Il Modello Standard e il bosone di Higgs

Luca Lista

INFN

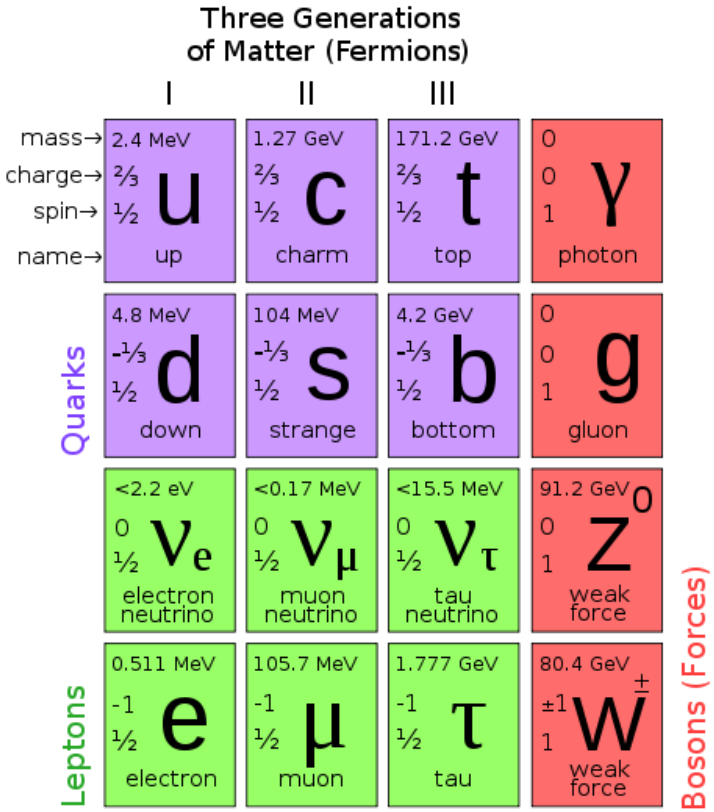
Il Modello Standard

$$\underbrace{SU(2)_L}_{g} \otimes \underbrace{U(1)_Y}_{g'}$$

$$\Big\Downarrow \, \mathrm{H}$$

$$\underbrace{U(1)_Q}_{e}$$

$$Q = T_3 + Y/2, \quad \tan\theta_W = g'/g$$
$$e = g \sin\theta_W$$



Three Generations of Matter (Fermions)

		I	II	III	
Quarks	mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon
		4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
Leptons		<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
		0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force

Bosons (Forces)

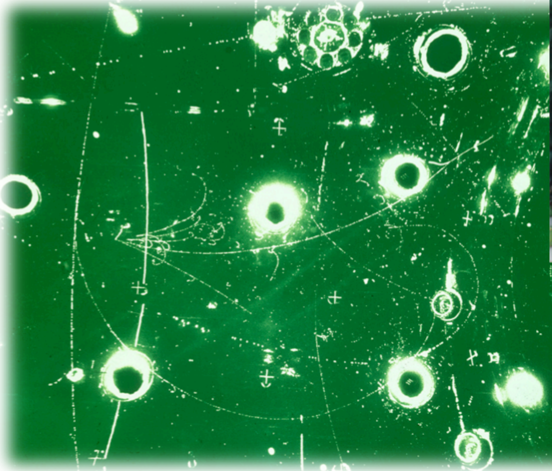
$$M_Z = \sqrt{g^2 + g'^2}\,\frac{\nu}{2} = \frac{M_W}{\cos\theta_W}$$

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

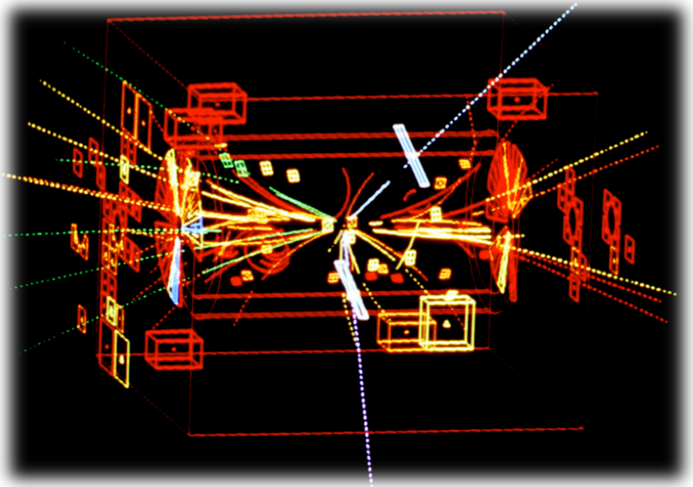
Doppietti leptoni (L) (ν_L, ℓ^-_L):Y = −1
Doppietti quark (u, d): Y = 1/3
Singoletti leptoni (R) ℓ^-_R: Y = −2
Singoletti quark (R) q_R: Y= 4/3, -2/3

L’osservazione di W e Z

- Gargamelle (CERN, 1973) misurò reazioni di un fascio di neutrini prodotti dal PS (protoni da 28 GeV)
  - Segnatura: vertice di interazione senza produzione di leptoni
- UA1 e UA2 (CERN, 1983) osservarono la produzione diretta di W e Z in collisioni p-p^{bar} all’SPS a 450+450 GeV

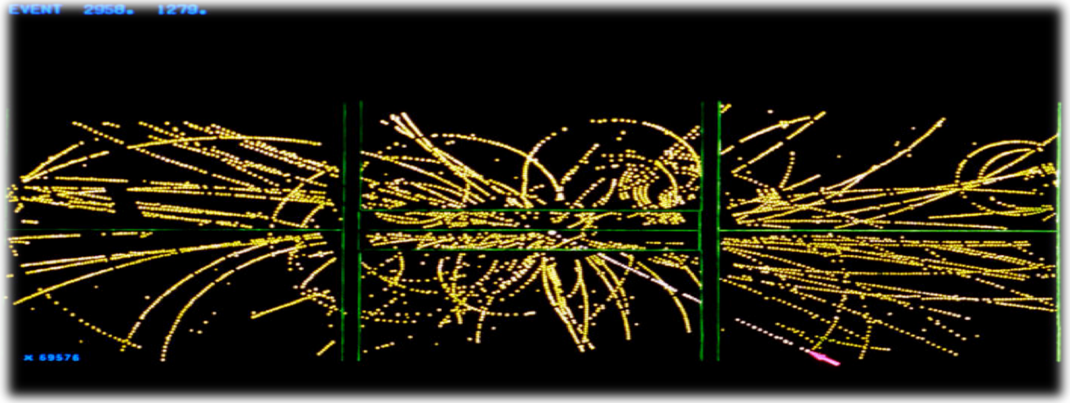


F. J. Hasert et al.,
Phys. Lett. B46, 138 (1973)

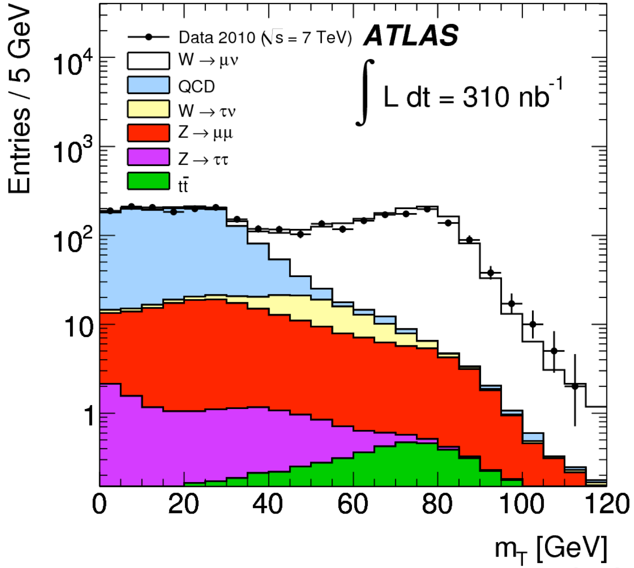


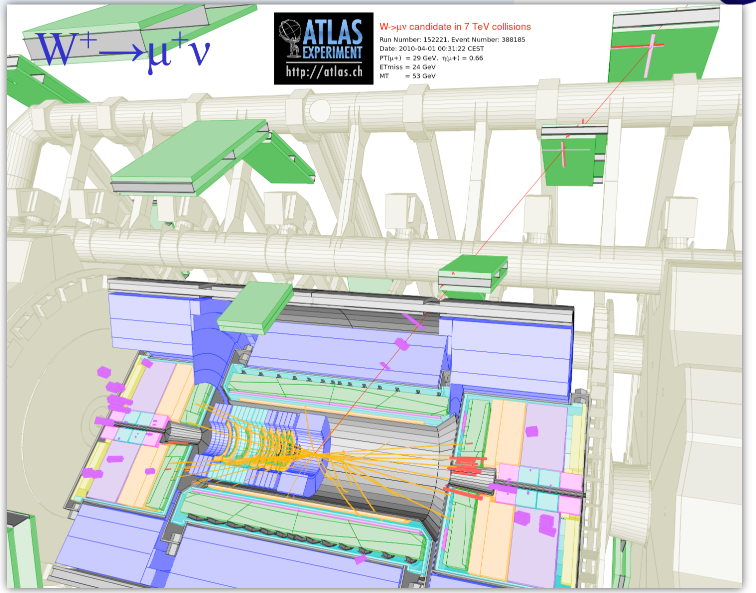
$Z \rightarrow \mu^+\mu^-$

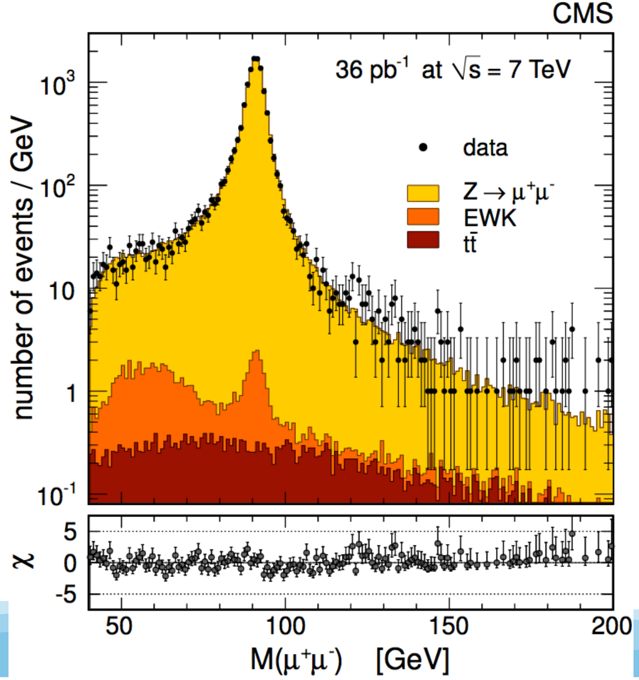
$W \rightarrow l\nu$

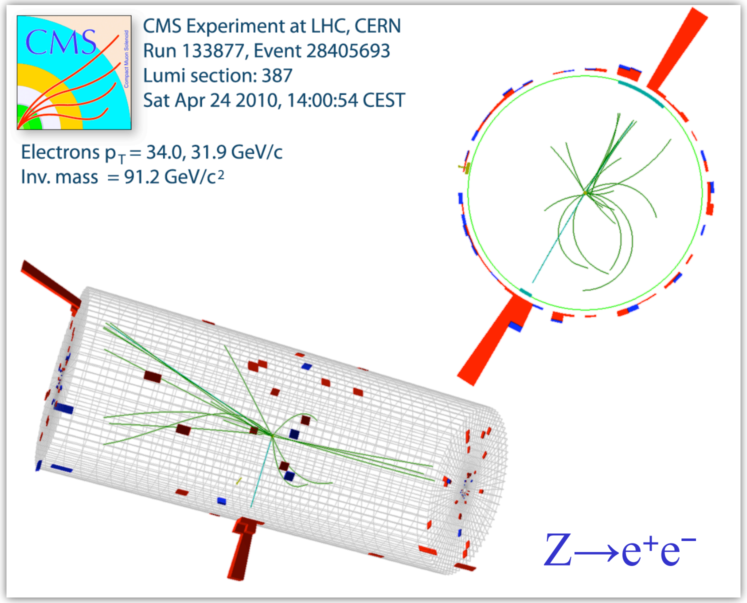


W e Z ad LHC (7 TeV)



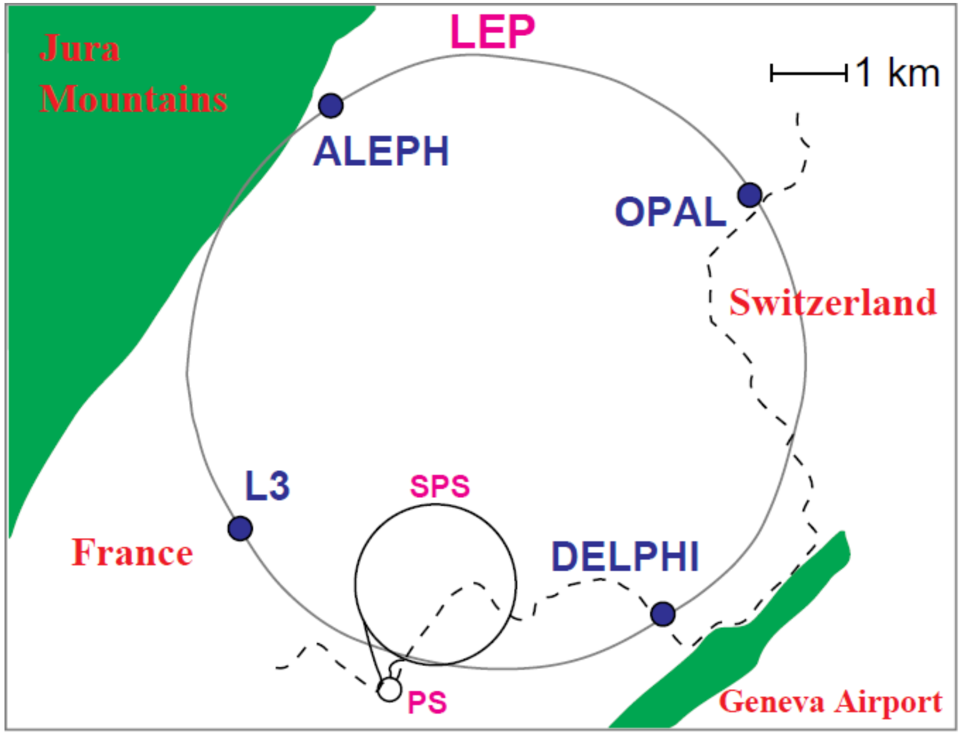


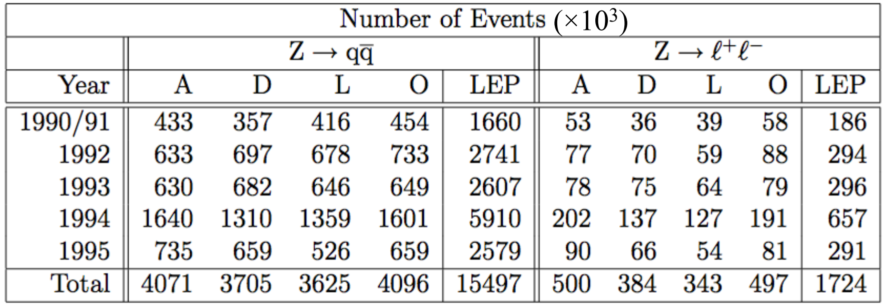




Verifiche del Modello Standard

- Misure di precisione al LEP e SLC in collisioni elettrone-positrone con energia (1989-2000)
  - Il LEP usò l'attuale tunnel di LHC
- Energia nel c.m. intorno alla massa della Z (risonanza!)
- Misure di precisione da milioni di decadimenti della Z



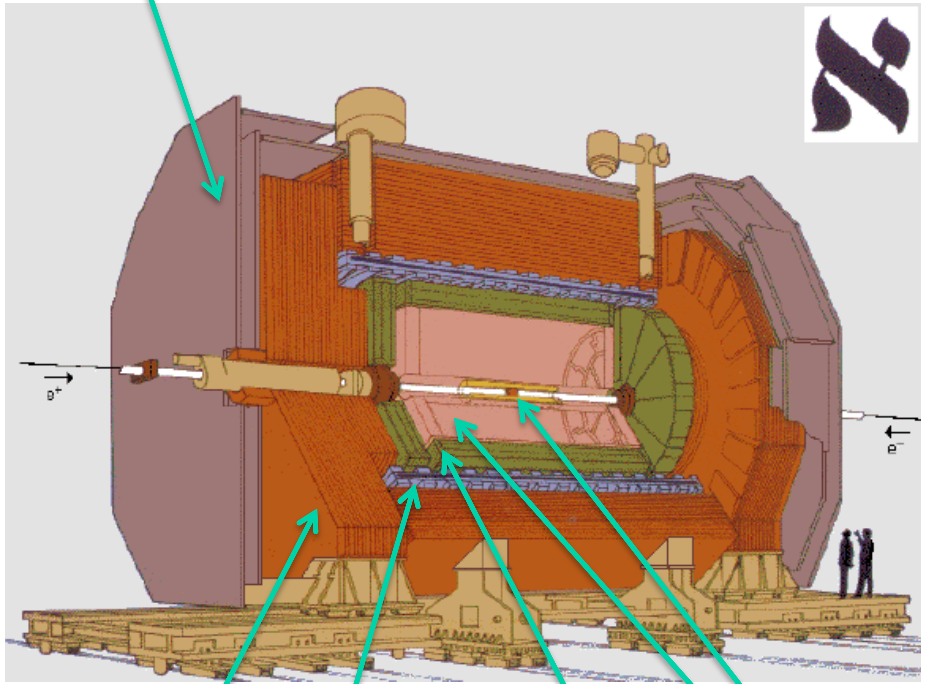


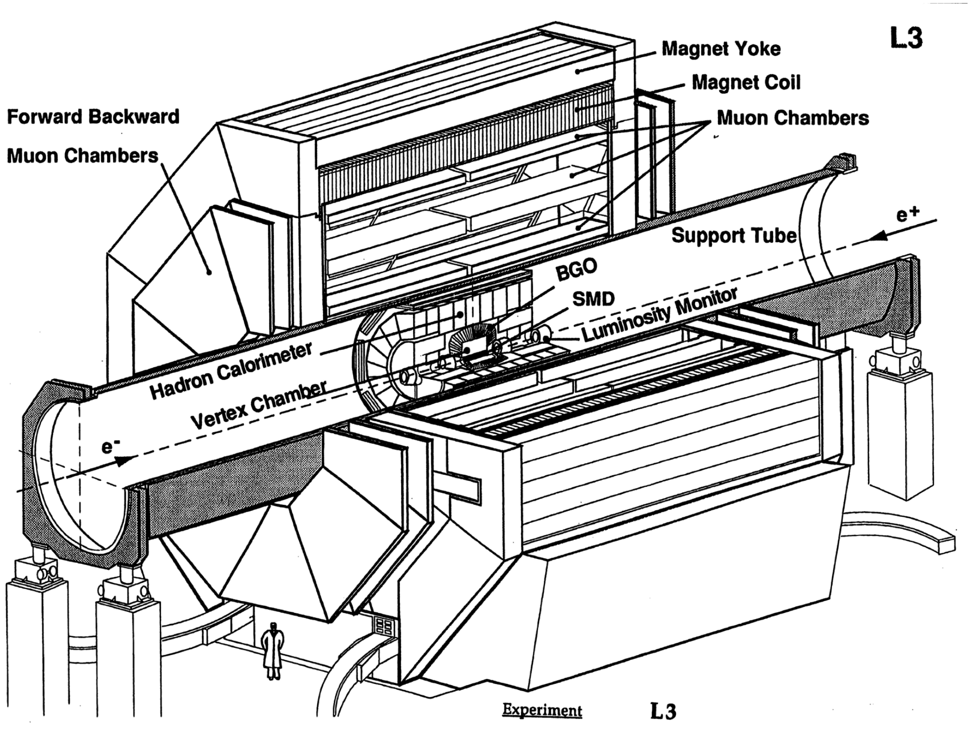
Number of Events ($\times 10^3$)										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

$$\begin{aligned} m_Z &= 91.1875 \pm 0.0021 \text{ GeV} \\ \Gamma_Z &= 2.4952 \pm 0.0023 \text{ GeV} \\ \rho_\ell &= 1.0050 \pm 0.0010 \\ \sin^2 \theta_{\text{eff}}^{\text{lept}} &= 0.23153 \pm 0.00016 \,. \end{aligned}$$

Due esperimenti LEP: א e L3

Muon detector





Vertex detector

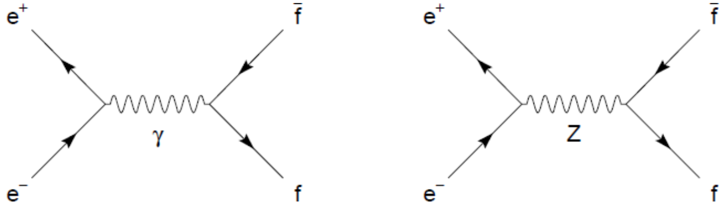
Hadron
calorimeter

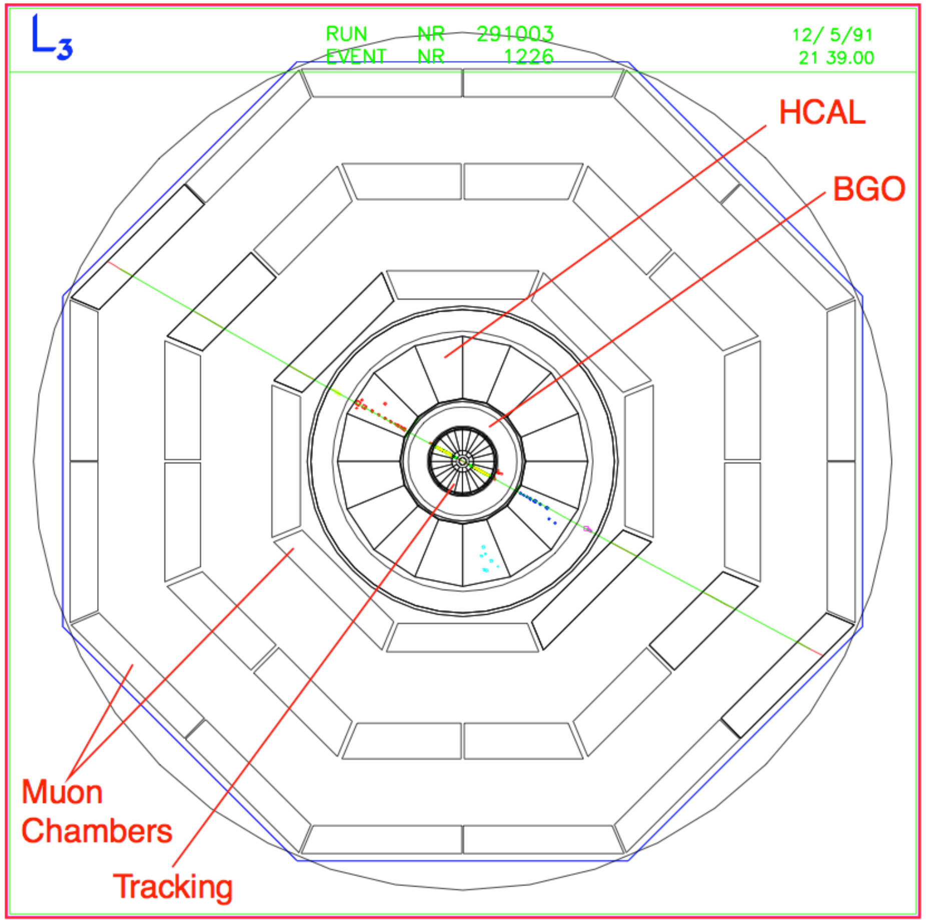
Superconducting
magnet solenoid

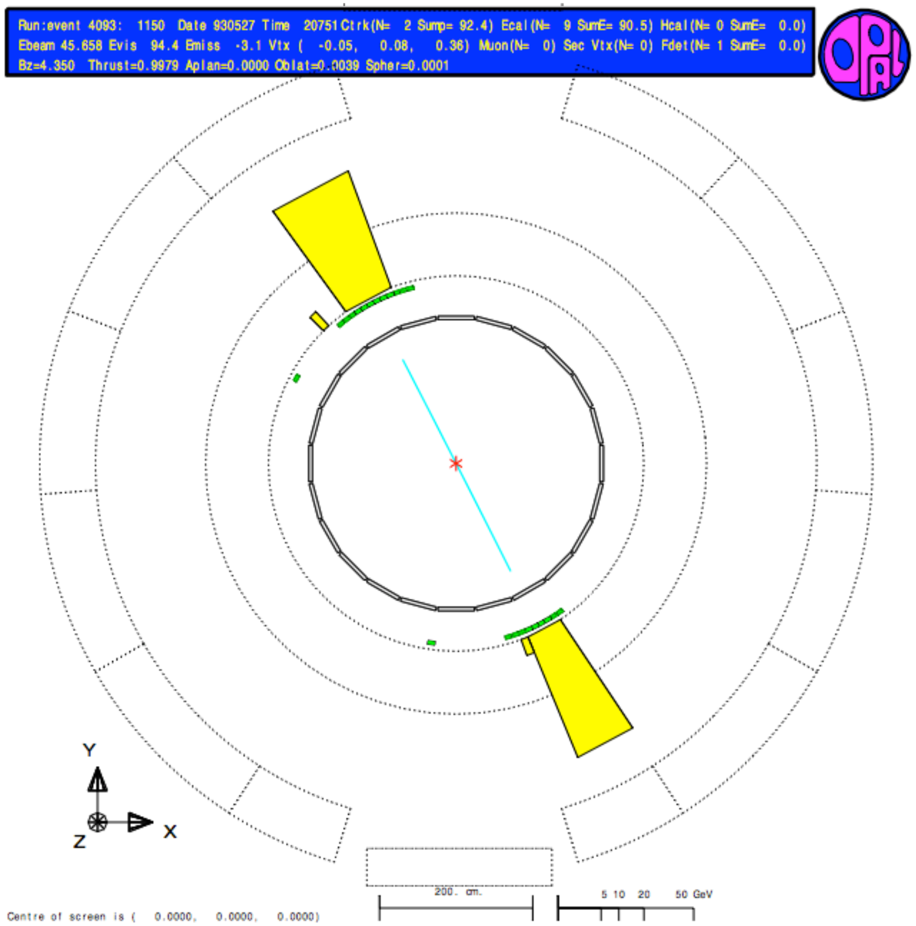
Tracker (TPC + inner drift chamber)

