Capitolo 12 Test del Modello Standard (scoperta del quark top e ricerca dell'Higgs a LEP e TEVATRON)

Corso di Fisica Nucleare e Subnucleare II

Professor Carlo Dionisi

A.A. 2012-2013

Prima Parte: quark top

Dopo la scoperta del b-quark, divenne evidente che ci doveva essere il suo partner di isospin, il quark top, per completare la terza generazione.
Dopo i fallimenti delle ricerche fatte a Slac, Desy e al CERN,dal 1990, fino al 2010 con la partenza di LHC, solo il Tevatron di Fermilab e' stato in grado di produrre il quark top con energia nel CdM da 1.8 a 1.96 TeV.

The Top Quark

leptons **Charge**

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \quad \begin{matrix} -1 \\ 0 \end{matrix}$$

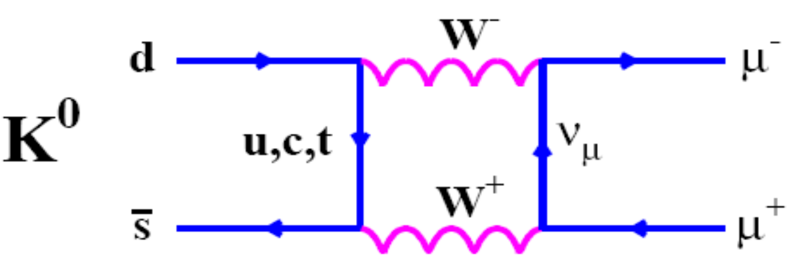
quarks e.g. proton (uud)

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{matrix} +\frac{2}{3} \\ -\frac{1}{3} \end{matrix}$$

+ anti-particles

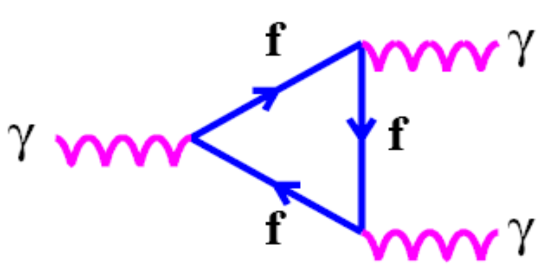
The existence of the TOP QUARK is predicted by the Standard Model and is required to explain a number of observations:

Example: absence of the decay $K^0 \rightarrow \mu^+\mu^-$



In the Standard Model the top quark cancels the contributions from the u and c quarks

Example: Electro-magnetic anomalies



This triangle diagram leads to infinities in the theory unless

$$\sum_f Q_f = 0$$

where the sum is over all fermions (and colours)

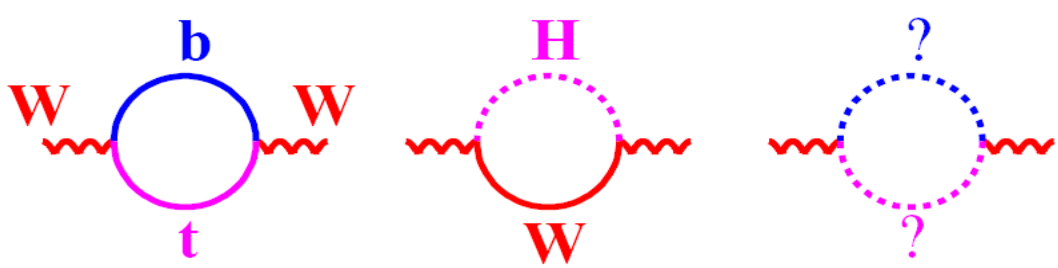
$$\sum_f Q_f = [3 \times (-1)] + [3 \times 0] + [3 \times 3 \times \tfrac{2}{3}] + [3 \times 3 \times (-\tfrac{1}{3})] = 0$$

Rivediamo le correzioni radiative di M_W e M_t

Confrontiamo il valore di $M_W(\alpha; M_Z; G_F)$ *all'ordine piu' basso con le misure sperimentali.*

- ★ PREDICT $M_W = 80.937\ \mathrm{GeV}$
- ★ MEASURE $M_W = 80.426 \pm 0.034\ \mathrm{GeV}$

- ➔ Lowest order prediction is <u>inconsistent</u> with the measurement
- ➔ Need to include higher order diagrams - radiative corrections !



$\mathbf{M}^2_{\mathbf{top}}$ $\qquad \ln(\mathrm{m_H})$ $\qquad$?

$$M_W{}^2 \sin^2\theta_W = \frac{\pi\alpha_{em}}{\sqrt{2}G_\mu}(1+\Delta r)$$

where $\Delta r = AM^2_{top} + B\ln(m_H)$

and where A and B are calculable constants.

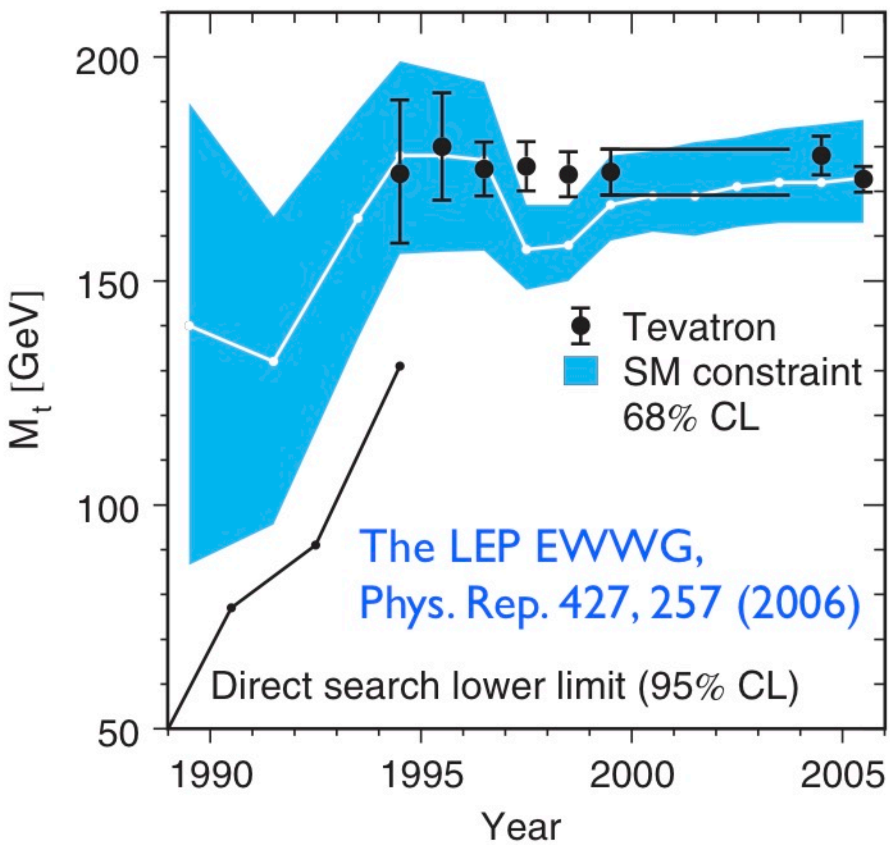
By making precise measurements we are sensitive to particles which are not being produced directly - thus placing constraints on possible new particles/physics beyond the Standard Model.

For example:

- ★ In 1994 precise measurements gave a prediction of the (then undiscovered) top-quark mass:

  $M_{top}^{\mathbf{pred}} = 175 \pm 20$ GeV
- ★ Later in 1994 it was discovered:

  $M_{top} = 174.1 \pm 5.4$ GeV

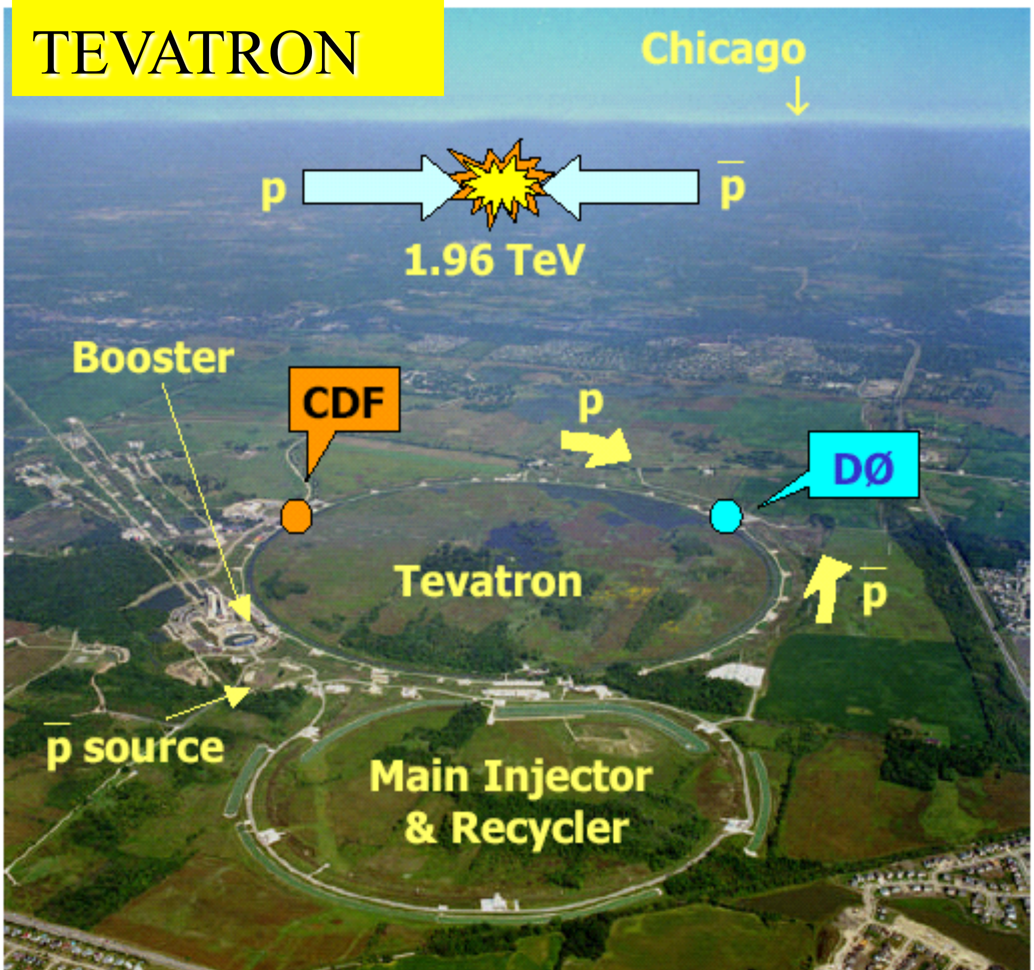


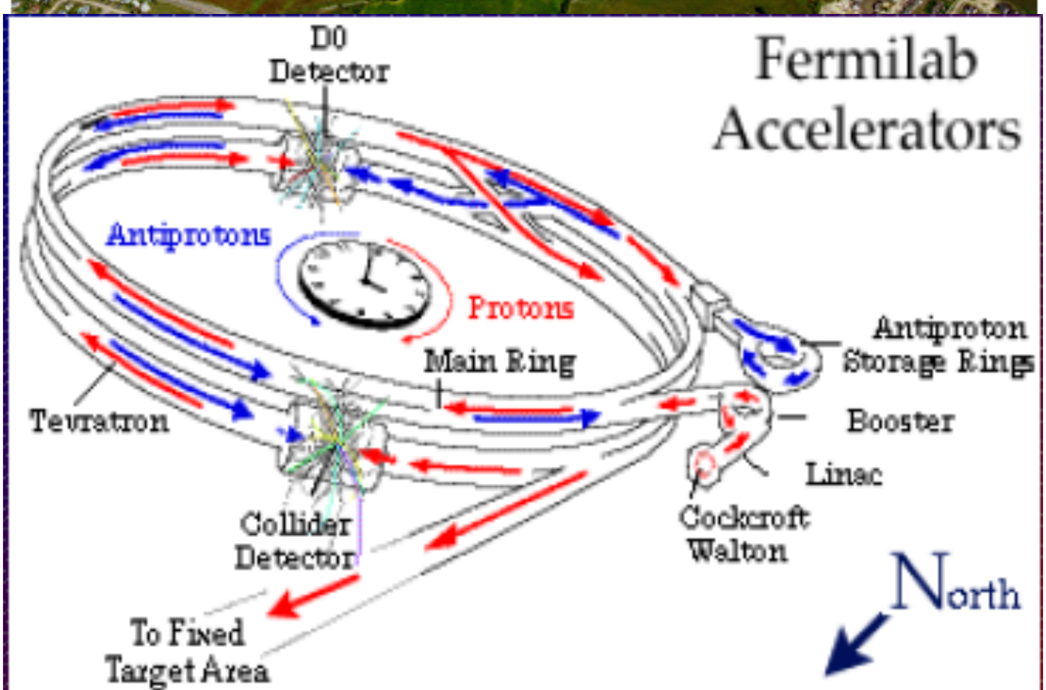
La figura mostra l’evoluzione delle misure dirette e indirette, dal fit elettrodebole , della massa del quark top all’aumentare negli anni della precisione delle misure dei dati.

Scoperta del quark top

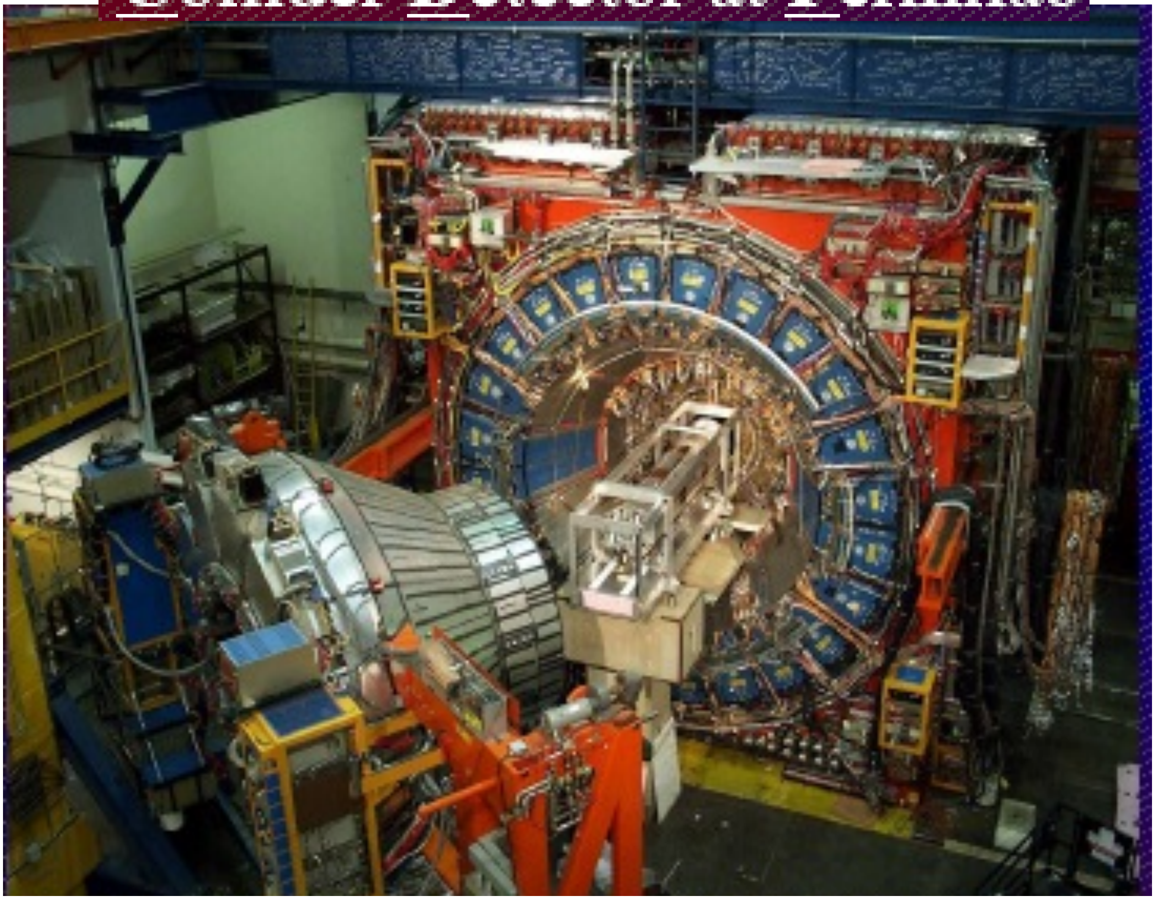
- **Il quark top e' stato scoperto nelle collisioni p p-bar nel rivelatore CDF al collisore Tevatron nel 1994.**

