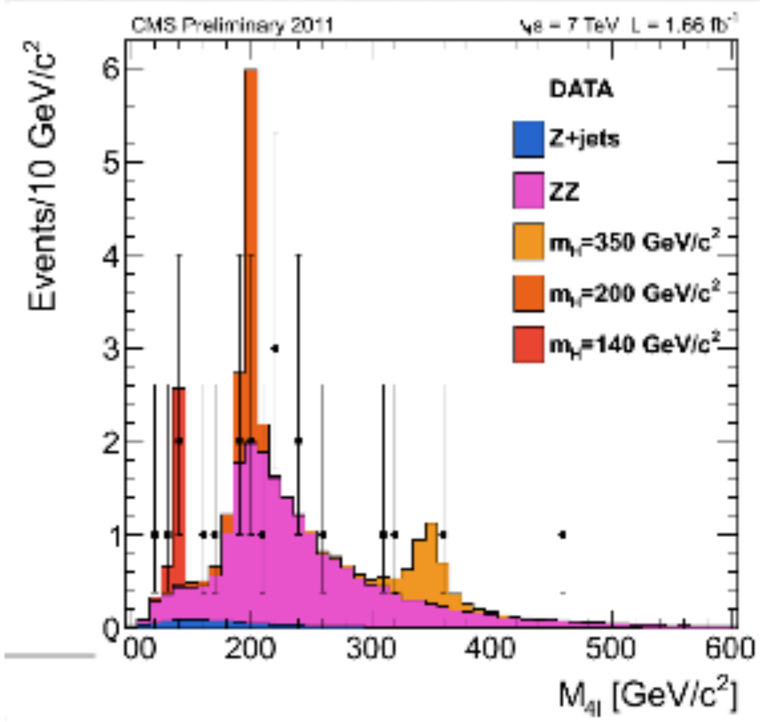






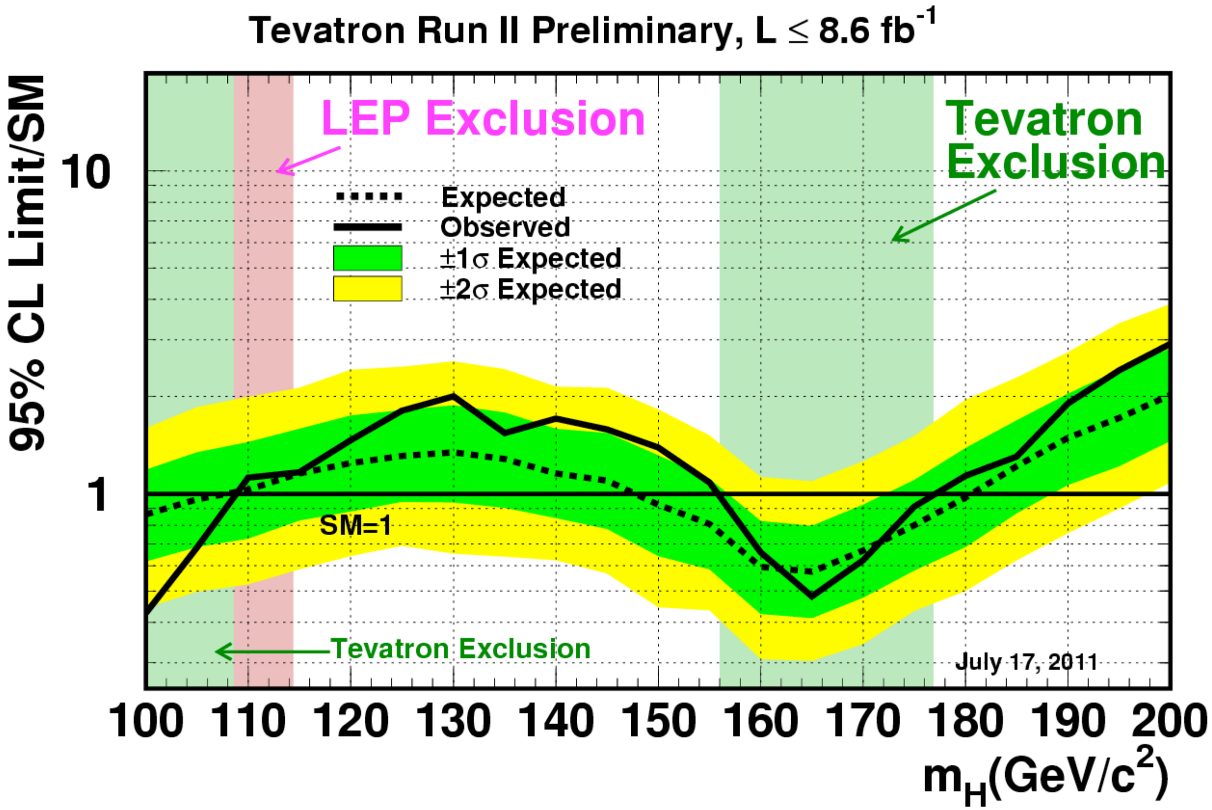
The golden channel: H->ZZ->4l





Atlas results with 2.1 fb -1 LP result Phys. Lett. B 705 (2011) 435-451

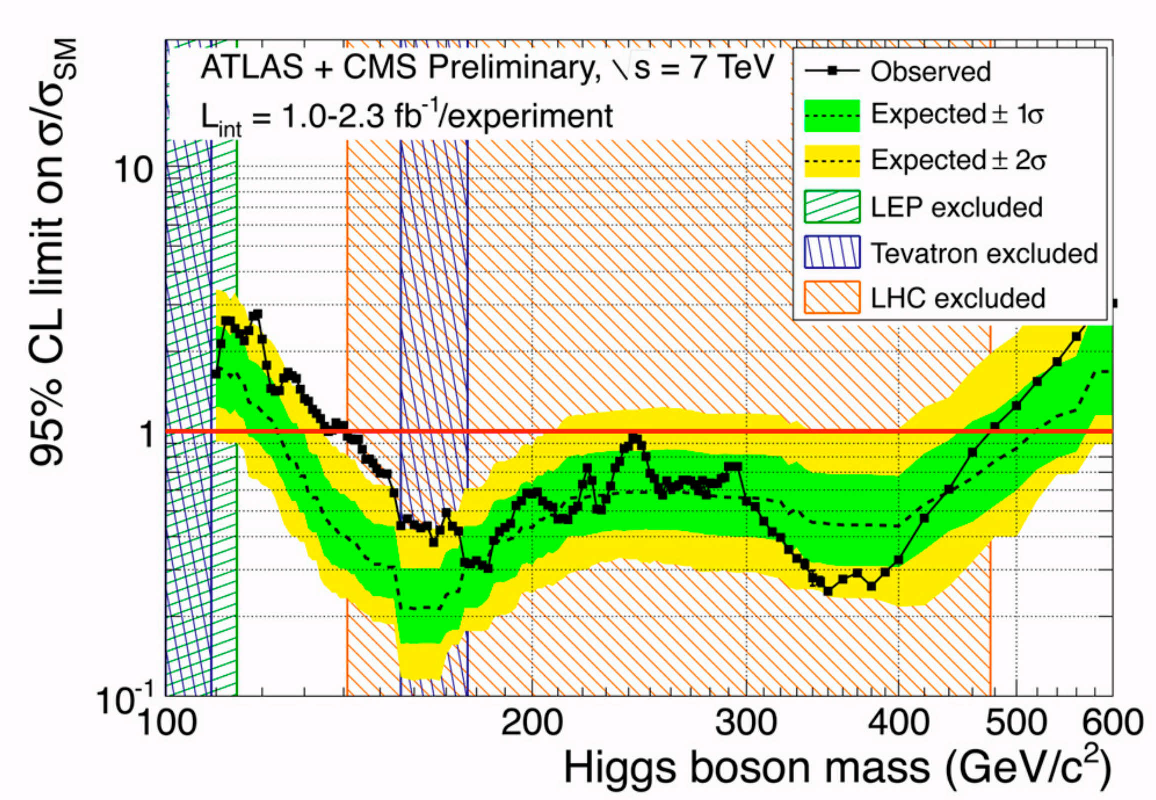
Higgs: limiti su m_H: LEP + Tevatron



EPS 2011 Higgs Combination with integrated luminosities up to 8.6 fb-1.
95% C.L. exclusion for SM Higgs with mH 156-177 GeV/c^2, and also 100-108 GeV/c^2
(cfr. http://tevnphwg.fnal.gov/results/SM_Higgs_Summer_11/)

Higgs: limiti su m_H: LEP + Tevatron + LHC

REL. ON 18/11/2011



http://atlas.ch/news/2011/ATLAS-CMS-combined-limits-higgs.html
http://www.nature.com/news/higgs-hunt-enters-endgame-1.9399
http://cms.web.cern.ch/news/atlas-and-cms-combine-summer-11-search-limits-standard-model-higgs