Karlsruher Institut für Technologie

Higgs from Loops

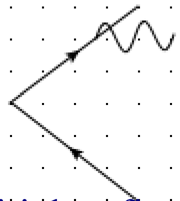
G. Quast, A. Raspereza

Course "Higgs Physics"

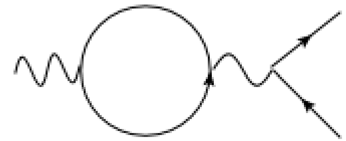
Lecture 7, 14/06/2012

To take home from last lecture

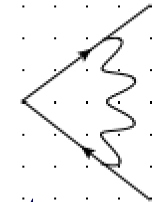
Higher orders modify tree-level diagrams:



initial or final state radiation



propagator loop "vacuum polarization"



vertex correction

- running coupling constants: $\alpha \rightarrow \alpha(s)$ (holds for strong, em and weak interactions)
- modified decay widths: $\Gamma \rightarrow \Gamma\,(1+c\ \alpha(s) + \ldots)$ (for em and strong interactions)
- Z couplings → "effective couplings", or
  $\sin^2(\Theta_w) \rightarrow \mathbf{\sin^2(\Theta_w)^{eff}}$ and $\rho=1 \rightarrow \rho^{eff}=(1+\mathbf{\Delta\rho})$
- relation between $\sin^2(\Theta_w)$ from W and Z masses and $\sin^2(\Theta_w)^{eff}$: $\mathbf{\Delta r}$
- large vertex corrections in diagrams involving b and t -quarks: $\mathbf{\Delta\rho_b}$

Corrections depend
- **quadratically** on top quark mass
- **logarithmically** on Higgs boson mass

Need precision calculations and precision measurements to become sensitive to Higgs in loops

Precison tests of ew theory in the 90ties
(LEP, SLC, Tevatron)

Measurements in $e^+ e^-$ at LEP – the four experiments

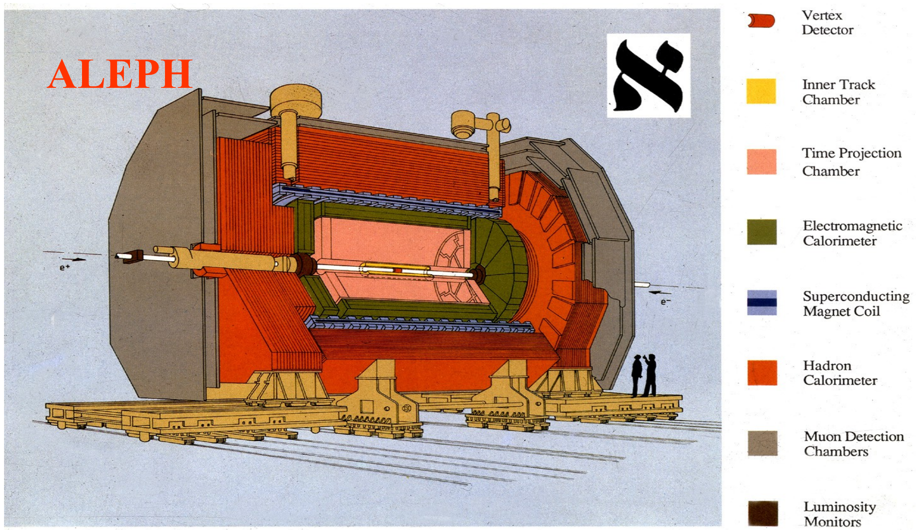
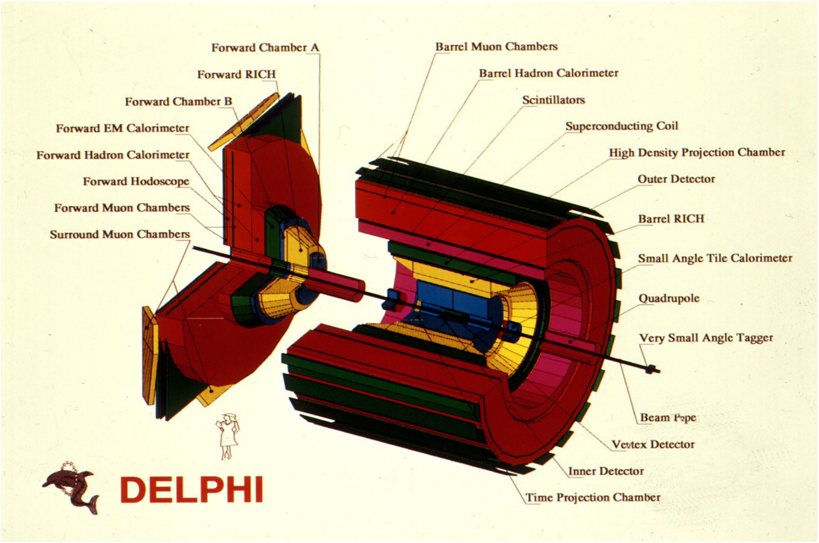
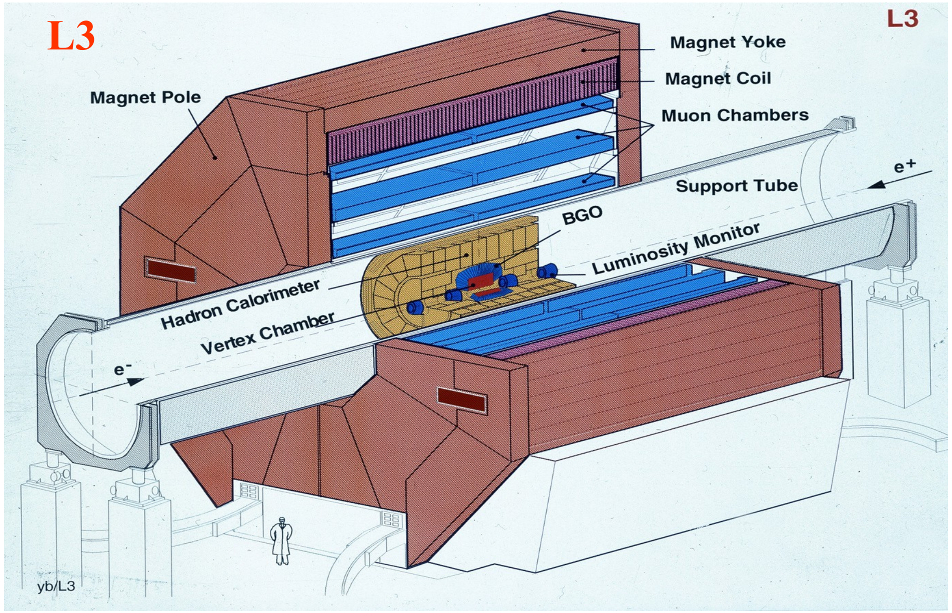
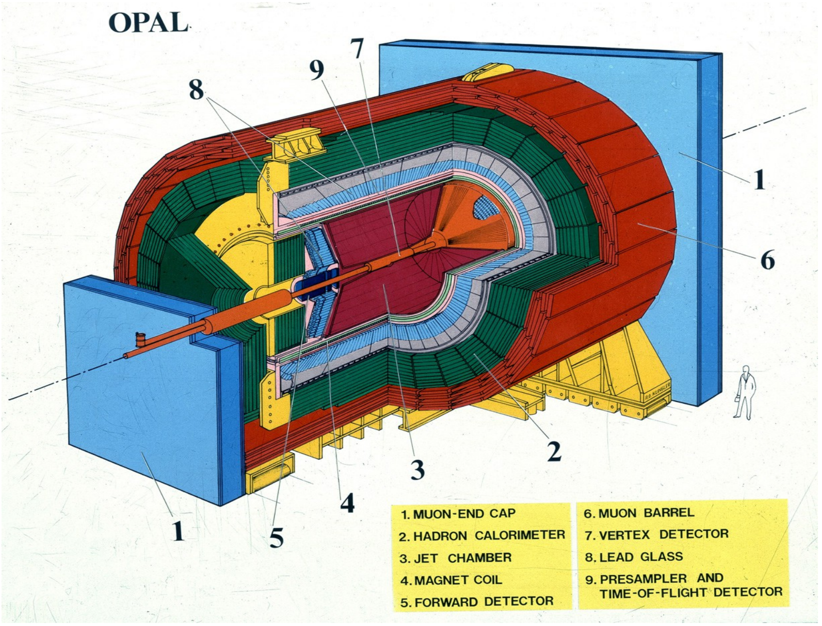