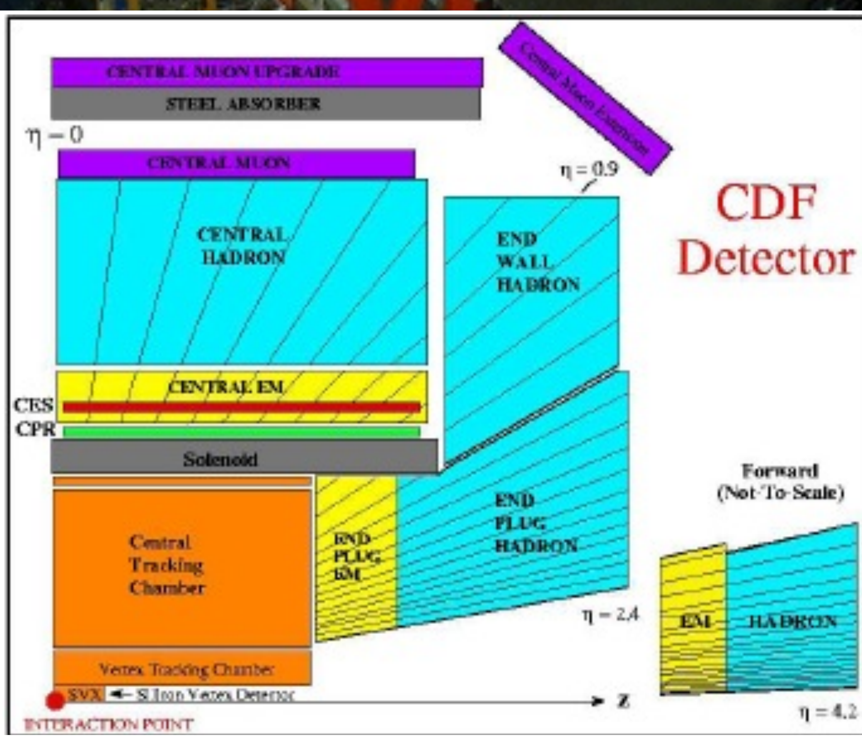
Con una sezione d' urto di produzione di $\cong$ 5 pb, confrontata con una sezione d' urto totale di circa 60 mb, ci aspettiamo di produrre una coppia di quark top ogni 10^{10} collisioni p p-bar.
Come vedremo, con una vita media di circa 10^{-24} s il quark top decade prima di poter adronizzare e decade in uno stato finale formato da getti adonici da coppie di b-quark, mescolati o con leptoni o con getti adronici da quark leggeri.


TEVATRON
Chicago
p
p̄
1.96 TeV
Booster
CDF
p
DØ
Tevatron
p̄
p̄ source
Main Injector
& Recycler

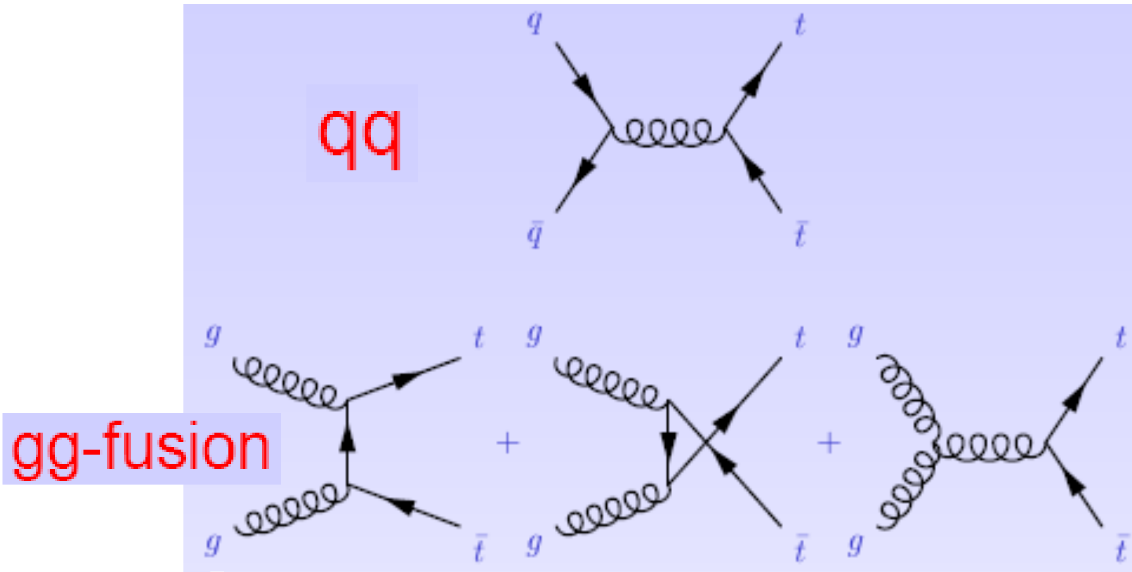

D0
Detector
Fermilab
Accelerators
Antiprotons
Protons
Main Ring
Antiproton
Storage Rings
Tevratron
Booster
Linac
Collider
Detector
Cockcroft
Walton
North
To Fixed
Target Area

Collider Detector at Fermilab





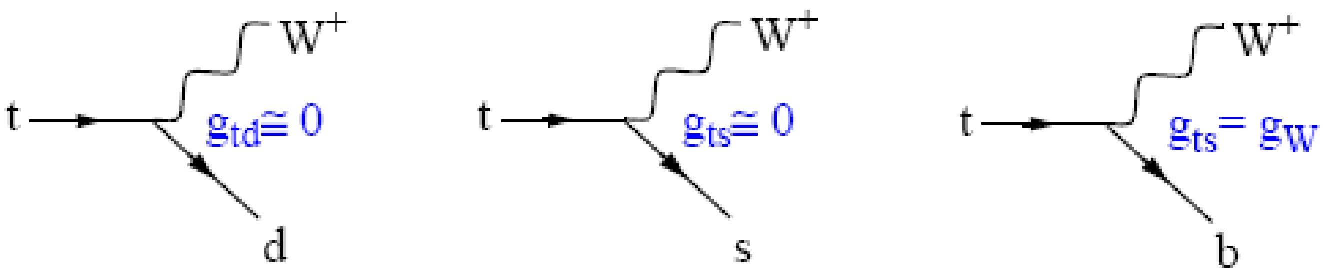
Top quark: produzione coppia (t t-bar)



	Run 1 1.8 TeV	Run II 1.96 TeV	LHC 14 TeV
qq gg	90% 10%	85% 15%	5% 95%
σ (pb)	5 pb	7 pb	600 pb

Top quark: decadimento

- Il quark top, essendo piu' pesante anche del bosone W, puo' decadere solo via:



- Poiche' $g_{ts} \cong 0$ e $g_{td} \cong 0$ l' unico modo di decadimento del quark top e:

$$t \rightarrow W^+ + b$$

Con una frequenza proporzionale a:

$$\alpha_W = g_W^2 / 4\pi \approx 4,2 \times 10^{-3}$$

Per formare uno stato tipo toponio serve un tempo O(10-22 s)

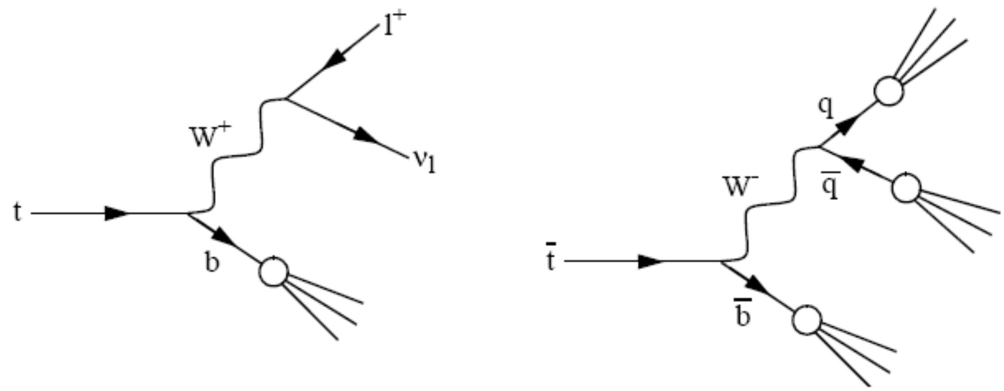
$$\Gamma \sim \alpha_W m_t \sim 1\ GeV$$

$$\tau_t \approx 4 \times 10^{-25} s$$

La vita media e' quindi TROPPO CORTA affinche' il quark top possa ADRONIZZARE !

Top quark: decadimento

Quindi il top decade in b-quark e W che a sua volta decade in leptoni o quark:



Lo stato finale quindi risulta formato di jet e leptoni mescolati:

$$p + \bar{p} \longrightarrow t + \bar{t} + X$$

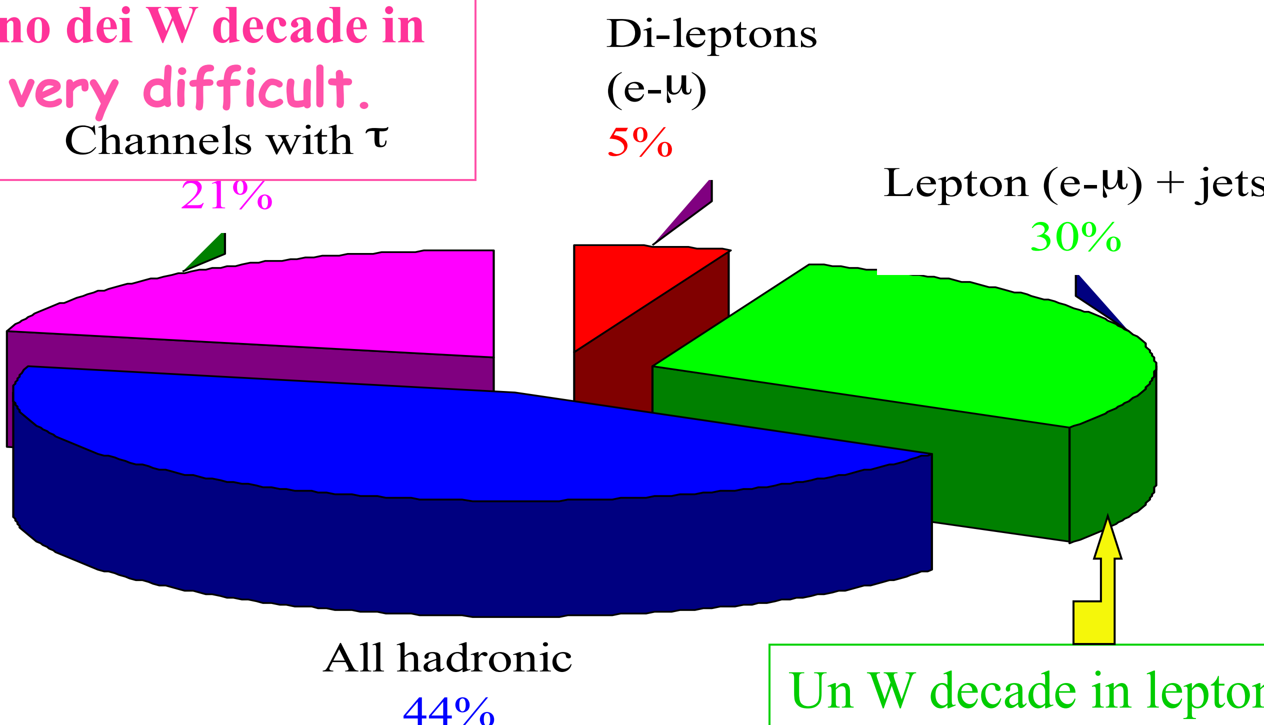
$$\bar{t} \longrightarrow W^- + \bar{b}, \qquad W^- \longrightarrow \begin{cases} l^- + \bar{\nu}_l \\ q + \bar{q} \end{cases}$$

$$t \longrightarrow W^+ + b, \qquad W^+ \longrightarrow \begin{cases} l^+ + \nu_l \\ q + \bar{q} \end{cases}$$

• Configurazioni per i decadimenti del top:

Entrambi I W decadono in leptoni e o m:
Easy

Uno dei W decade in τ: very difficult.



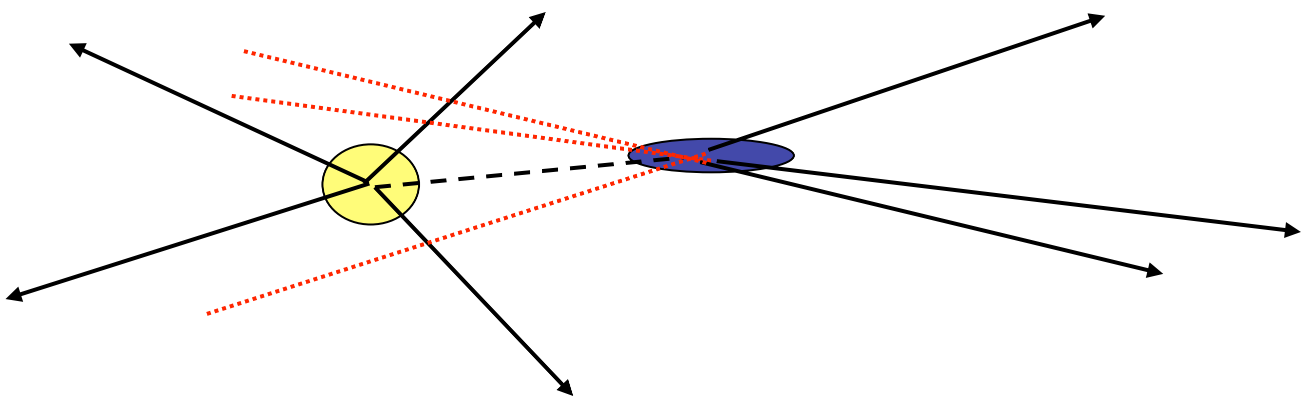
Un W decade in leptoni e o μ e l' altro in getti:
Medium

Entrambi i W decadono in adroni:
Difficult

- **La maggior parte dei risultati derivano dai canali:**

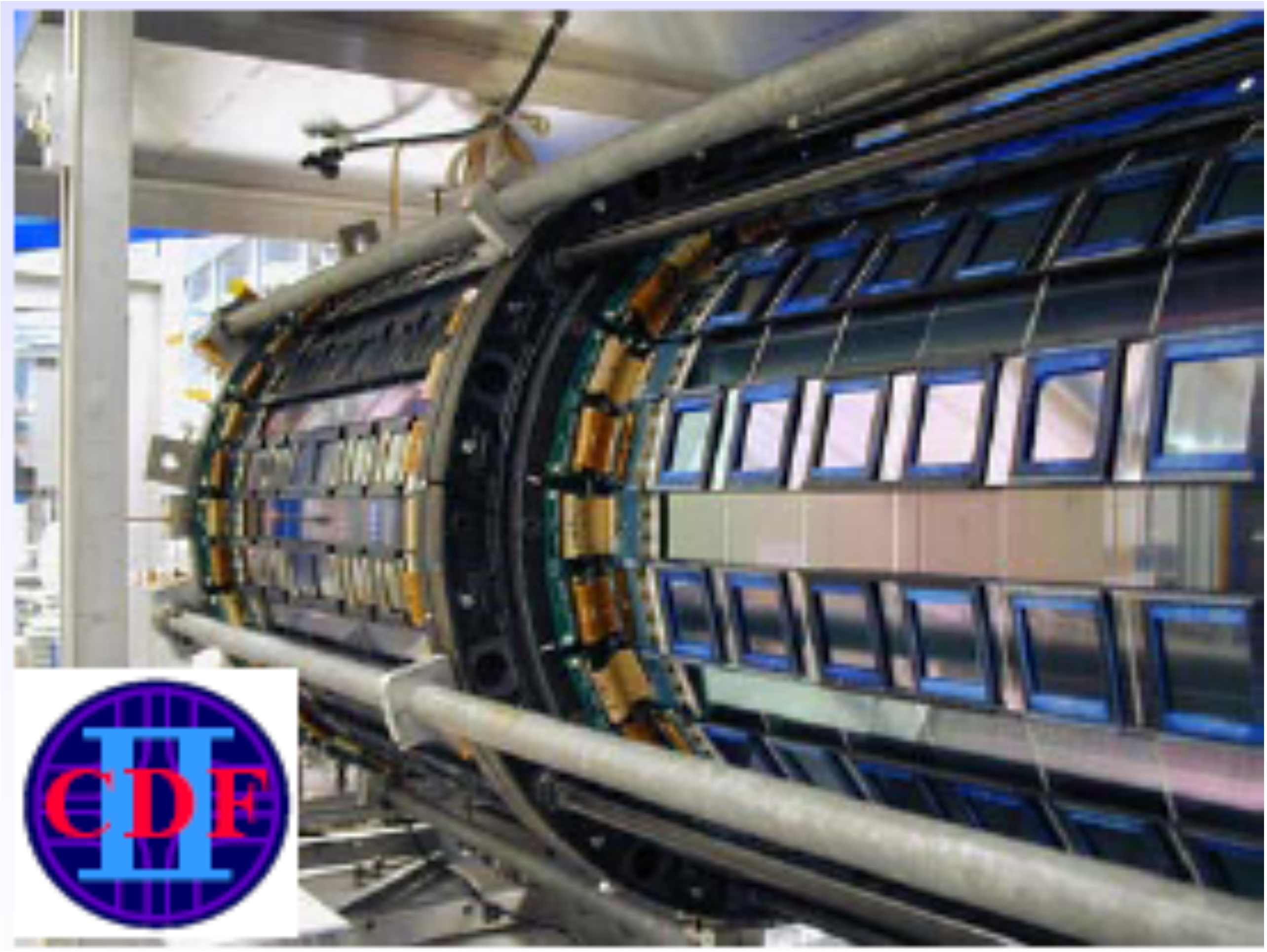
  i) due leptoni piu' jet;
  ii) un leptone piu' jet.