Electromagnetic calorimeter

$e^+e^- \to \mu^+\mu^-, e^+e^-$

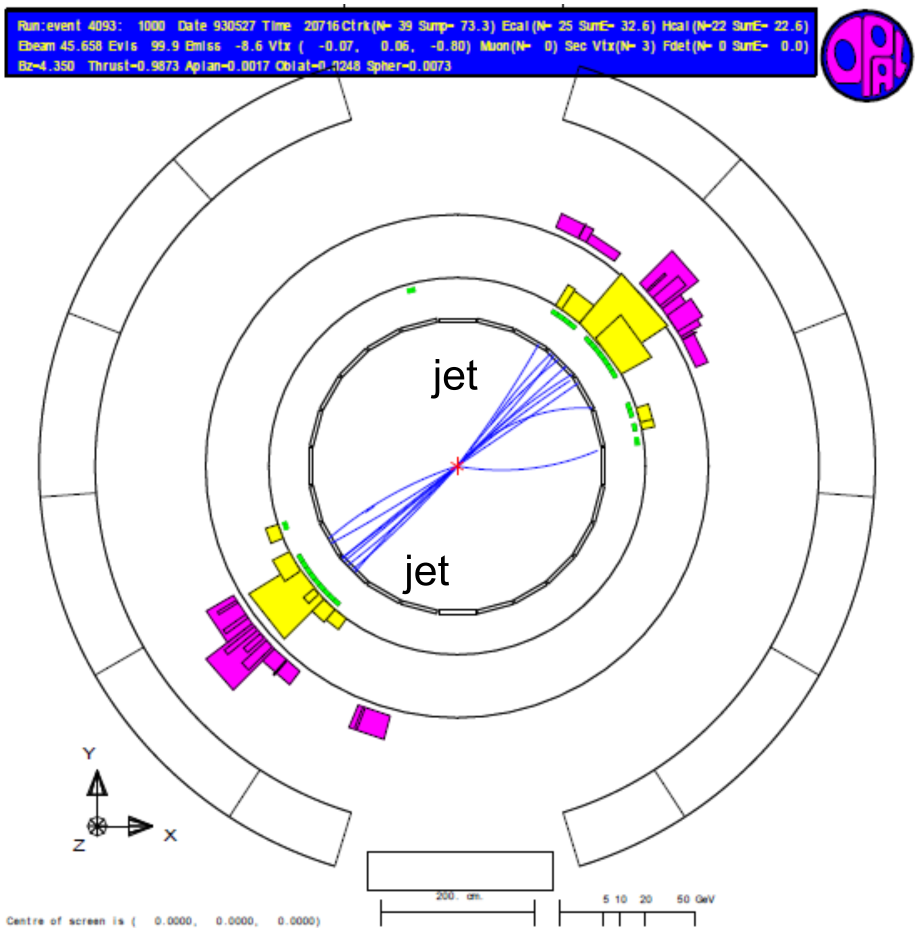






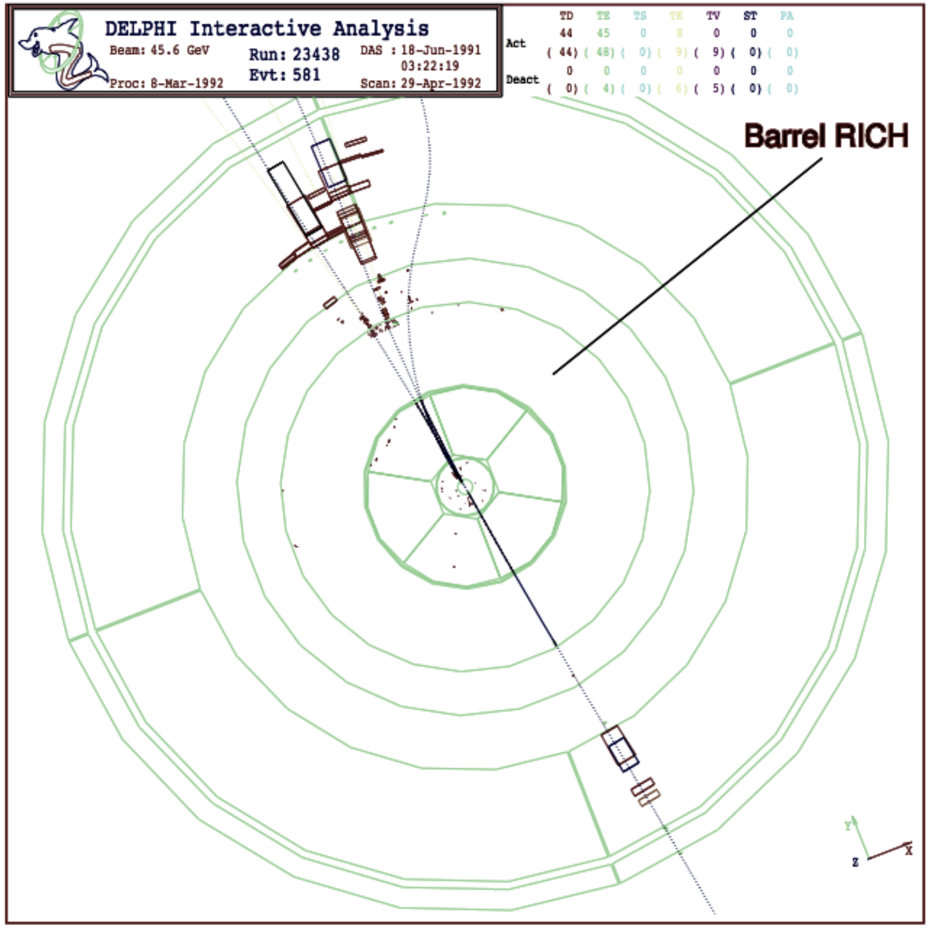
```
Run:event 4093:  1150  Date 930527 Time  20751 Ctrk(N=  2 Sump= 92.4) Ecal(N=  9 SumE= 90.5) Hcal(N= 0 SumE=  0.0)
Ebeam 45.658 Evis  94.4 Emiss  -3.1 Vtx (  -0.05,   0.08,   0.36) Muon(N=  0) Sec Vtx(N= 0) Fdet(N= 1 SumE=  0.0)
Bz=4.350  Thrust=0.9979 Aplan=0.0000 Oblat=0.0039 Spher=0.0001
```

$e^+e^- \to qq, \tau^+\tau^-$



```
Run:event 4093:  1000  Date 930527 Time  20716 Ctrk(N= 39 Sump= 73.3) Ecal(N= 25 SumE= 32.6) Hcal(N=22 SumE= 22.6)
Ebeam 45.658 Evis  99.9 Emiss  -8.6 Vtx (  -0.07,   0.06,  -0.80) Muon(N=  0) Sec Vtx(N= 3) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
```

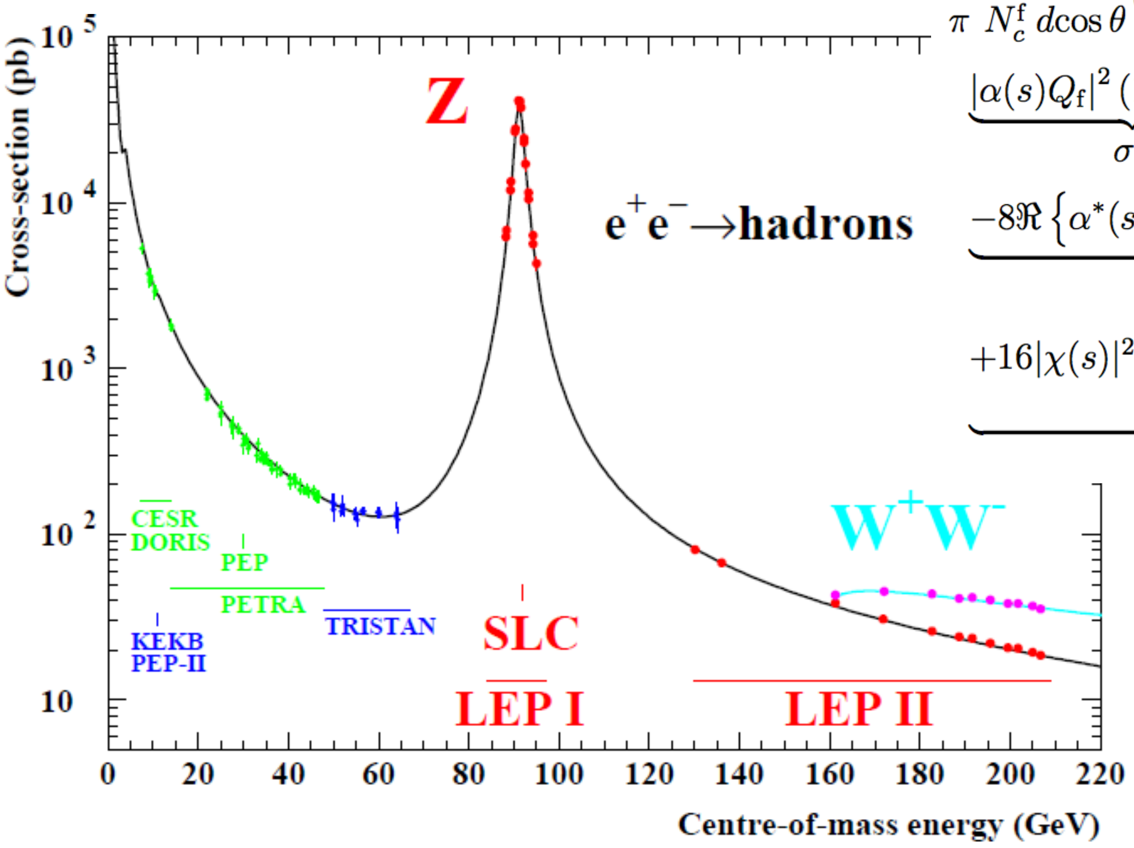
```
Centre of screen is (  0.0000,  0.0000,  0.0000)
```



```
DELPHI Interactive Analysis
Beam: 45.6 GeV          Run: 23438     DAS : 18-Jun-1991
                                              03:22:19
Proc: 8-Mar-1992        Evt: 581       Scan: 29-Apr-1992
```

	TD	TE	TS	TK	TV	ST	PA
Act	44	45	0	8	0	0	0
	(44)	(48)	(0)	(9)	(9)	(0)	(0)
Deact	0	0	0	0	0	0	0
	(0)	(4)	(0)	(6)	(5)	(0)	(0)

Line shape della Z



$$\frac{2s}{\pi}\frac{1}{N_c^{\mathrm{f}}}\frac{d\sigma_{\mathrm{ew}}}{d\cos\theta}(\mathrm{e^+e^-}\to \mathrm{f\bar{f}}) \;=$$

$$\underbrace{\left|\alpha(s)Q_{\mathrm{f}}\right|^2(1+\cos^2\theta)}_{\sigma^\gamma}$$

$$\underbrace{-8\Re\left\{\alpha^*(s)Q_{\mathrm{f}}\chi(s)\left[\mathcal{G}_{\mathrm{Ve}}\mathcal{G}_{\mathrm{Vf}}(1+\cos^2\theta)+2\mathcal{G}_{\mathrm{Ae}}\mathcal{G}_{\mathrm{Af}}\cos\theta\right]\right\}}_{\gamma\text{–Z interference}}$$

$$\underbrace{\begin{array}{c}+16|\chi(s)|^2\left[(|\mathcal{G}_{\mathrm{Ve}}|^2+|\mathcal{G}_{\mathrm{Ae}}|^2)(|\mathcal{G}_{\mathrm{Vf}}|^2+|\mathcal{G}_{\mathrm{Af}}|^2)(1+\cos^2\theta)\right.\\ \left.+8\Re\left\{\mathcal{G}_{\mathrm{Ve}}\mathcal{G}_{\mathrm{Ae}}{}^*\right\}\Re\left\{\mathcal{G}_{\mathrm{Vf}}\mathcal{G}_{\mathrm{Af}}{}^*\right\}\cos\theta\right]\end{array}}_{\sigma^{\mathrm{Z}}}$$

Dove:

$$\chi(s) \;=\; \frac{G_{\mathrm{F}}m_{\mathrm{Z}}^2}{8\pi\sqrt{2}}\frac{s}{s-m_{\mathrm{Z}}^2+is\Gamma_{\mathrm{Z}}/m_{\mathrm{Z}}}$$

$$\begin{aligned}\mathcal{G}_{\mathrm{Vf}} &= \sqrt{\mathcal{R}_{\mathrm{f}}}\,(T_3^{\mathrm{f}}-2Q_{\mathrm{f}}\mathcal{K}_{\mathrm{f}}\sin^2\theta_{\mathrm{W}})\\ \mathcal{G}_{\mathrm{Af}} &= \sqrt{\mathcal{R}_{\mathrm{f}}}\,T_3^{\mathrm{f}}\,.\end{aligned}$$

⇨ Parametri del Modello Standard con
fattori di forma dovuti a correzioni di ordine superiore

Correzioni di ordine superiore

- Le correzioni radiative modificano le relazioni dello SM al tree level:

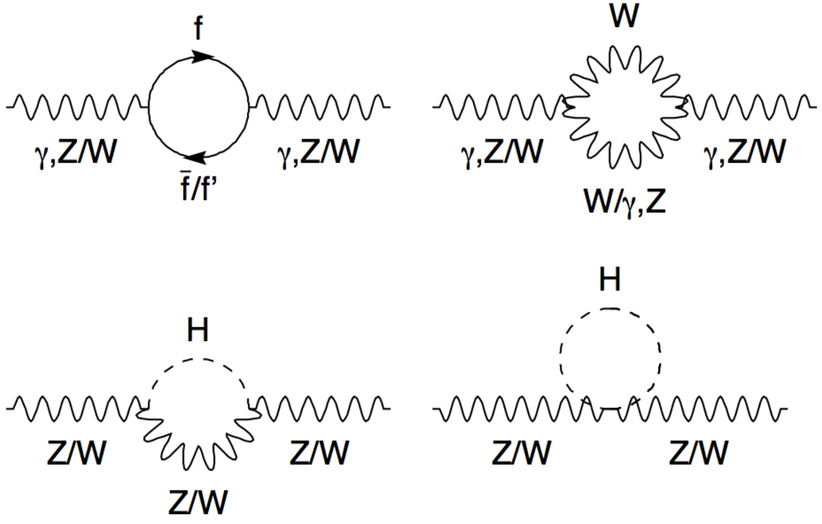
$$\rho_0 = \frac{m_{\rm W}^2}{m_{\rm Z}^2\cos^2\theta_{\rm W}} = 1 \quad \Rightarrow \quad \rho = 1 + \Delta\rho$$

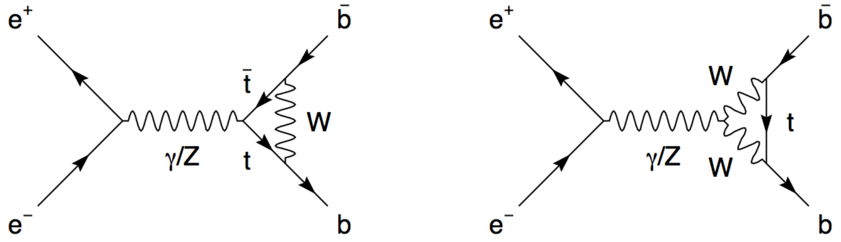
$$\frac{g_{\rm Vf}}{g_{\rm Af}} = \Re\left(\frac{\mathcal{G}_{\rm Vf}}{\mathcal{G}_{\rm Af}}\right) = 1 - 4|Q_{\rm f}|\sin^2\theta_{\rm eff}^{\rm f}$$

$$\begin{aligned}\sin^2\theta_{\rm eff}^{\rm f} &\equiv \kappa_{\rm f}\sin^2\theta_{\rm W}\\ g_{\rm Vf} &\equiv \sqrt{\rho_{\rm f}}\,(T_3^{\rm f} - 2Q_{\rm f}\sin^2\theta_{\rm eff}^{\rm f})\\ g_{\rm Af} &\equiv \sqrt{\rho_{\rm f}}\,T_3^{\rm f}\,,\end{aligned}$$

$$\begin{aligned}\Delta\rho_{\rm se} &= \frac{3G_{\rm F}m_{\rm W}^2}{8\sqrt{2}\pi^2}\left[\boxed{\frac{m_{\rm t}^2}{m_{\rm W}^2}} - \frac{\sin^2\theta_{\rm W}}{\cos^2\theta_{\rm W}}\left(\boxed{\ln\frac{m_{\rm H}^2}{m_{\rm W}^2}} - \frac{5}{6}\right) + \cdots\right]\\ \Delta\kappa_{\rm se} &= \frac{3G_{\rm F}m_{\rm W}^2}{8\sqrt{2}\pi^2}\left[\frac{m_{\rm t}^2}{m_{\rm W}^2}\frac{\cos^2\theta_{\rm W}}{\sin^2\theta_{\rm W}} - \frac{10}{9}\left(\ln\frac{m_{\rm H}^2}{m_{\rm W}^2} - \frac{5}{6}\right) + \cdots\right]\end{aligned}$$

$$\begin{aligned}\rho_{\rm f} &\equiv \Re(\mathcal{R}_{\rm f}) = 1 + \Delta\rho_{\rm se} + \Delta\rho_{\rm f}\\ \kappa_{\rm f} &\equiv \Re(\mathcal{K}_{\rm f}) = 1 + \Delta\kappa_{\rm se} + \Delta\kappa_{\rm f}\end{aligned}$$

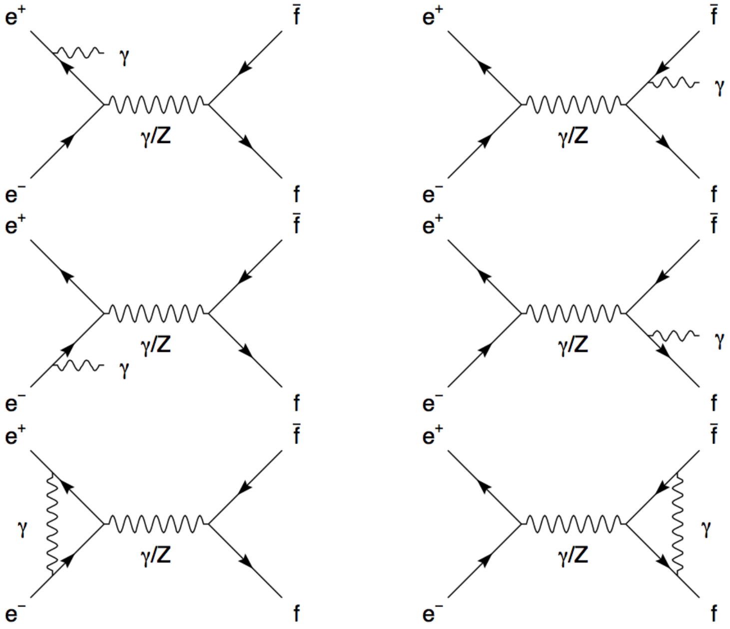


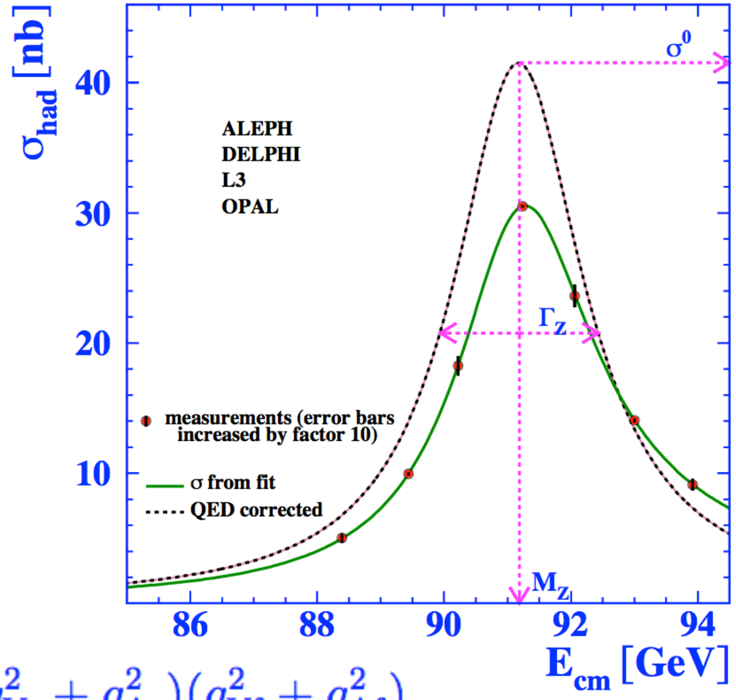


La produzione bb risente particolarmente della presenza del quark t

Correzioni radiative

- La radiazione di stato iniziale (e finale) distorce la line shape della Z





$$\sigma_{f\bar{f}} \propto (g_{Ve}^2 + g_{Ae}^2)(g_{Vf}^2 + g_{Af}^2)$$

$$\sigma_{f\bar{f}}^{Z} = \sigma_{f\bar{f}}^{peak} \frac{s\Gamma_Z^2}{(s - m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

$$\sigma(s) = \int_{4m_f^2/s}^{1} dz H_{QED}^{tot}(z,s)\sigma_{ew}(zs)$$

$$\sigma_{f\bar{f}}^{peak} = \frac{1}{R_{QED}}\sigma_{f\bar{f}}^{0} \qquad \sigma_{f\bar{f}}^{0} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

$$R_e^0 \equiv \Gamma_{had}/\Gamma_{ee},\ R_\mu^0 \equiv \Gamma_{had}/\Gamma_{\mu\mu} \text{ and } R_\tau^0 \equiv \Gamma_{had}/\Gamma_{\tau\tau}$$