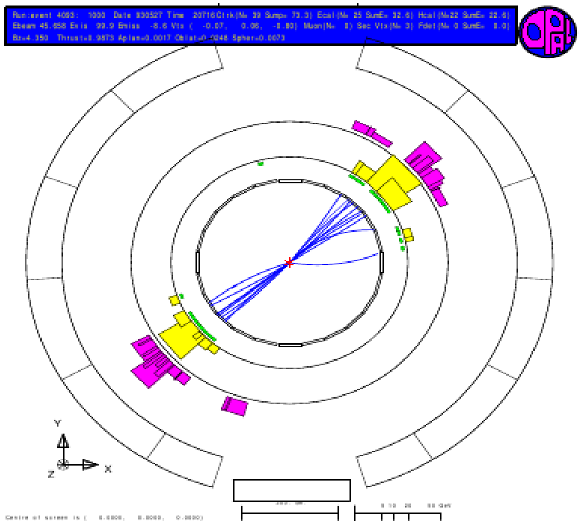
Fig. 1 - The ALEPH Detector

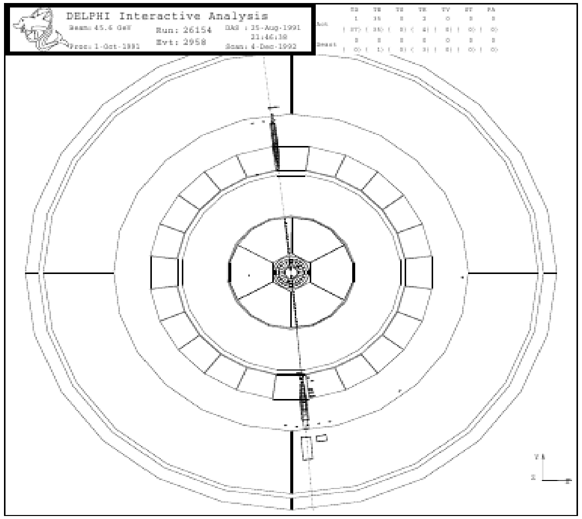




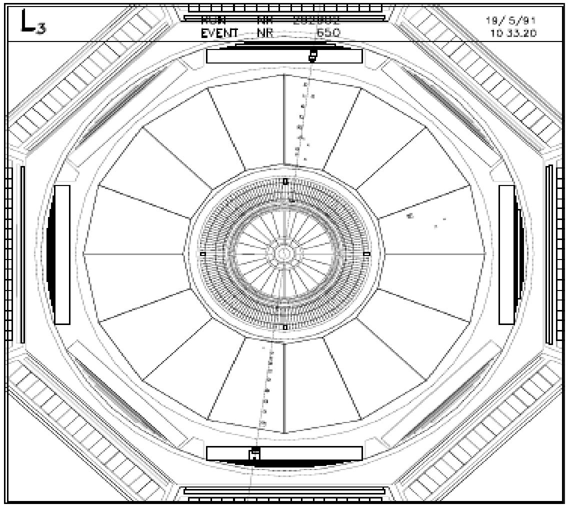


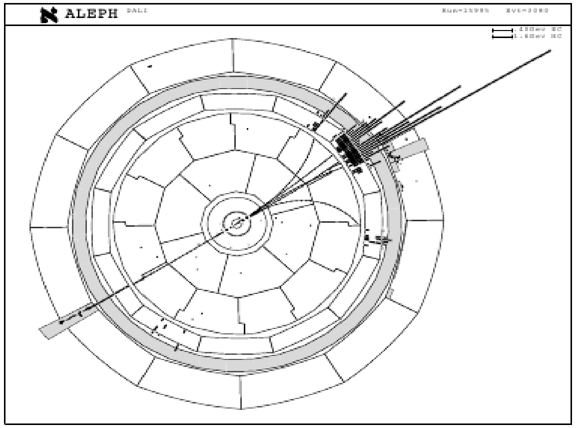
Measurements in $e^+ e^-$ at LEP



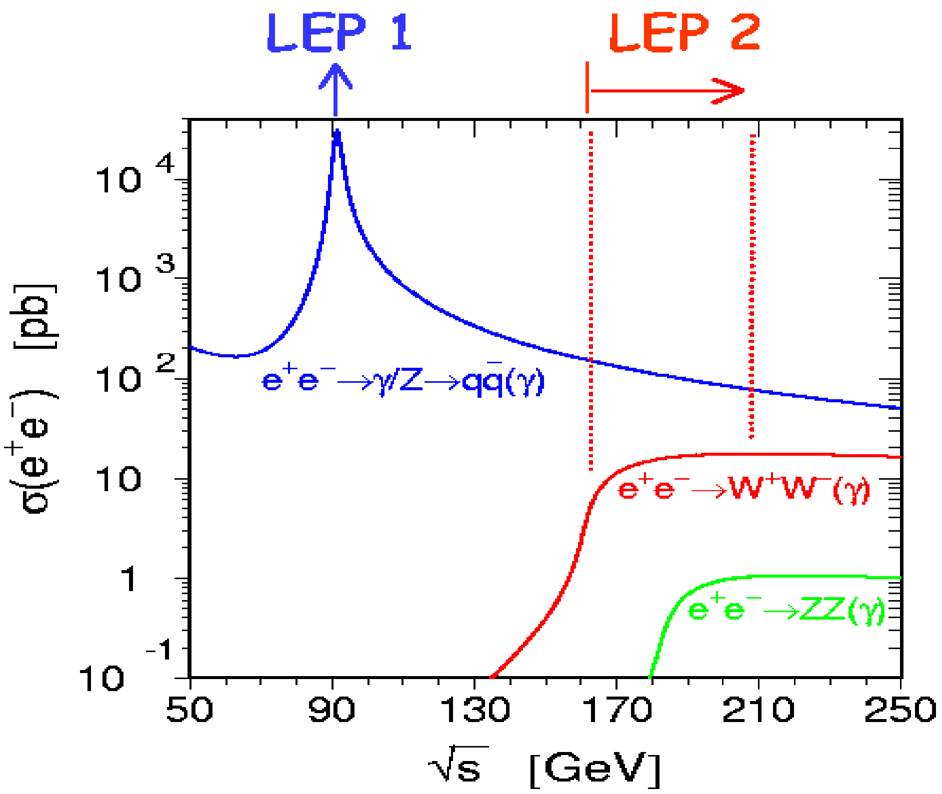


Event Displays from LEP experiments





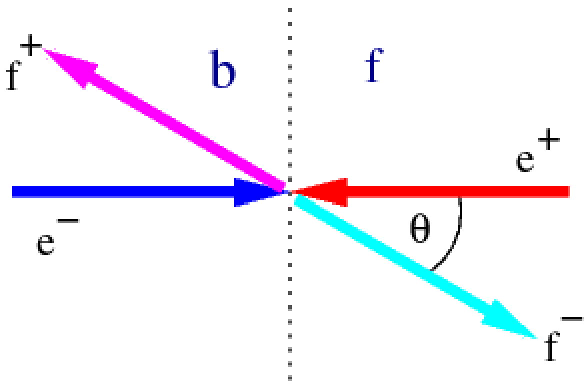
Measurements in $e^+ e^-$ at LEP



LEP 1: measurement of Z boson parameters (16 million Z's)

LEP 2: measurement of W and Z boson pair production, W boson Parameters (40'000 W pairs)

Measurements: differential cross section



total cross section

$$\sigma_{tot} \equiv \int_{-1}^{1} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

depends on $(1+\cos^2\Theta)$ terms only

Forward-backward asymmetry

$$A_{FB} \equiv \frac{\int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta - \int_{-1}^{0} \frac{d\sigma}{d\cos\theta}\, d\cos\theta}{\sigma_{tot}}$$

depends on $\cos^2\Theta$ terms only

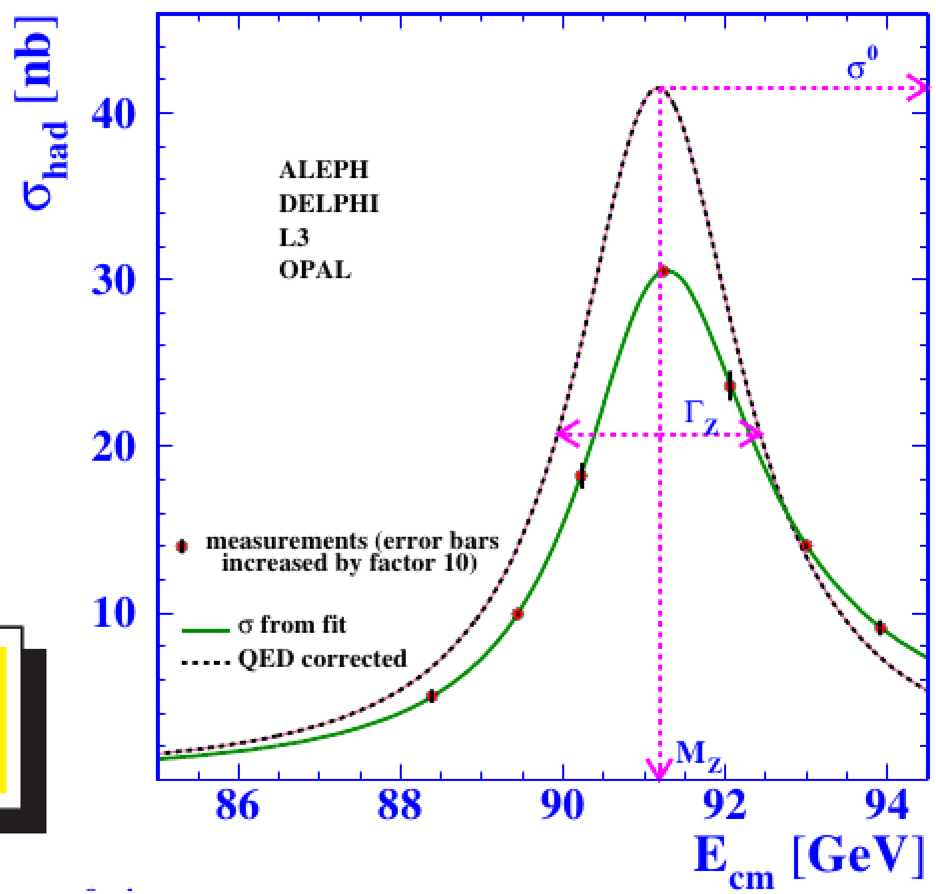
Principle:

Extract combinations of Z-couplings to fermions form measurements of σ_{tot} and A_{FB} in different channels and at different energies

Measurement of cross sections:

- Determine canditate events for signal process
- Subtract background passing selection critetea
- Determine selection efficiency: from Monte- Carlo simulation or using "data-driven" mehtods
- Normalize corrected number of signal events to luminosity

$$\sigma(E_i) = \frac{N_{\bar{f}f}^{\text{cand}}(E_i) - N_{\bar{f}f}^{\text{bkg}}(E_i)}{\varepsilon_{ac}(E_i)} \frac{1}{\int L\,(E_i)},$$



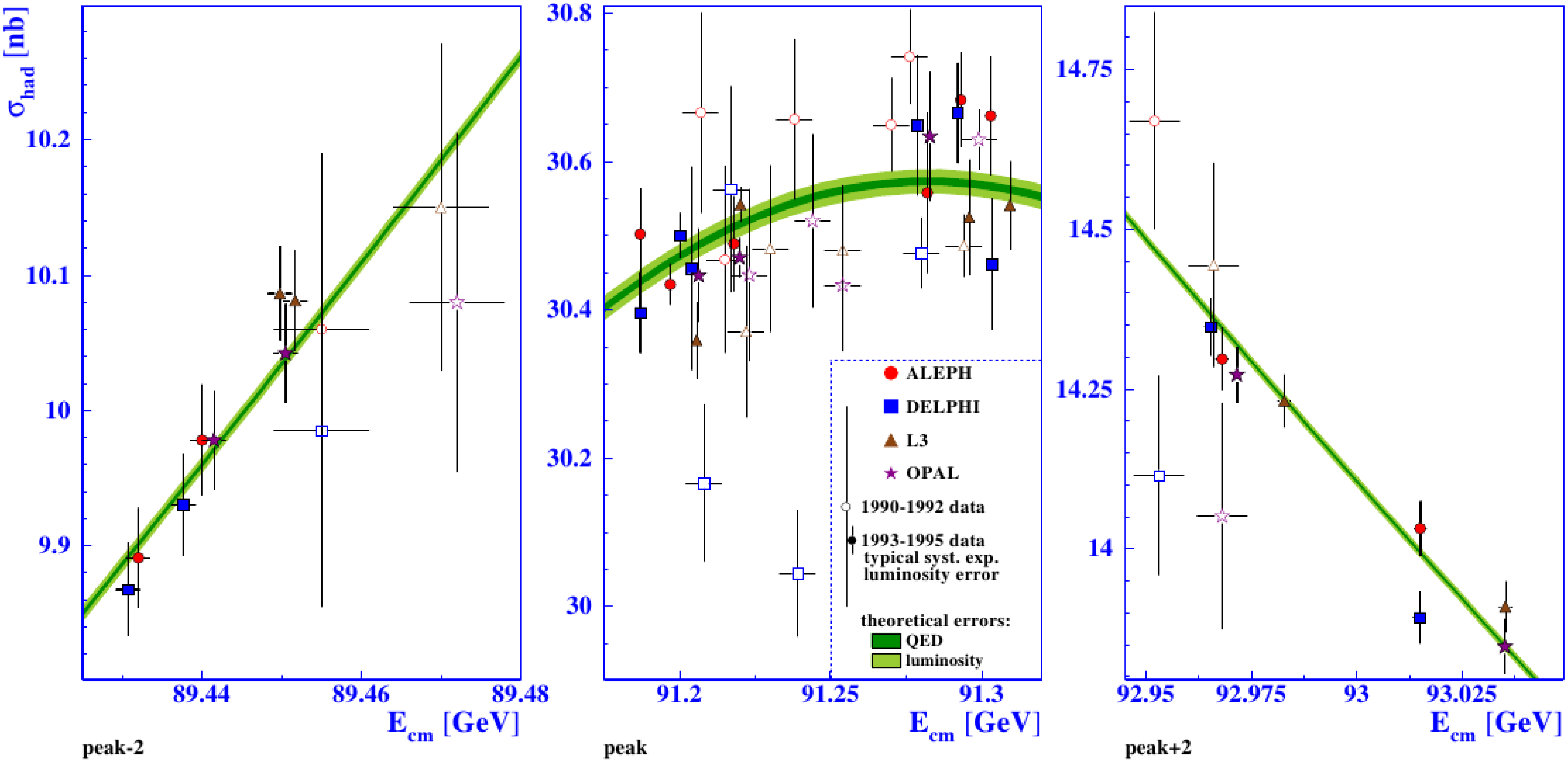
photonic corrections are large, but well known theoretically

Luminosity determination:

count number of events in reference reaction with well-known cross section: $\int L = n_{ref} / \sigma_{ref}$

reference reaction @ LEP: $e^+e^- \rightarrow e^+e^-$ at small angles ("Bhabha scattering")

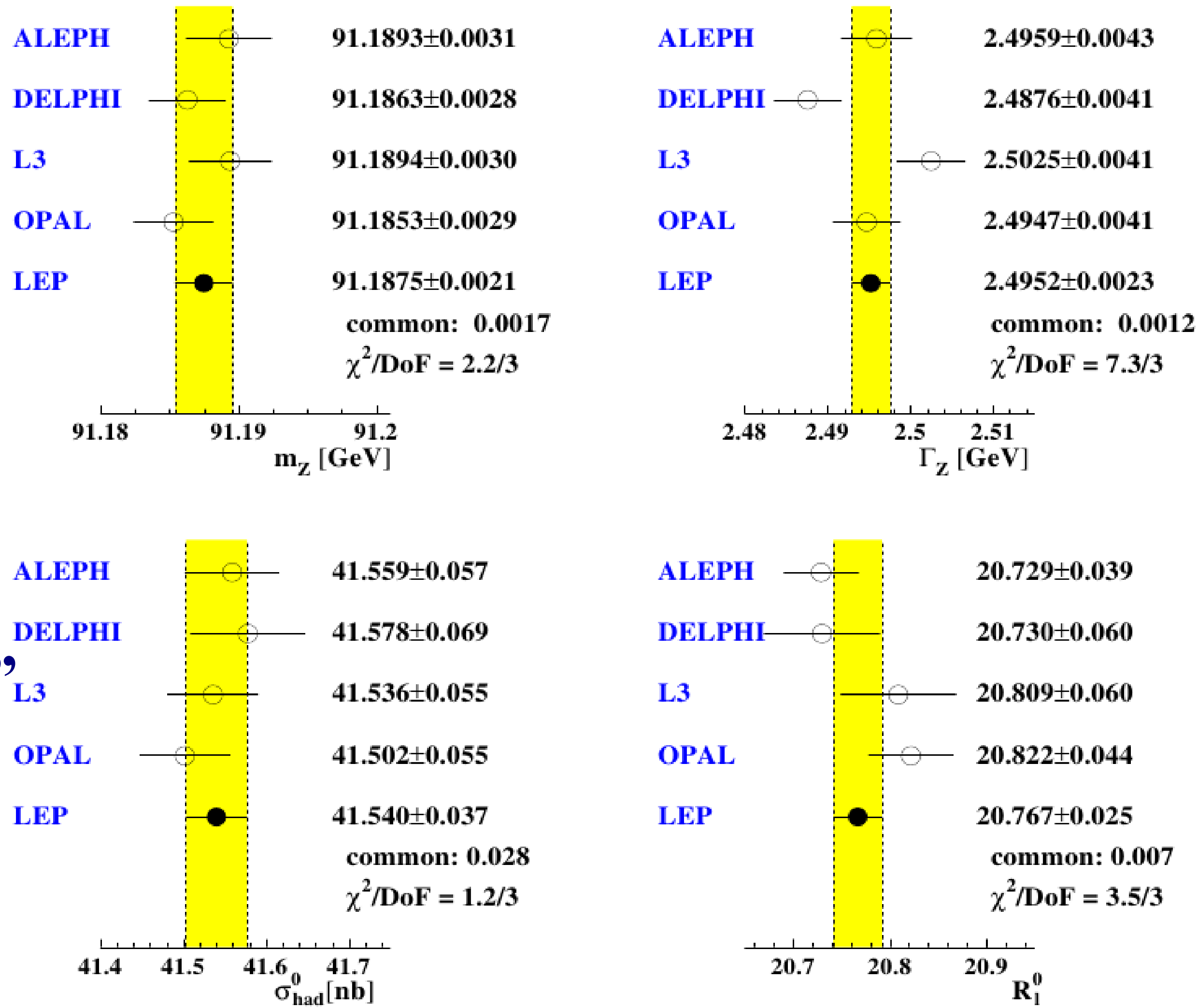
Precision measurements: Z line shape



The challenge: combining more than 800 individual measurements

(different channels, CM-energies and data taking periods)