- Selezione:
  - Si cercano i decadimenti leptonici dei W:
    - Leptoni di alto Et;
    - Energia trasversa mancante.
  - Ri richiedono almeno 3 addizionali jet energetici.
  - Almeno uno dei jet e' b-tagged (i.e. contiene un hadrone B).



B hadrons dal decadimento del top viaggiano per alcuni mm prima di decadere.
Questi decadimenti con un accurato rivelatore tracciante puo' essere osservato.
Altre tecniche di b-tagging che usano I leptoni danno un rapporto segnale fondo, S/N, molto peggiore.

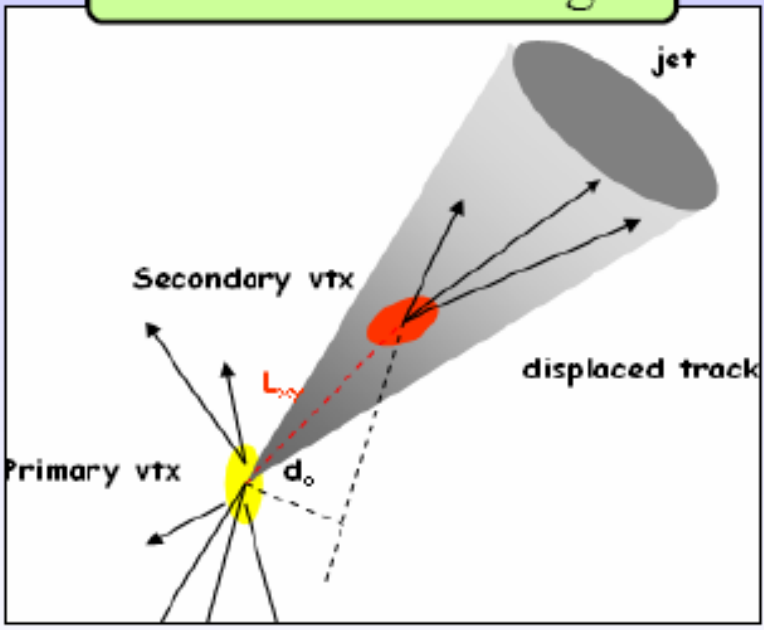
Silicon detectors



Run II: silicon detectors cover a large region of acceptance

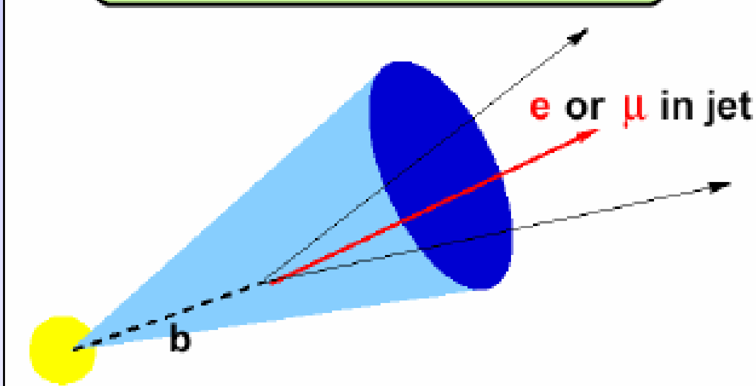
Tagging a b-quark

Silicon Vertex tag



B mesons travel ~ 3 mm before decaying:
- Search for secondary vertex

Soft lepton tagging



- $b \to \ell\nu c$ (BR ~ 20%)
- $b \to c \to \ell\nu s$ (BR ~ 20%)

Search for non-isolated soft lepton in a jet

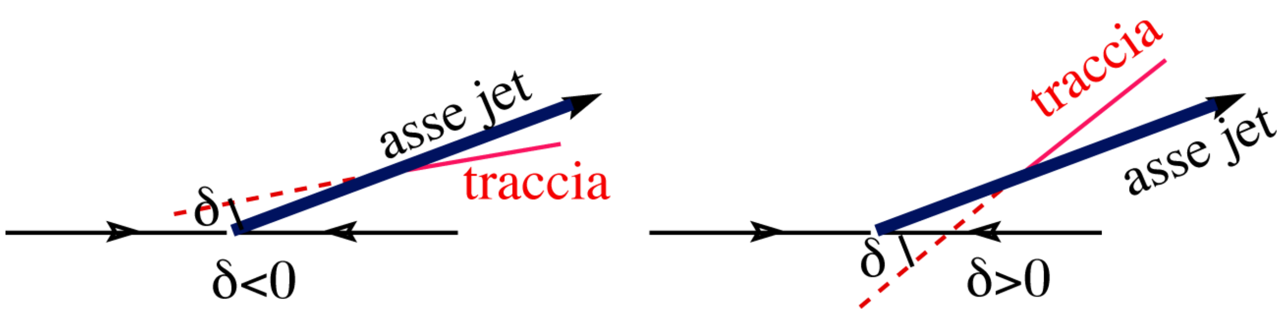
Il Tagging del quark b

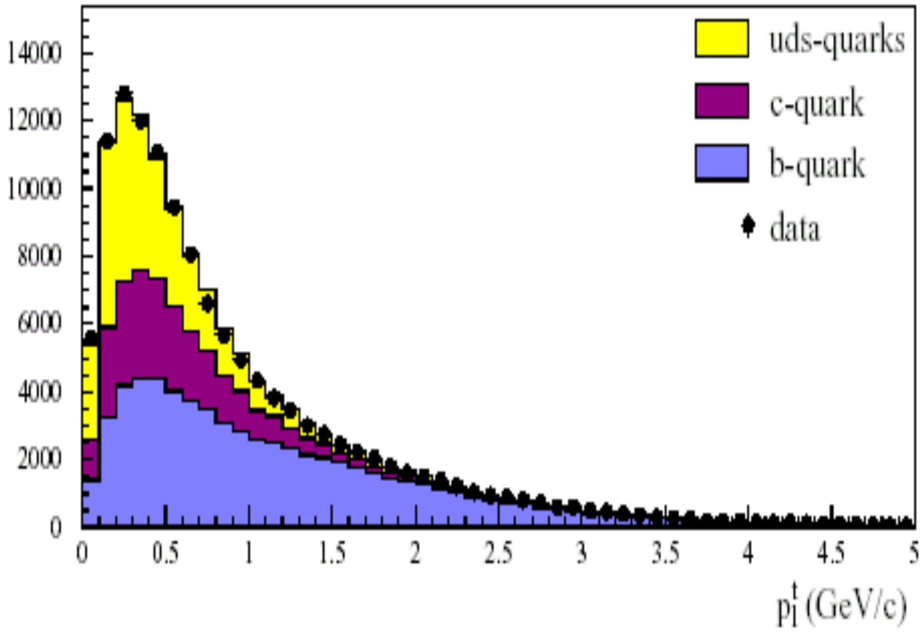
Tutti i quark vengono osservati come jet di adroni.
Come distinguerne il sapore?

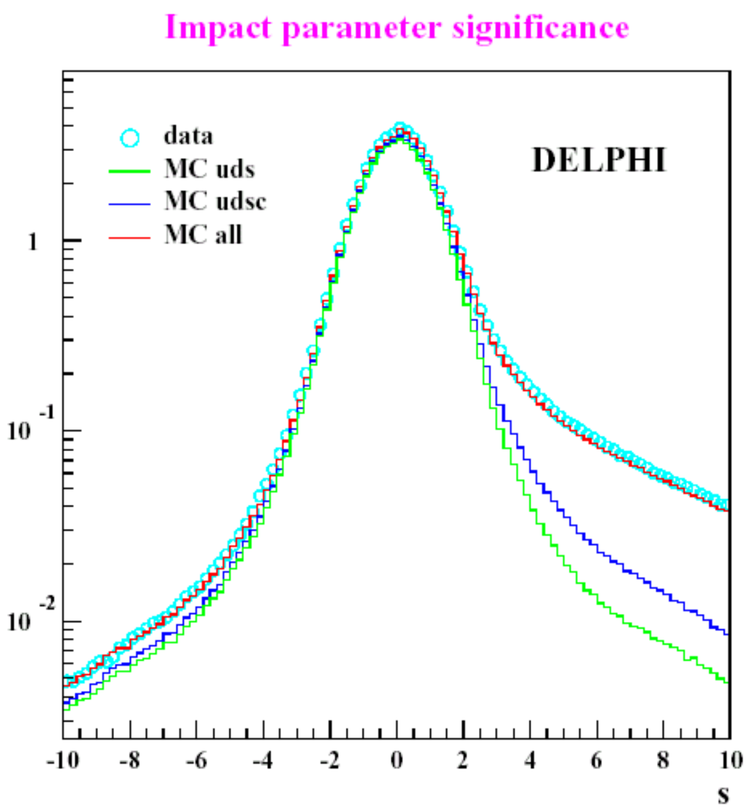
Per il *b* è possibile (anche per il *c*) (***b*-tagging**) perché:

1) la massa del *b* è più grande di tutti gli altri, $m_b \approx 5$ GeV
   momento trasversale al jet p_T più grande
2) la vita media è relativamente lunga (1 ps)
   vertici secondari rivelabili con i microvertici ($\gamma \approx 7$)
3) "parametri d'impatto" abbastanza grandi

p_T del leptone dal decadimento del q rispetto all'asse del jet







Si aggiustano i “tagli” sulle variabili cinematiche ottenendo tipicamente efficienza ≈40%, reiezione ≈ 500

• Un candidato t t-bar

e + 4 jet event

40758_44414

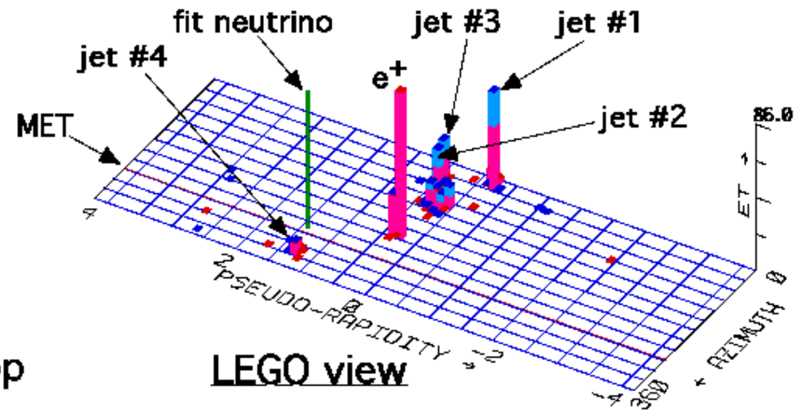
24-September, 1992

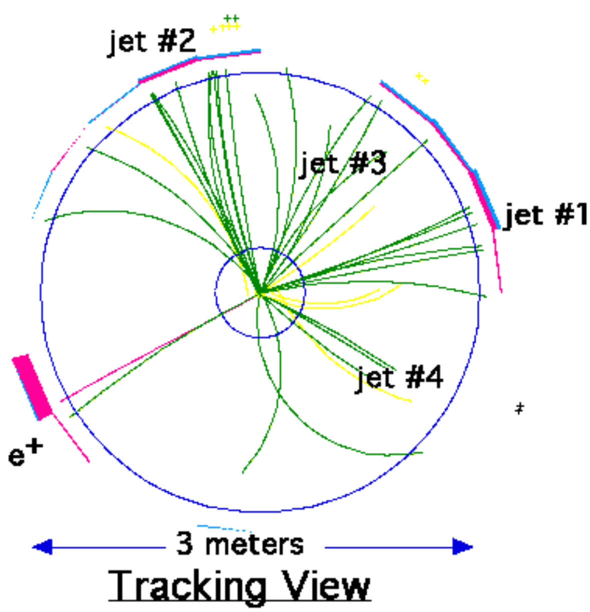
TWO jets tagged by SVX

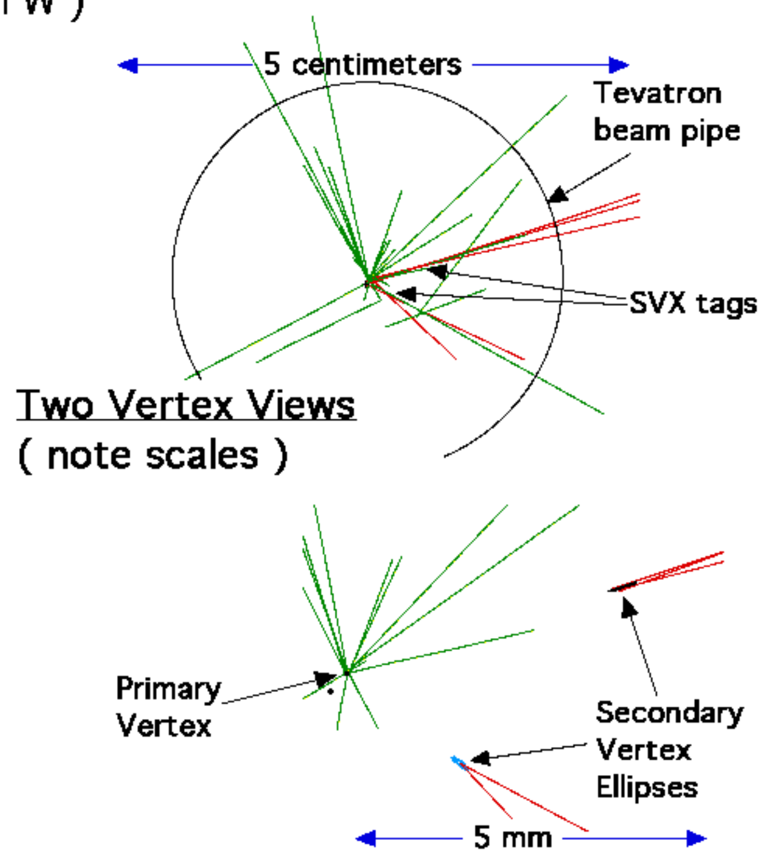
fit top mass is 170 +- 10 GeV

e^+, Missing E_t, jet #4 from top

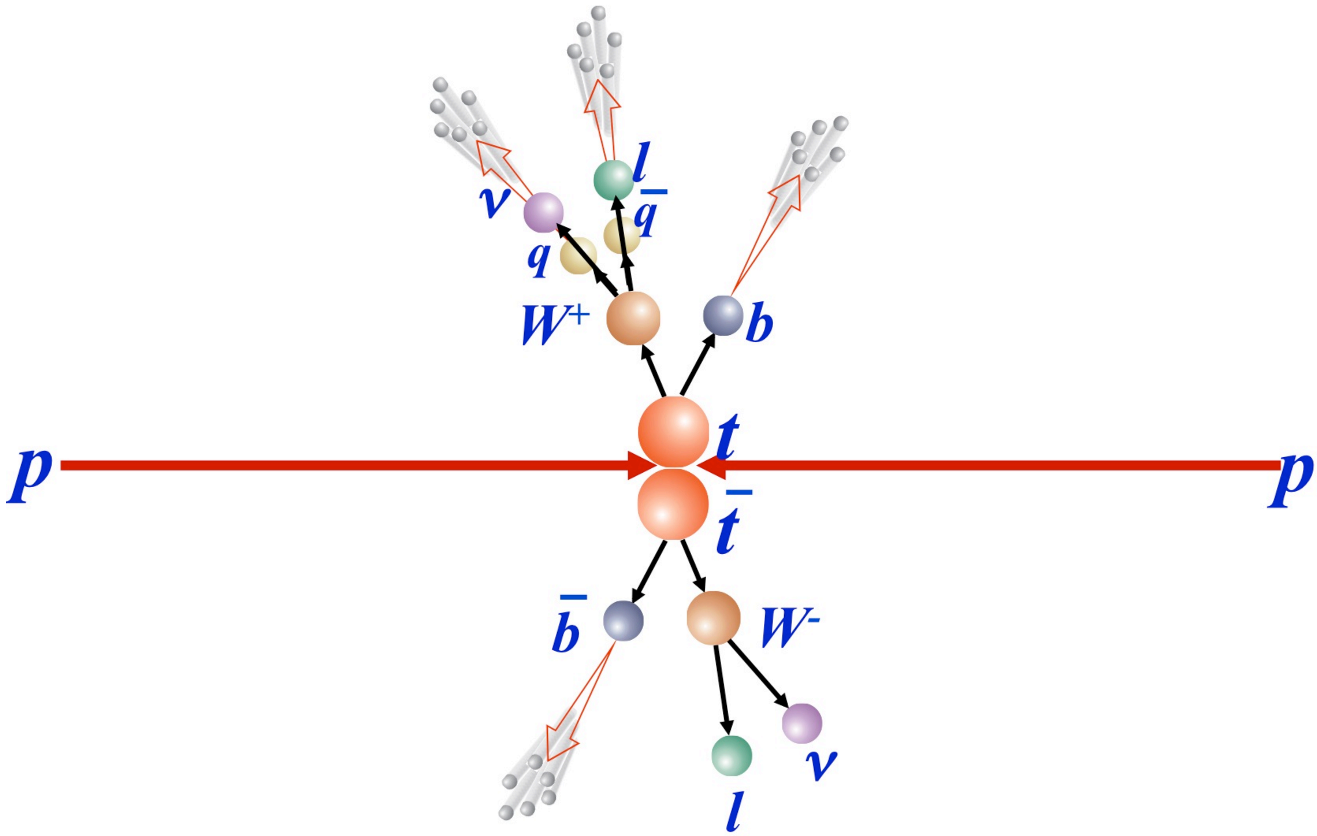
jets 1,2,3 from top (2&3 from W)