Numero di neutrini leggeri

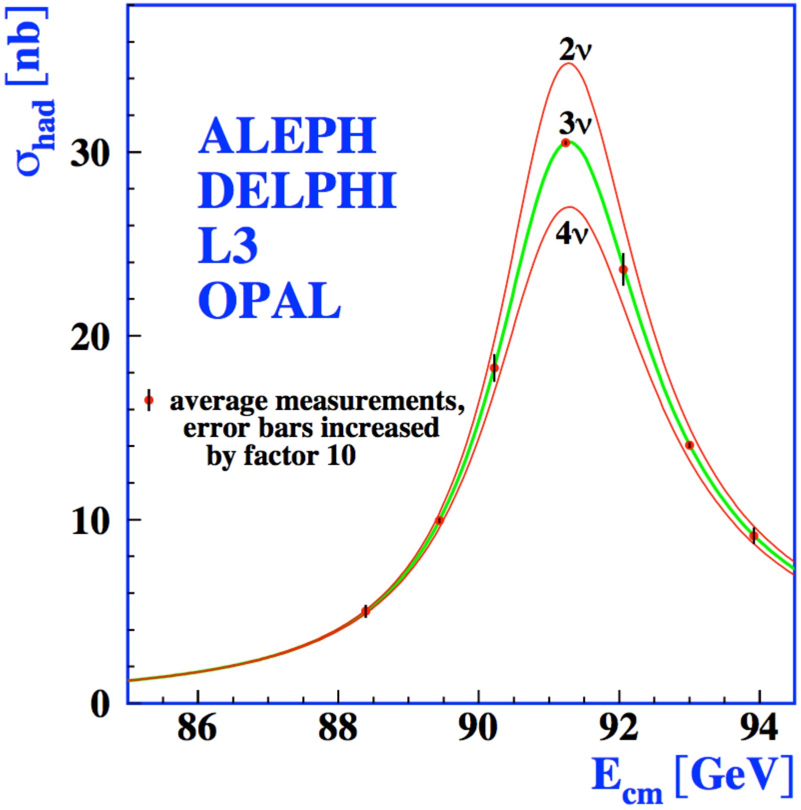
- Il numero di famiglie di neutrini si ricava indirettamente dalla larghezza totale della Z e dalle larghezze parziali di decadimento

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\mathrm{had}} + \Gamma_{\mathrm{inv}}$$

$$R^0_{\mathrm{inv}} = N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\ell\ell}}\right)_{\mathrm{SM}}$$

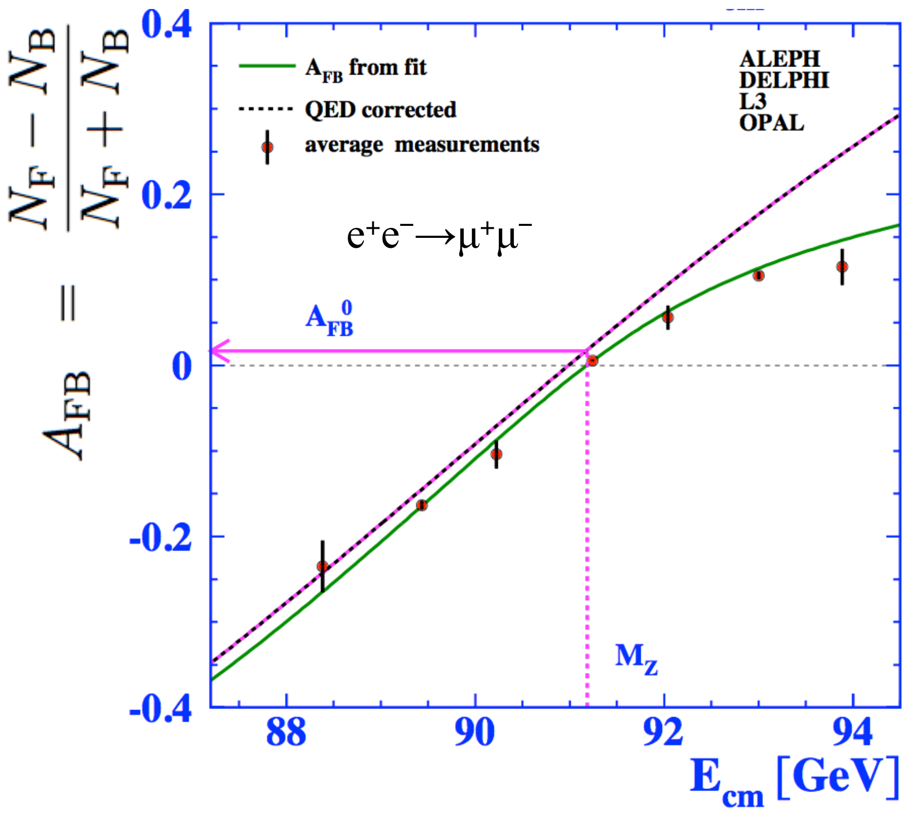
$$N_\nu = 2.9840 \pm 0.0082$$

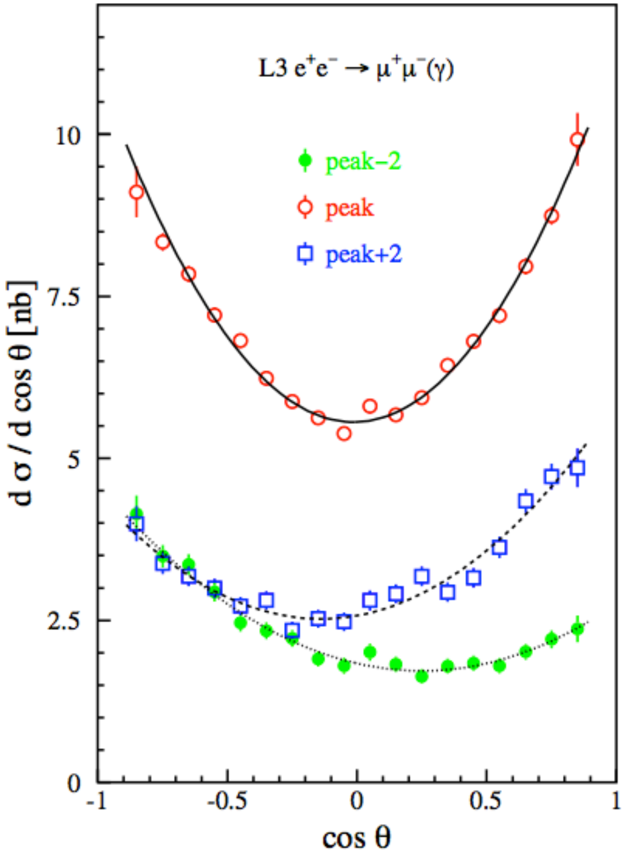
… ovviamente, se i neutrini sono leggeri ($m_\nu < m_Z/2$)



Asimmetria FB

- Misura della sezione d'urto differenziale in funzione di θ

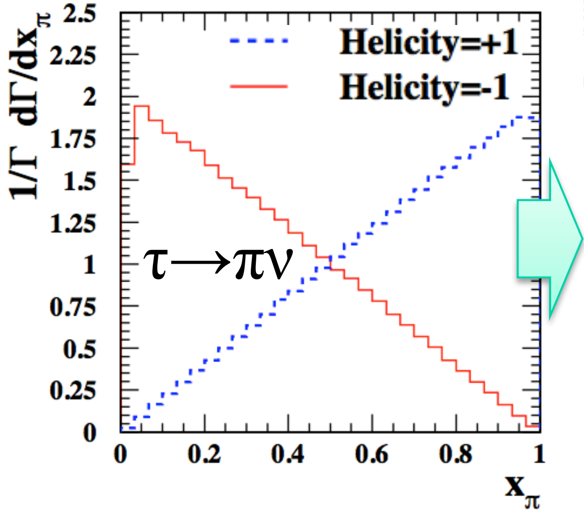


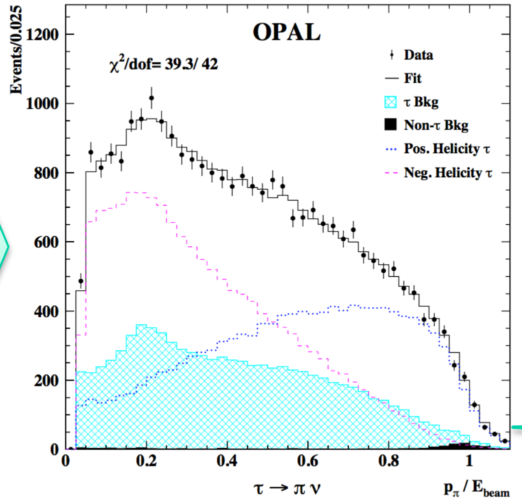


$$A_{FB}^{0,f} = \frac{3}{4}\frac{2g_{Ve}g_{Ae}}{g_{Ve}^2 + g_{Ae}^2}\frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

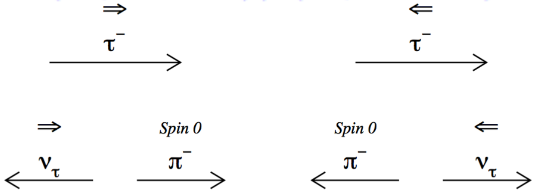
$$\mathcal{A}_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2} = 2\frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2}$$

Polarizzazione stati finali (τ)





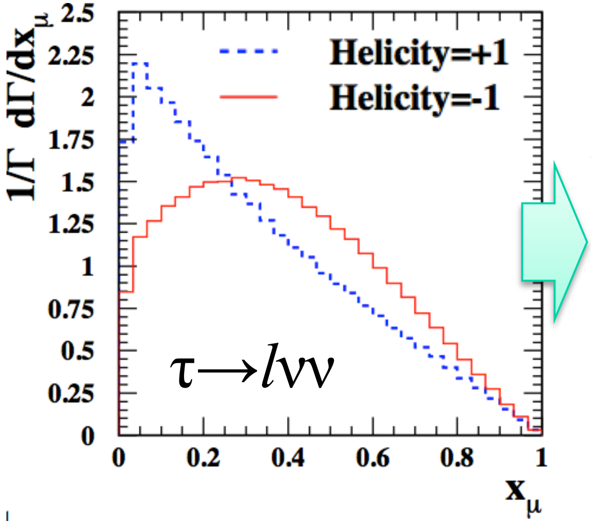
$$\mathcal{P}_\tau \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

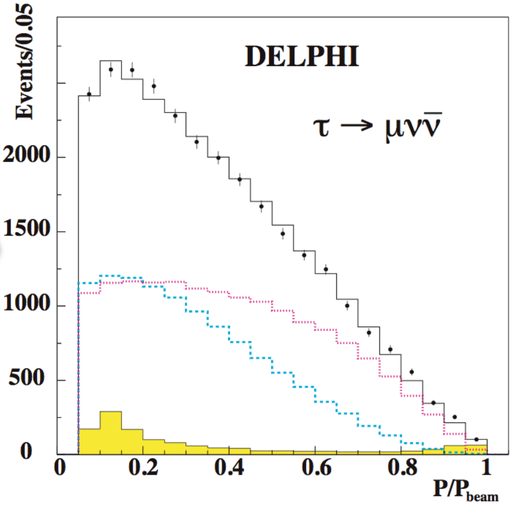


$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\pi} = \frac{1}{2}(1 + \mathcal{P}_\tau \cos\theta_\pi)$$

θ_π nel sist. di riferimento a riposo del τ

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx_\pi} = 1 + \mathcal{P}_\tau(2x_\pi - 1) \qquad x_\pi = E_\pi/E_\tau$$





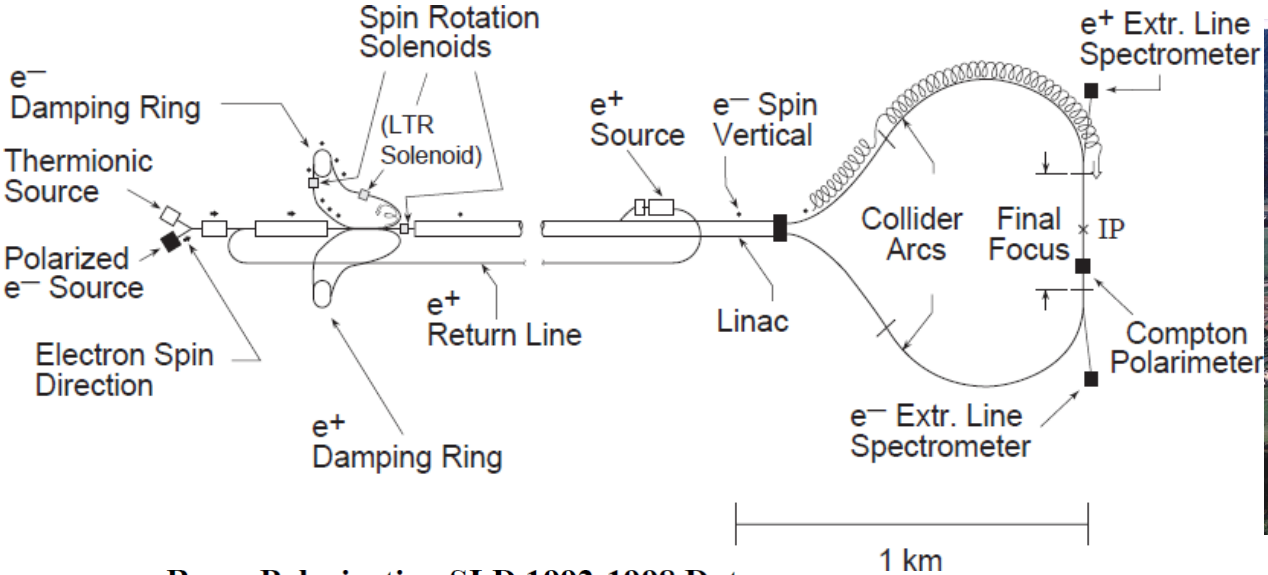
Momenti misurati nel sistema del laboratorio

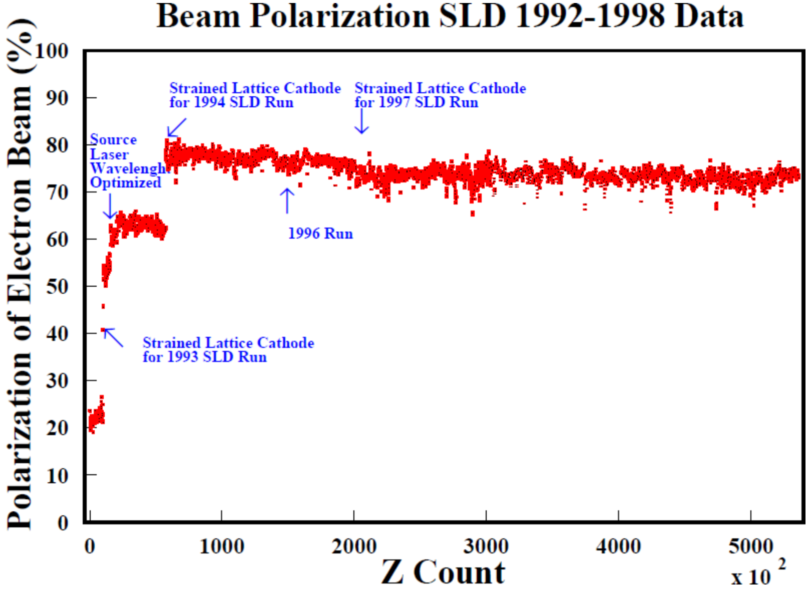
Due neutrini nello stato finale!

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx_\ell} = \frac{1}{3}\left[(5 - 9x_\ell^2 + 4x_\ell^3) + \mathcal{P}_\tau(1 - 9x_\ell^2 + 8x_\ell^3)\right]$$

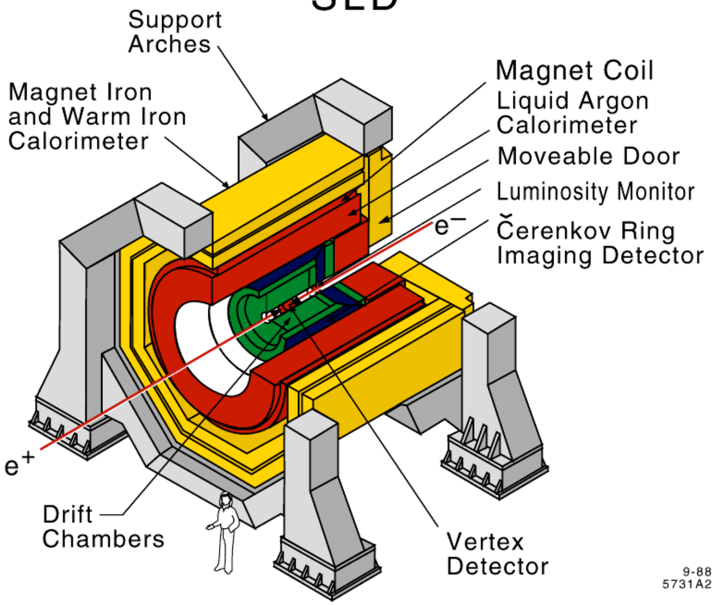
Per decadimenti con ρ e a_1 si possono fare studi più complessi delle variabili angolari

SLC/SLD a SLAC





SLD



Polarizzazione dei fasci

- La sezione d'urto dipende dalla polarizzazione dei fasci collidenti

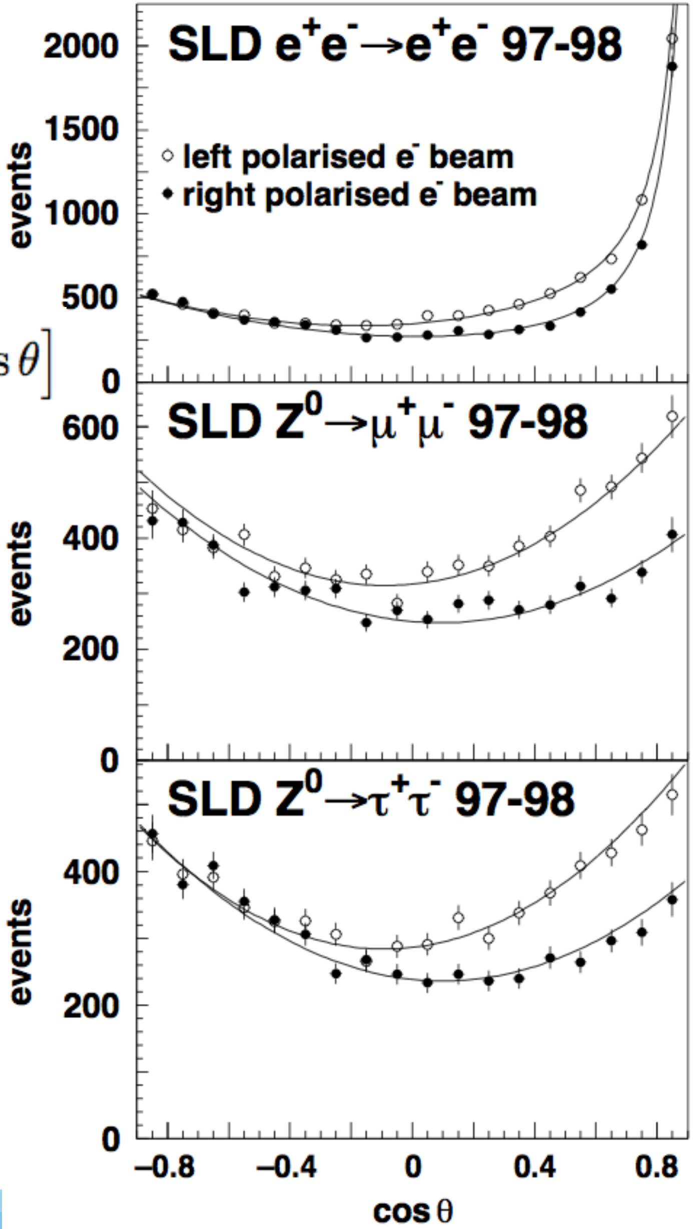
$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma_{f\bar{f}}^{tot}\left[(1-\mathcal{P}_e\mathcal{A}_e)(1+\cos^2\theta)+2(\mathcal{A}_e-\mathcal{P}_e)\mathcal{A}_f\cos\theta\right]$$

$$\mathcal{A}_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2+g_{Af}^2} = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2}$$

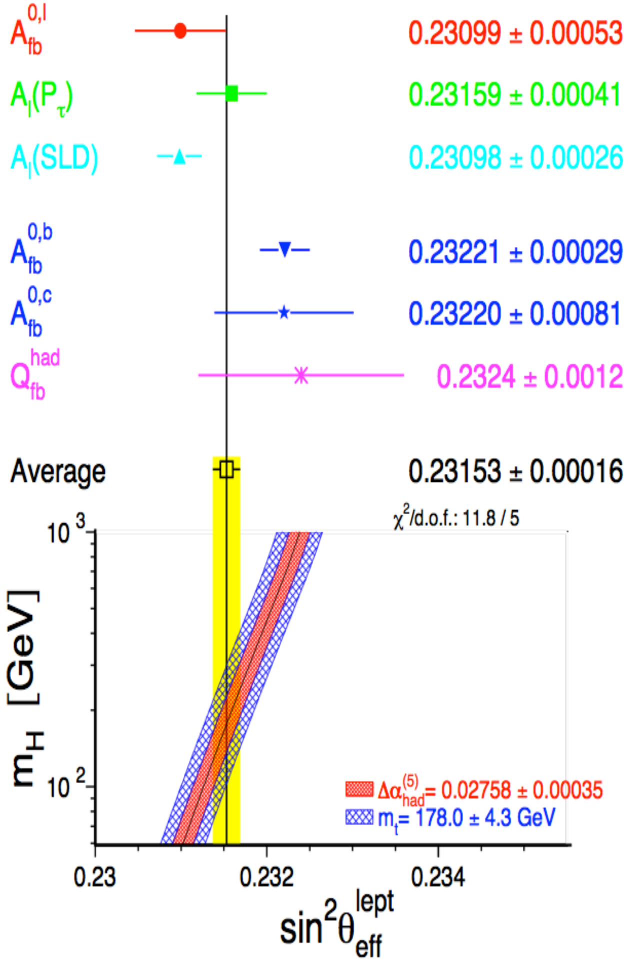
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}\frac{1}{\langle|\mathcal{P}_e|\rangle}$$

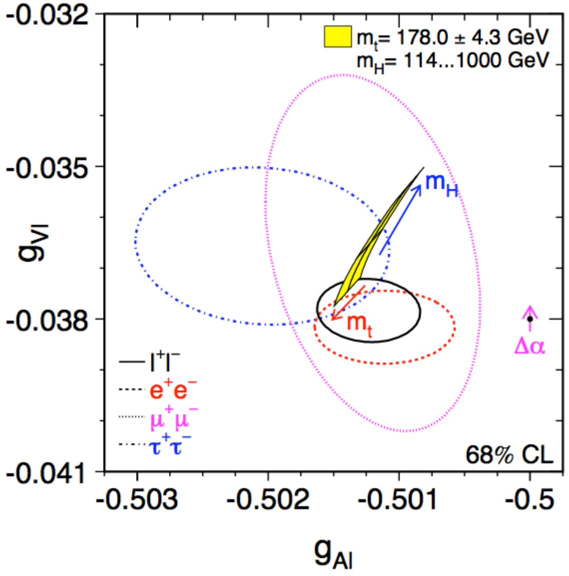
$$A_{LRFB} = \frac{(\sigma_F-\sigma_B)_L - (\sigma_F-\sigma_B)_R}{(\sigma_F+\sigma_B)_L + (\sigma_F+\sigma_B)_R}\frac{1}{\langle|\mathcal{P}_e|\rangle}$$

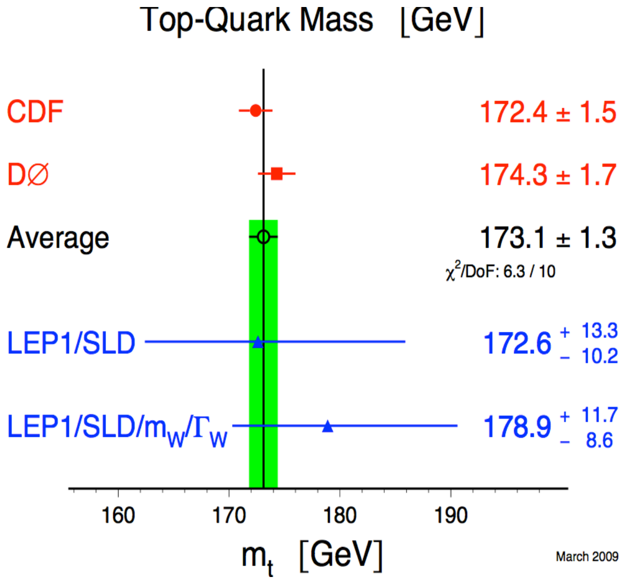


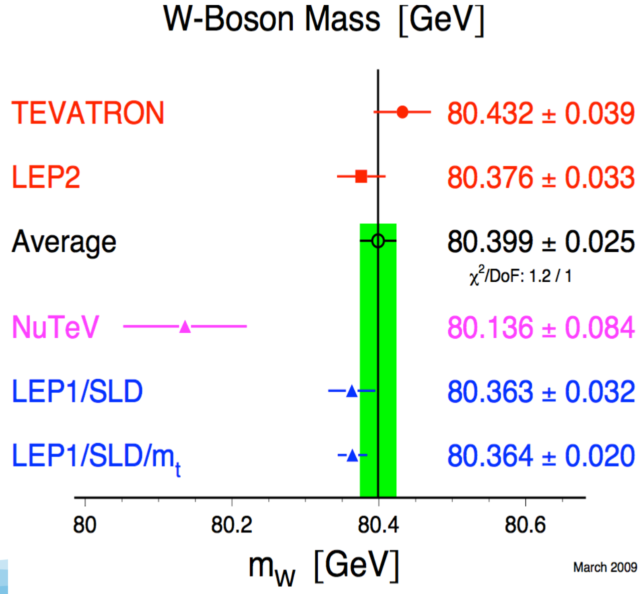
Mettendo tutto insieme ...