Precision measurements: Z line shape for leptons and hadrons



Parametrization of cross section using **"pseudo-observables"**

- m_Z
- Γ_Z
- $\sigma^o_{had} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$
- $R_e = \Gamma_{had} / \Gamma_{ee}$
- $R_\mu = \Gamma_{had} / \Gamma_{\mu\mu}$
- $R_\tau = \Gamma_{had} / \Gamma_{\tau\tau}$

partial decay width

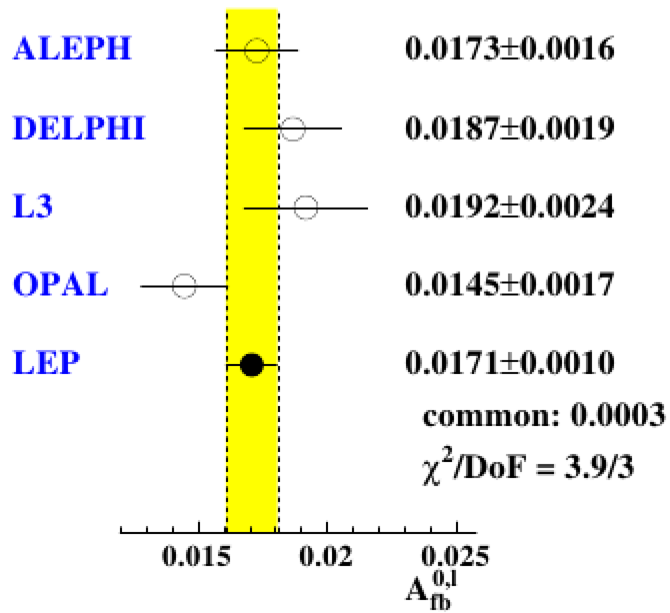
$\Gamma_{ff} \propto \left(g_{Vf}{}^2 + g_{Af}{}^2\right)$ for f=e, μ, τ

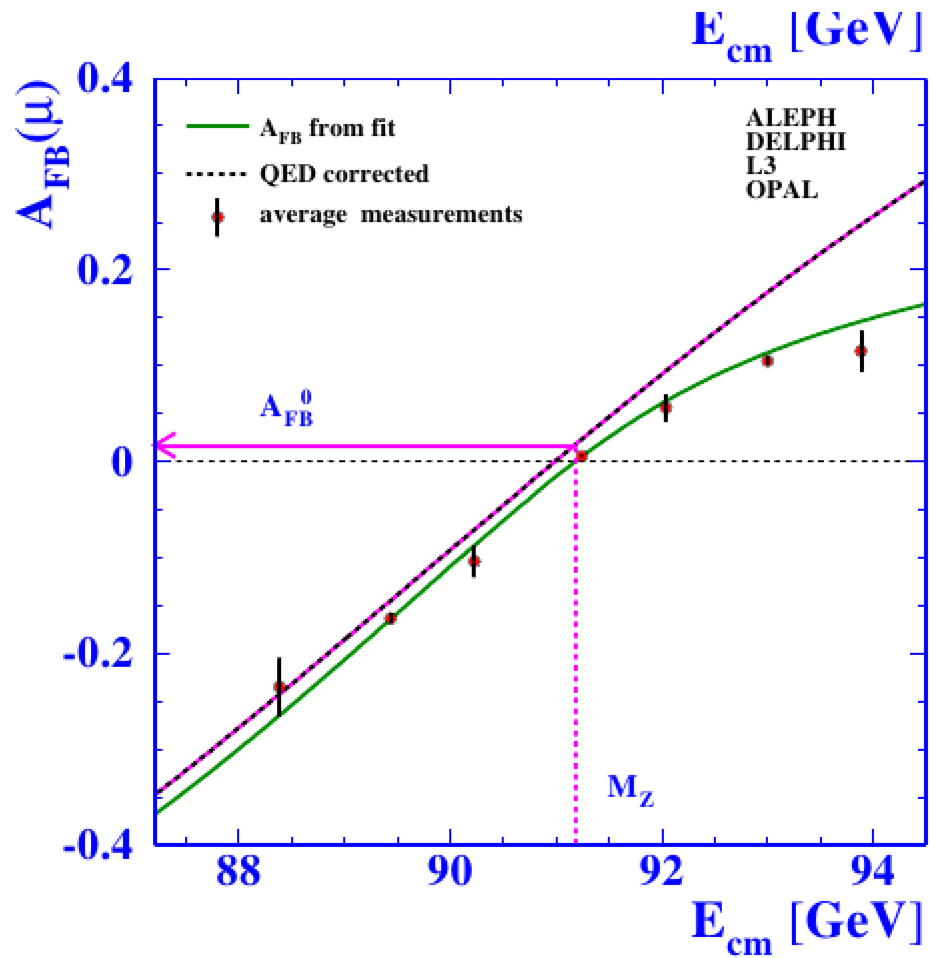
Precision measurements: forward-backward asymmetries of lepton pairs

$$A_{FB} = \frac{N_{forw} - N_{back}}{N_{tot}} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta}{\sigma_{tot}}$$

pseudo-observables:

$$A_{FB}^{0,f} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \quad \text{with} \quad \mathcal{A}_f = \frac{2 g_{Vf}/g_{Af}}{1 + \left(g_{Vf}/g_{Af}\right)^2}$$





More Precision measurements – tau lepton polarisation

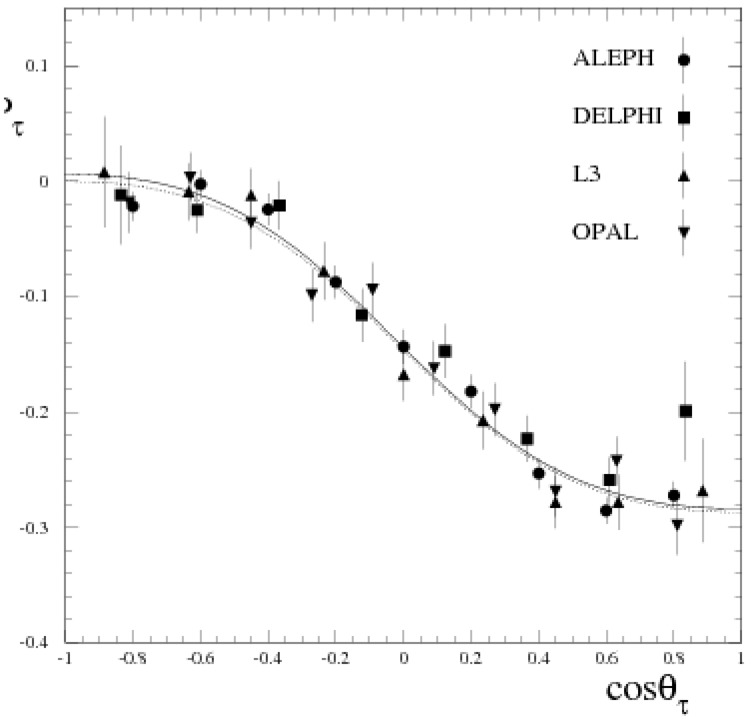
in $e^+e^- \to \tau^+\tau^-$:

Spin in final state can be measured assuming V-A structure in τ decay

average τ polarization depends on e and τ couplings

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

Measured P_τ vs $\cos\theta_\tau$



allows precise measurement of vector and axial vector couplings of τ to Z !

More Precision measurements – with polarized e-beam

Measurements at SLAC linear collider:

polarized e^- colliding with unpolarized **e^+** at $\sqrt{s}=M_Z$

measurements analogous to LEP, but

can determine σ and A_{FB} for left- and right-handed e^-

observables at SLAC:

$$A_{LR} = \frac{1}{\mathcal{P}_e}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto \mathcal{A}_e$$

$$A_{fb,LR} = \frac{1}{\mathcal{P}_e}\left(A_{fb,L} - A_{fb,R}\right) \propto \mathcal{A}_f$$

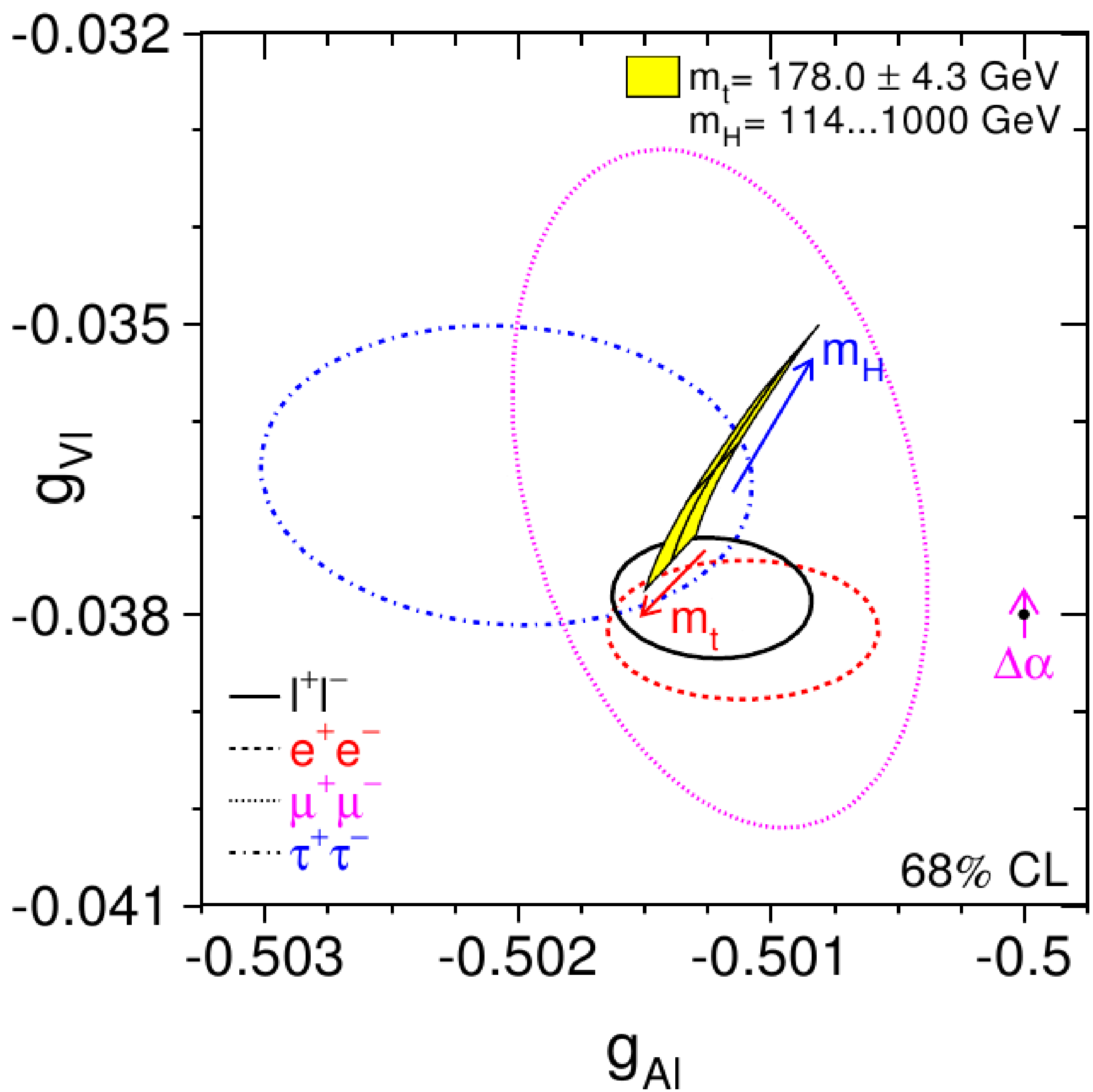
A_{LR} is most sensitive single measurement to $\sin^2\theta_W^{eff}$

Determination of lepton couplings to Z boson

Combination of previously shown measurements gives most precise values of lepton couplings.