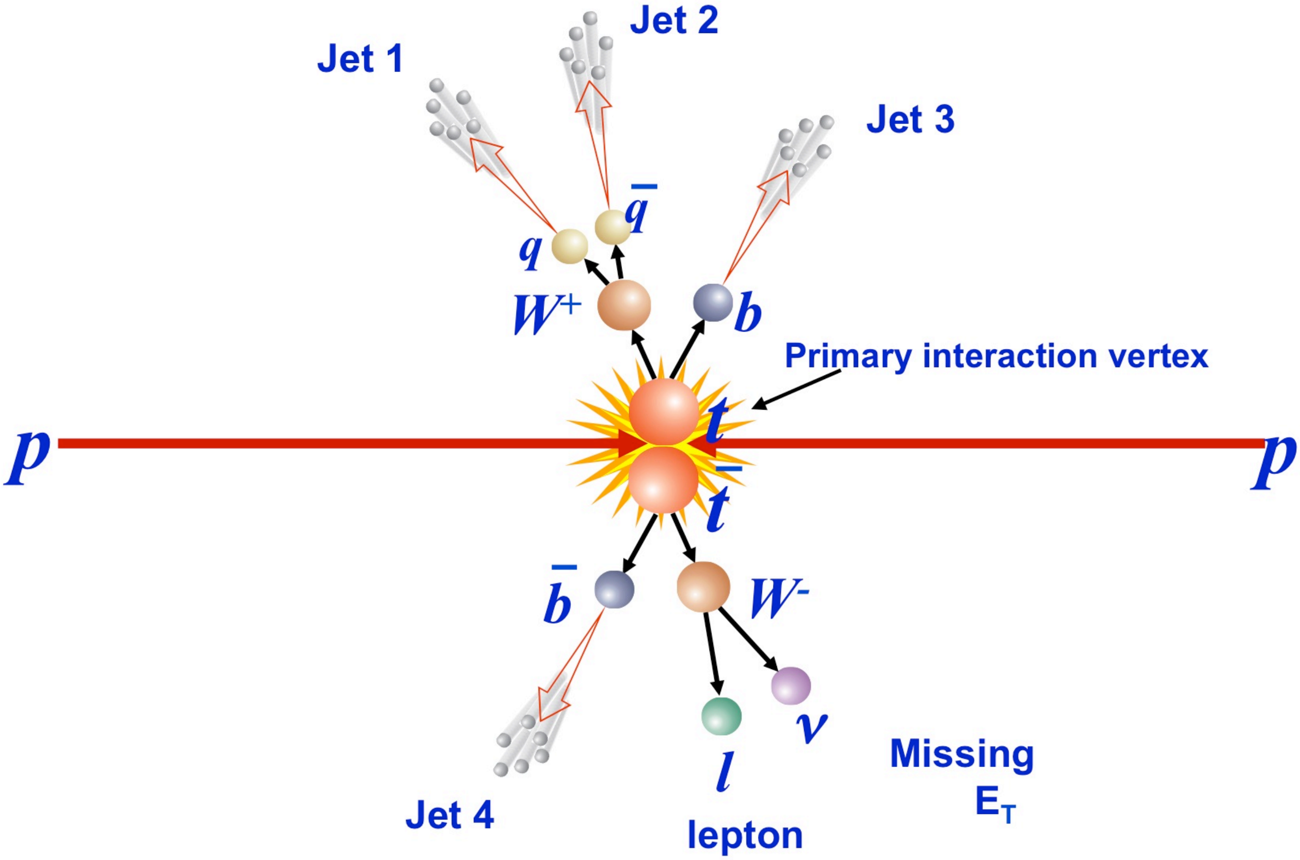
Top Mass: the channels



Lepton + jets

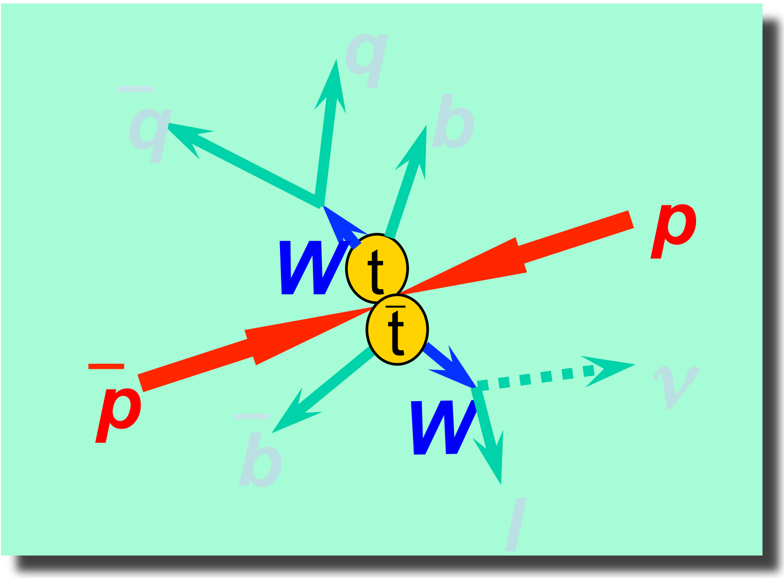
- Reasonable branching fraction
- Medium bkg levels:
  - W+jets
  - QCD multijet
- Benefits from in-situ jet energy calibration using hadronic W
- Has traditionally yielded the best results

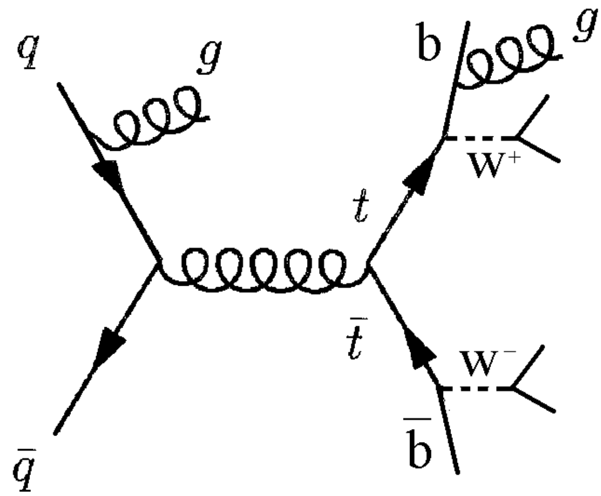
Top Mass: the challenge



- In general, don't know which jet comes from which parton
- In the l+jets case e.g., detector sees 4 jets, a lepton, missing ET, and an interaction vertex
- No displaced vertices to isolate signal from background
- Must try all permutations
- No clean and sharp mass peaks

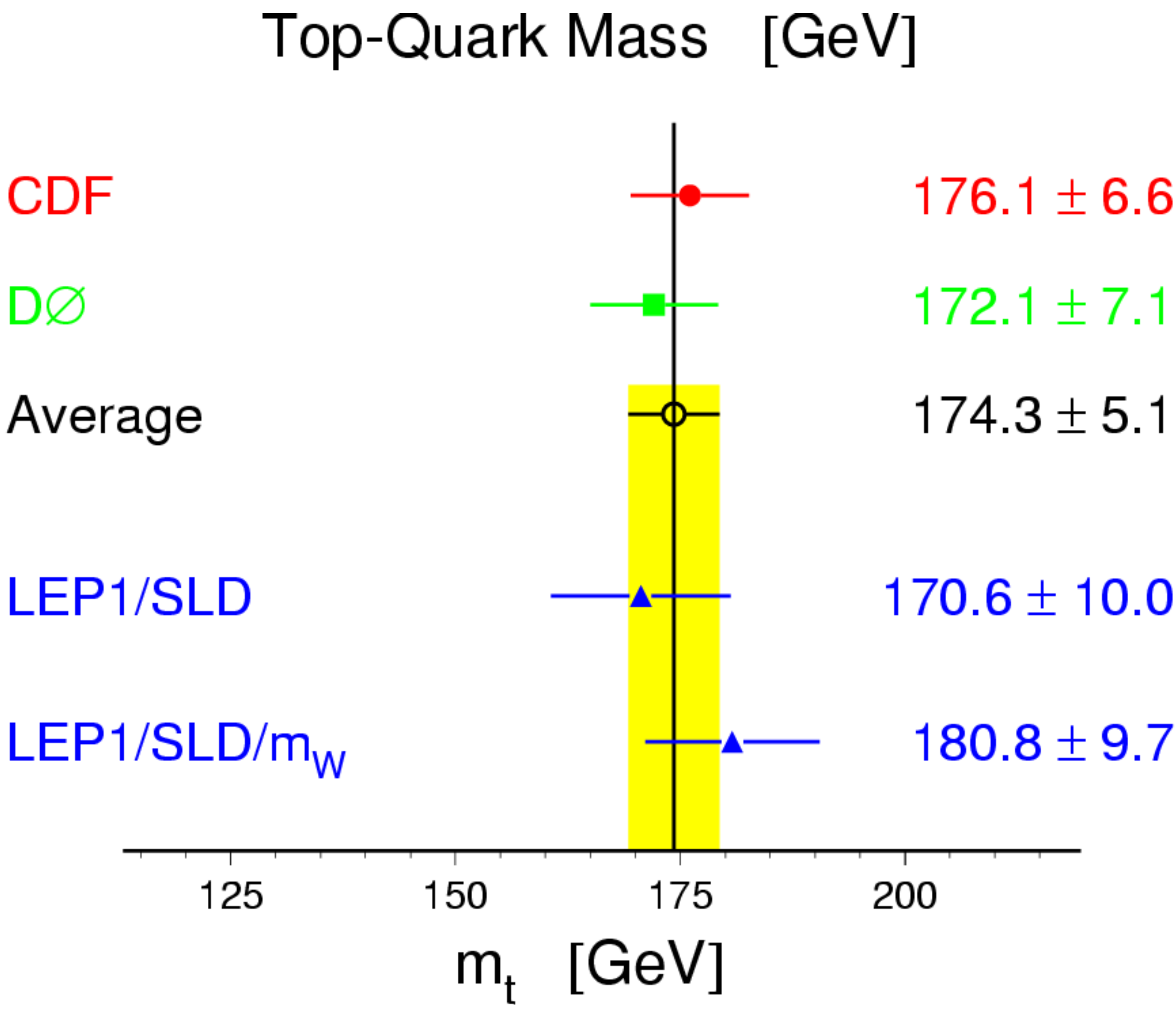
$t\bar{t} \rightarrow l\nu b\, q\bar{q}\bar{b}$





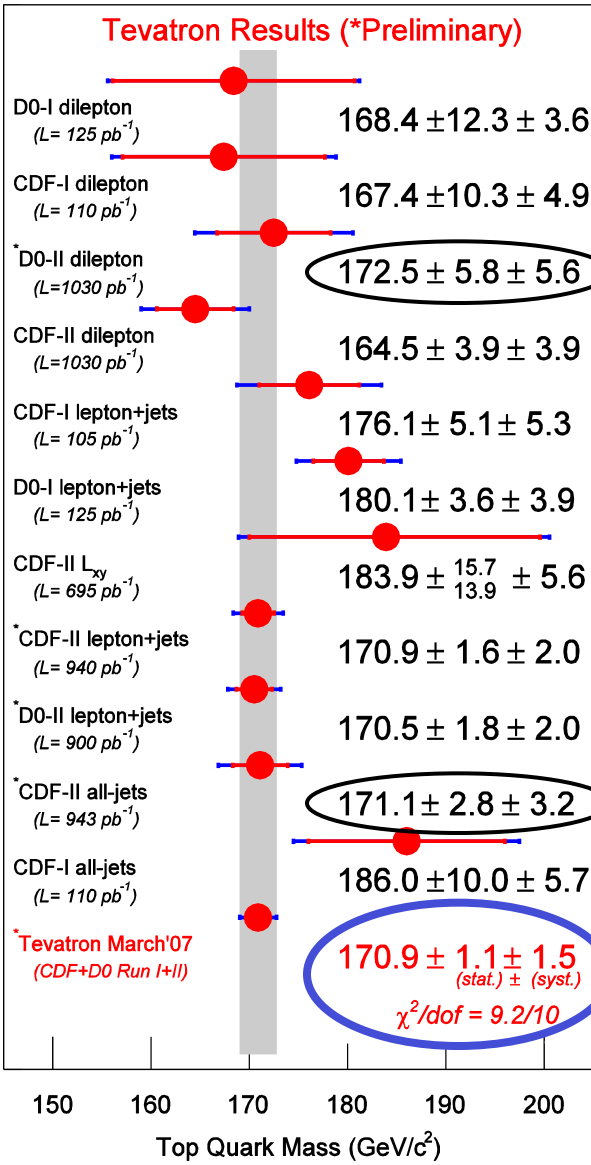
- Measuring the top mass
  - Use lepton+jet sample
  - All kinematics known, but:
    - P_z^ν
  - 3 constraints:
    - $M(l\nu) = M(qq) = M_W$
    - $M(l\nu b) = M(qqb)$
    - **2C kinematic fit**
  - Combinatoric ambiguity
    - 2 combination if double b-tag
    - 6 combination if single b-tag
    - Gluon radiation can give extra jets!
  - MC to check/correct for systematic effects

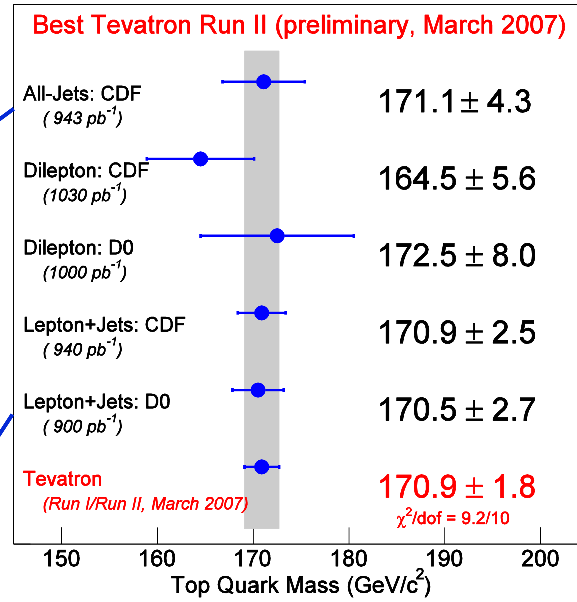
- **La massa del top e le misure di precisione**



Determinazione indiretta

Massa del Top: Media Mondiale





m_{top} oggi e' nota con una incertezza del 1.1% !