Universalità leptonica



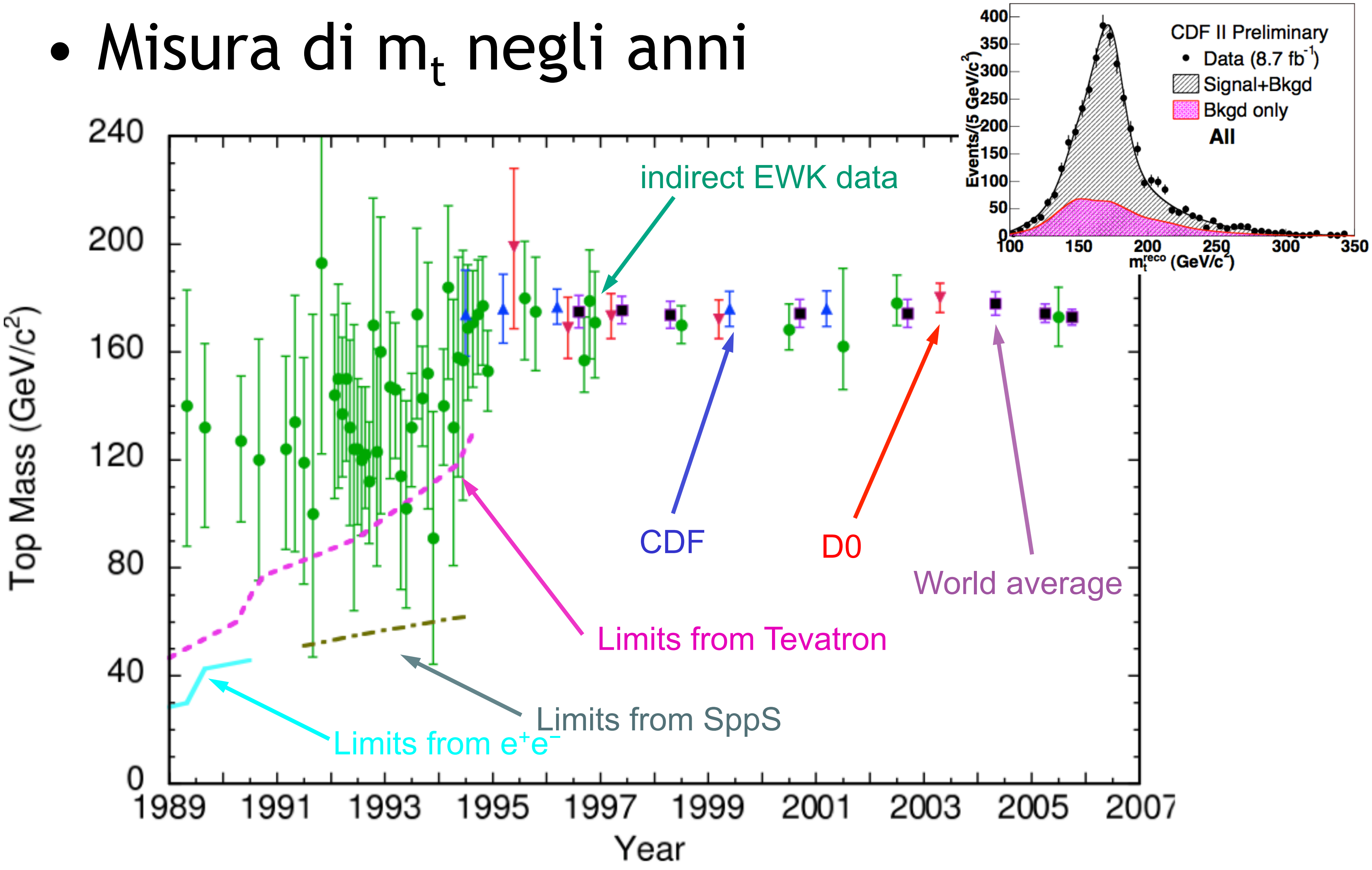




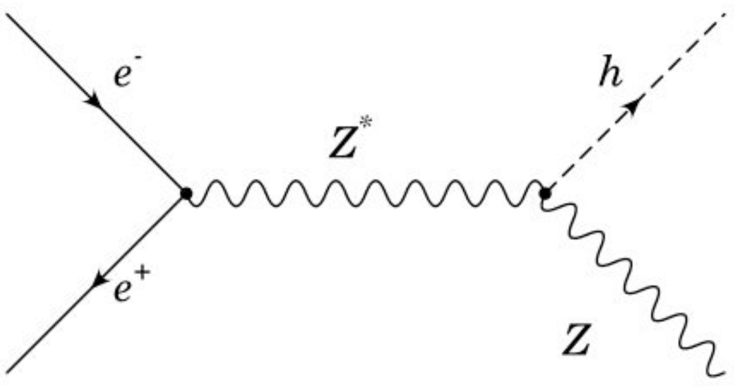
http://lepewwg.web.cern.ch/LEPEWWG/

La massa del quark top

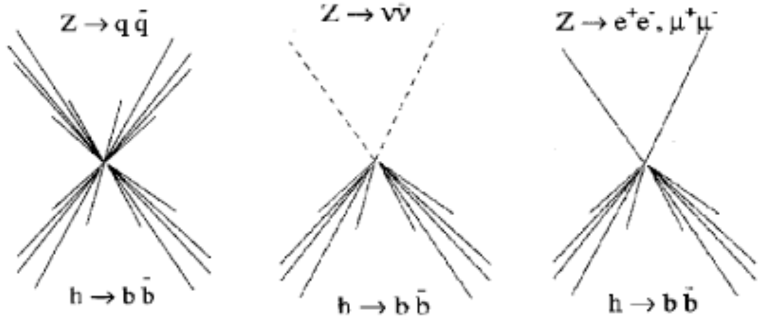
- Misura di m_t negli anni

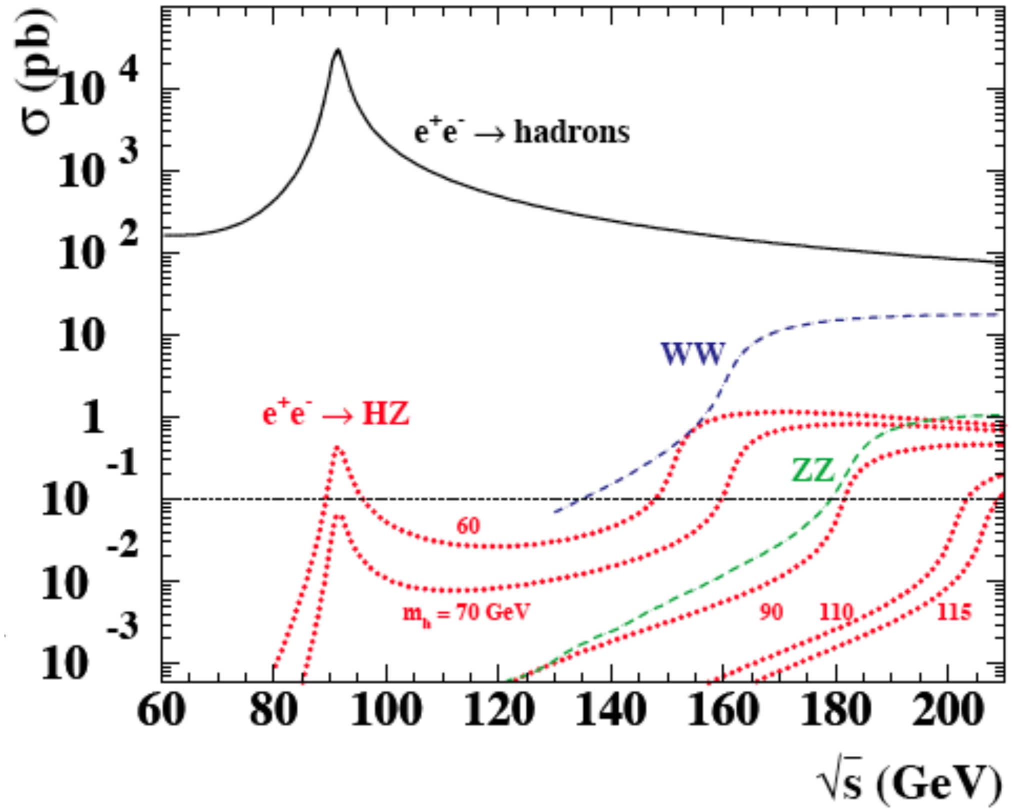


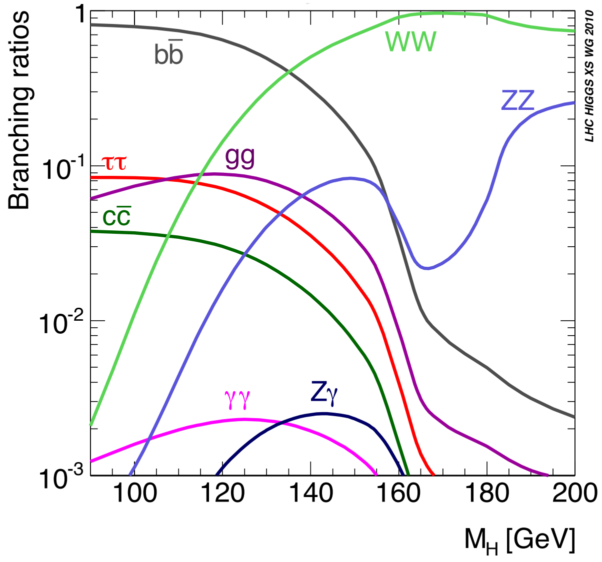
Produzione di Higgs a LEP



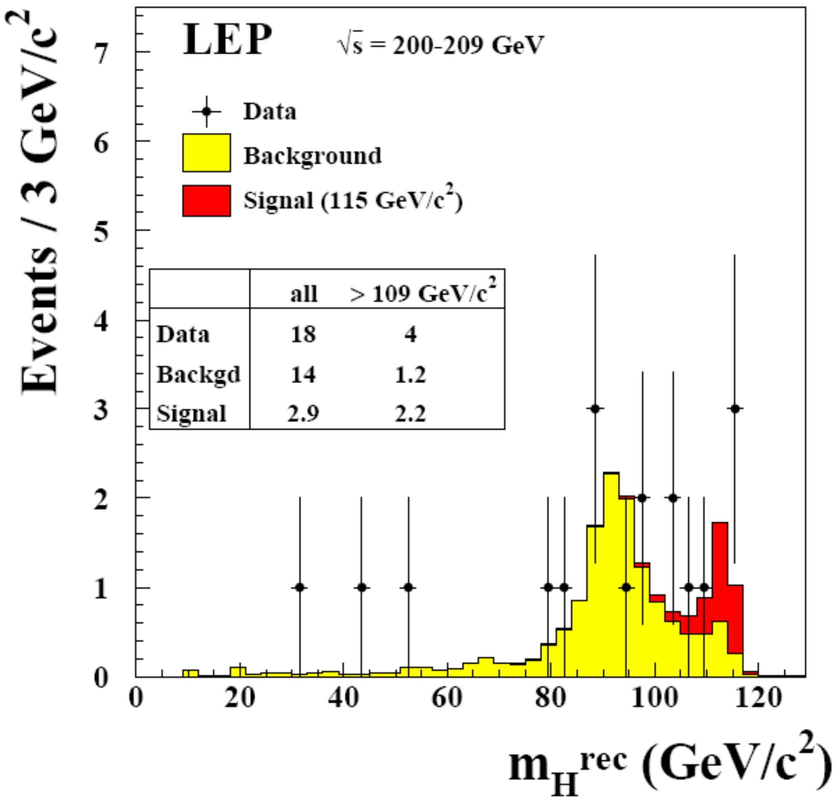
- Necessario avere $\sqrt{s} \geq m_H + m_Z$
- $\sqrt{s}_{max}$ = 209 GeV → sensibilità fino a m_H ~118 GeV
- L'Higgs decade prevalentemente in bb alle energie di LEP
- I possibili decadimenti della Z producono segnature sperimentali diverse



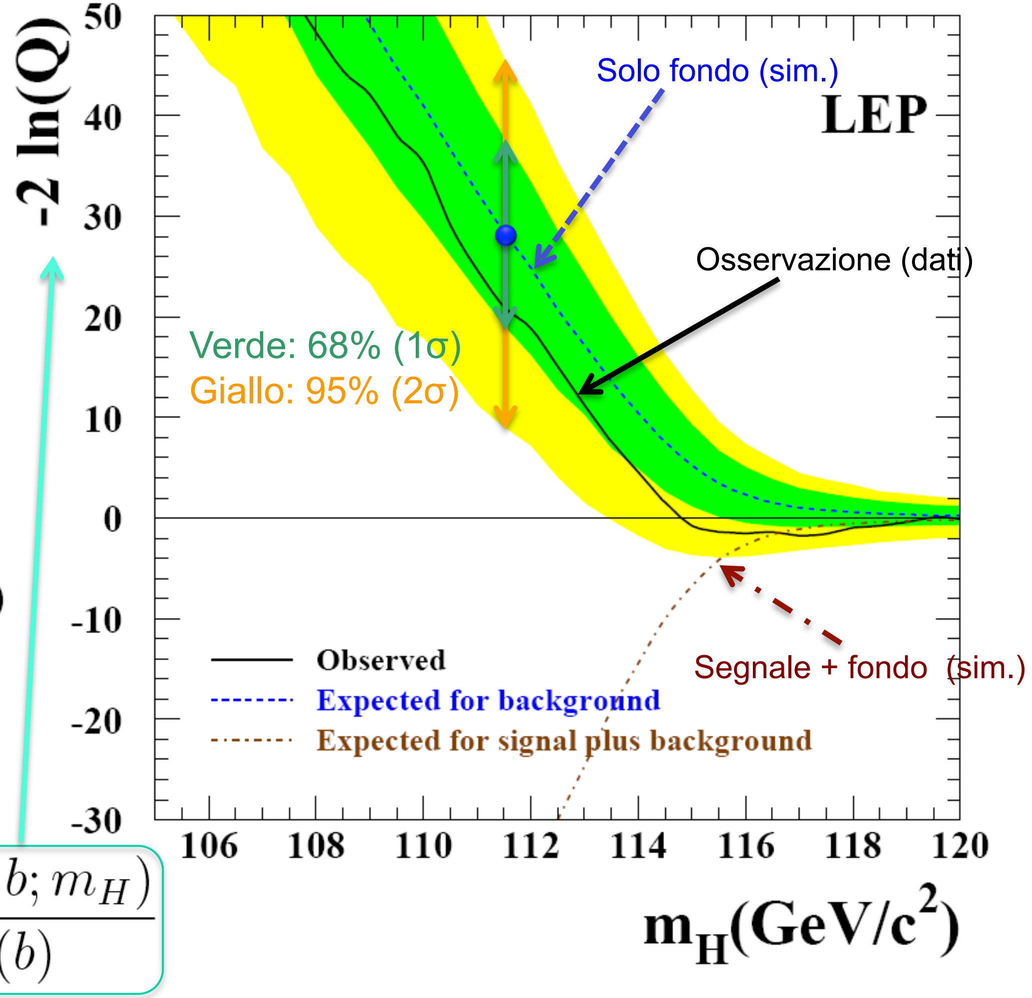




Ricerca dell'Higgs vs m_H



	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2



Solo fondo (sim.)

Osservazione (dati)

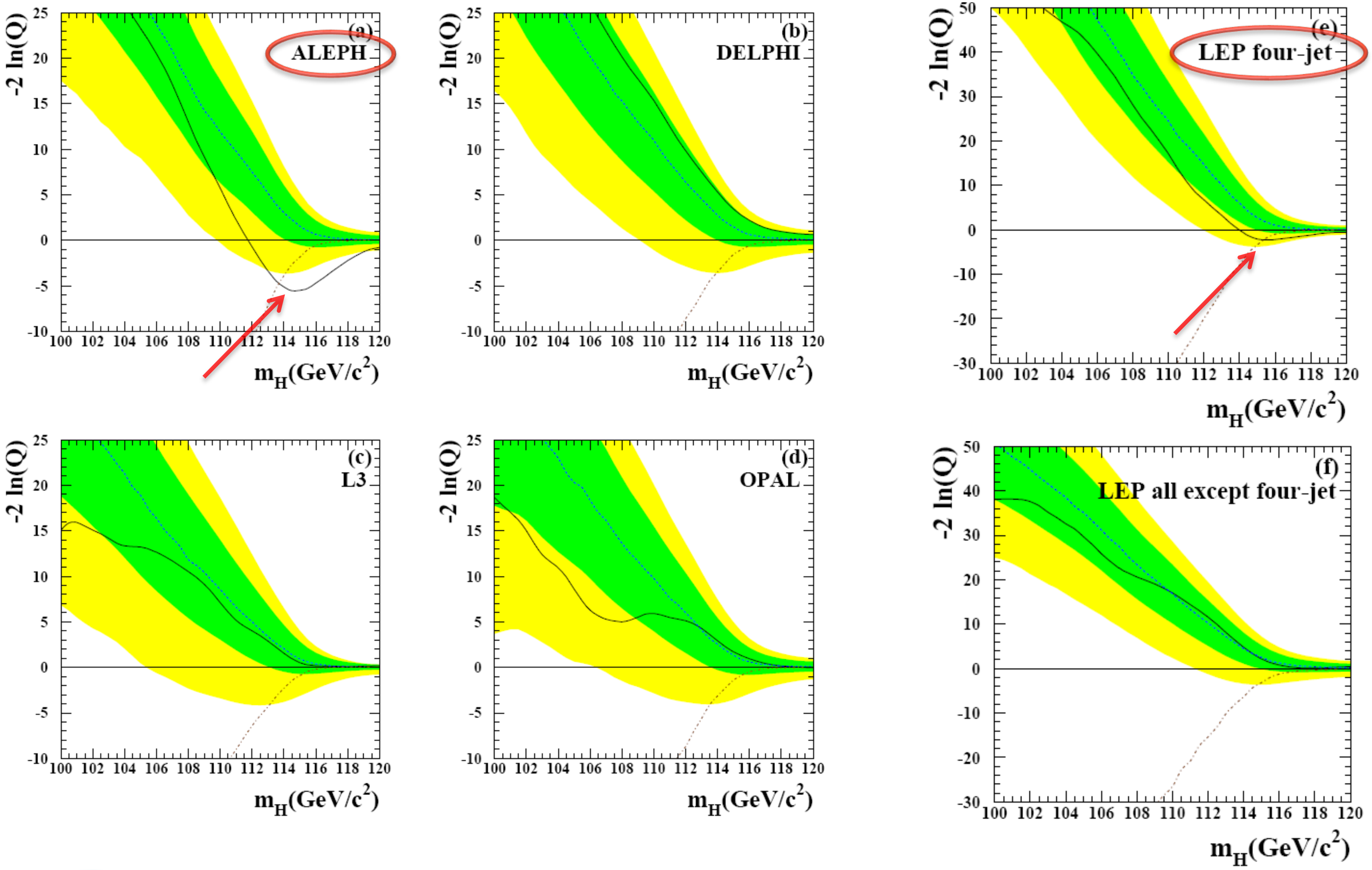
Verde: 68% (1σ)

Giallo: 95% (2σ)