Consistent with "lepton universality" → combine all into leptonic g_V and g_A

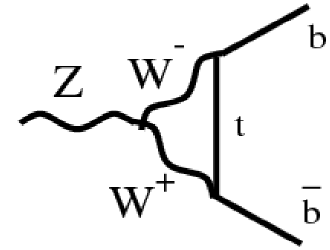
Measurements are sensitive to top and Higgs boson masses

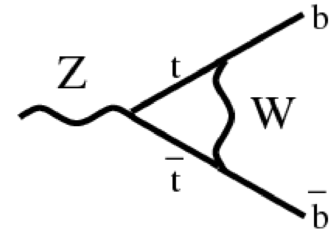


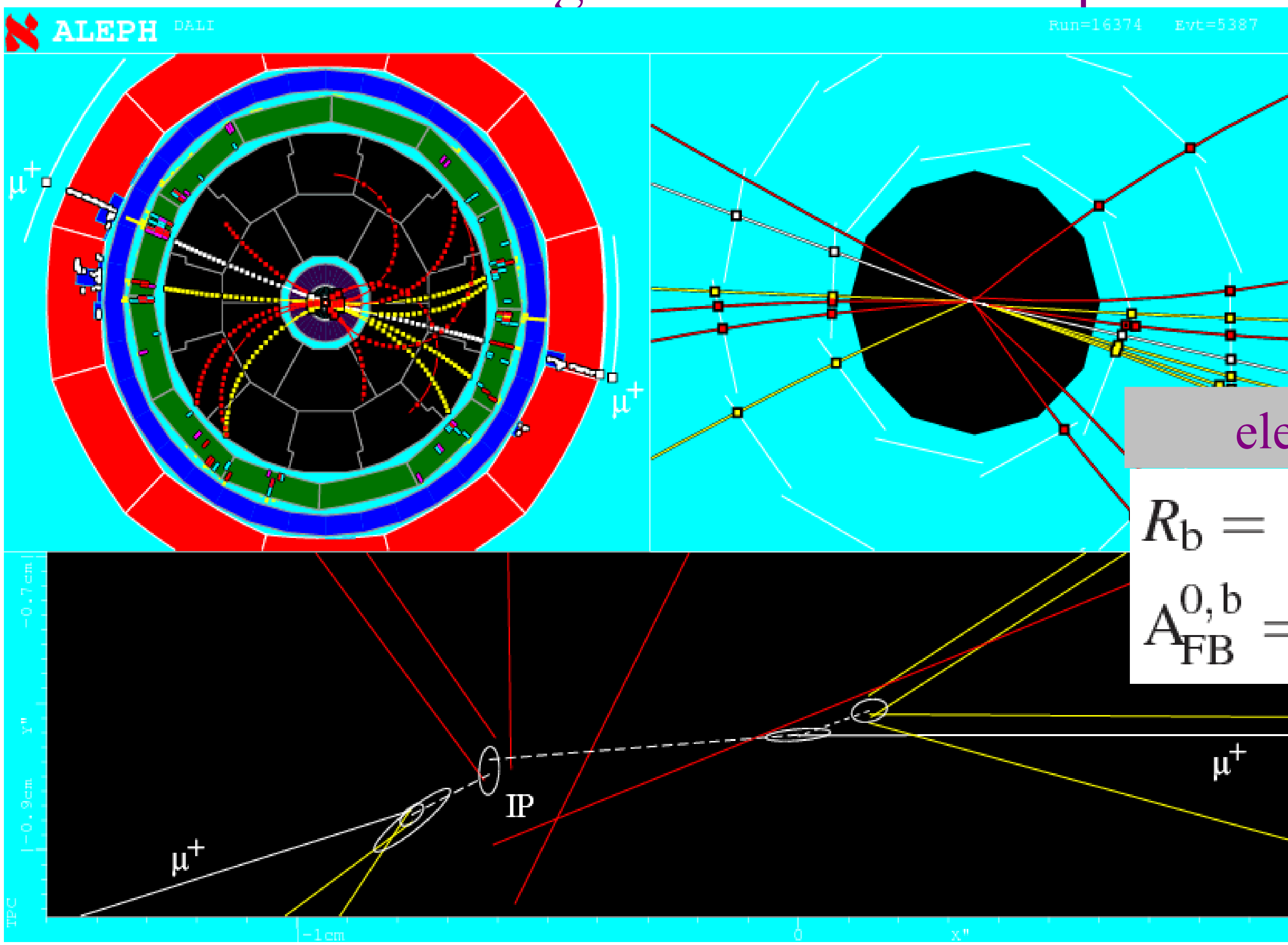
More Precision measurements – heavy quarks

b-quarks – are (relatively) long-lived
– are heavy
– decay in cascades → can be distinguished from other quarks

special relation to top quark:







electroweak observables

$$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} \Rightarrow \rho_b$$

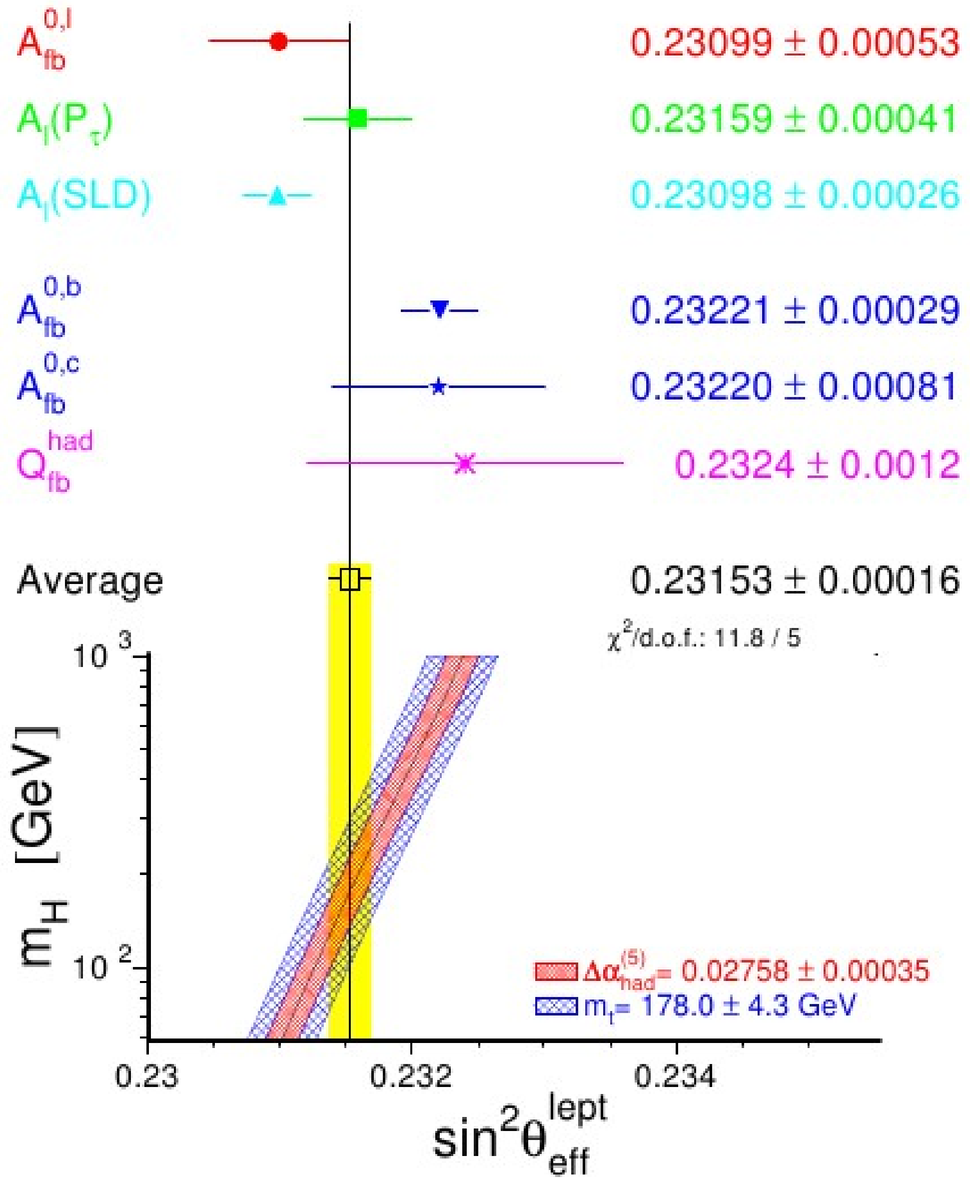
$$A_{FB}^{0,b} = \frac{4}{3}\mathcal{A}_e\mathcal{A}_b \Rightarrow \sin^2\theta_{eff}^{lept}$$

Summary of asymmetry-type measurements

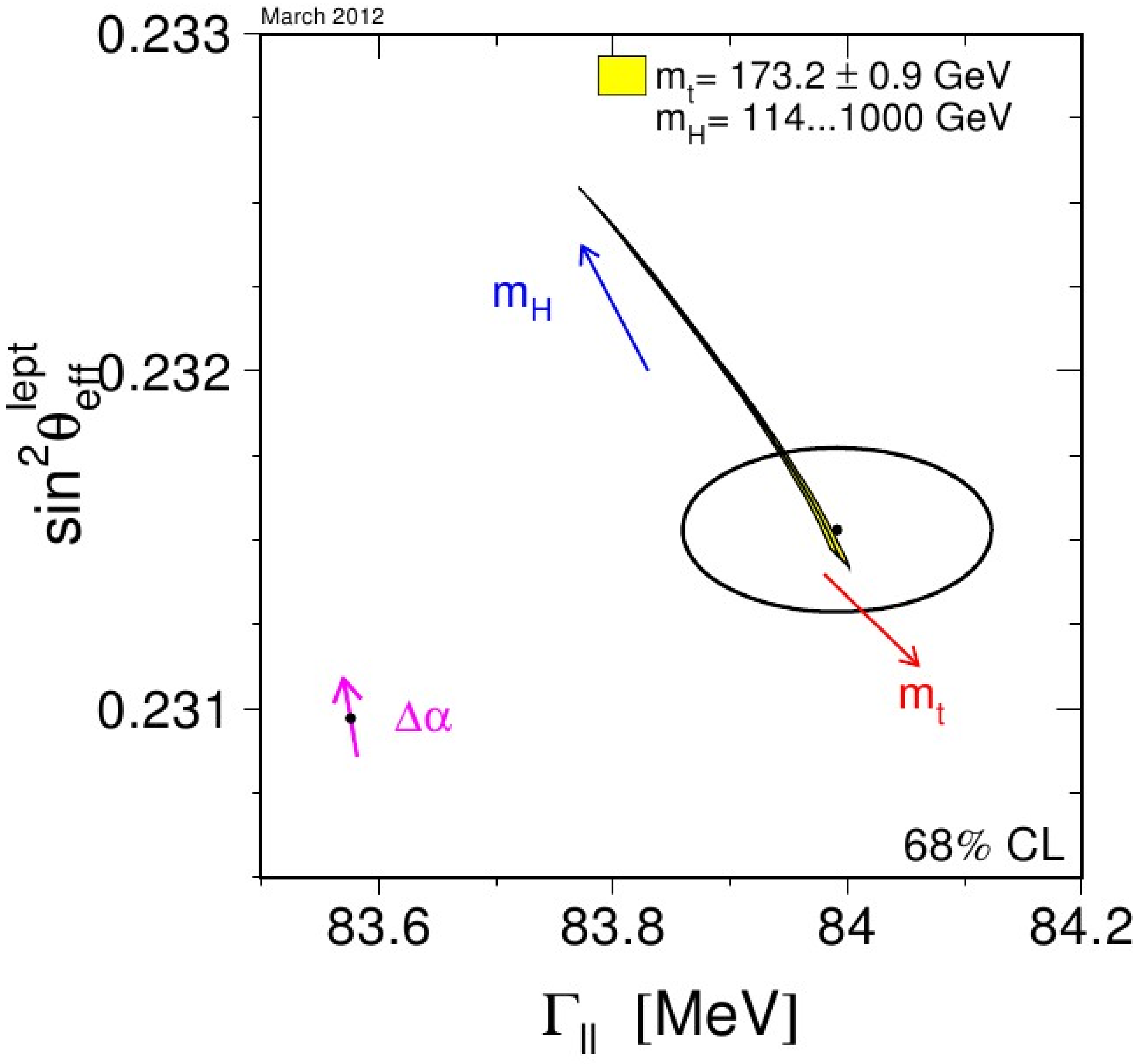
Asymmetry-type measurements depend on vector and axial vector couplings, g_V and g_A, and hence on **$\sin^2\theta_W^{eff}$**

Average of $\sin^2\theta_W^{eff}$ very sensitive to Higgs mass

There is, however, some "tension" between the most precise measurements !