170.9 ± 1.1 (stat) ± 1.5 (syst) GeV/c^2

Bibliografia

Chi desidera approfondire l'argomento puo' utilizzare:

i) Appendice 7: Lezioni di Marco Rescigno;

ii) le Tesine sul quark top presentate negli A.A. precedenti che si trovano nel sito: /people/dionisi

Seconda Parte: Ricerca dell' Higgs a LEP e TEVATRON

Nota Bene: la parte di Teoria sulla rottura spontanea della simmetria, meccanismo di Higgs, fa parte del programma e viene svilupppata nelle pagine 507-524 del Burcham and Jobes. Vedi inoltre i capitoli 13 e 14 di seguito.

Nel seguito di questo capitolo vengono invece presentate in modo schematico le ricerche del bosone di Higgs a LEP e al Tevatron.
Dettagli su queste ricerche si possono trovare nelle tesine fatte dagli studenti nei vari A.A. e "postate" nel sito : people/dionisi.

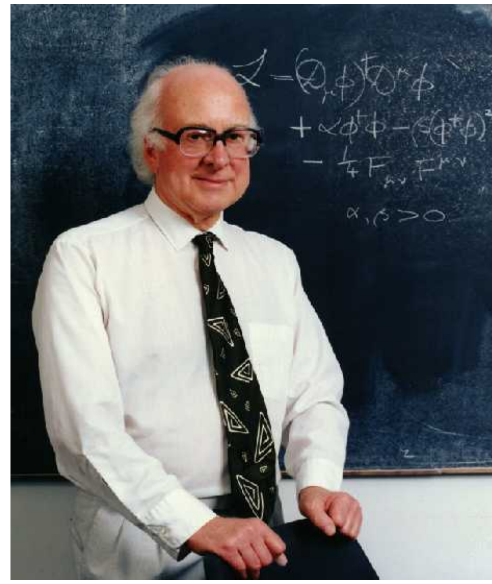
Le ricerche e la scoperta a LHC sono discusse nel prossimo capitolo 13.

Higgs search

♦Il bosone di Higgs fino a luglio 2012 e' stato il tassello mancate del Modello Standard.

♦Nel Modello Standard ha il ruolo fondamentale di generare la massa dei bosoni W e Z e dei fermioni.

♦ Tuttavia ci sono modelli con meccanismi piu' complessi di quello di Higgs che prevedono una "fisica Nuova" con nuove particelle ancora da scoprire. Vedi il capitolo 15.

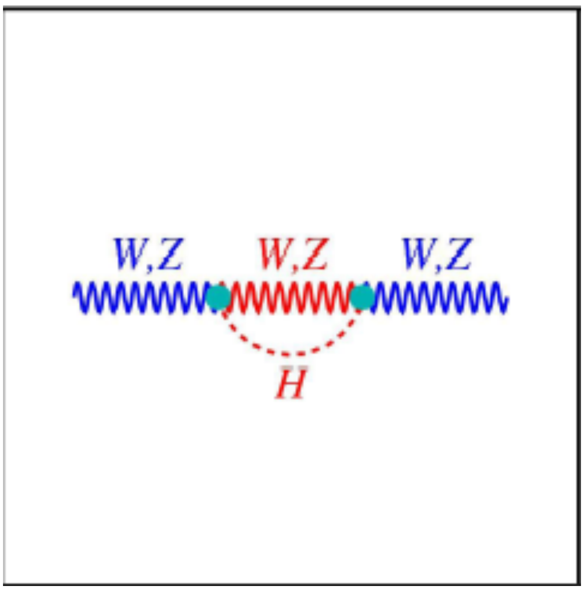


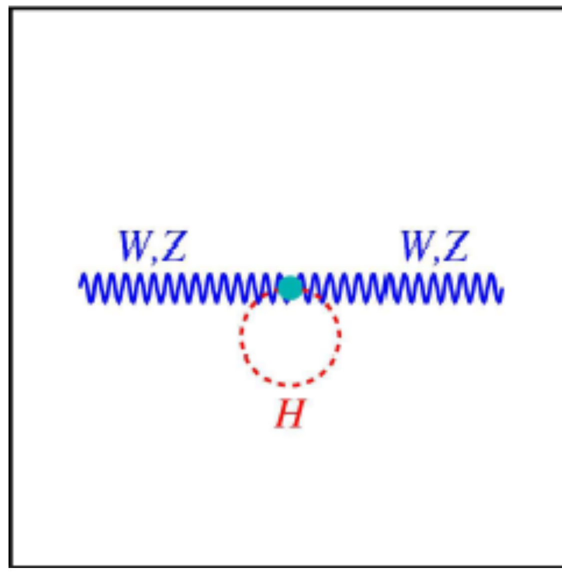
Prof. Peter Higgs

P.W. Higgs, Phys. Lett. 12 (1964) 132

Ricerca Indiretta dell' Higgs

- Come abbiamo visto, il contributo dei loop dell' Higgs alle correzioni radiative, vedi figure, e' logaritmico; la sensibilita' del fit ai dati delle misure elettrodeboli e' quindi ridotta.





Il limite indiretto combinando I dati elettrodeboli e':

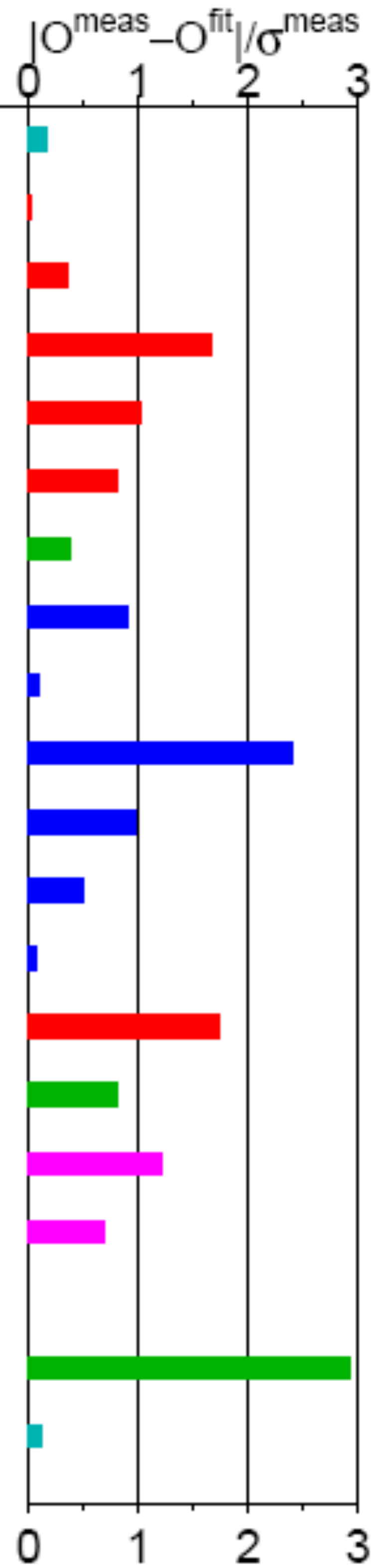
$M_H < 219$ GeV al 95 % di C.L.

Results of global electroweak fits

Fit to data from LEP, SLD, Tevatron (M_W, M_t)...

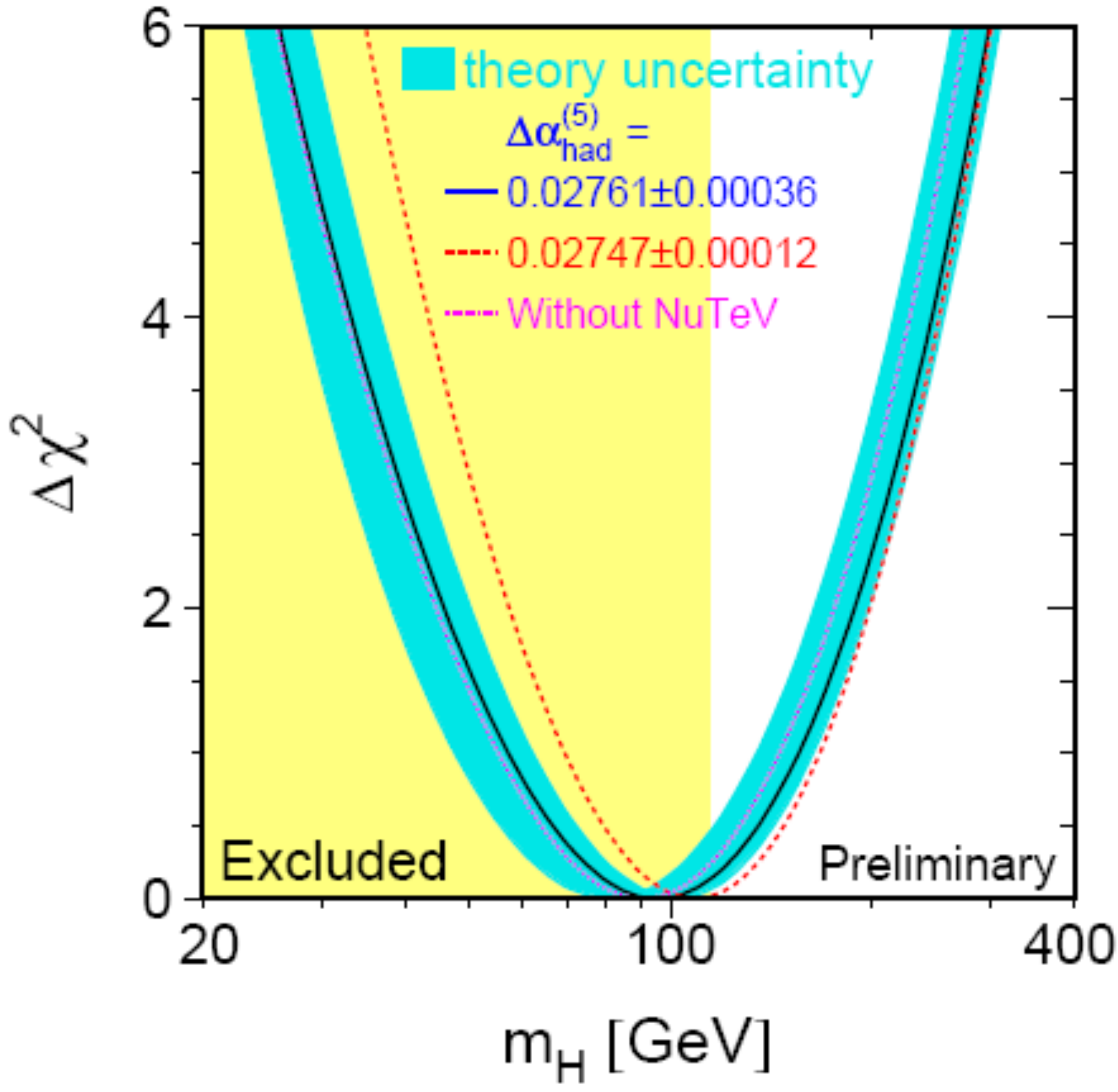
Summer 2003

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90



Standard Model Higgs

Electroweak fits $\Rightarrow M_{\rm H} < 219$ GeV (95% CL).



Theoretical arguments - self consistency of SM up to scale $\Lambda^{\rm GUT} \approx 10^{16}$ GeV $\Rightarrow 130 < M_{\rm H} < 190$ GeV.

$M_{\rm H}$ higher - theory non-perturbative,

$M_{\rm H}$ lower - vacuum unstable.

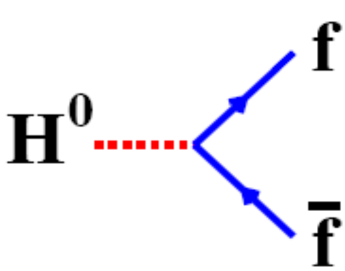
Ricerca Diretta dell' Higgs a LEP

There is one final ingredient to the Standard Model - the Higgs Boson.

The Standard Model requires the existence of a new neutral SCALAR (i.e. spin-0) particle - the HIGGS boson.

Higgs Boson and Mass

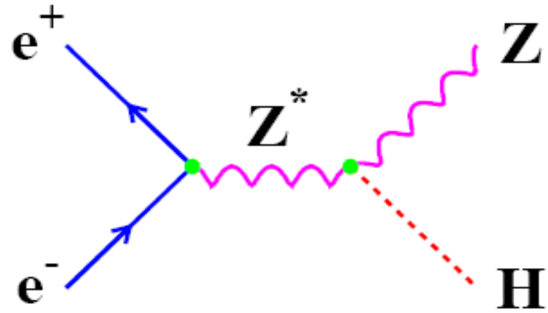
- ★ The Higgs Boson (discovered in 2012) is the particle responsible for the MASS of ALL particles (including the $W^{\pm}$ and Z^0).
- ★ The Higgs Field has a non-zero vacuum expectation value, it is a property of the vacuum.
- ★ As particles move through the vacuum they interact with the non-zero Higgs field
- ★ It is this interaction that gives fermions mass
- ★ The strength of the Higgs coupling to fermions is proportional to mass



$$g_{Hff} = (\sqrt{2}G_F)^{\frac{1}{2}} m_f$$

Higgs Production at LEP

IF $m_H < \sqrt{s} - M_{Z^0}$

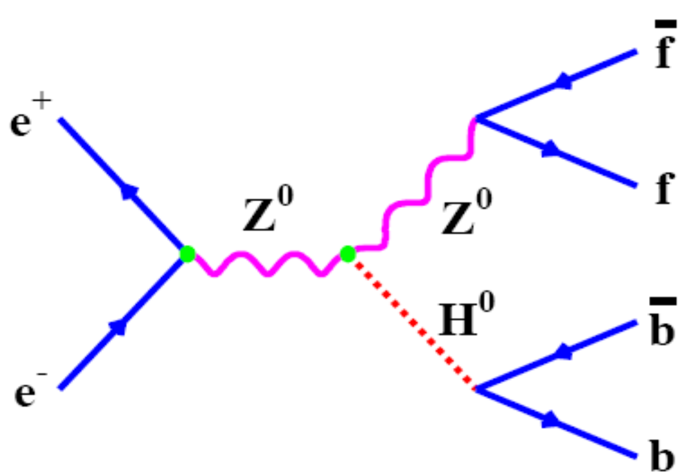


In 2000 LEP operated with $\sqrt{s} \approx 207$ GeV, therefore had the potential to discover the Higgs Boson IF $m_H < 116$ GeV

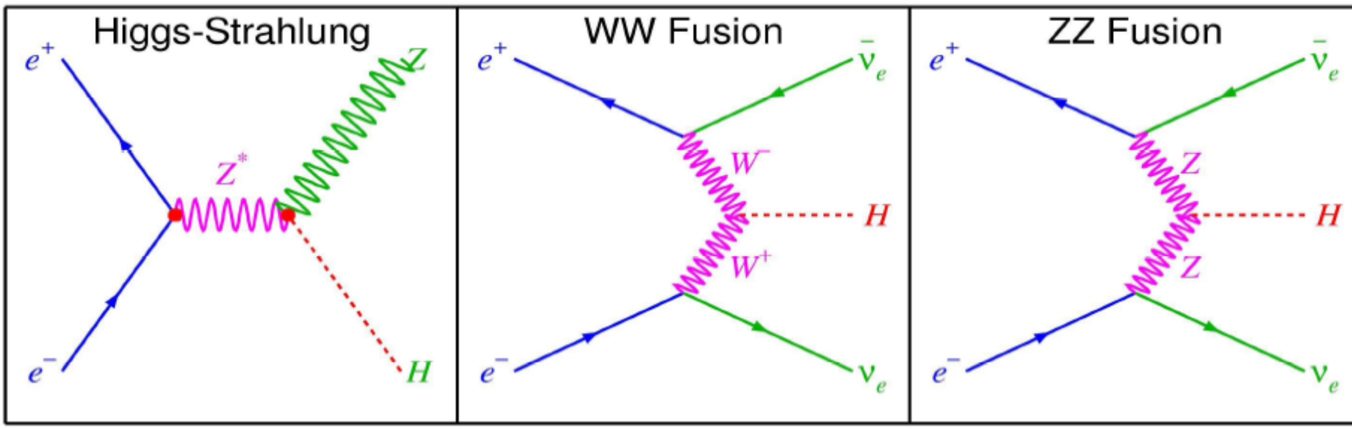
Higgs Decay

- ★ The Higgs boson 'couples' to mass.
- ★ Consequently partial widths proportional to m^2 of the particle involved
- ★ The Higgs Boson decays preferentially to the most massive particle kinematically allowed (*i.e.* energy conservation)
- ★ For $m_H < 116$ GeV this is the b-quark