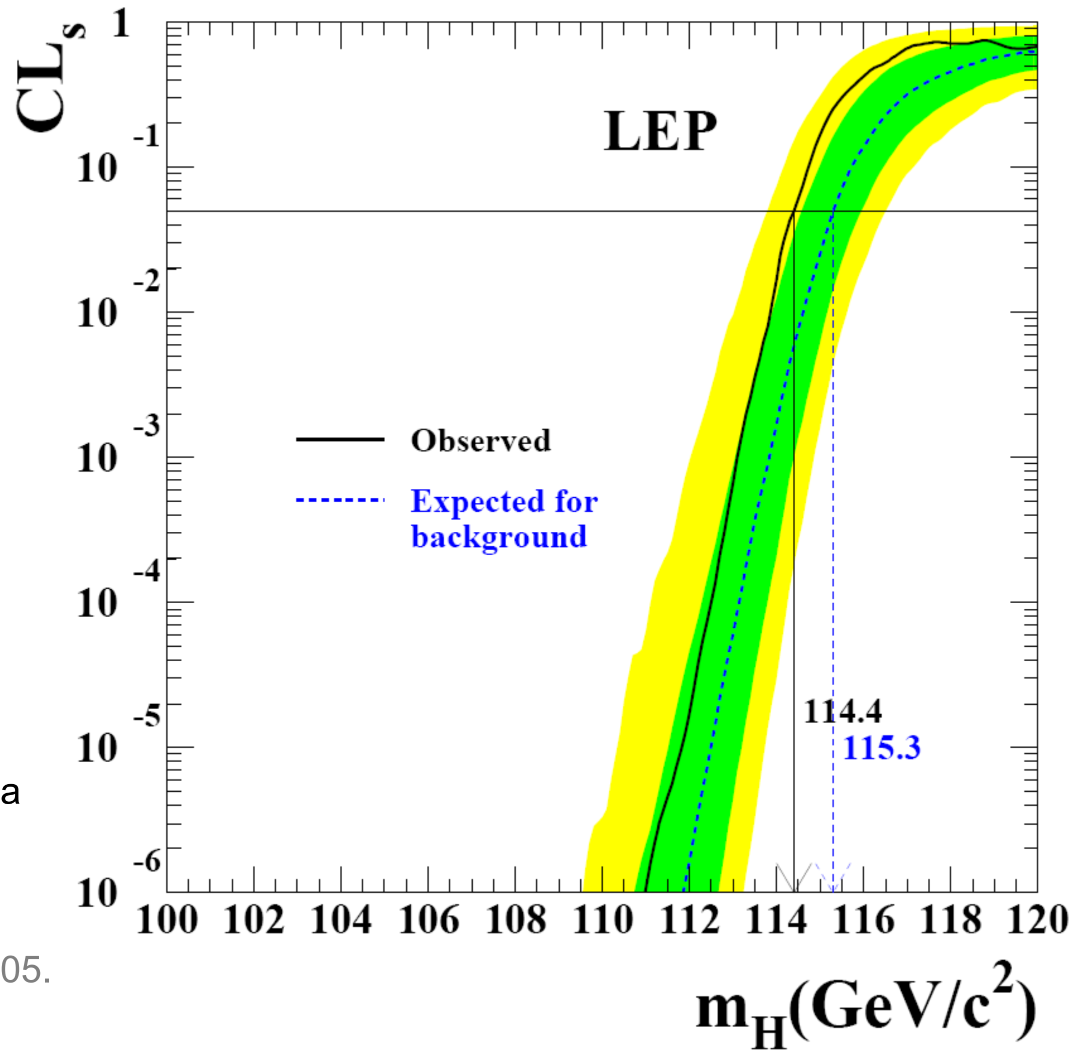
Segnale + fondo (sim.)

$$-2\ln Q = -2\ln\frac{L(s+b;m_H)}{L(b)}$$

Canali e esperimenti



C.L. dell'ipotesi di segnale



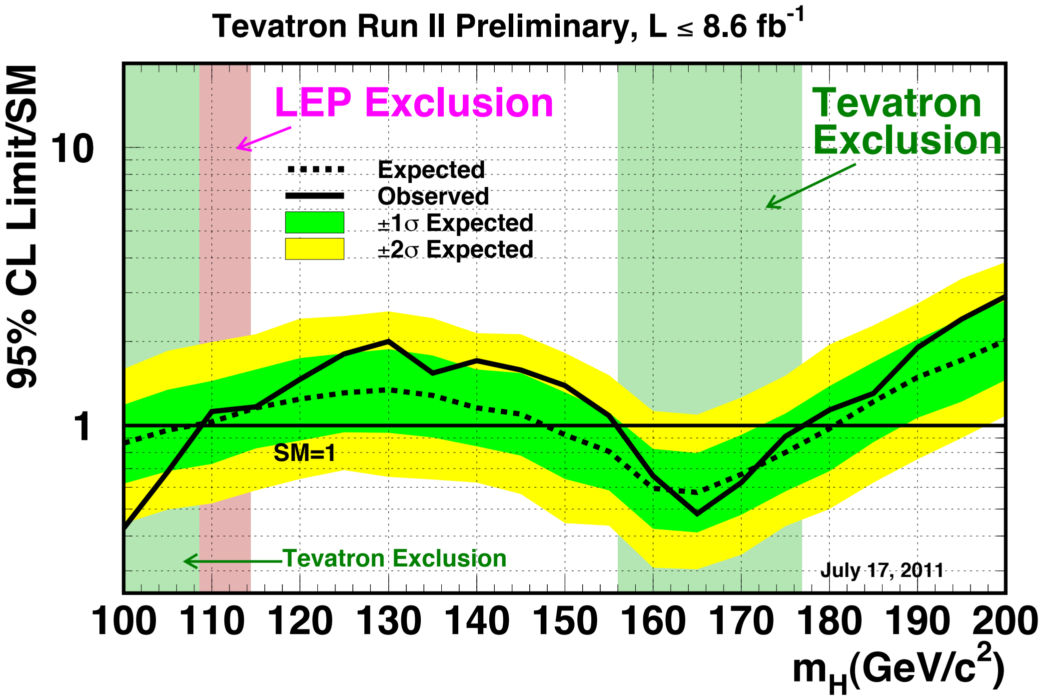
Approccio frequentista modificato (CLs)

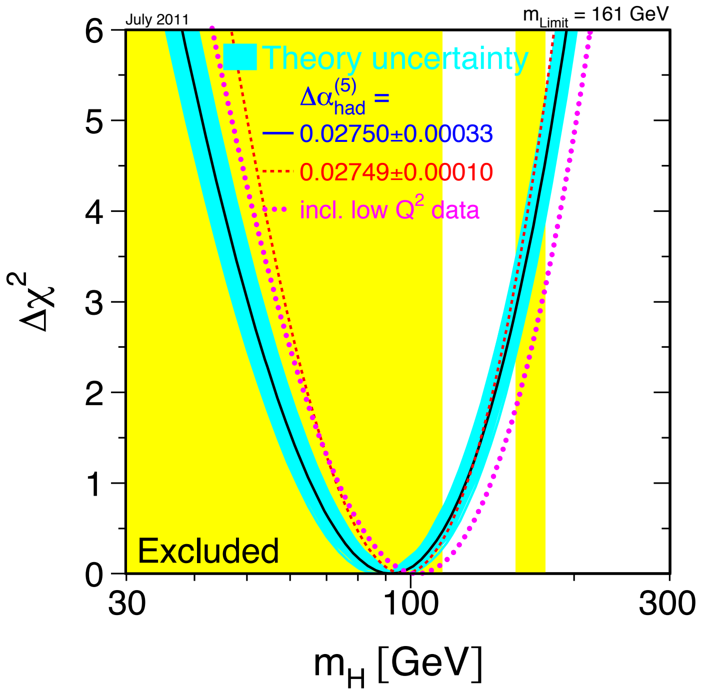
A.L. Read,
CERN OPEN-2000-205.

Intervallo escluso: m_H<114.4 GeV al 95% CL (atteso: m_H<115.3 GeV)

Prima di LHC

- Il bosone di Higgs è stato cercato al Tevatron dopo LEP
  - Sono stati stabiliti nuovi limiti alla bosone di Higgs
- Le misure di precisione dei parametri elettrodeboli al LEP permettono di determinare in maniera indiretta, con limitata precisione, l’intervallo di massa preferito, **se** esiste il bosone di Higgs



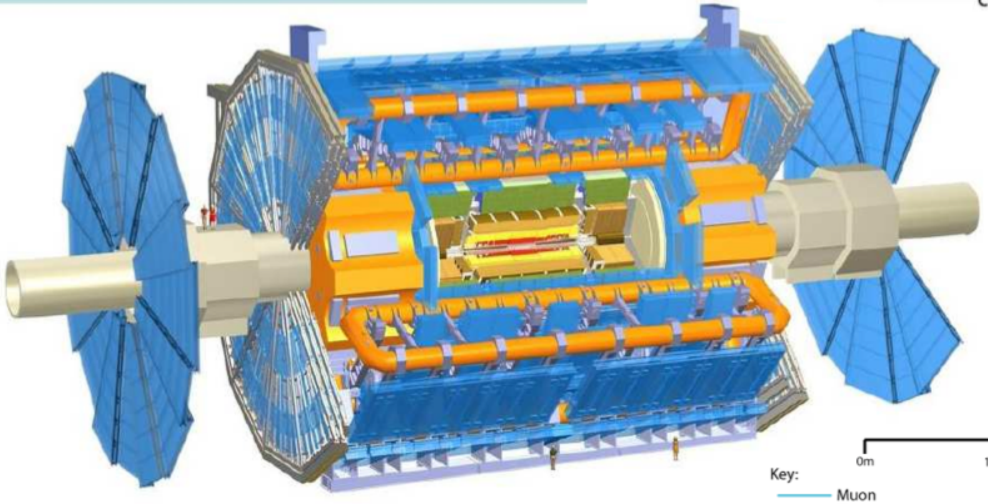


ATLAS e CMS ad LHC

Muon Spectrometer: |η|<2.7
Air-core toroids with gas based muon chambers
$\sigma(p_T)/p_T$ = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t

CERN AC - ATLAS V1997

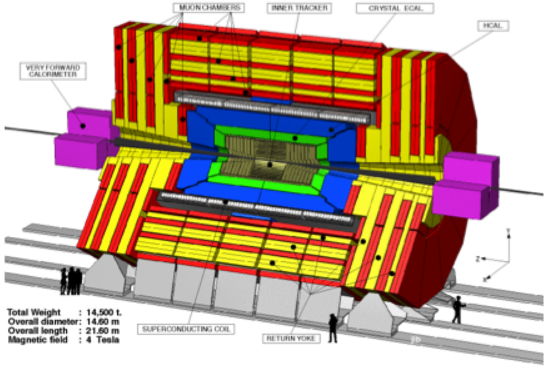


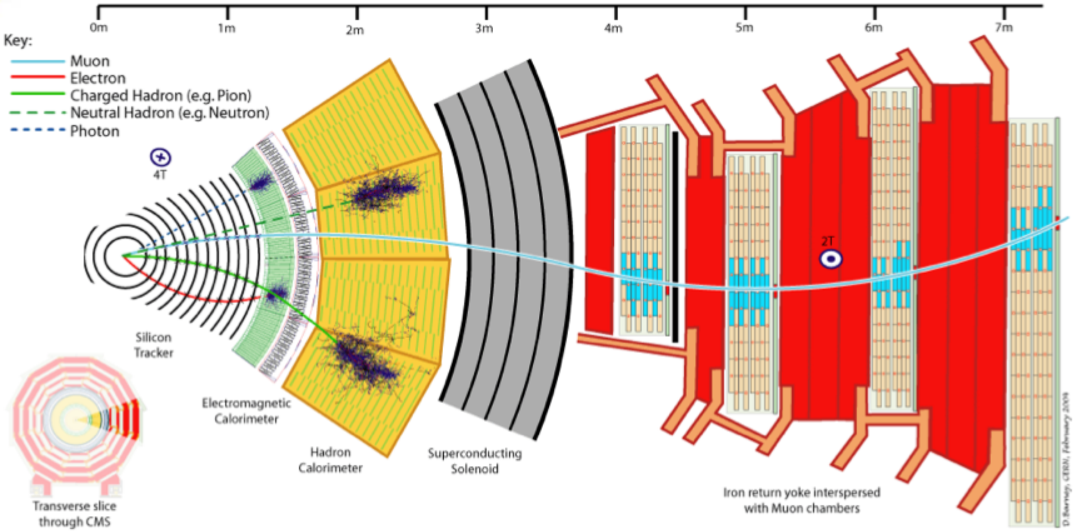
Inner Detector: |η|<2.5, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma(p_T)/p_T = 0.05\%\ p_T \oplus 1\%$

Hadronic Calorimeter: |η|<4.9
Fe/scintillating Tiles (central), Cu/W LAr (fwd)
$\sigma(E_{jet})/E_{jet} = 50\%\ \sqrt{E} \oplus 3\%$

EM Calorimeter: |η|<3.2
Pb-LAr Accordion
$\sigma(E)/E = 10\%\ \sqrt{E} \oplus 0.7\%$

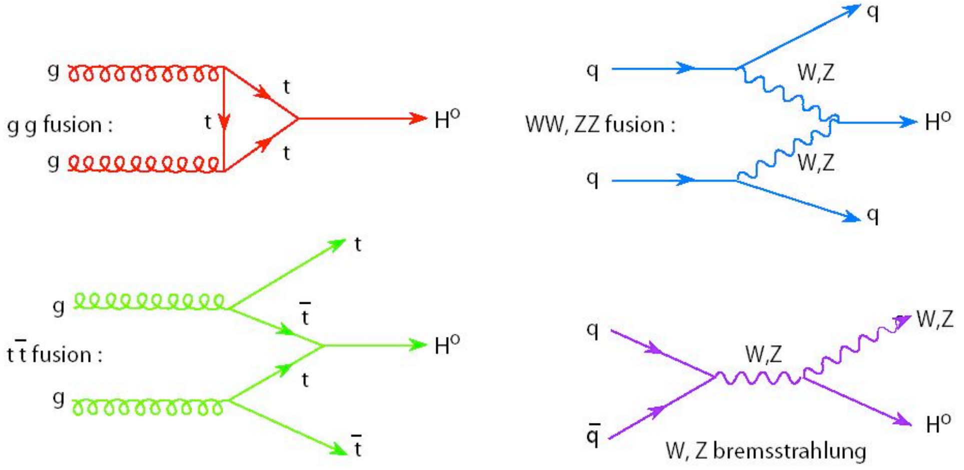
Barrel assembly + 2 endcaps ; successive layers outwards from the collision region:
- silicon pixel and strip tracker
- lead-tungstate crystal EM calorimeter
- brass/scintillator hadronic calorimeter
- 3.8 T superconducting solenoid
- gas-ionization muon chambers embedded in the steel return yoke

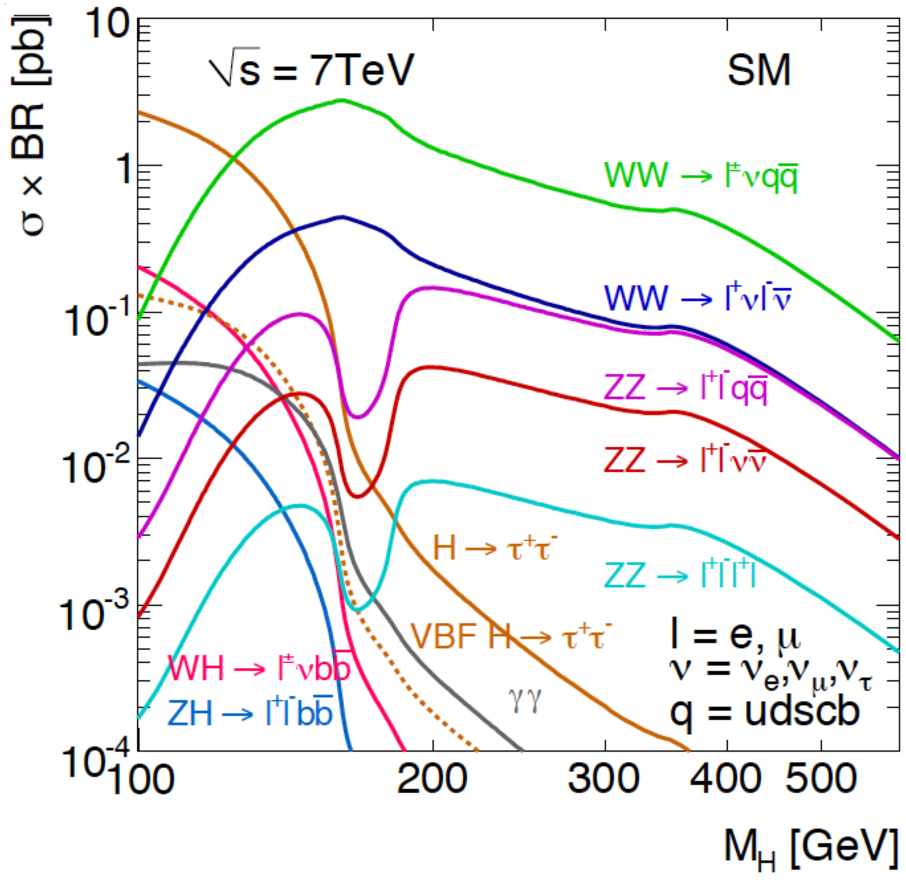




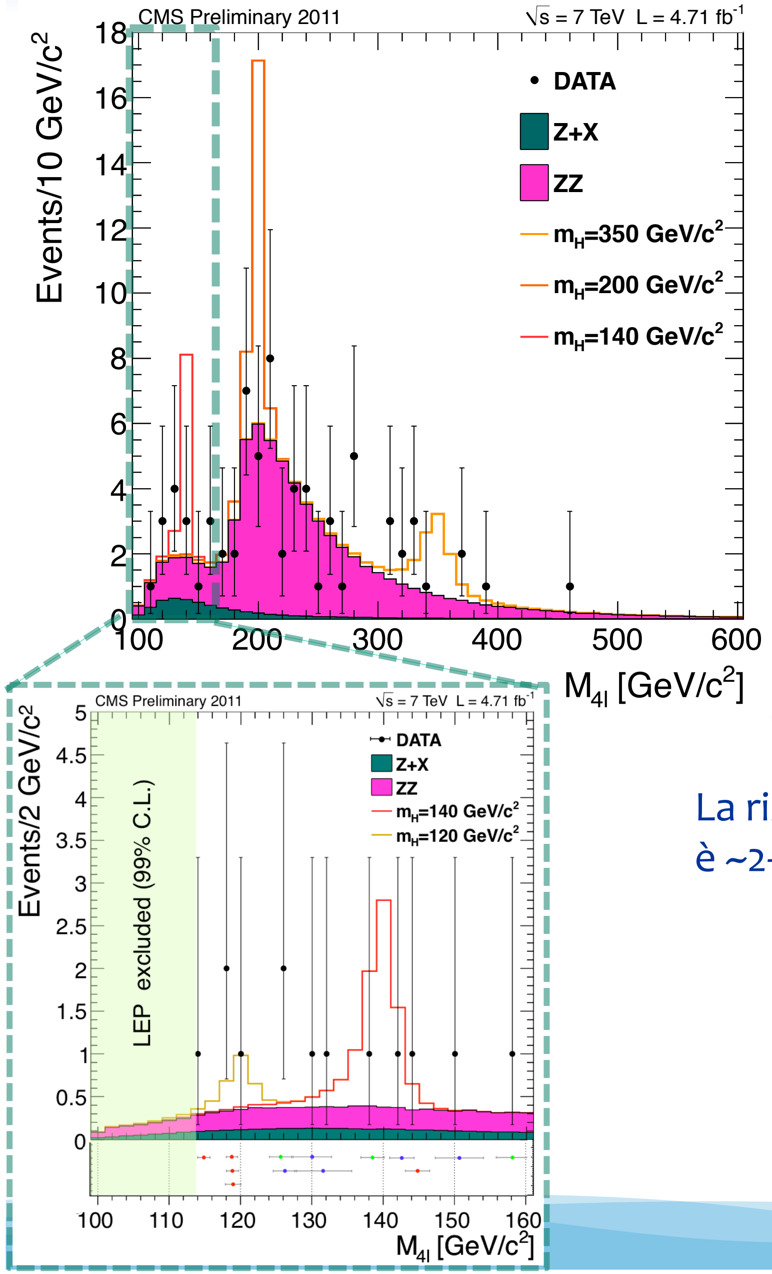
Produzione di Higgs a LHC

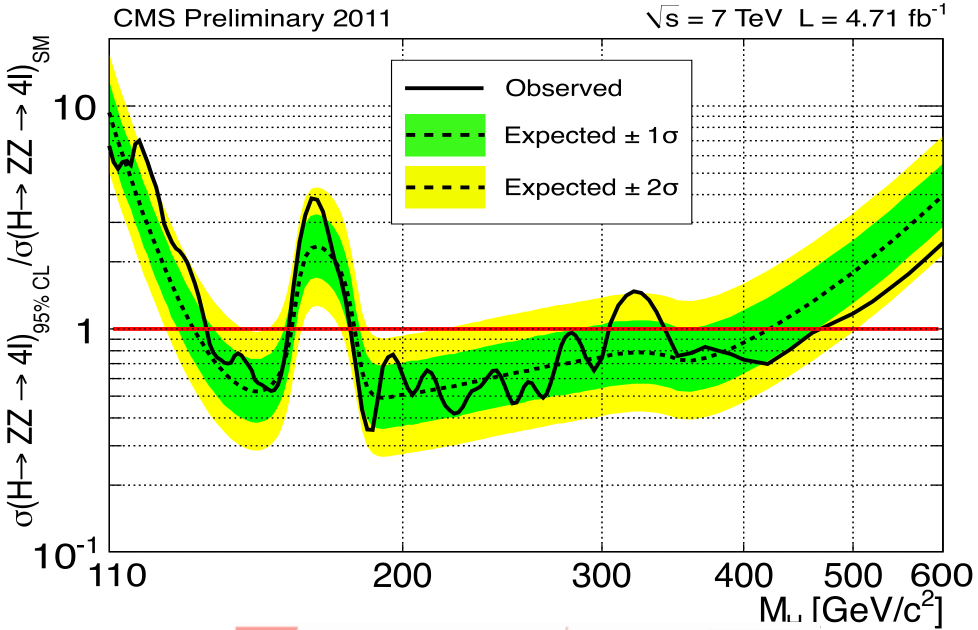
- Il bosone di Higgs interagisce più facilmente con particelle pesanti (top, Z, W, b, …)
- I meccanismi più abbondanti sono “gluon fusion” e “vector-boson fusion”



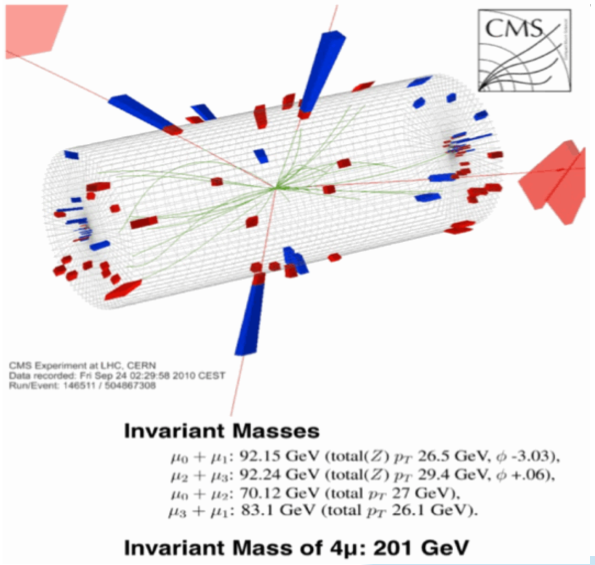


Il canale "golden": H→ZZ →4l (l=e, μ)