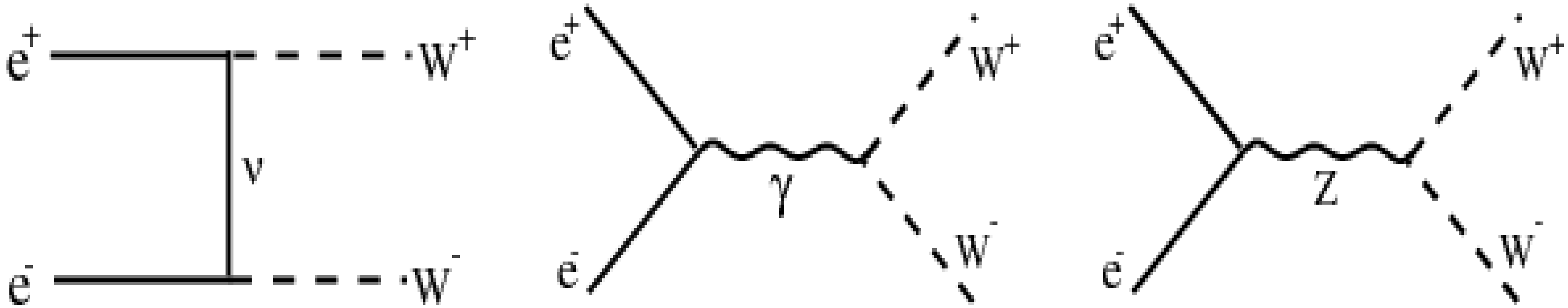


Combination of precision measurements: Γ_{lept} and $\sin^2\theta_W{}^{eff}$



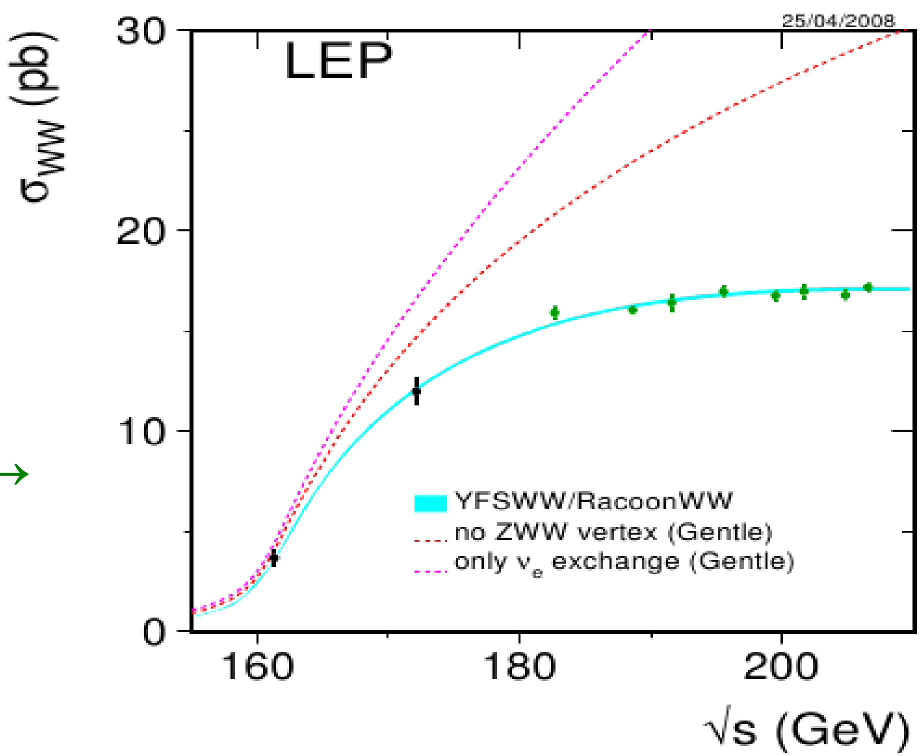
Γ_{lept} and $\sin^2\theta_W{}^{eff}$ together provide strong constraint on Higgs mass !

W pair production at LEP II



$e^+e^- \rightarrow W^+W^-$ cross section in EW theory remains finite only if photon, Z and neutrino exchange are all taken into account -

experimentally well confirmed →



Remark: there is also a Higgs diagram, but negligible in e^+e^- !

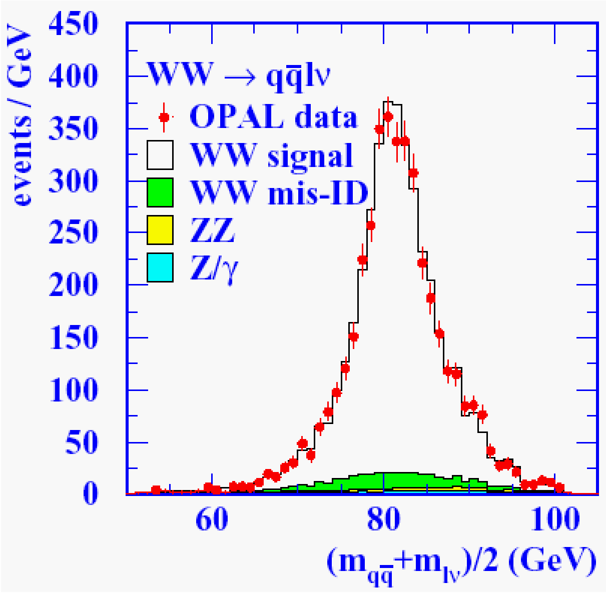
W Boson mass

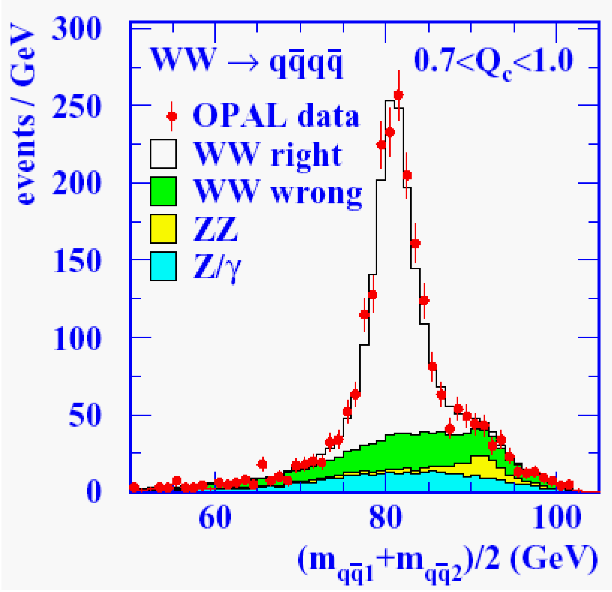
W-Boson mass

from reconstructed objects in detectors by LEP experiments ALEPH, DELPHI, L3 and OPAL and by Tevatron experiments CDF & D0

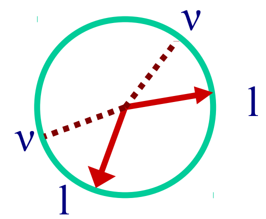
(LHC not yet ...)

very difficult, dominated by systematic errors

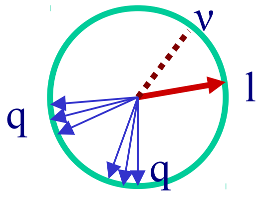




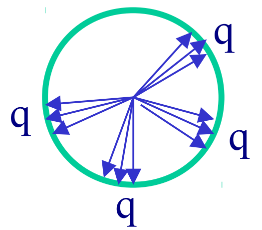
@LEP: W pair events:



BR ~ 10%

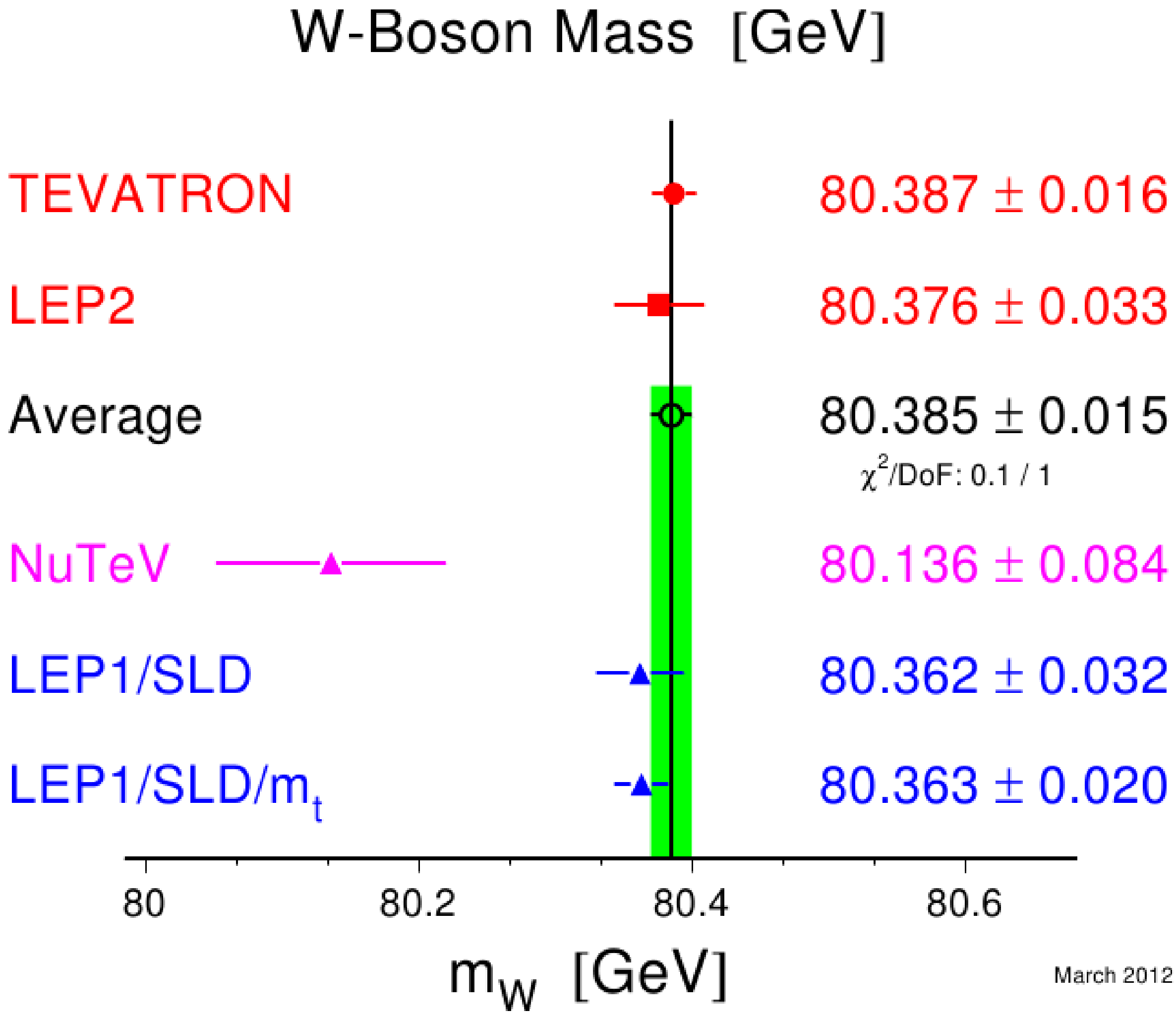


BR ~ 44%



BR ~ 46%

W Boson mass – world average 2012



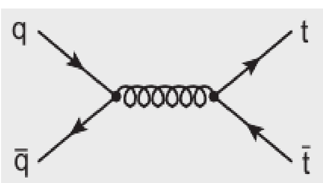
Remember: Relevance of W mass: determines on-shell weak angle

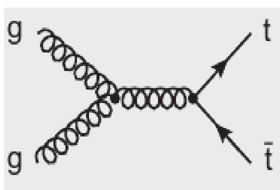
One more ingredient: need the top quark mass

top quark mass

measured from reconstructed objects in detectors by Tevatron experiments CDF & D0 (LHC on the way ...)

– top quarks (mostly) produced in pairs via $q\bar{q}$ or gg





– dominant decay:

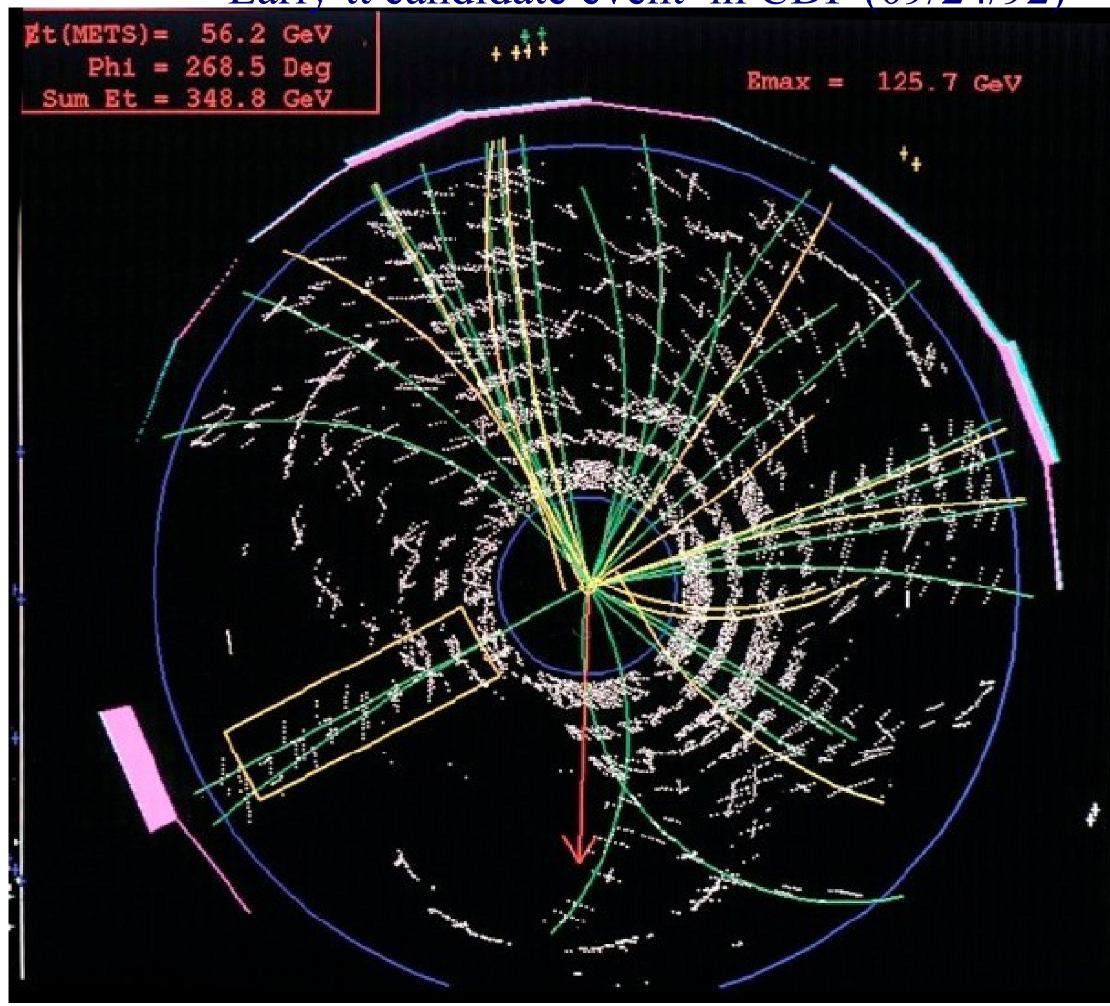
$t \rightarrow b + W^+$

$W \rightarrow q\bar{q}'$ or $l\nu$

signatures studied:

- fully hadronic
- lepton + jets
- di-lepton

Early $t\bar{t}$ candidate event in CDF (09/24/92)



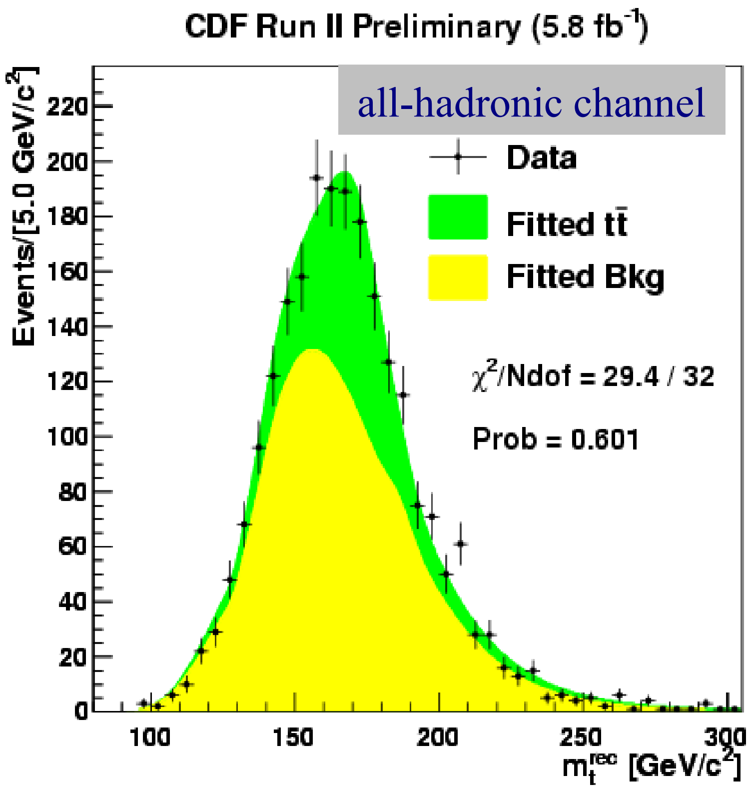
Signature: "lepton +jets"

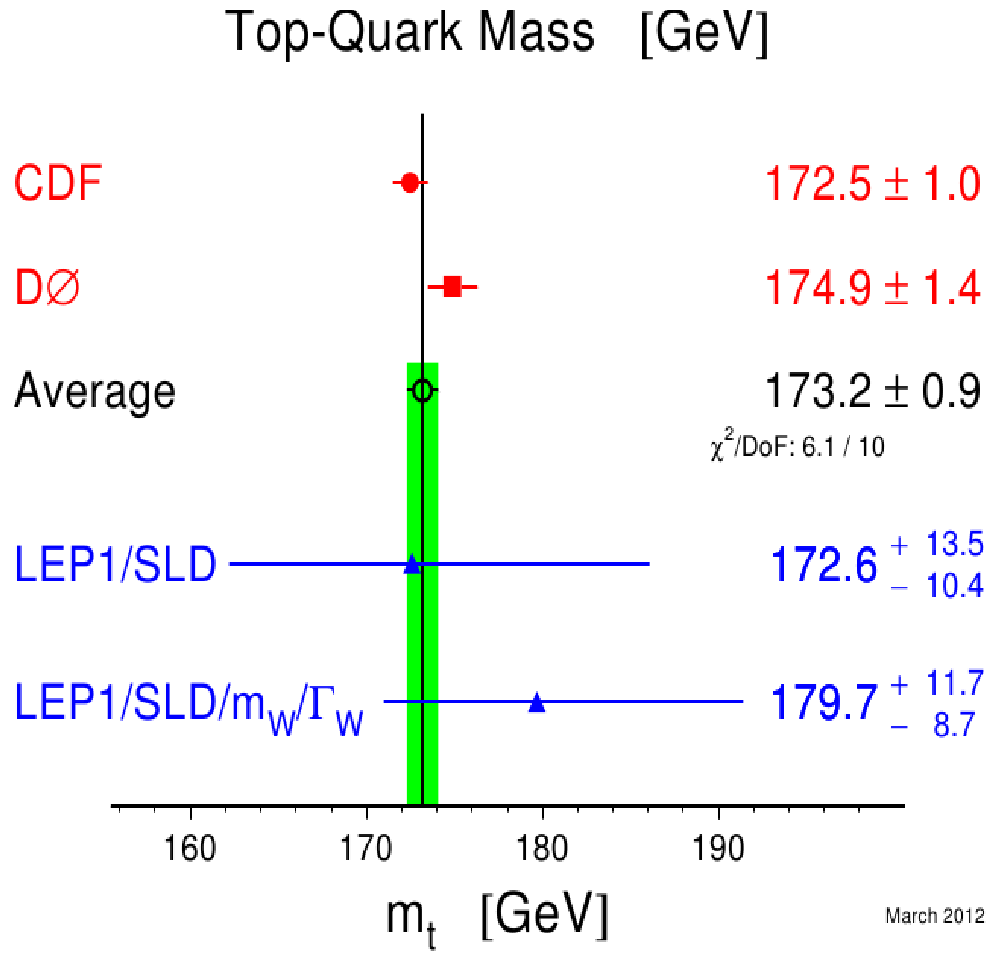
– 1 lepton – four jets

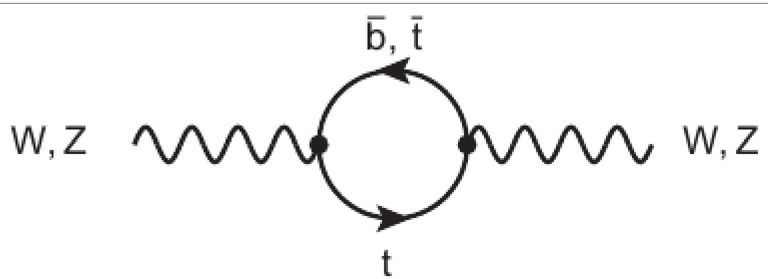
– missing transverse energy

One more ingredient: top quark mass

Example of observed mass distribution:







Remember: dominant radiative corrections arise from top ($\sim G_F m_t^2$) !

Top quark mass from loop corrections ...

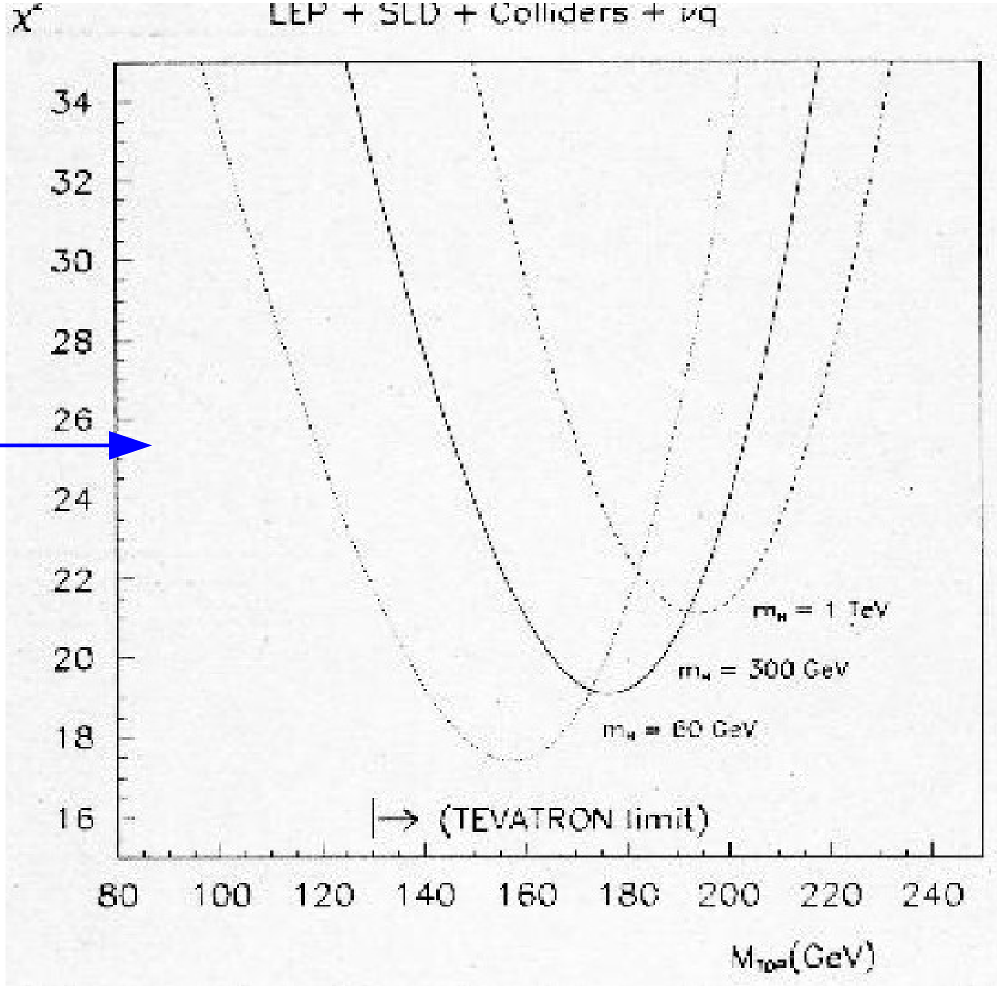
… at Moriond conference
in March 1994:

direct search for top at Tevatron:

$m_{\mathrm{t}} > 130\,\mathrm{GeV}/c^2$

from **radiative corrections**:

$m_{\mathrm{t}} = 177 \pm 11\,{}^{+18}_{-19}{}_{\mathrm{Higgs}}\,\mathrm{GeV}/c^2$



a little later in summer, direct **observation** of top quark (CDF):

$m_{\mathrm{t}} = 174 \pm 10\,{}^{+13}_{-12}{}_{\mathrm{syst}}\,\mathrm{GeV}/c^2$

Excellent agreement between
top from loops and from direct measurement!

M_H from individual precision measurements

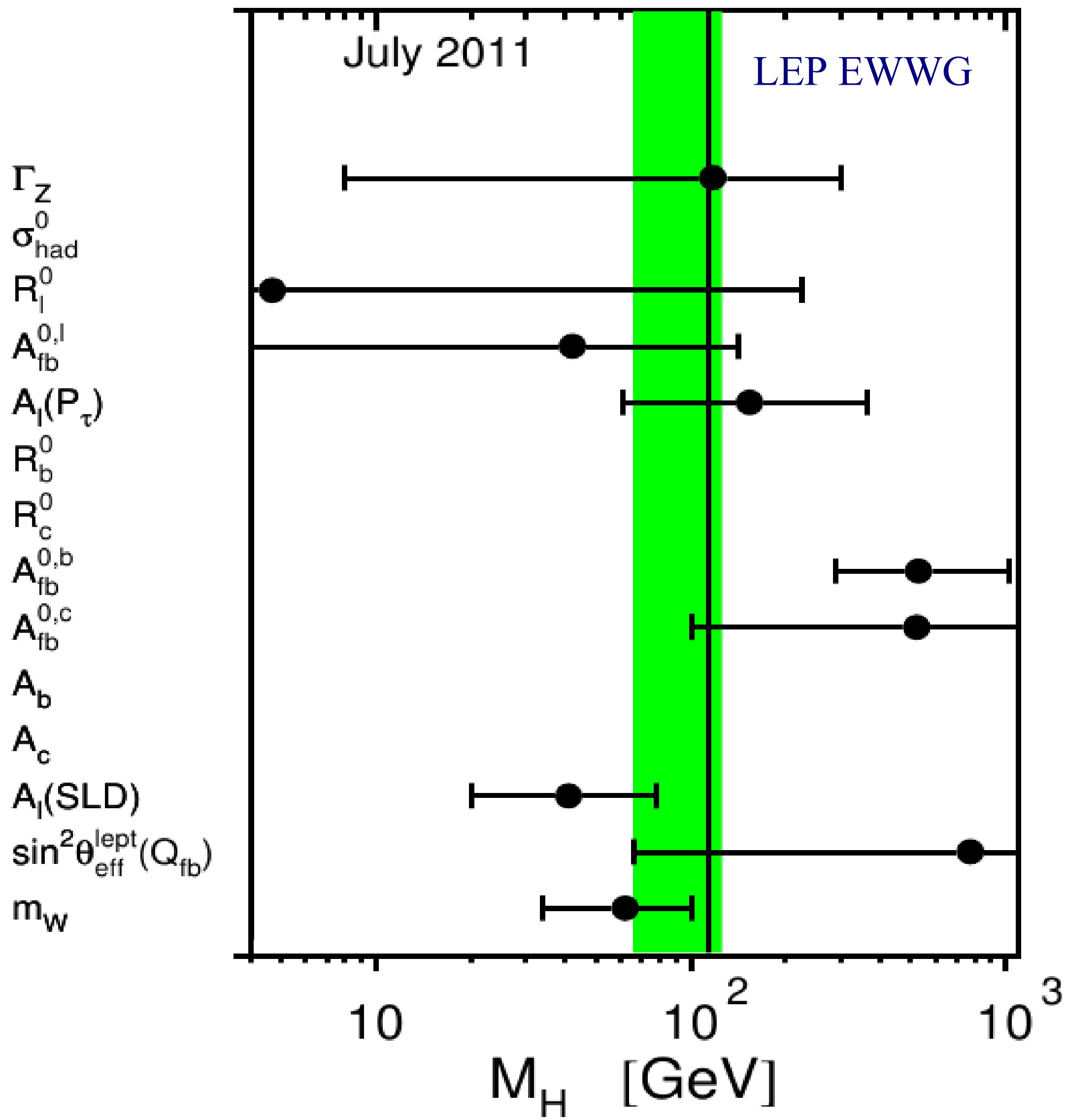
With known top mass, can now disentangle radiative effects from top and Higgs