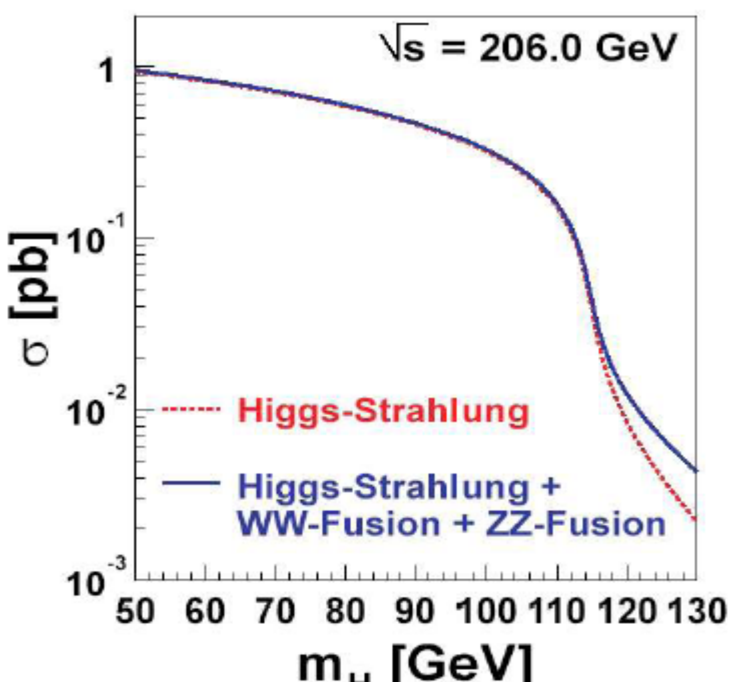
At LEP search for $e^+e^- \to H^0Z^0 \to b\bar{b}f\bar{f}$



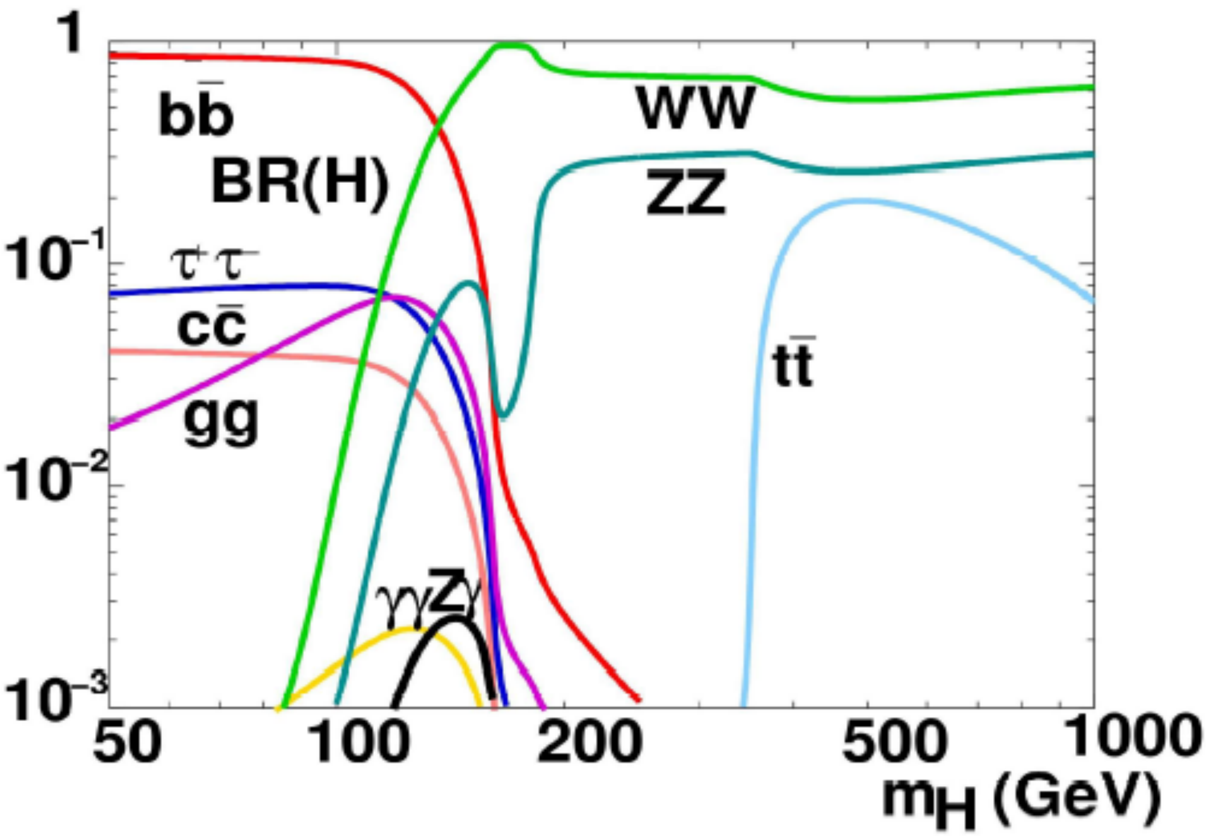
Higgs Production at LEP 2



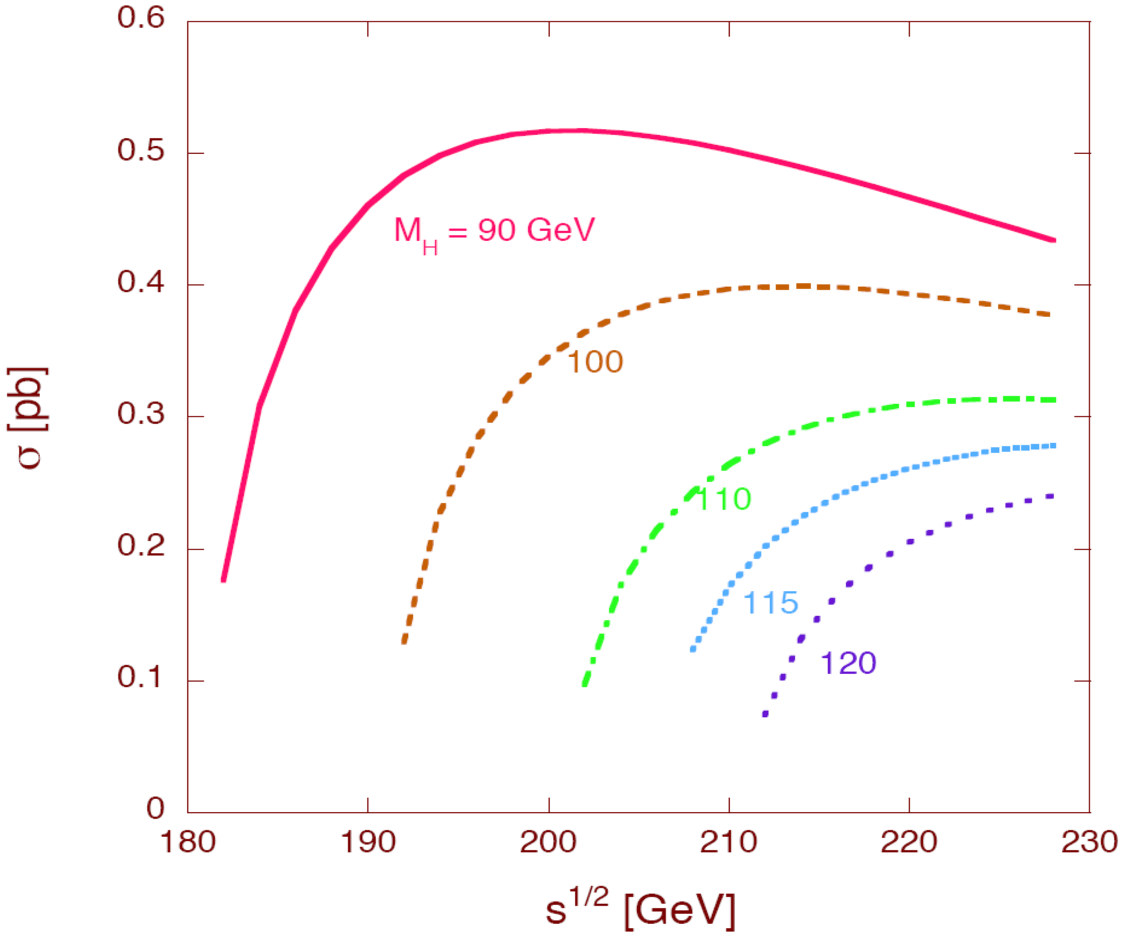
Higgs Production Cross-Section



Higgs Branching Ratios



- **Light Higgs decay:**
  - Higgs si accoppia alle particelle piu' pesanti cinematicamente
    - bb dominant mode up to M_{Higgs} ~ 135 GeV
    - Il decadimento in coppie WW sopra questo valore diventa il meccanismo dominante



+ important effect of ISR

LEP 2: sensitive nearly to kinematical limit

$$\boxed{M_H^{\max} = \sqrt{s} - M_Z}$$

LC: sensitive for $M_H \lesssim 0.7\sqrt{s}$

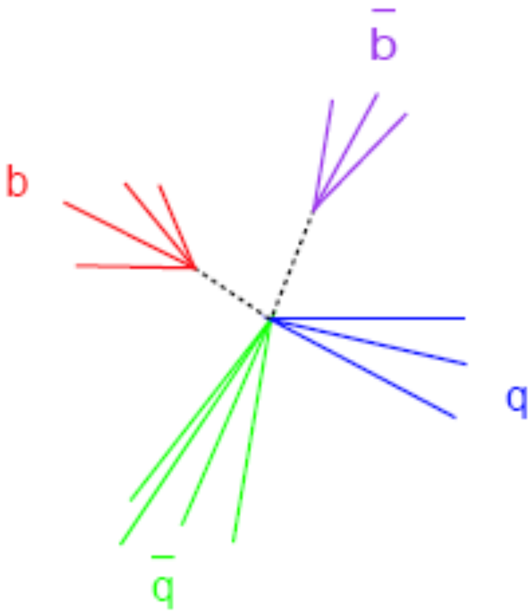
& measure excitation curve to determine

$$\delta M_H \approx 60 \text{ MeV} \sqrt{100 \text{ fb}^{-1}/\mathcal{L}} \text{ for } M_H = 100 \text{ GeV}$$

HZ search topologies

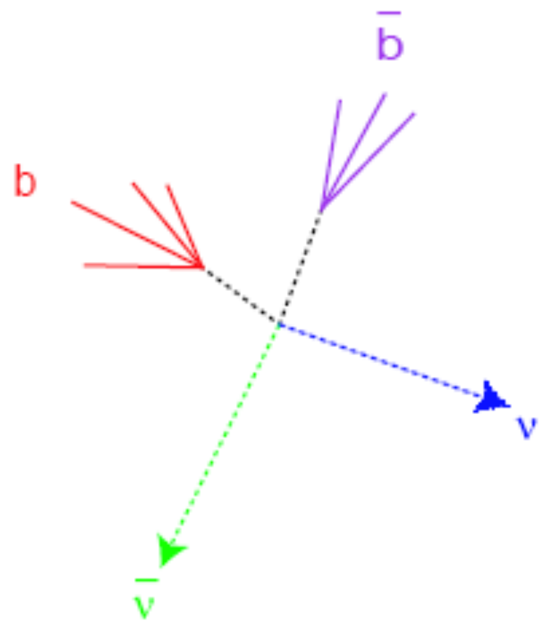
Four jets, 60%

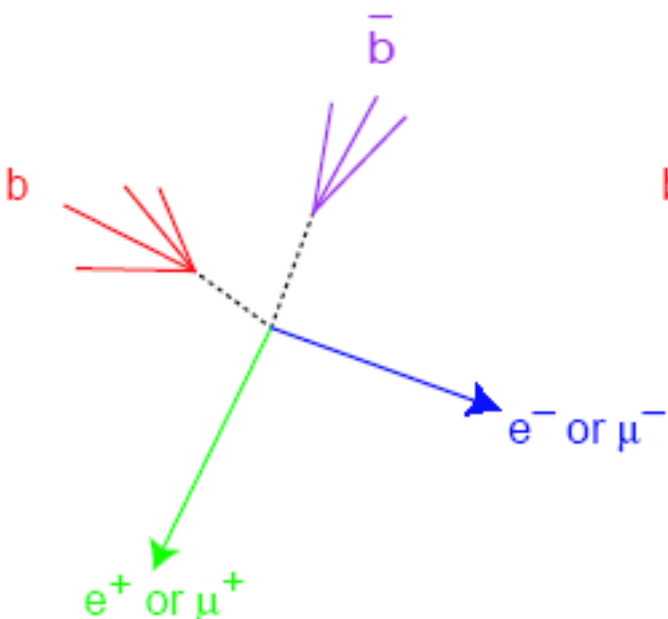
$$H \to b\overline{b}\,,\, Z \to q\overline{q}$$



Missing energy, 18%

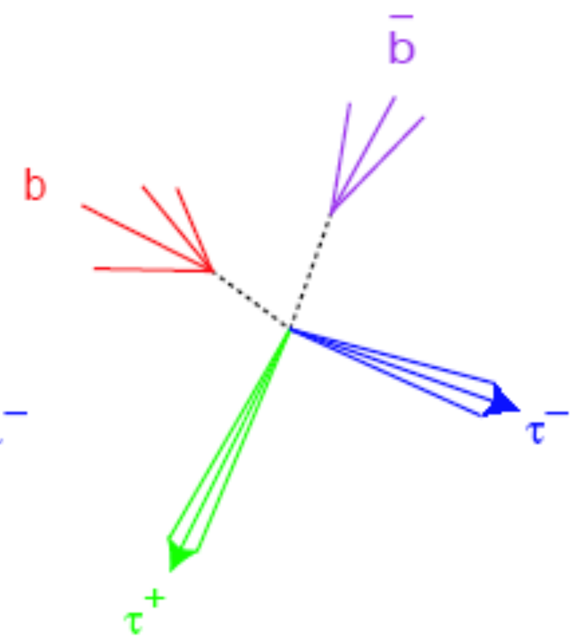
$$H \to b\overline{b}\,,\, Z \to \nu\overline{\nu}$$





Leptonic, 6%

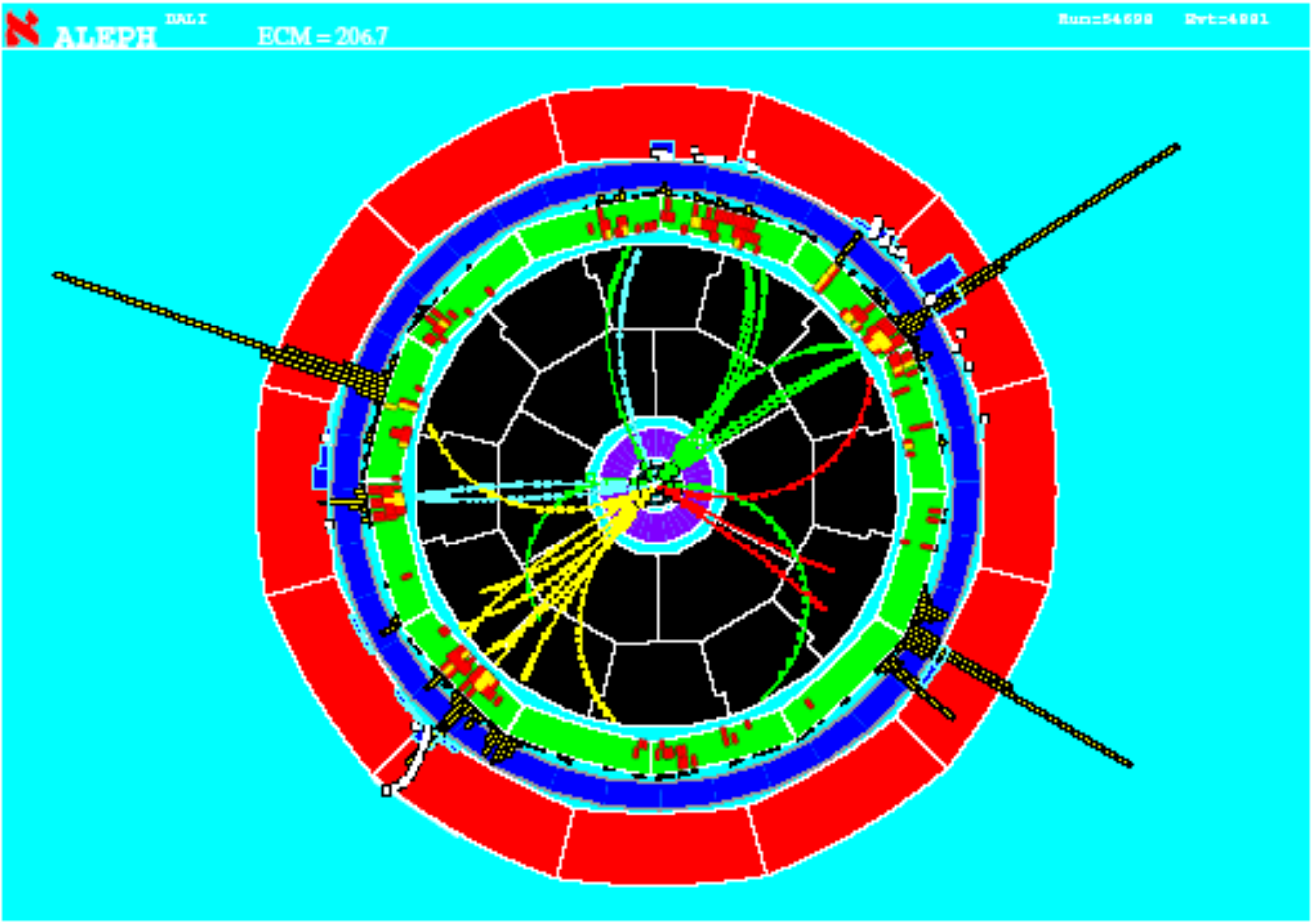
$$H \to b\overline{b}\,,\, Z \to \ell^+\ell^-$$