La risoluzione in massa
è ~2-3 GeV

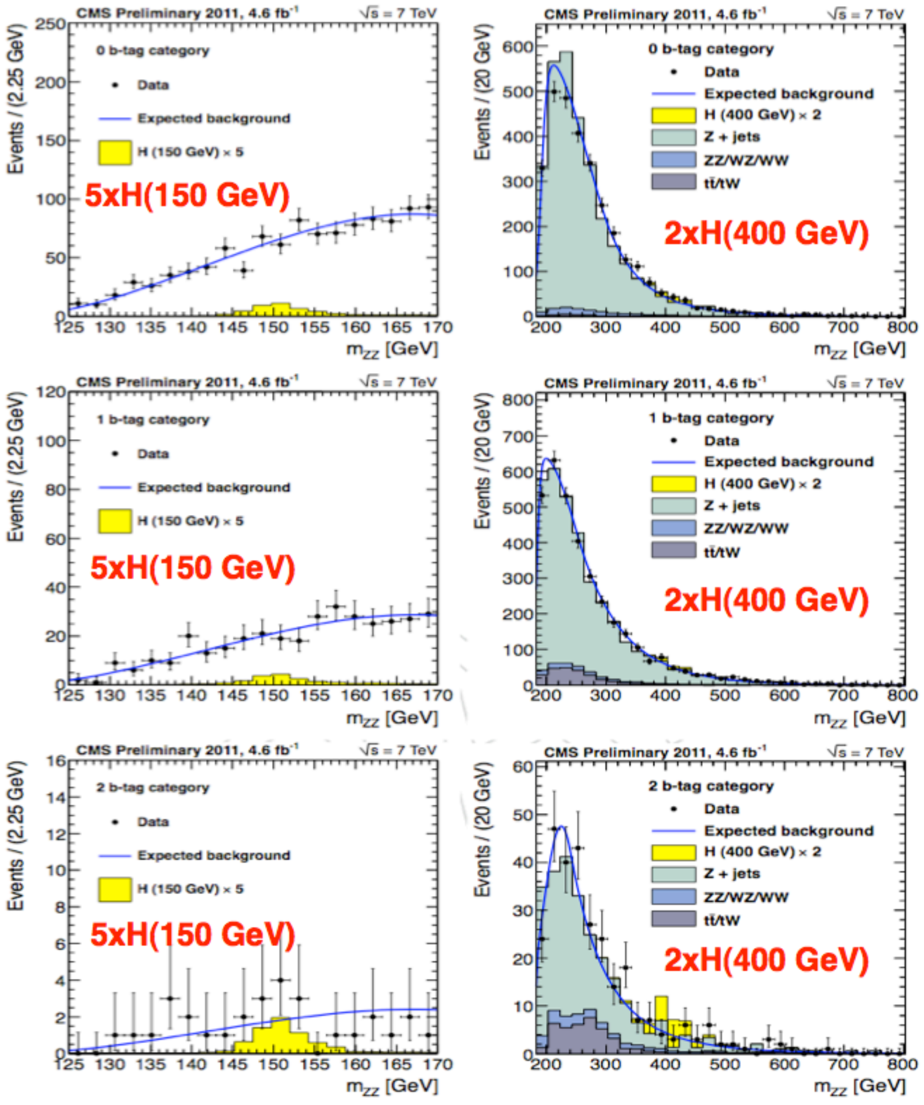

CMS Experiment at LHC, CERN
Data recorded: Fri Sep 24 02:29:58 2010 CEST
Run/Event: 146511 / 504867308

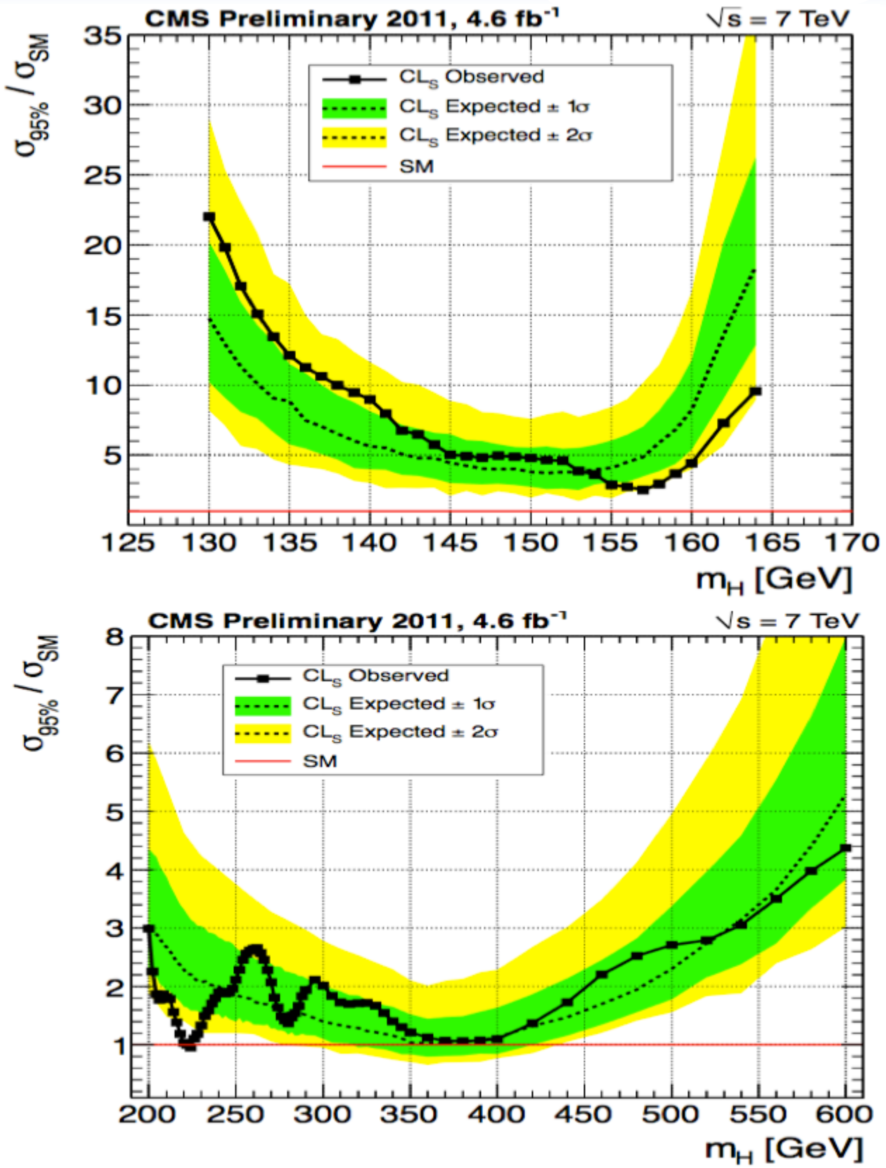
Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

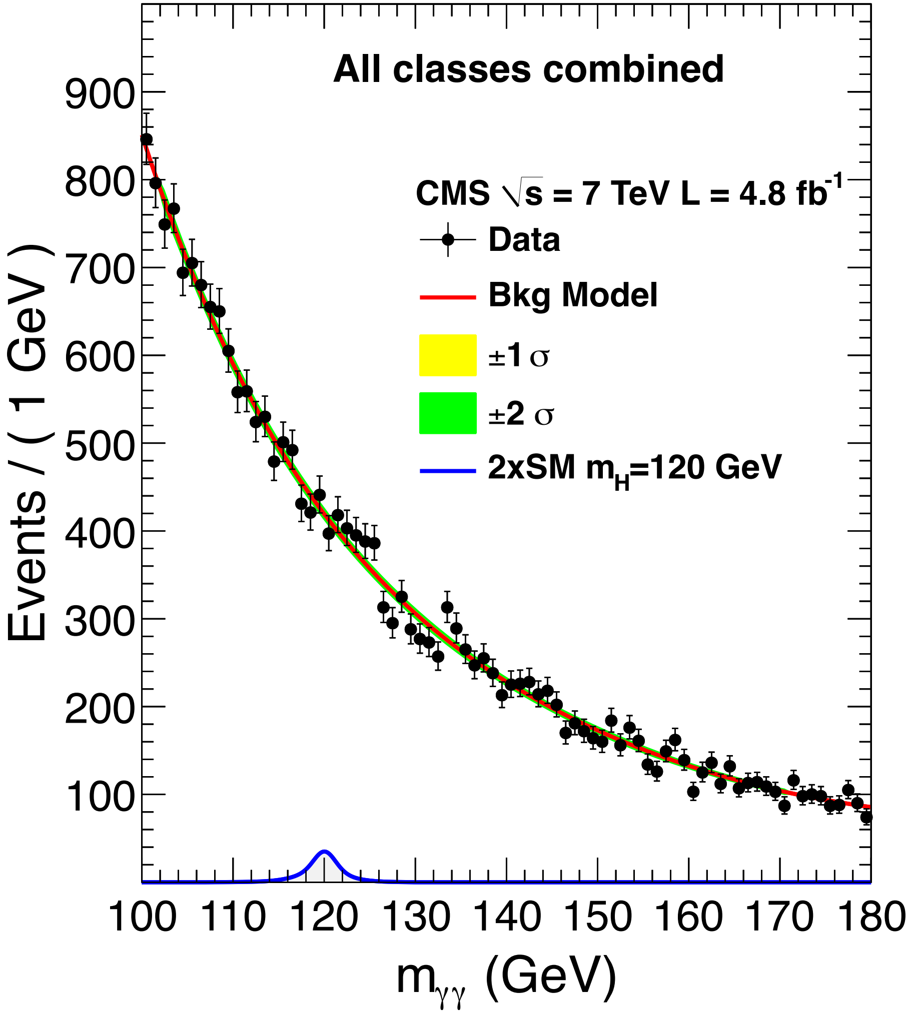
Il canale H→ZZ→2l2q (l=e, μ)

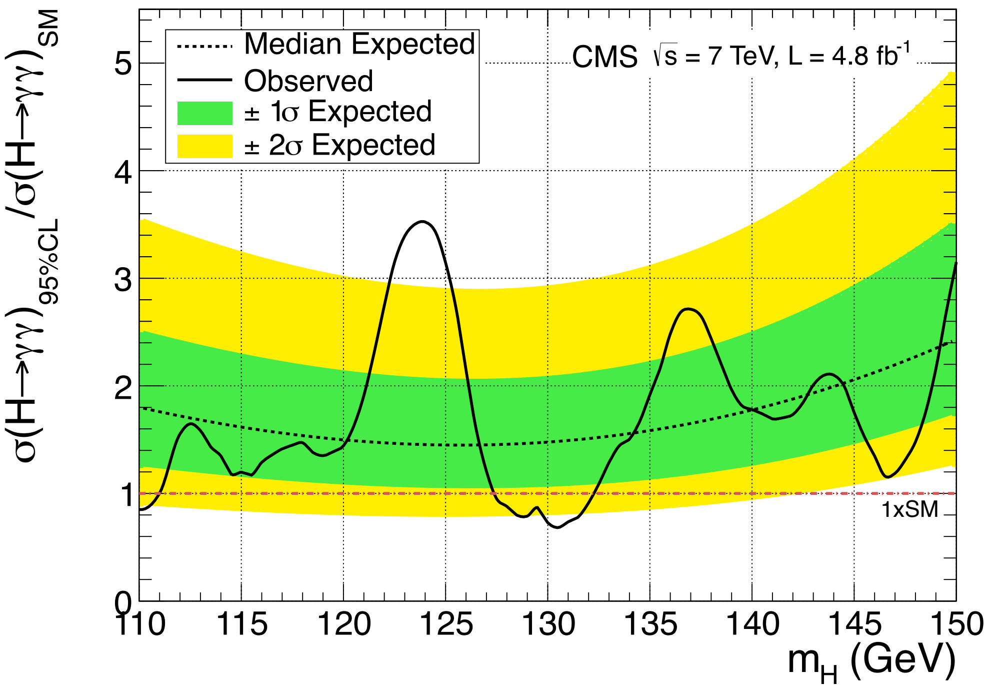




Il canale H→$\gamma\gamma$

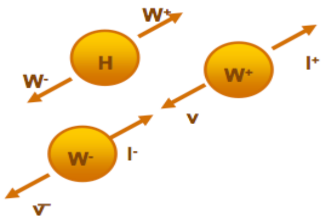
- Canale con molto fondo

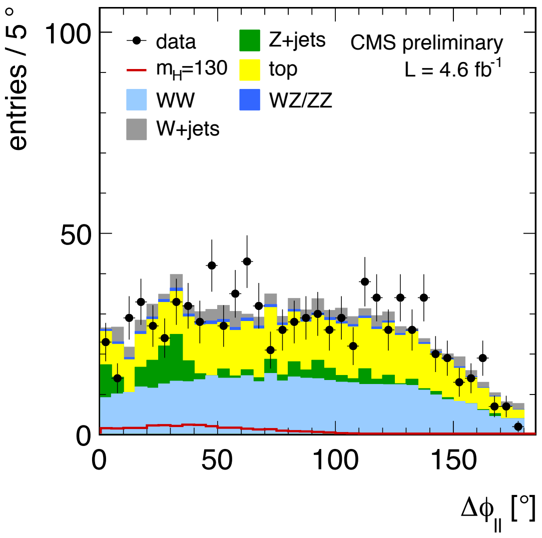


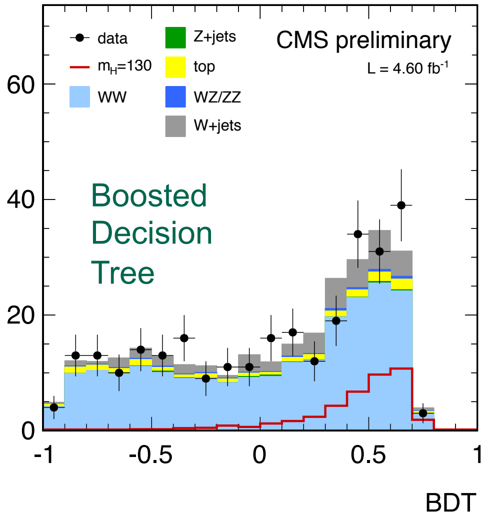


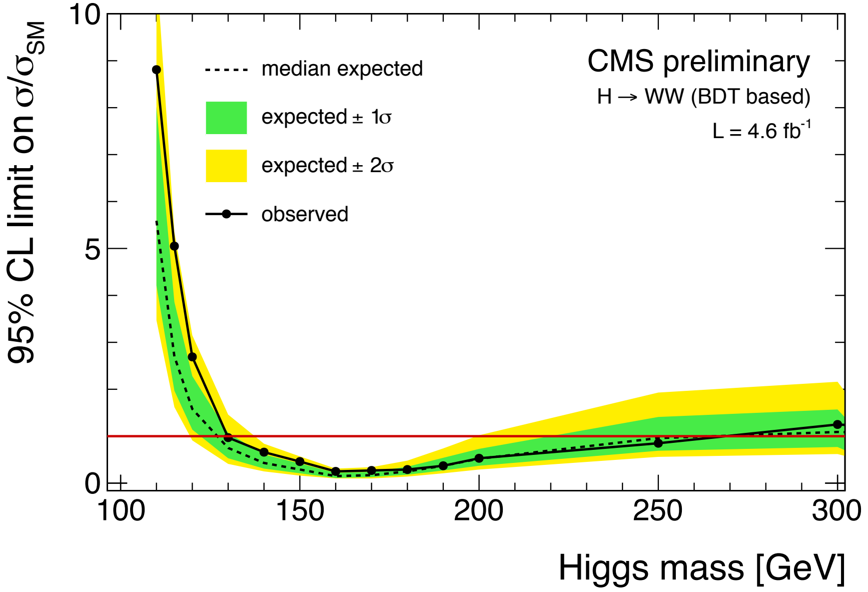
$H \rightarrow WW \rightarrow 2l2\nu$

- Non è possibile ricostruire la massa del bosone per la presenza dei neutrini
- Il segnale si discrimina dal fondo per la diversa distribuzione angolare (il bosone di Higgs a spin zero)
  - I due leptoni tendono ad essere allineati in eventi Higgs
- Un'analisi multivariata permette di massimizzare la separazione segnale/fondo