(provided nothing else is in the loops …)

→

M_H from precision measurements

with large errors



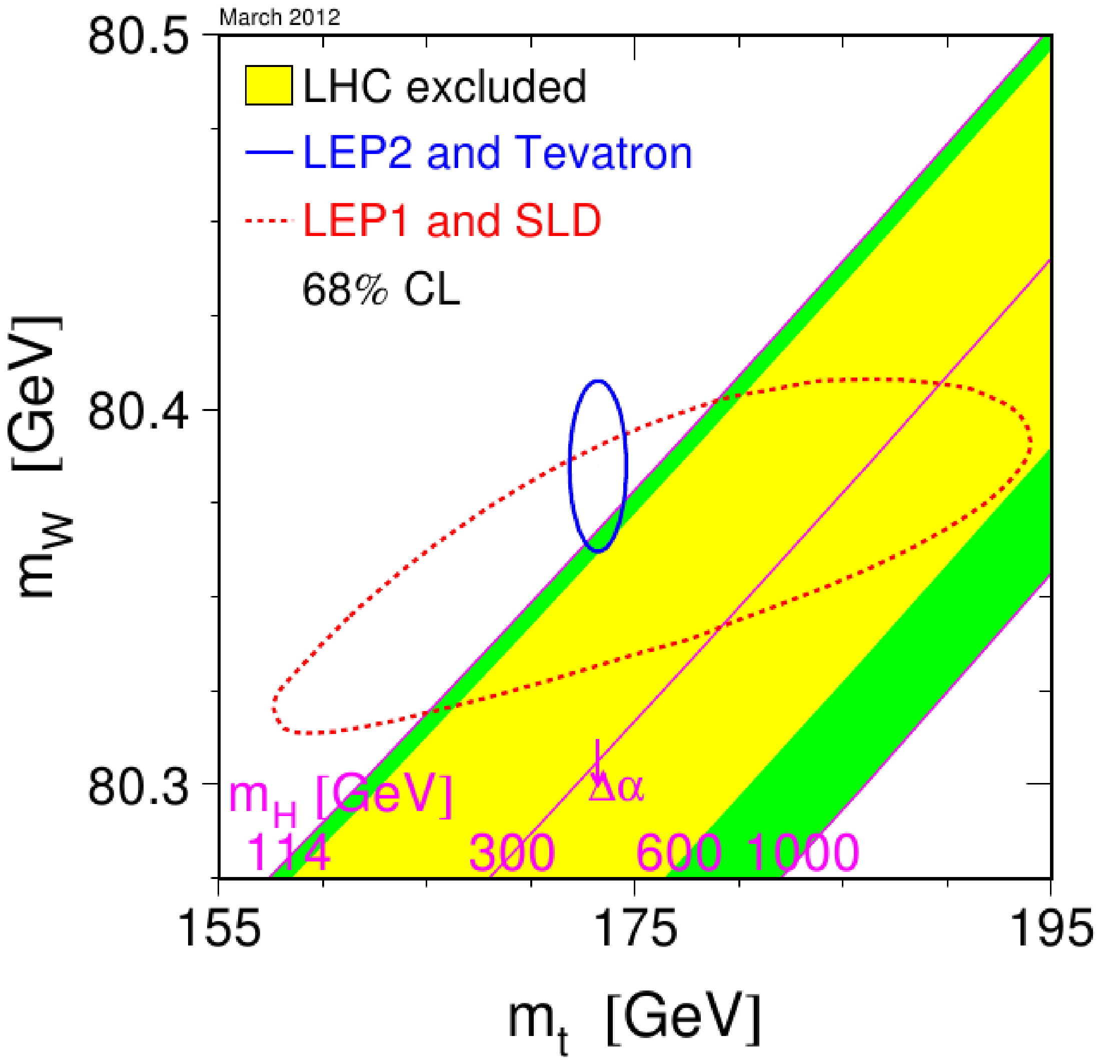
Putting it all together ….

... in a rather complicated plot:

top quark vs. W boson mass

1. direct measurements
2. indirect determination from precision variables: $O := O(\alpha, G_F, M_Z, m_t, M_H)$ solved numerically ("Newton's method) for m_t and M_H (using SM)
3. W mass predicted for different values of M_H

nice consistency check, prefers low value for Higgs mass !



Putting it all together ….

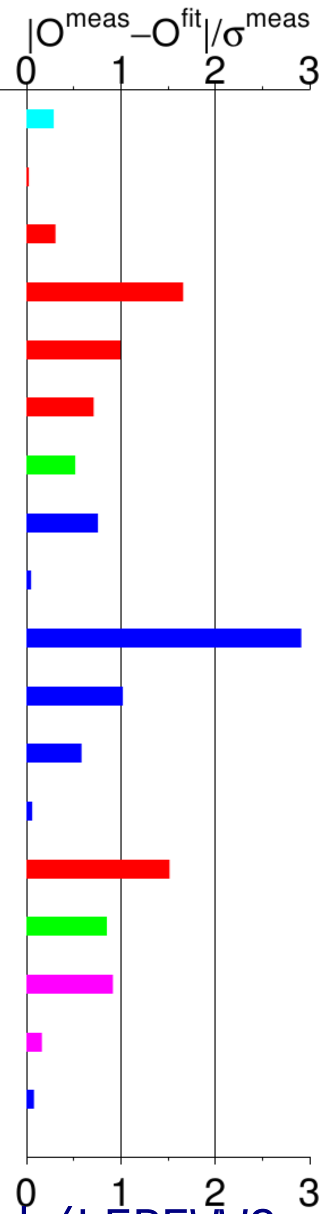
… in an overall fit

of Higgs boson mass within the minimal Standard Model

"pull plot" and overall value of χ^2 to identify potential problems

good overall consistency, but there is one "outlier"; the measurement of the b-quark forward backward asymmetry.

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
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	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



July 2011

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

Putting it all together ….

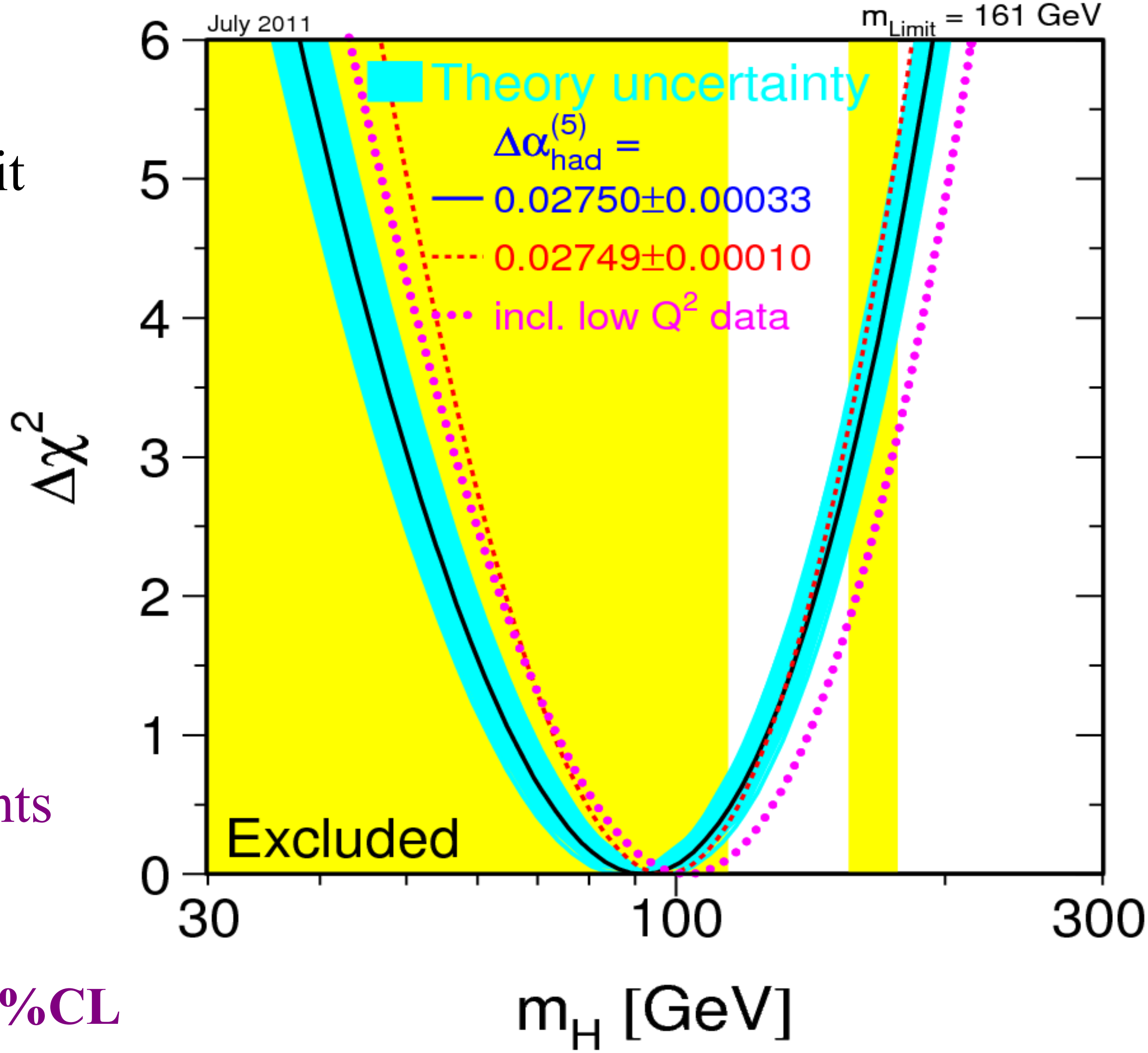
… profiled χ^2

for M_H from overall fit within the minimal Standard Model

"Blue Band Plot"

Precision measurements predict mSM Higgs boson to be light,

M_H <161GeV/c^2@95%CL



Loops affect theory itself

Conclusions on results from precision measurements

Standard Model established as a renormalizable field theory:

– in agreement with (almost) all experimental results, prec. ~0.1%

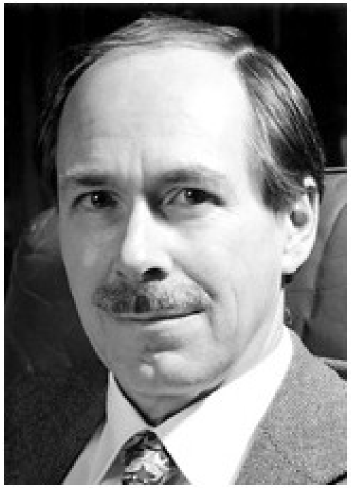
– quantum corrections seen and well established

– indirect determination of top quark mass

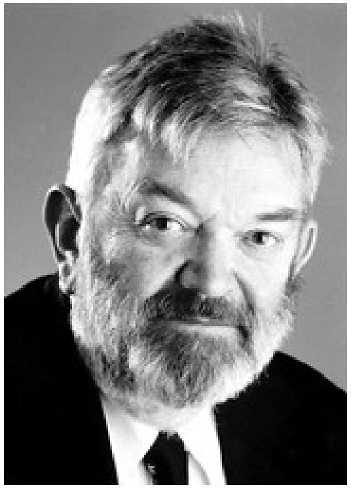
– triple gauge boson couplings confirmed with prec. 1%