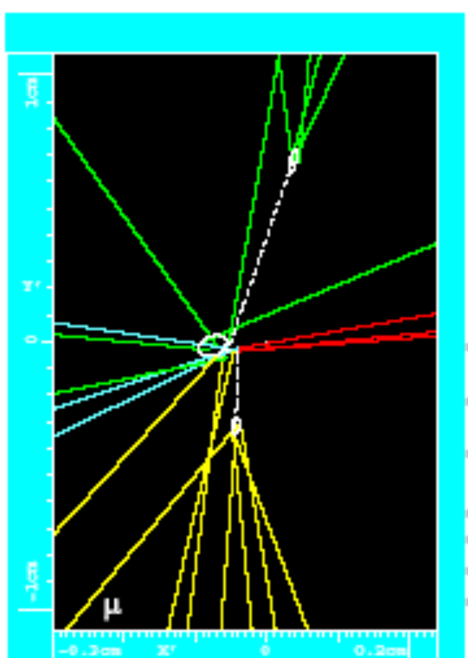
Tau channels, 9%

$$H \to b\overline{b}(\tau^+\tau^-)\,,\, Z \to \tau^+\tau^-(q\overline{q})$$

ALEPH Higgs Event



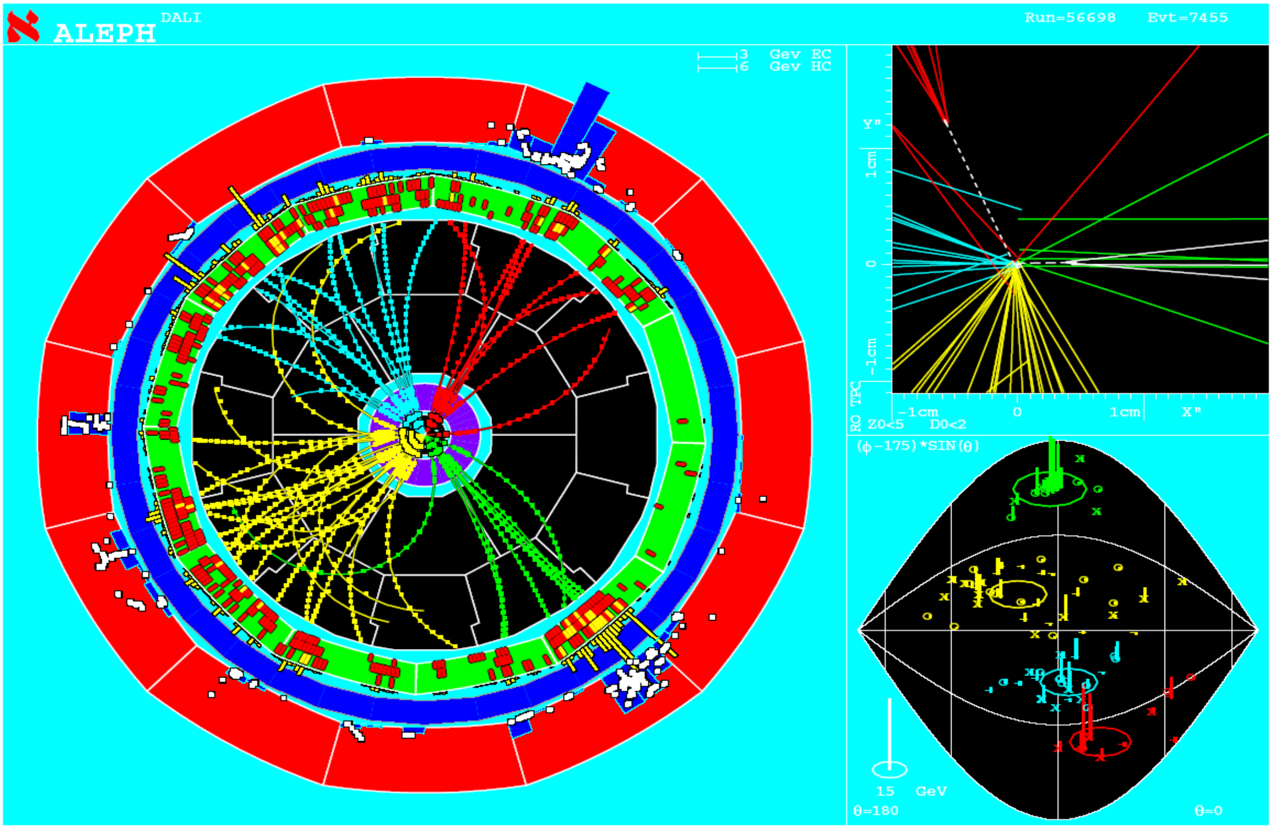
Filename: DC054698_004881_000915_1311.PS_HI_XY_WW



Made on 4-Oct-2000 09:39:52 by DREVERMANN with DALI_F1.
Filename: DC054698_004881_001004_0937.PS_HI_XY_XY_TU

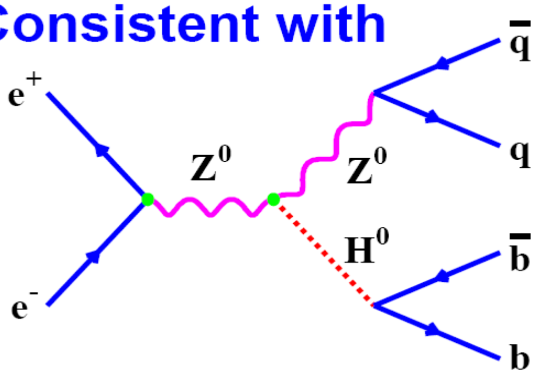
The Evidence....

4 Possible $e^+e^- \rightarrow Z^0H^0$ events observed in the final year of LEP operation. *e.g.*



Made on 30-Aug-2000 17:24:02 by konstant with DALI_F1.
Filename: DC056698_007455_000830_1723.PS

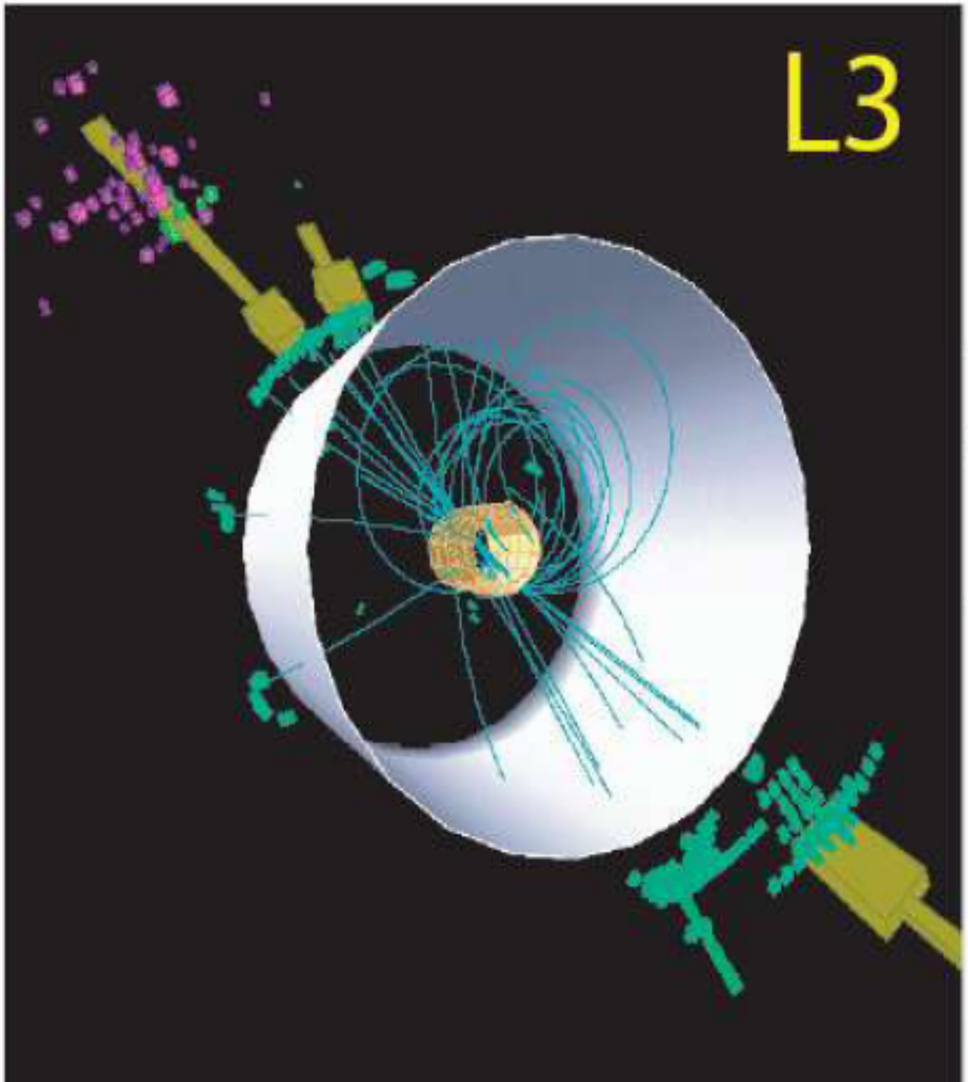
Consistent with



$$\boxed{m_{H^0} = 115\ \mathrm{GeV}}$$

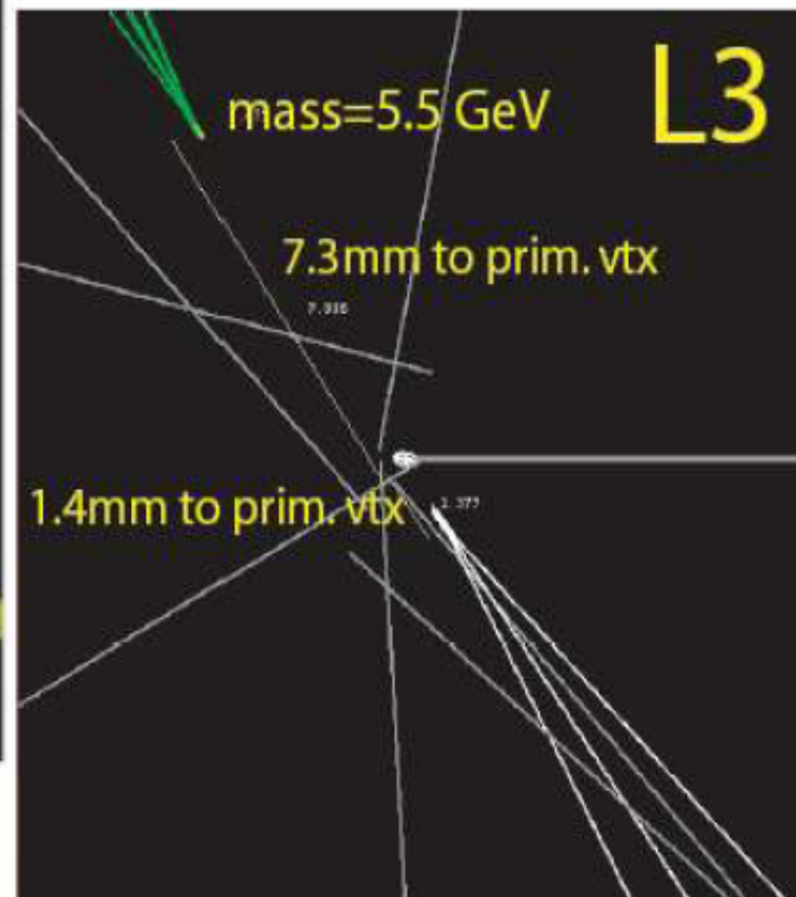
- ★ The evidence is tantalizing **BUT FAR FROM** conclusive
- ★ LEP operation ended in October 2000
- ★ WAIT another 3^+ years for LEP's successor at CERN - the Large Hadron Collider (LHC).