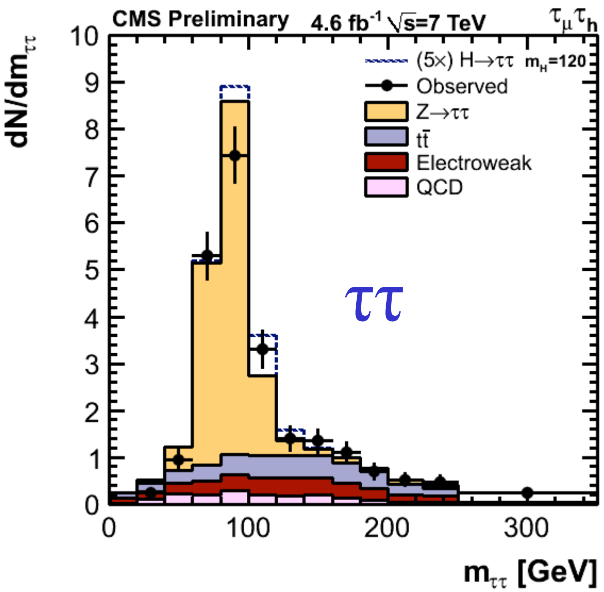


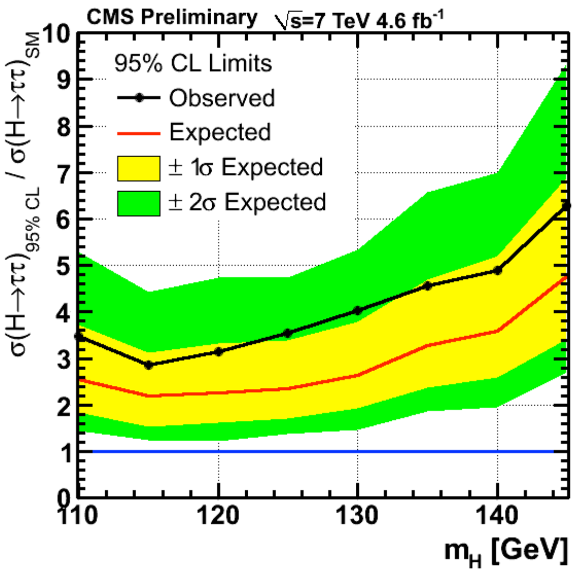


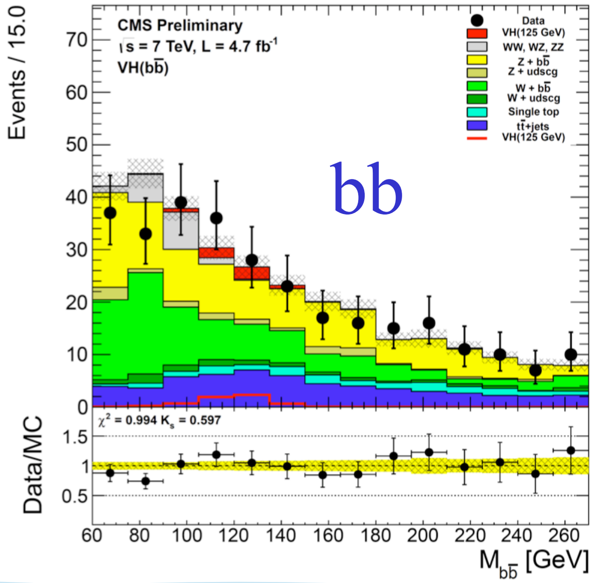


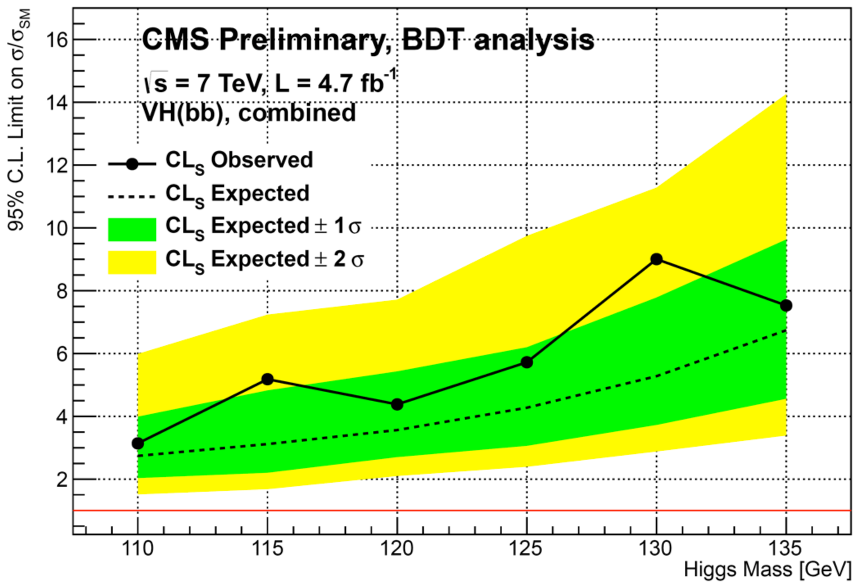


Altri canali sensibili a bassa massa



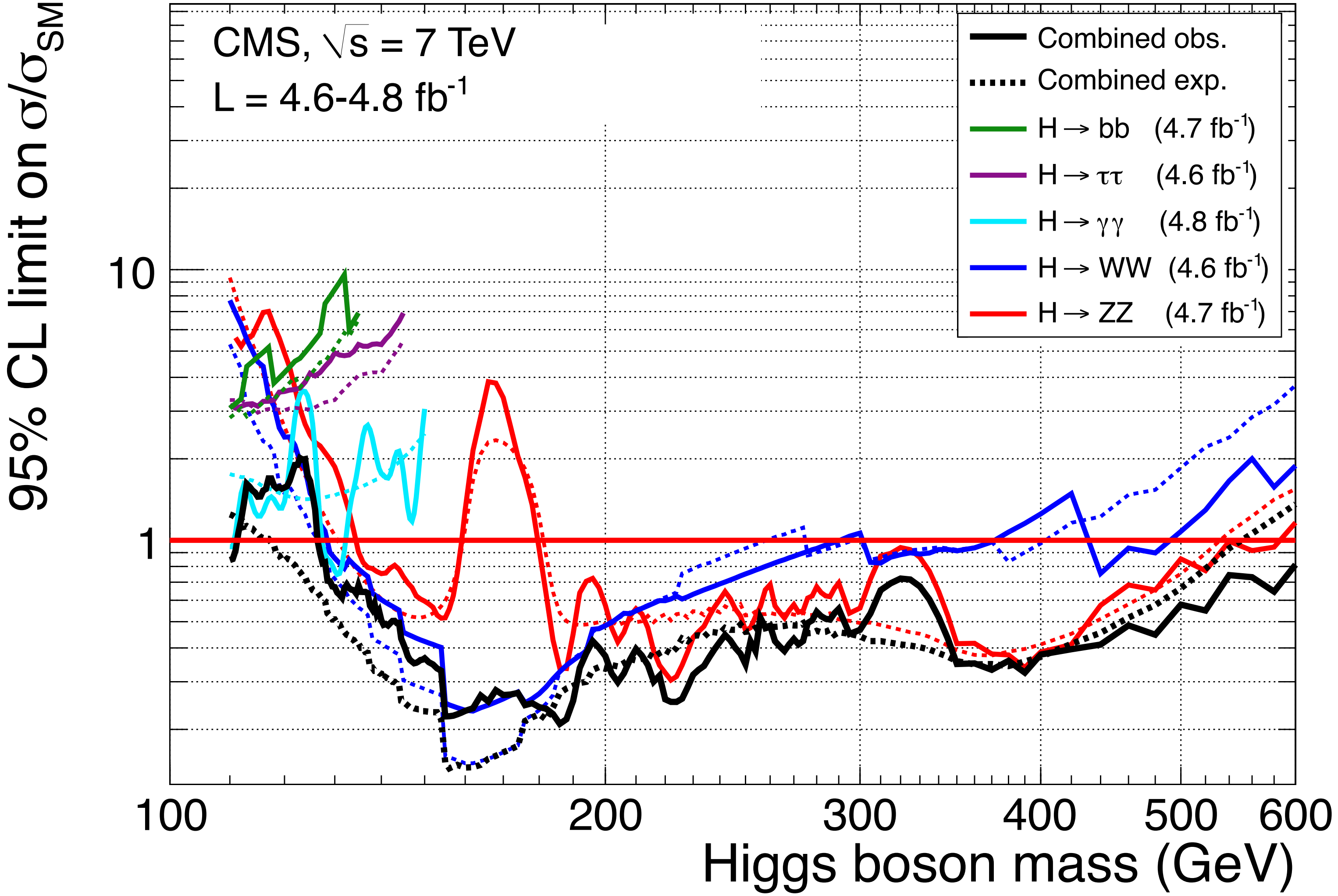






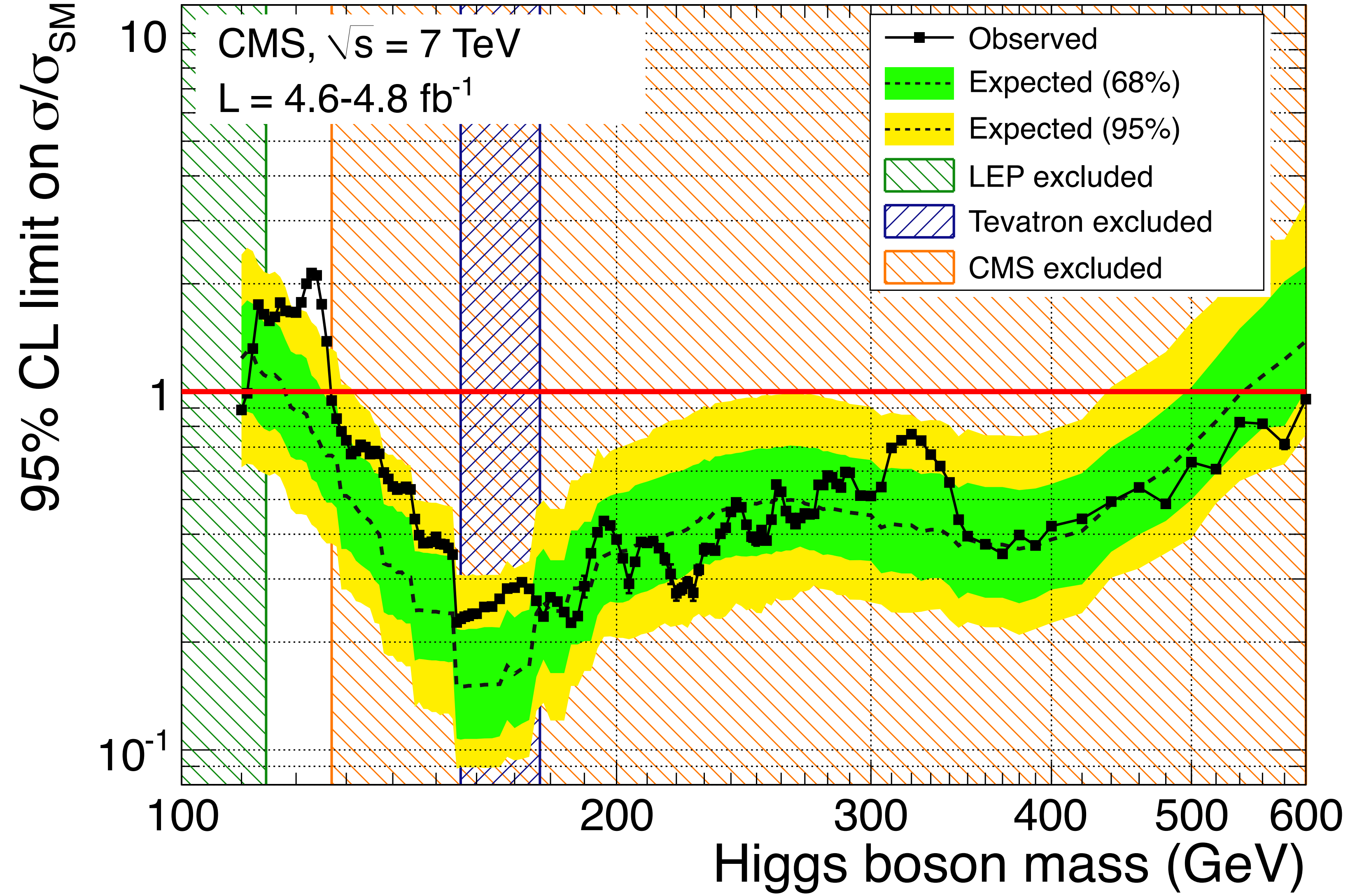
Limite combinato a σ/σ_{SM}

Phys. Lett. B 710 (2012) 26-48, arXiv:1202.1488

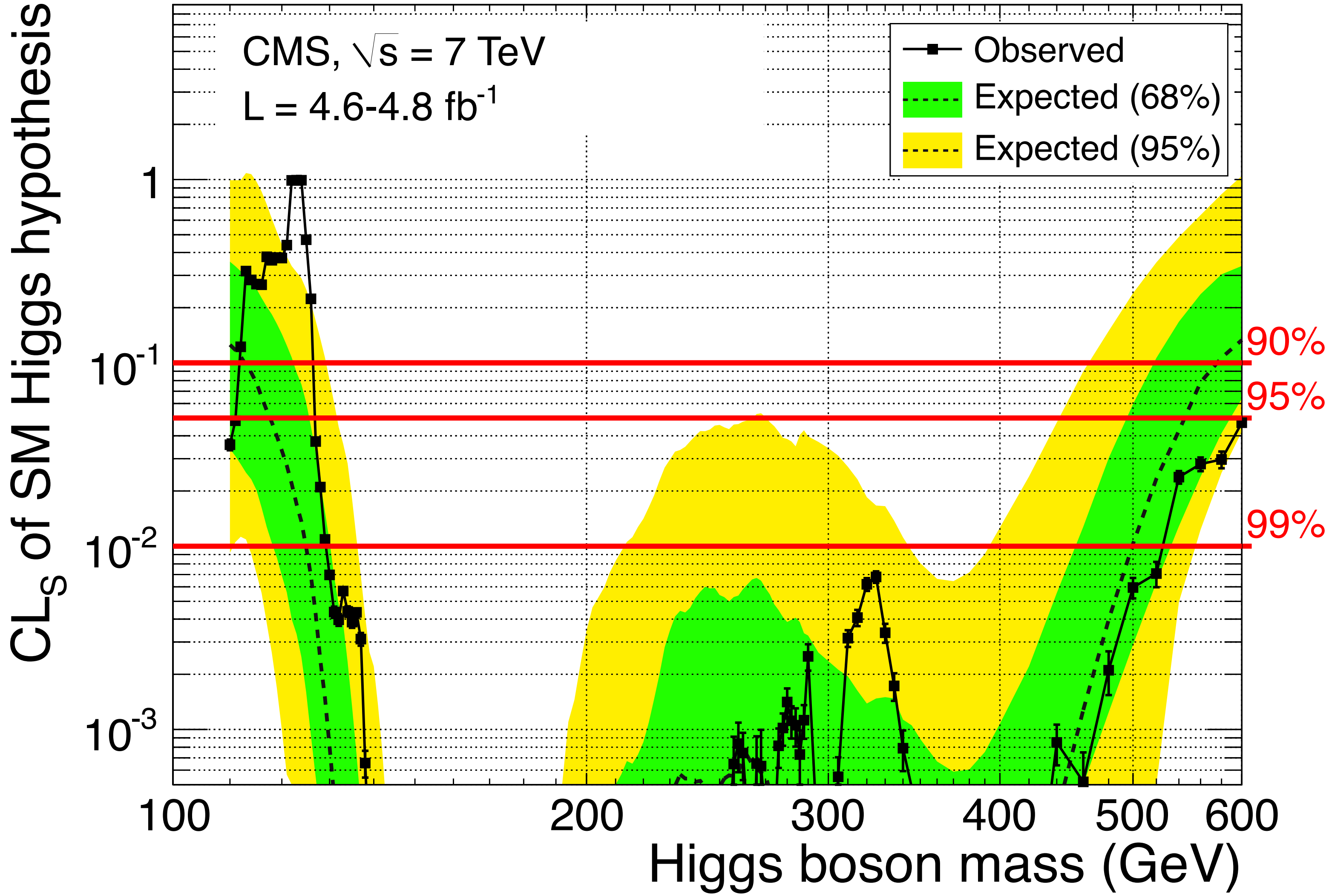


Intervallo escluso: 127–600 GeV al 95% CL (atteso: 114.5-543 GeV)

Esclusione al 95% CL

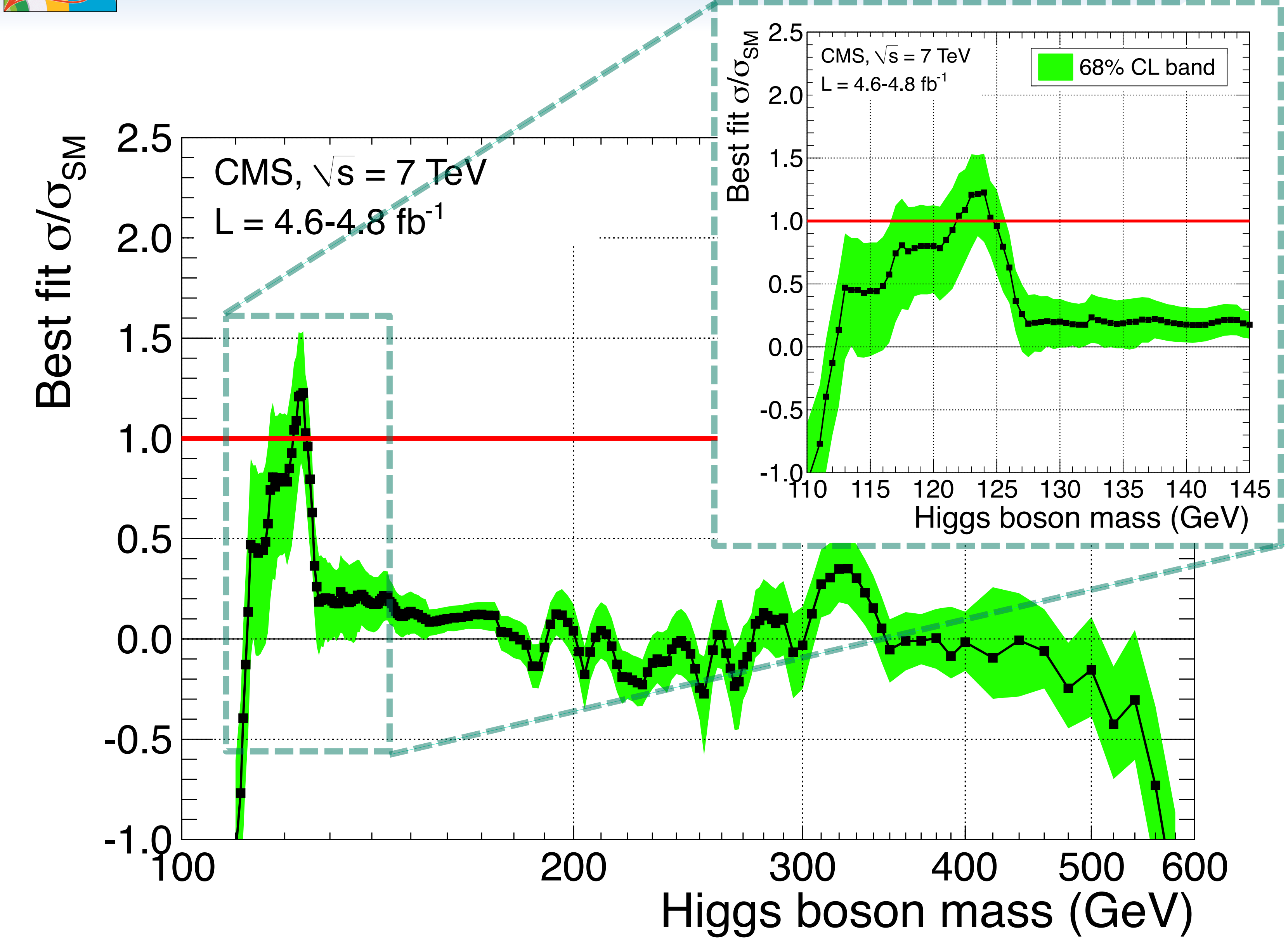


Dal 95% al 99% cosa cambia?



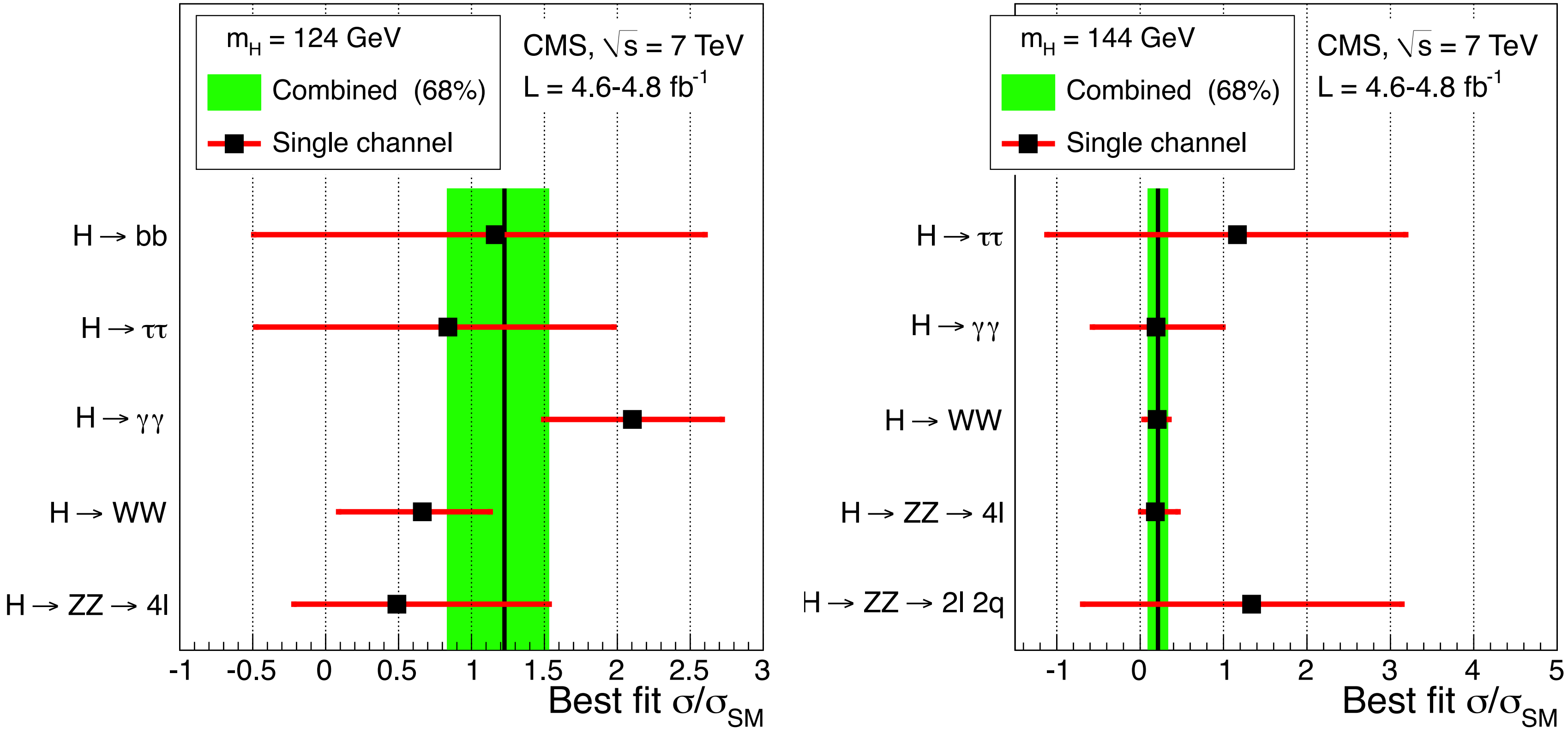
Intervallo escluso: 127–600 GeV at 95% CL, 129–525 GeV at 99% CL

“misura” della sezione d’urto



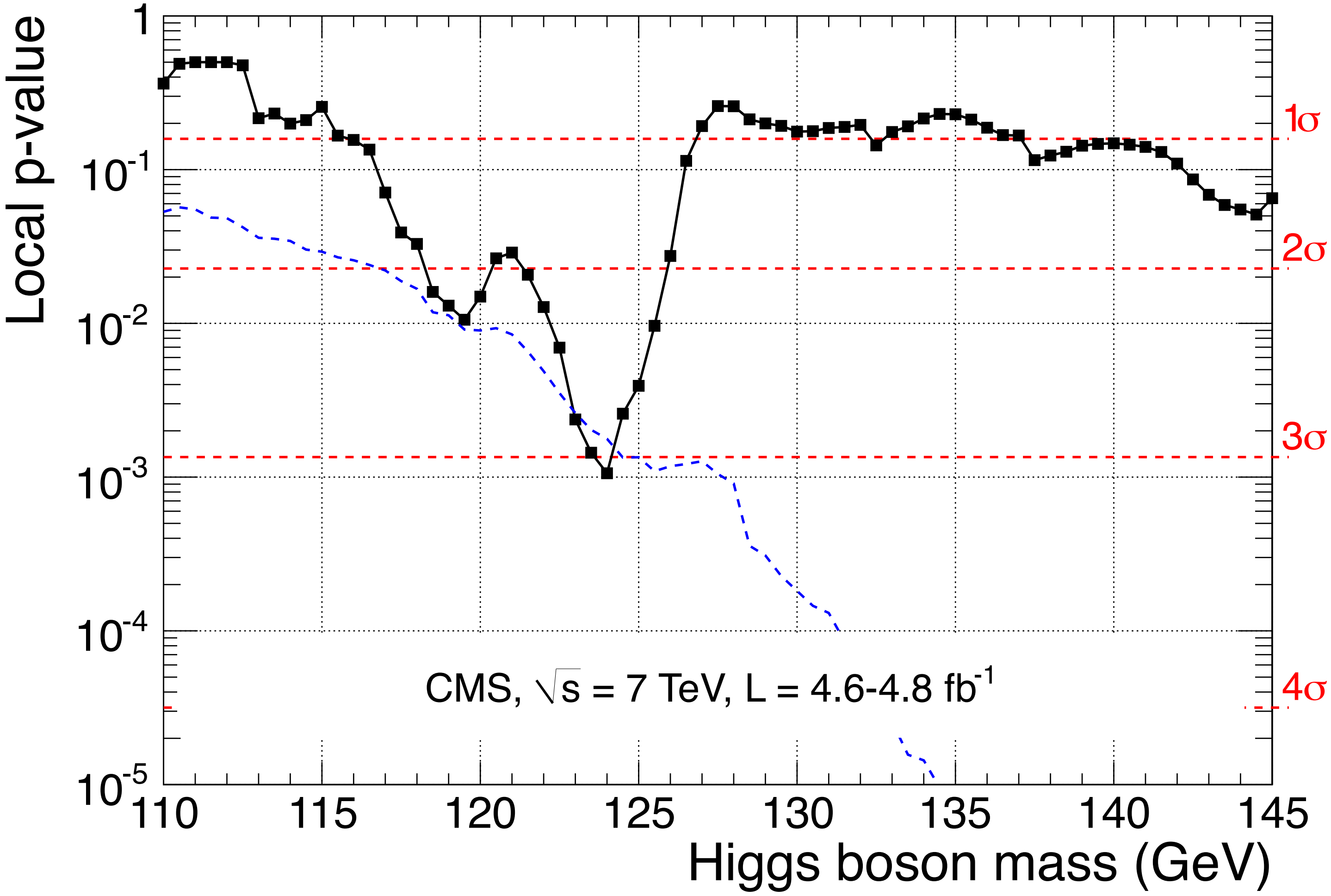
Confronto tra canali diversi

- Best fit σ/σ_{SM} separatamente nei vari canali
- Un modesto eccesso è presente consistentemente in tutti I canali nella regione di bassa massa.



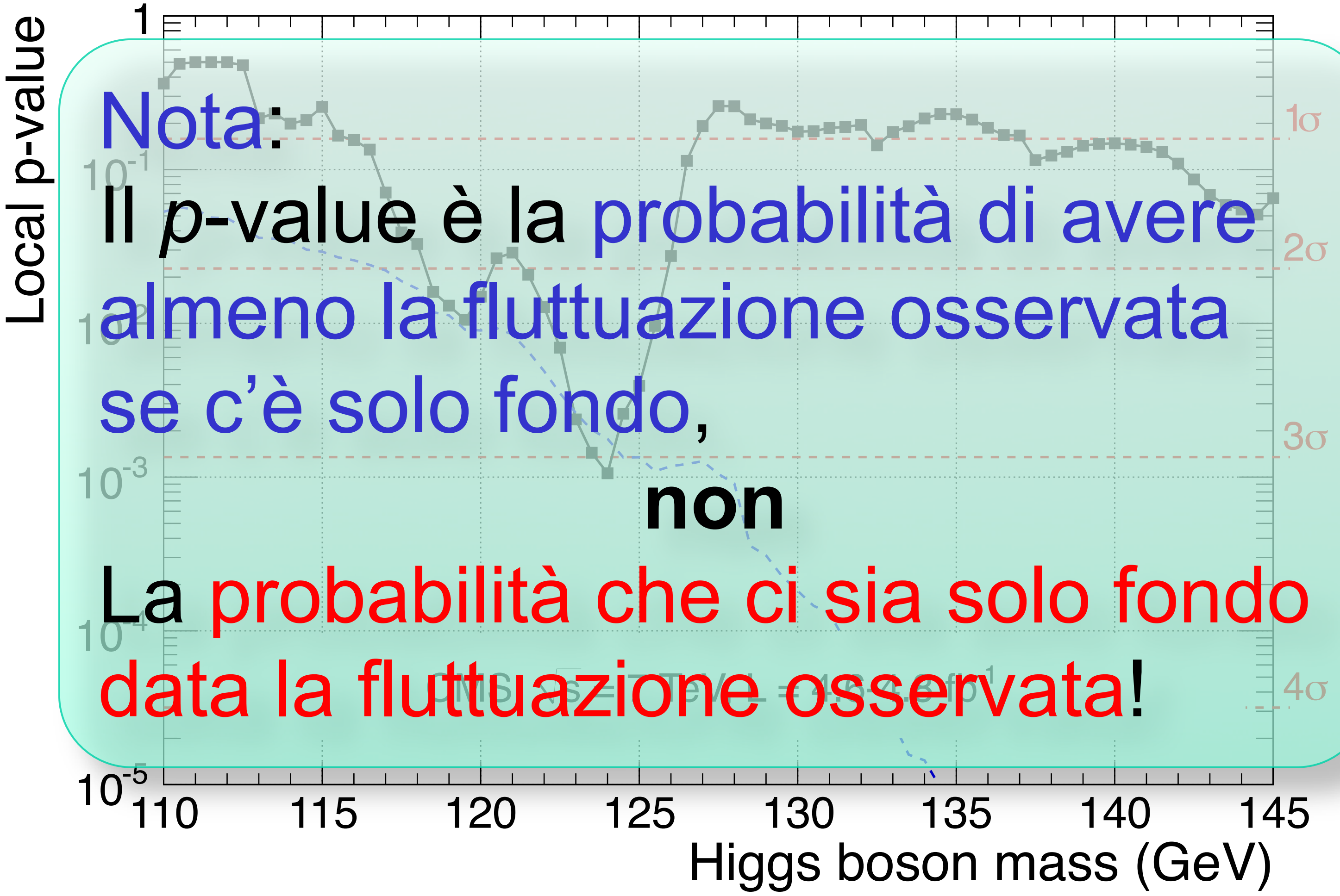
“Indizio” o fluttuazione?