– precision measurement constrain Higgs to be light

Theoretical work on proof of renormalizability awarded with Nobel prize in 1999



Gerardus 't Hooft



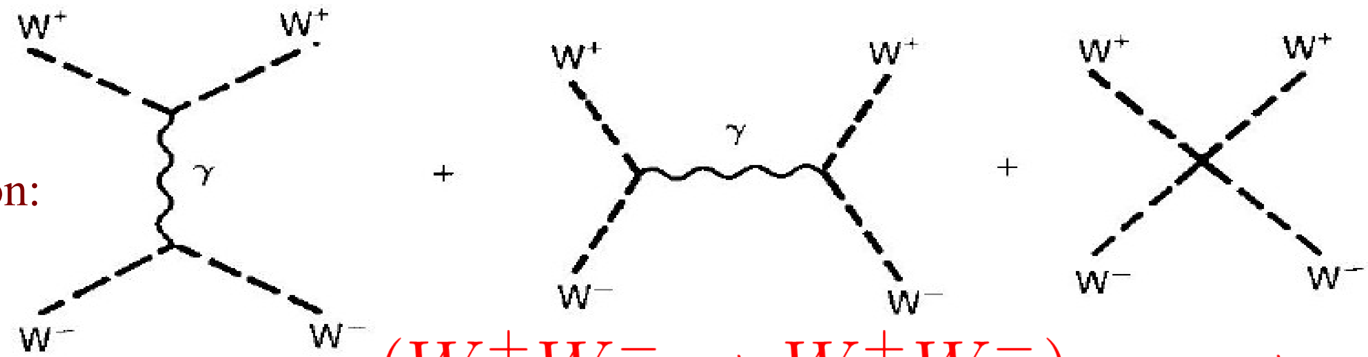
Martinus J.G. Veltman

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*

Theoretical constraints on Higgs boson mass

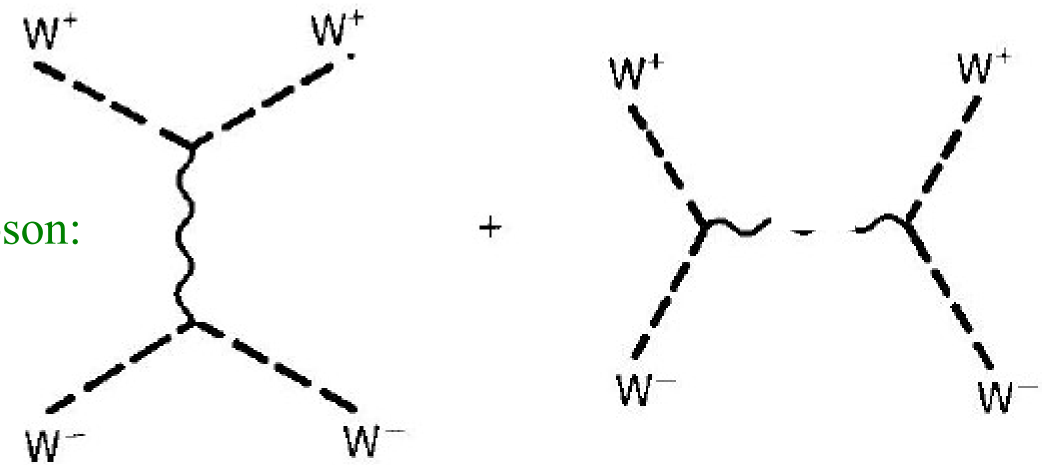
Diagrams with Higgs-Boson prevent divergencies:

Without Higgs boson:



$$\sigma(W^+W^- \rightarrow W^+W^-) \propto s \rightarrow \infty$$

additonal diagrams involving Higgs boson:

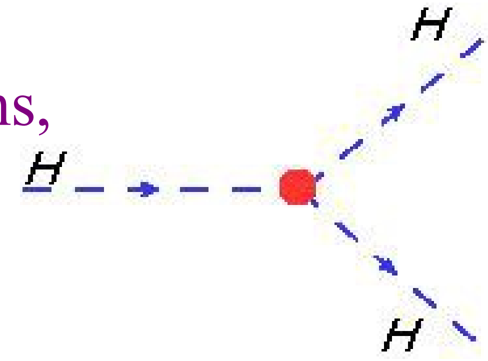


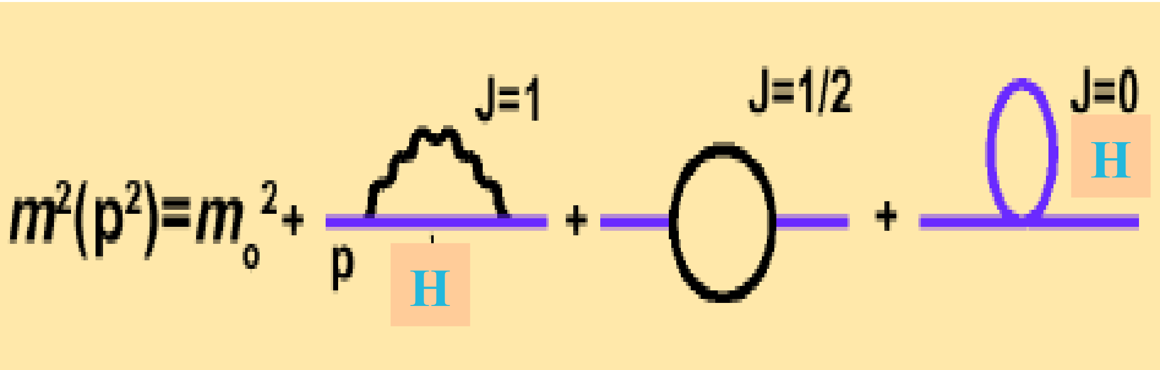
Cross section for WW scattering remains finite

Higgs must not be too heavy:: $< \sim 1$ TeV/c²

Theoretical constraints M_H loop corrections

Higgs propagator affeced by higher order corrections,
in particular from Higgs self couplings





Higgs in loops couples to itself with strength proportional to Higgs mass →
large corrections to Higgs mass and Higgs potential

– high Higgs mass: Higgs self-coupling becomes strongly interacting, breakdown of perturbation theory

– small Higgs mass: Higgs self-coupling becomes negative → unstable vacuum (in contradiction to age of universe)

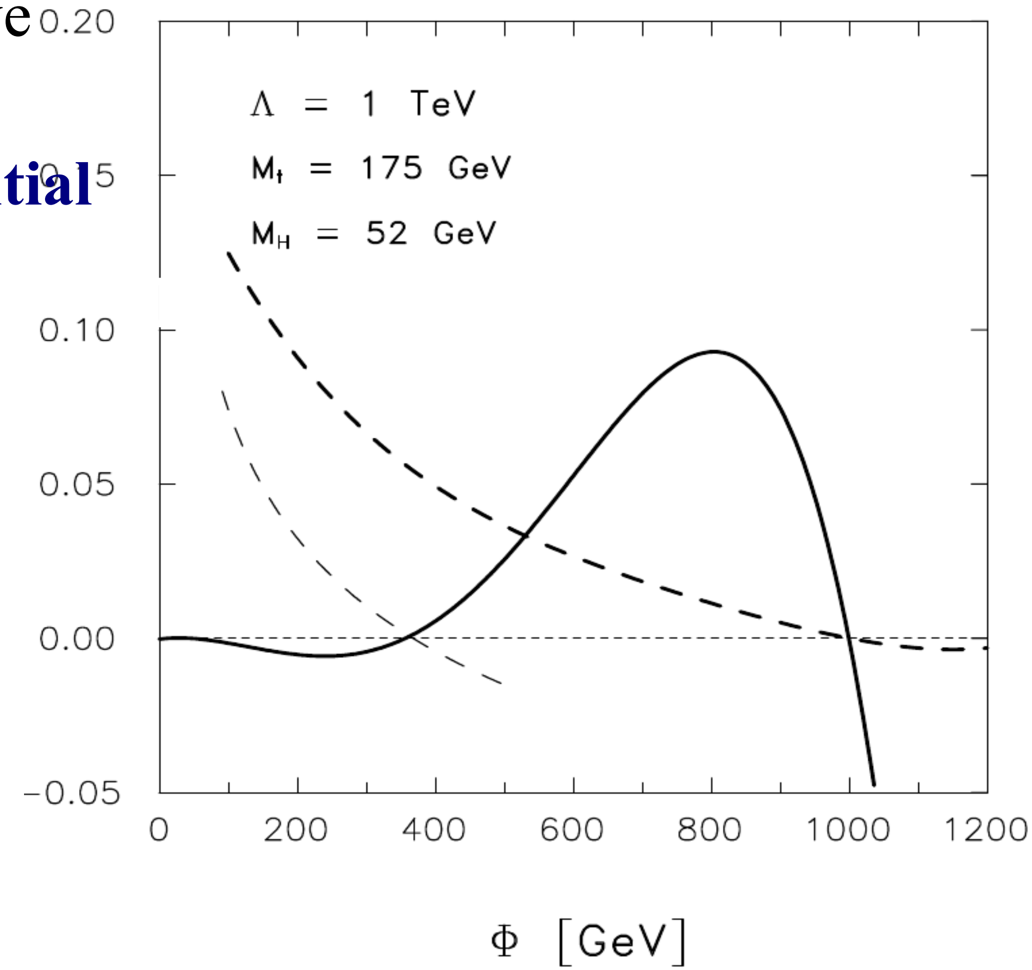
Theoretical constraints on M_H – vacuum stability

Example of renormalized Higgs Potential
Casas, Espinosa, Quiros (1996)

Loops (in particular top) drive quartic coupling negative above some scale Λ for small M_H

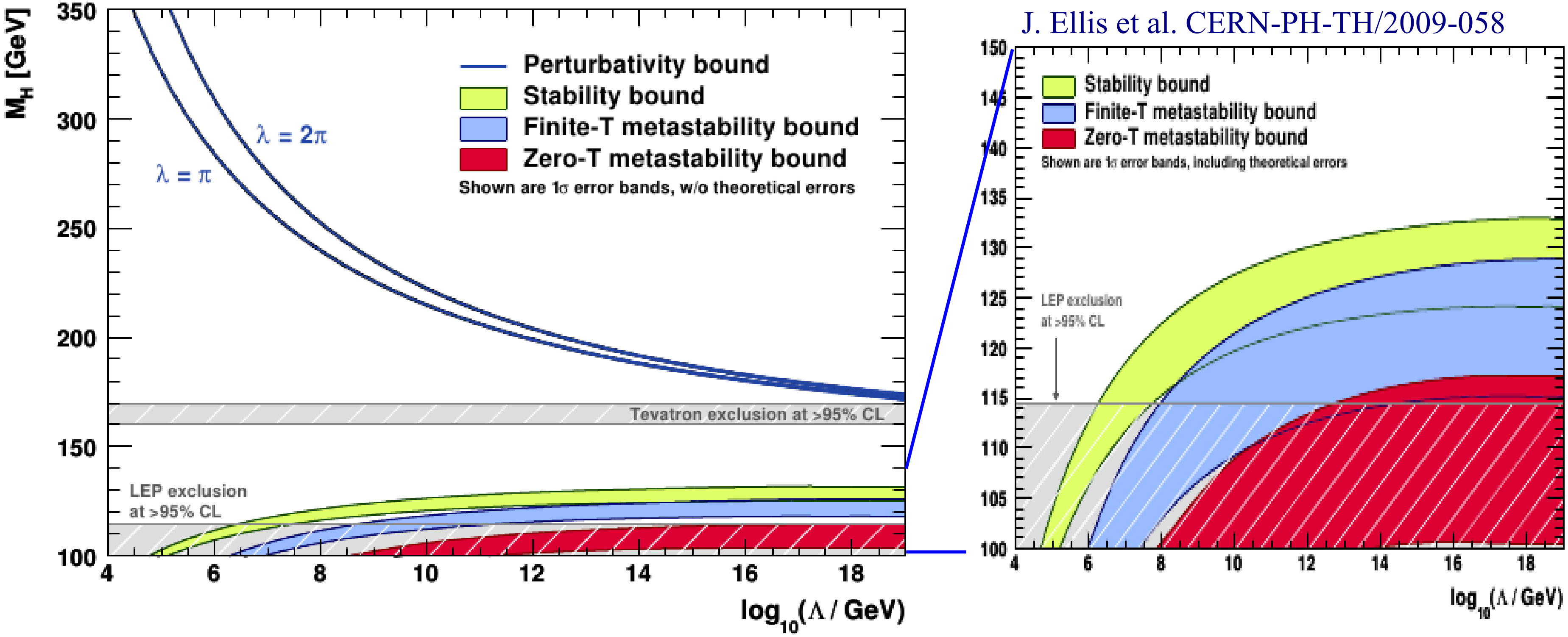
→ renormalized **Higgs potential** is either unbounded (inconsistent with the existence of the universe)

or in local minimum "false vacuum", (assume tunneling time > 14 billion years to derive limit on M_H)



Theoretical constraints on M_H – vacuum stability

→ beyond **energy scale Λ** new Physics must be present



→ **corridor of allowed values of Higgs mass within Standard Model**

Final remarks

We know that the Standard Model is incomplete:

– no candidate for dark matter

(would have to be heavy, stable and only weakly interacting)

– no explanation of "dark energy"

– inclusion of gravity causes problems

(Why are Higgs mass and Boson masses so "small" compared to the relevant scale, the Planck mass?)

There must be new physics, even if the Higgs boson will be found one day at a mass making the Standard Model self-consistent).

Summary:

Standard Model looks fine and gauge couplings
and Higgs mechanism appear to work,
although the model is clearly incomplete.

To be done:

– discovery of Higgs boson
– determination of Yukwa couplings to fermions
– test Higgs potential via measurement of Higgs self couplings

Will the model show inconsistencies and thus
point to way to extend it, or will it remain to
be a self-consistent theory for the part of reality
it describes ?