most significant $H\nu\nu$ candidate

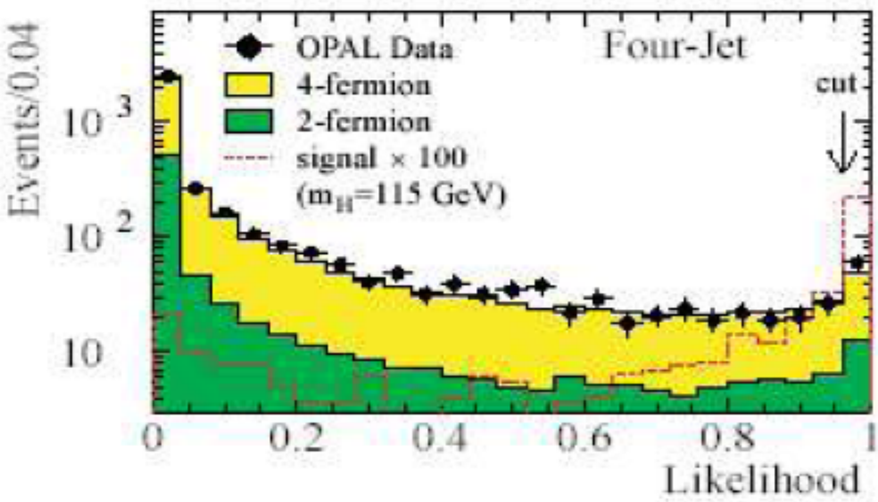


measured H mass=114.4 GeV
H mass resolution ~3 GeV

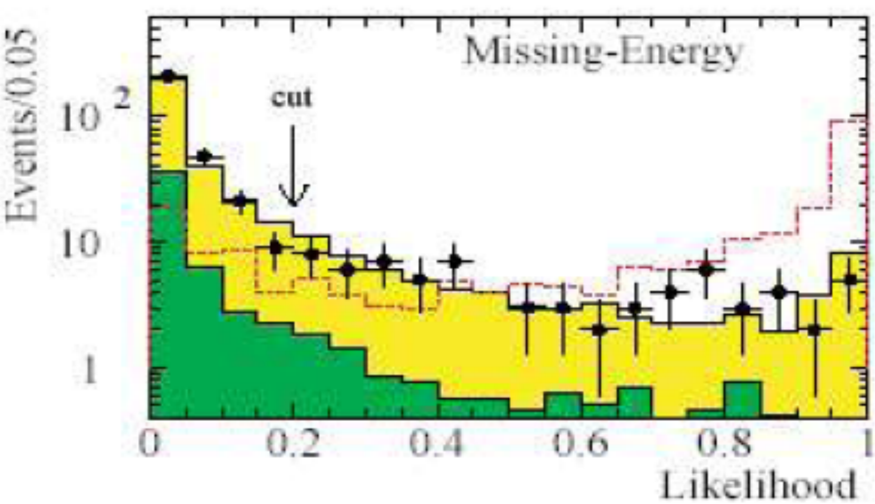
Secondary vtx's view



Strategia per l' analisi dell' Higgs

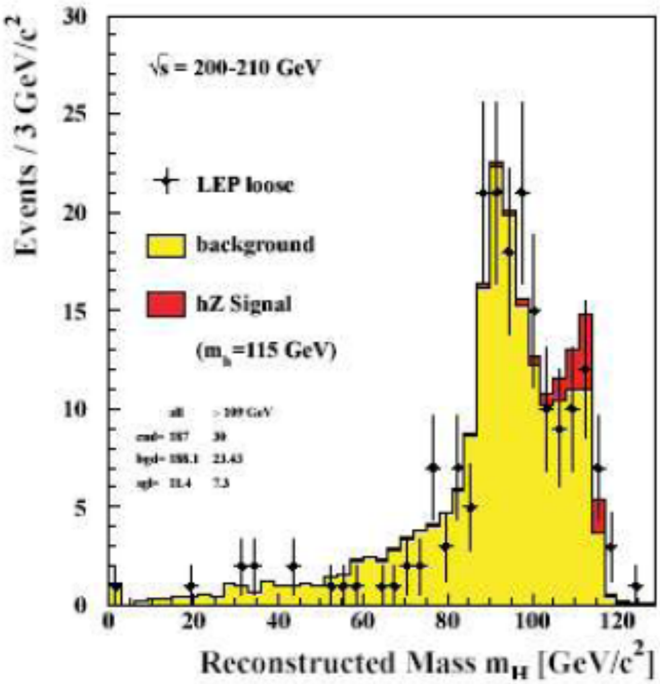


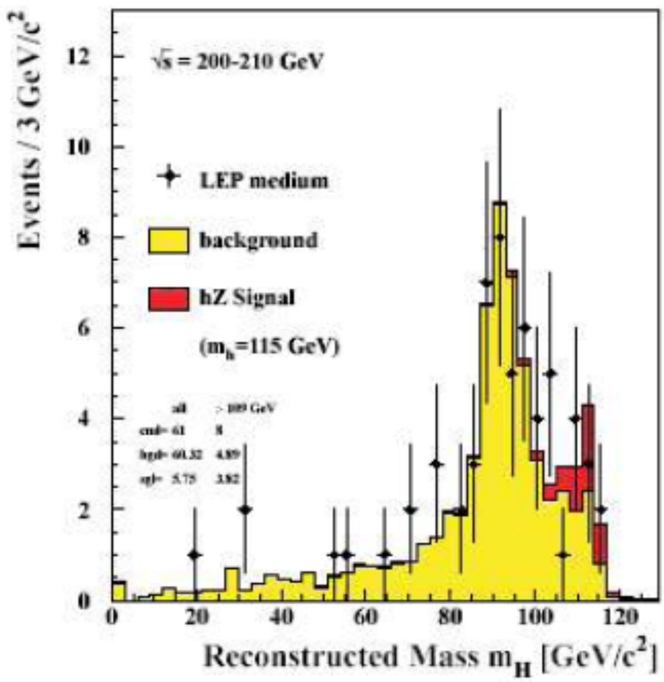
$Z\ H \rightarrow\ q\ \bar{q}\ b\ \bar{b}$



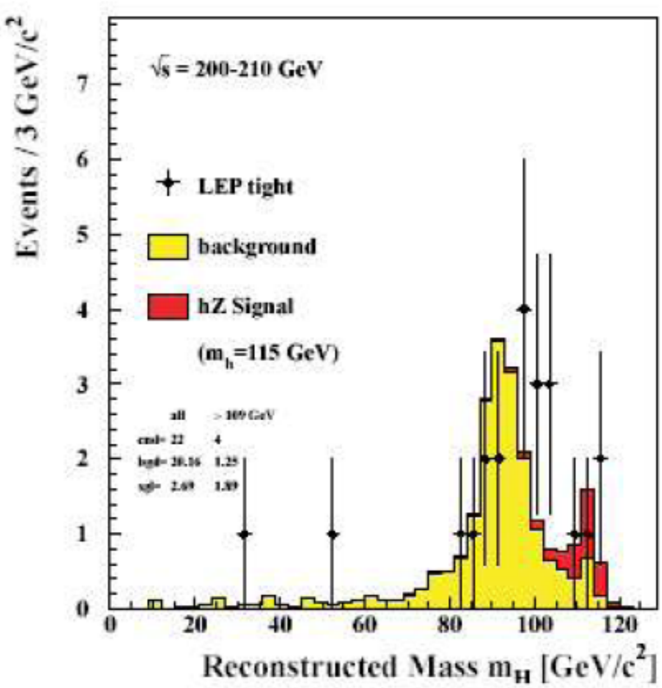
$Z\ H \rightarrow\ \nu\ \bar{\nu}\ b\ \bar{b}$

Higgs Mass Spectra

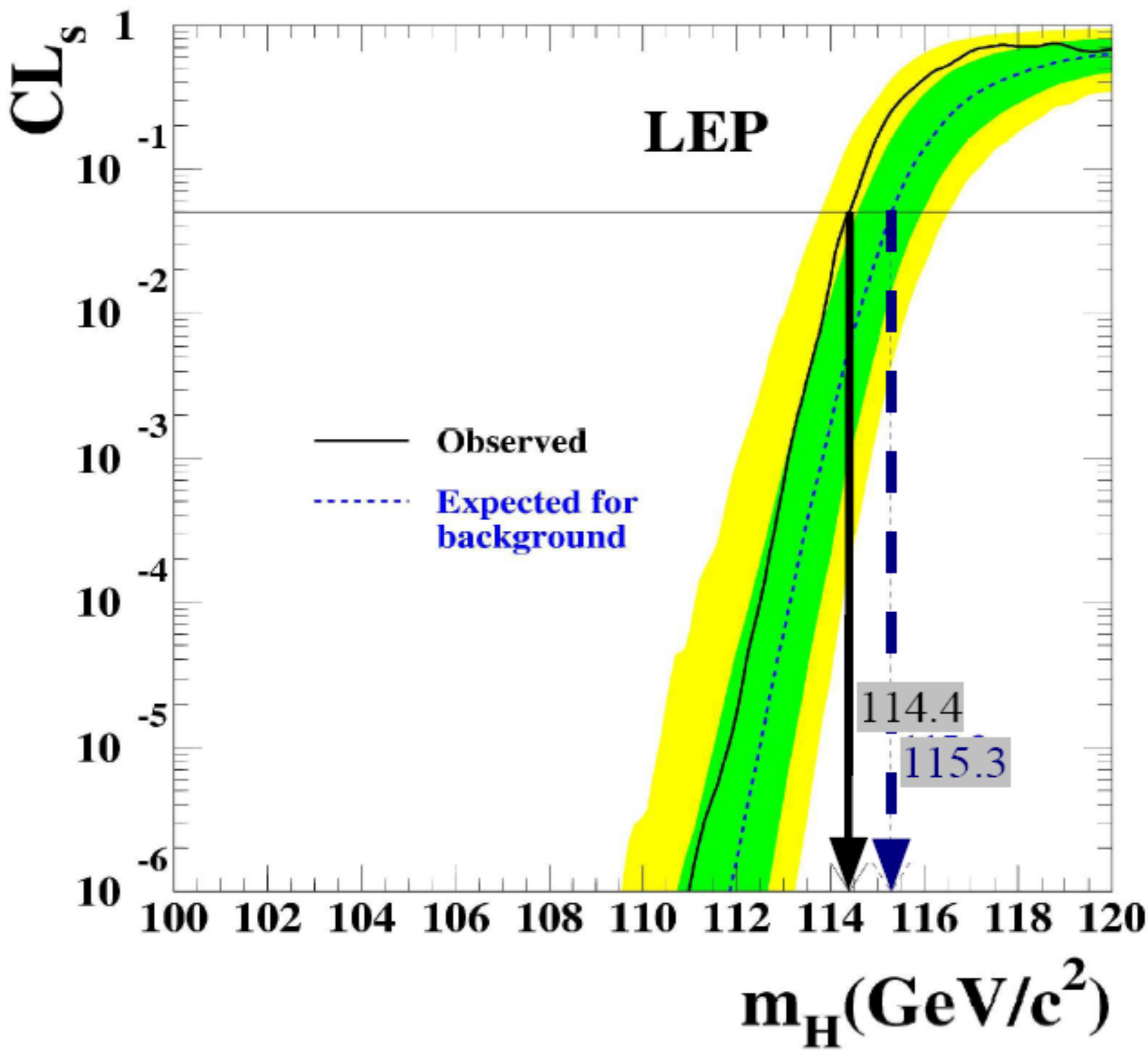




Tagli piu' stretti aumentano la purezza del campione ma si pagano in statistica.



Higgs Limit



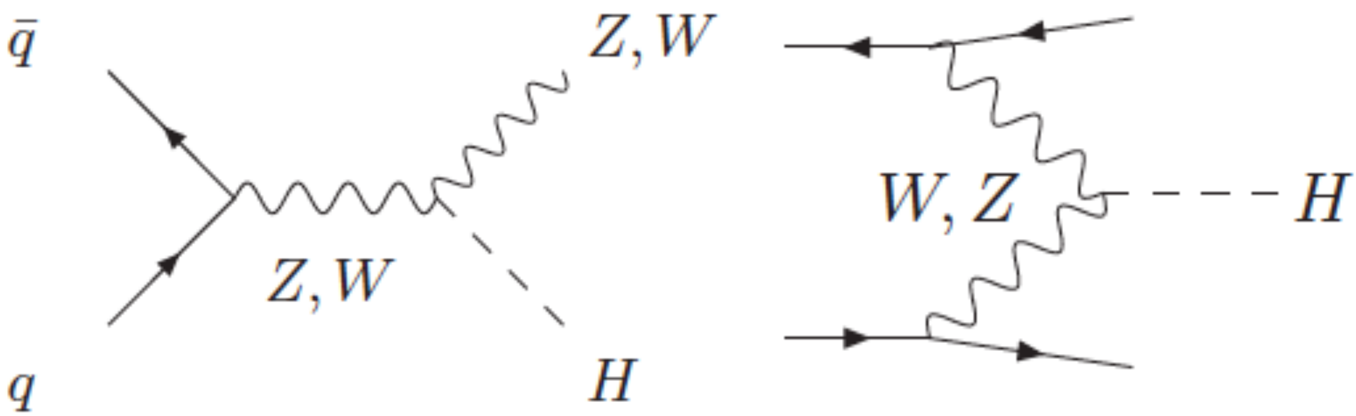
CL_s
LEP
Observed
Expected for background
114.4
115.3
$m_H(GeV/c^2)$

Limiti sulla Massa dell’ Higgs da LEP

❖ Fit ai dati di precisione elettrodeboli

$$M_H = 89^{+35}_{-26}\ \text{GeV},\ M_H \lesssim 185\ \text{GeV @ 95\% CL}$$

❖ Ricerche Dirette

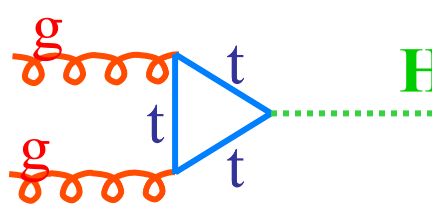


$$M_H > 114.4\ \text{GeV @ 95\% CL}$$

Higgs al Tevatron

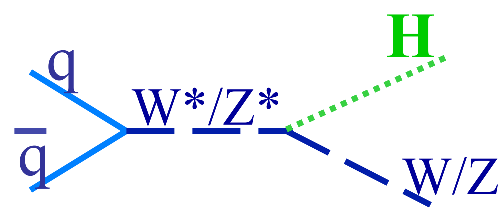
- Light (100 – 200 GeV) Higgs production:
  - Higgs couplings prefer higher masses
  - Main production mechanisms:
    - Virtual top quark loops

$\sigma \sim 1.0 - 0.1$ pb

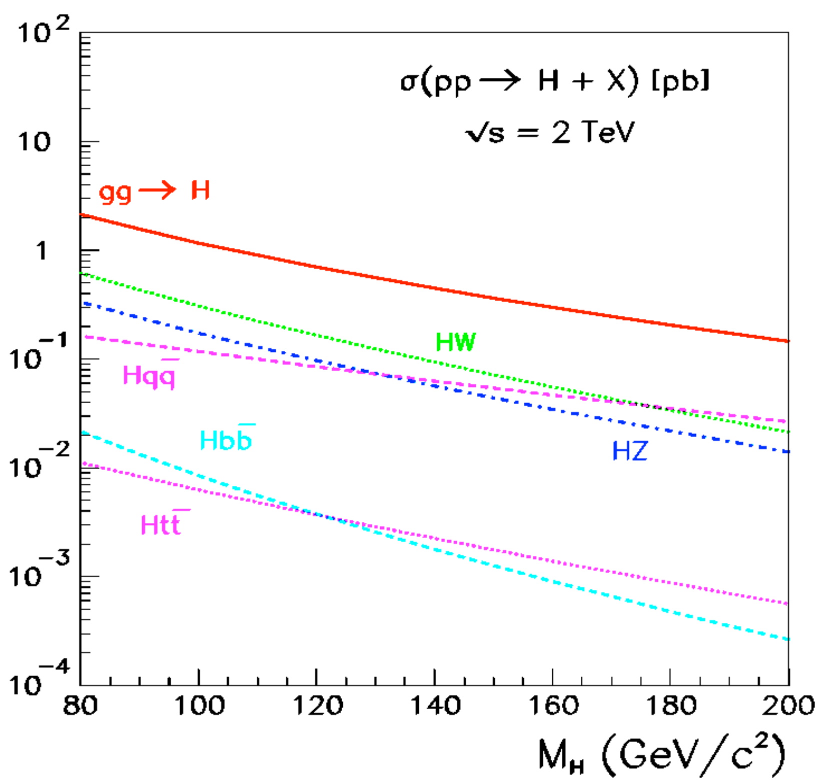


- Associated W/Z production

$\sigma \sim 0.5 - 0.02$ pb
$\sigma_W \sim 2 x \sigma_Z$



Cfr. Top quark $\sigma \sim 5$ pb



Tevatron
Ricerca dell' Higgs

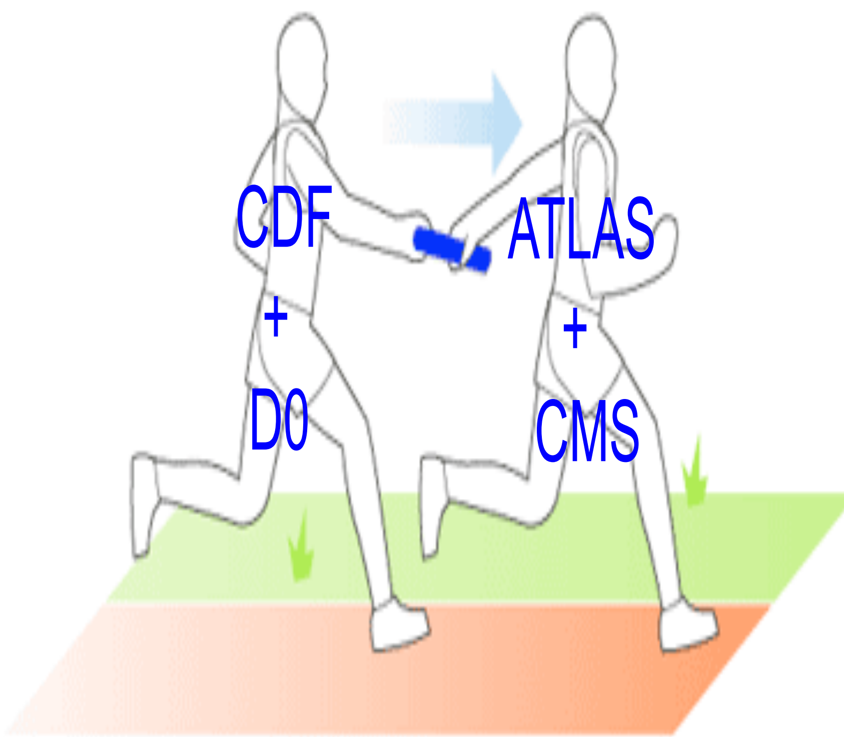
- CDF e D0 hanno preso dati al Tevatron fino al 30 settembre 2011

- i dati raccolti sono ≈ 10 fb-1 per entrambi gli esperimenti

- nel canale H→bb si e' trovata una evidenza di segnale di ≈3 sigma a 125 GeV

The Higgs Relay Race

The Tevatron "Baton"



Bibliografia

Appendice 9: Pippa Wells The Higgs saga at LEP

Burcham and Jobes: pagine 507-524

Vedi inoltre il capitolo 13 che segue