Probabilità di avere una fluttuazione del fondo ≥ di quella osservata



Significatività globale (LEE): 2.1σ (110-145GeV) or 1.5σ (110-600 GeV)

“Indizio” o fluttuazione?



Nota:

Il *p*-value è la probabilità di avere almeno la fluttuazione osservata se c’è solo fondo,

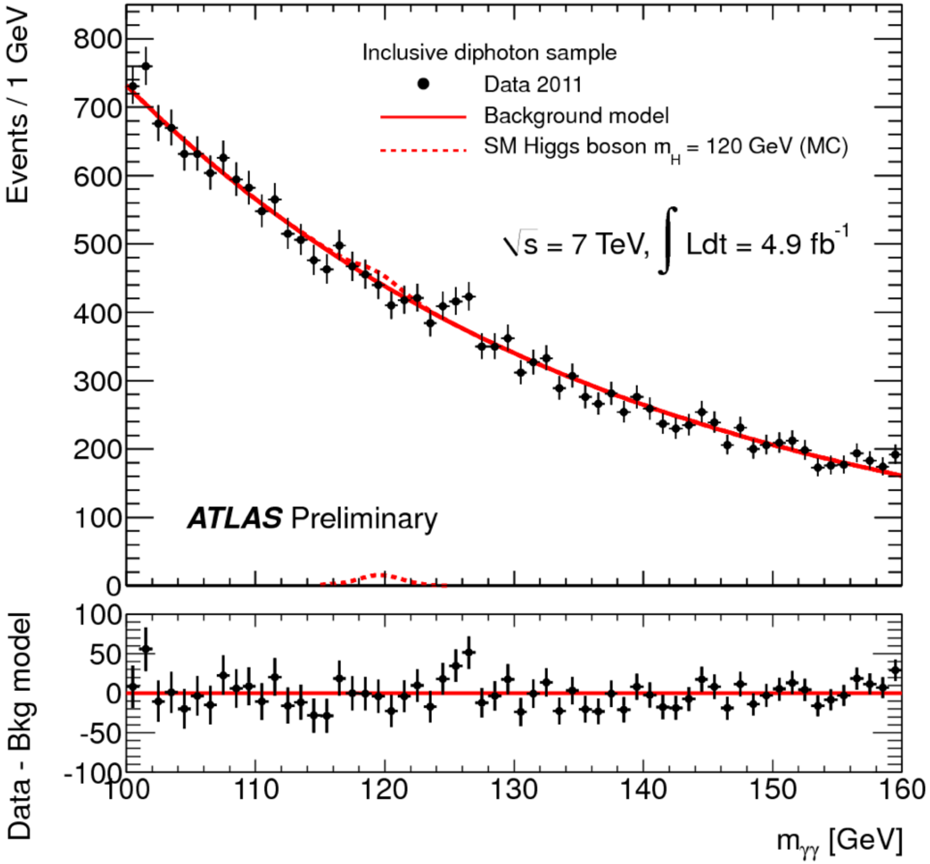
non

La probabilità che ci sia solo fondo data la fluttuazione osservata!

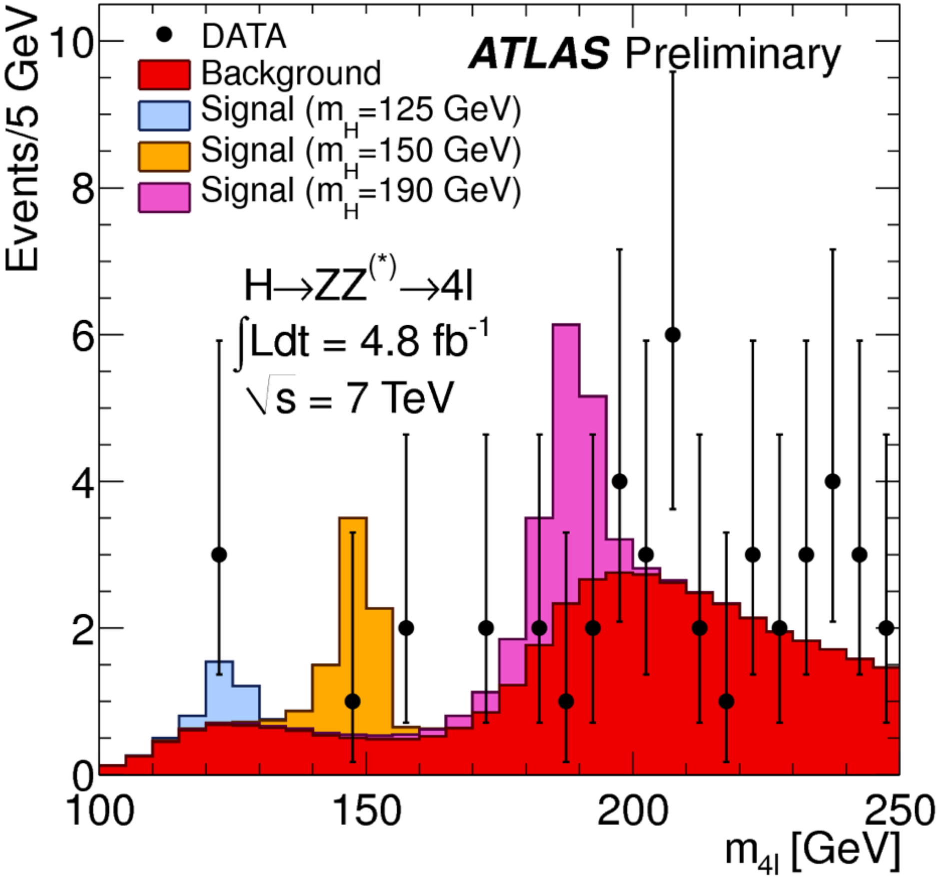
Significatività globale (LEE): 2.1σ (110-145GeV) or 1.5σ (110-600 GeV)

ATLAS: $\gamma\,\gamma$, 4l

arXiv:1202.1414

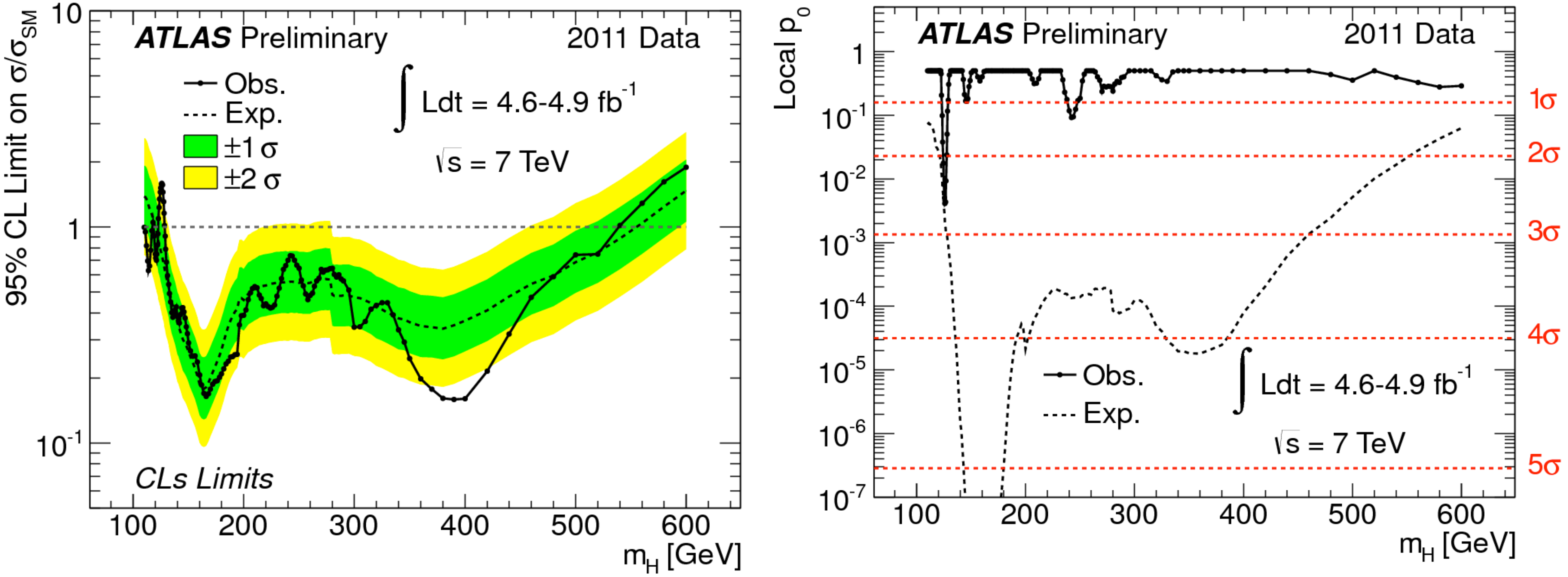


arXiv:1202.1415



ATLAS: limite combinato

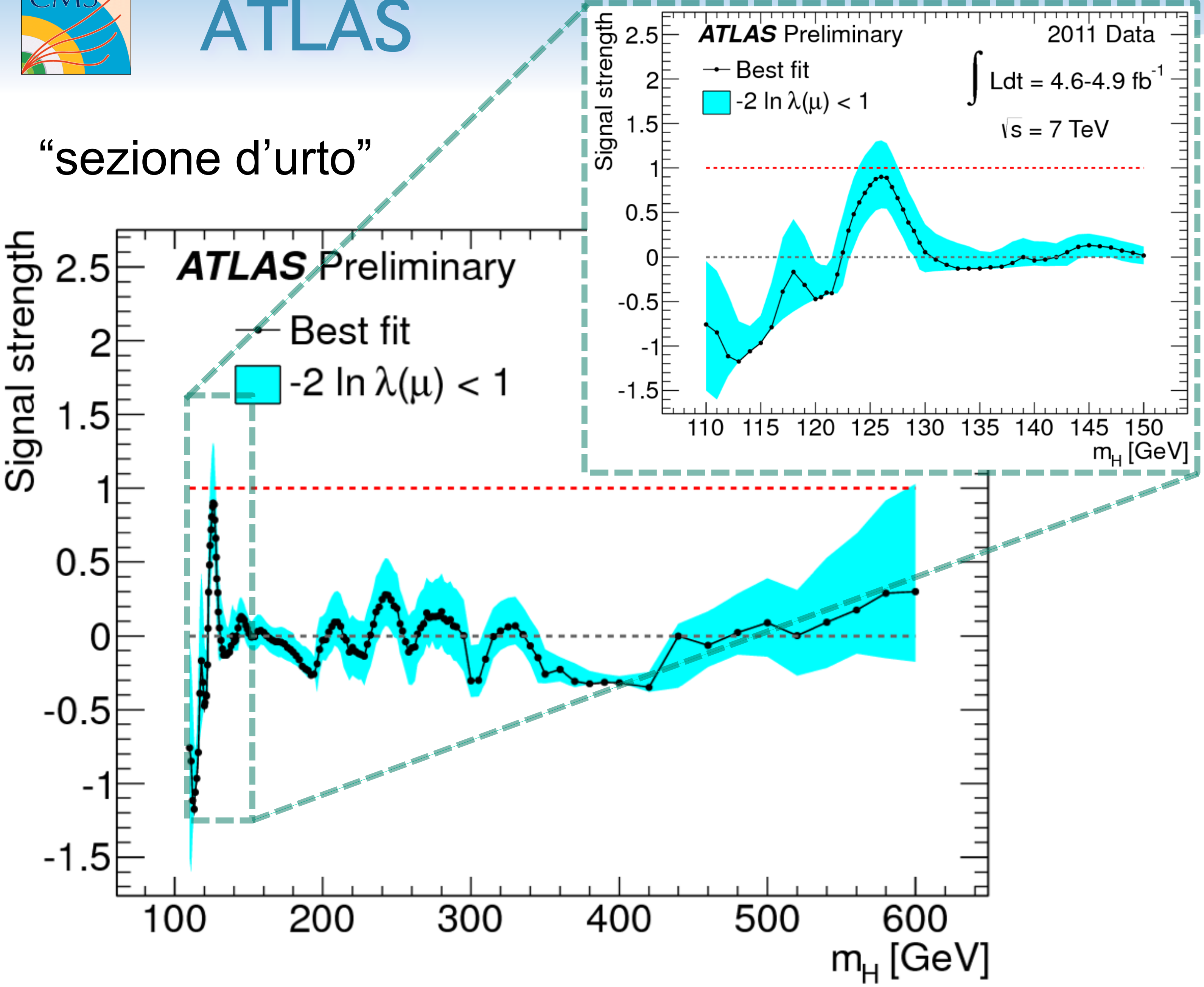
arXiv:1202.1408
ATLAS-CONF-2012-019



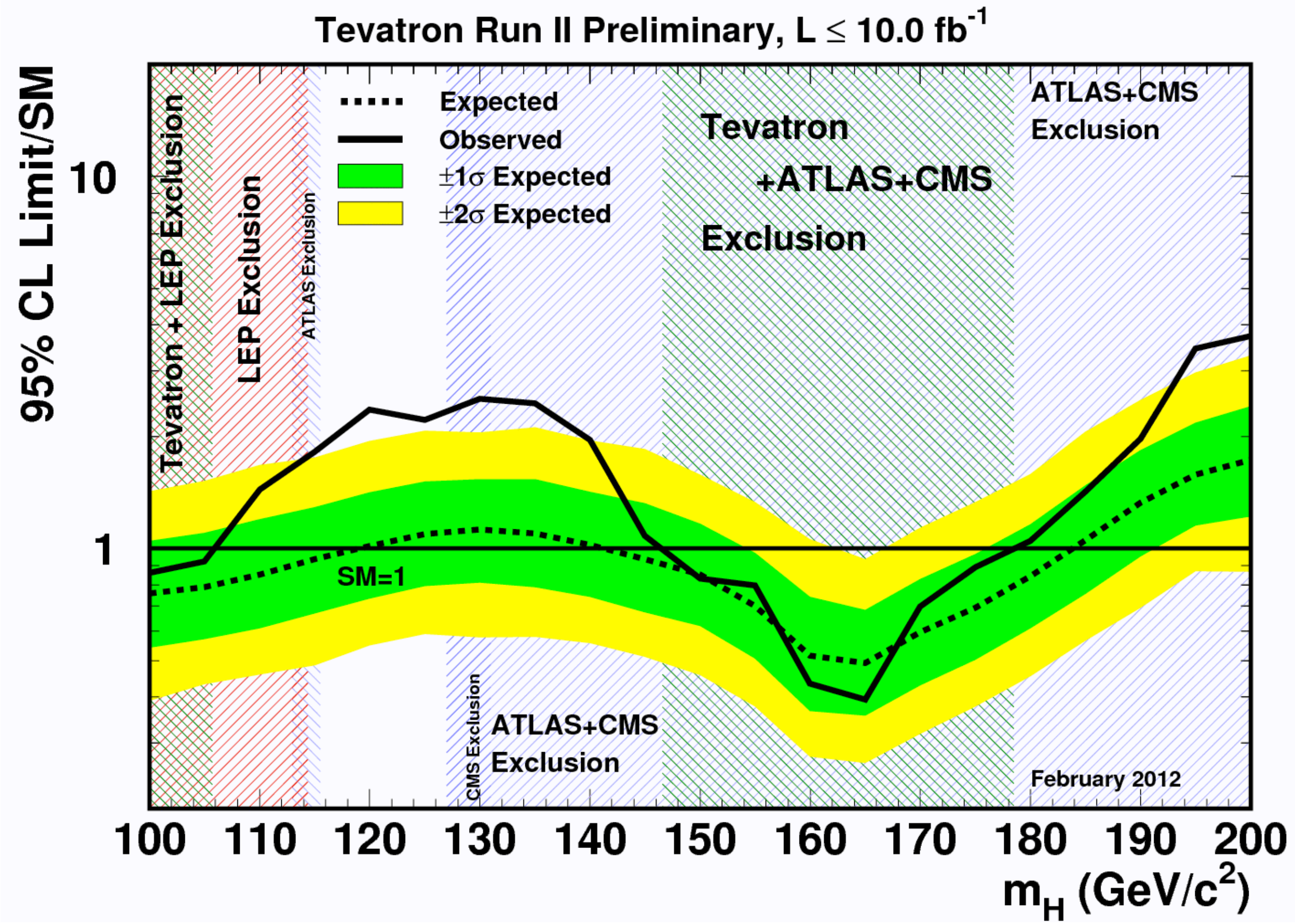
- Significatività locale: 2.8σ (γγ), 2.1σ (ZZ*→4l), 1.4σ (WW*→lνlν)
- Significatività globale (LEE) 2.2σ (110-600 GeV)
- Intervalli esclusi: (95% CL):110–115.5 GeV, 118.5-122.5 GeV, 129–539GeV (atteso: 120–550 GeV)

ATLAS

"sezione d'urto"



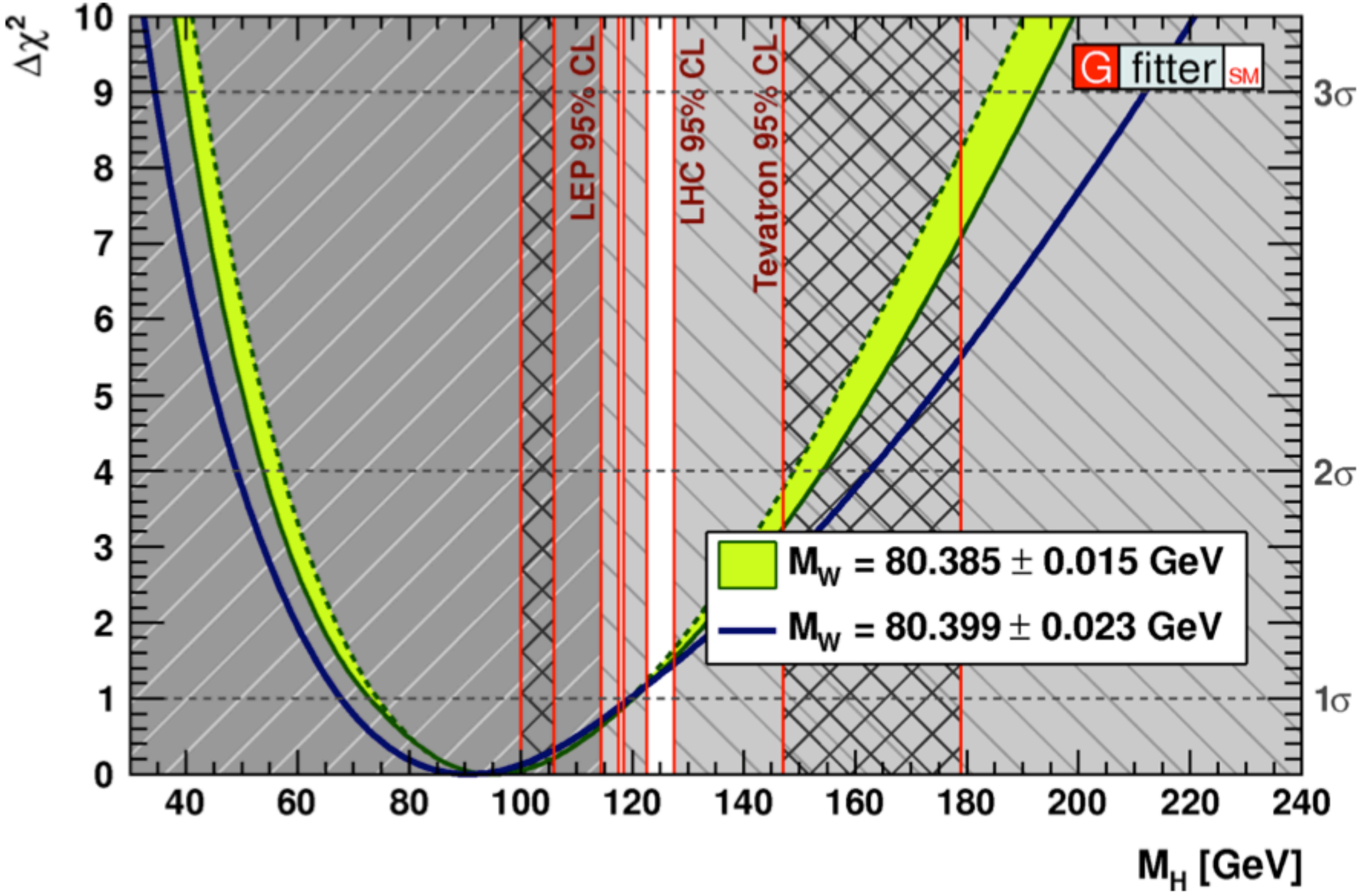
Ultimi risultati da Tevatron



arXiv:1203.3774

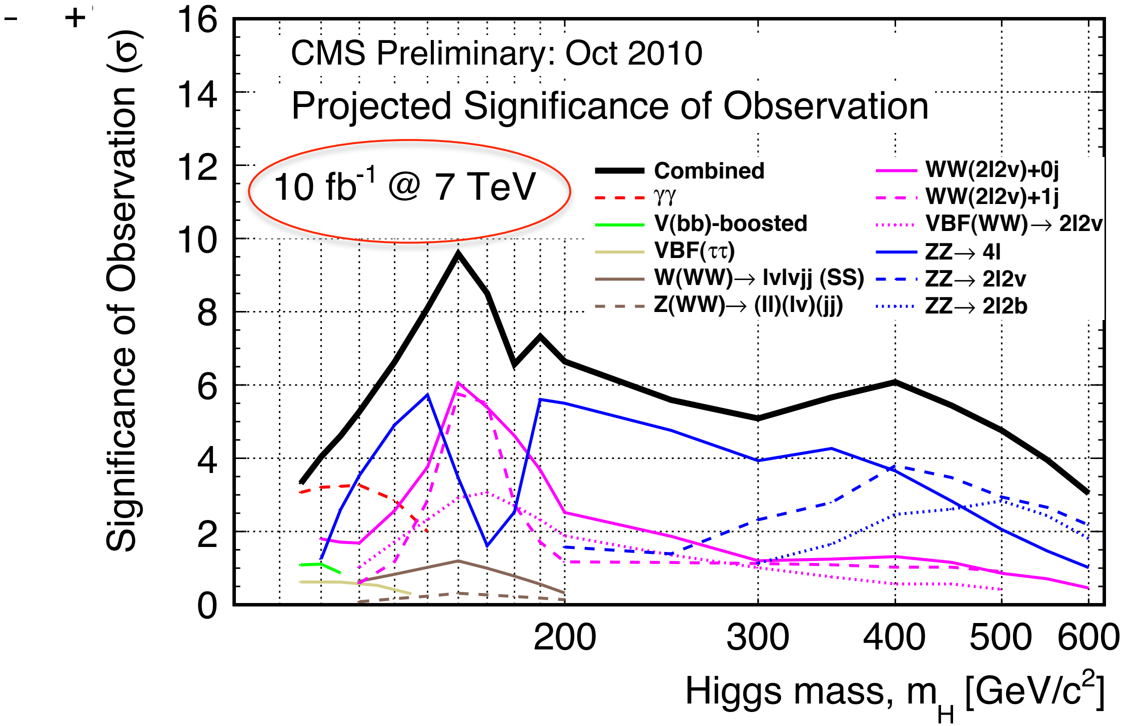
- Intervalli esclusi: 100-107 GeV, 147-179, attesi: 100-119 GeV, 141-184 GeV
- Significatività locale (120 GeV): 2.7σ, significatività globale (LEE); 2.2σ

Nuovo fit al modello standard



Conclusioni e prospettive

- L’energia è stata aumentata da 7 a 8 TeV. Le prime collisioni sono appena cominciate
- Nel 2012 LHC dovrebbe fornire circa 4 volte l’attuale luminosità integrata (~20fb^{-1})



- La scoperta o l’esclusione del bosone di Higgs è molto probabile entro il 2012